Muon Collider

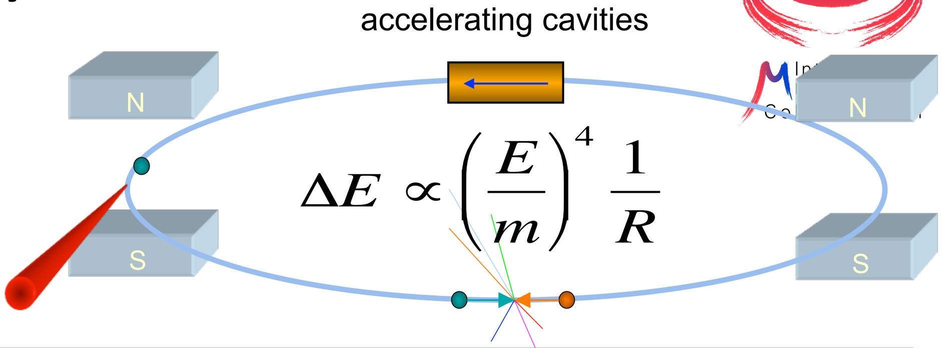
D. Schulte for the International Muon Collider Collaboration

eeFact
September 2022

High-energy Colliders

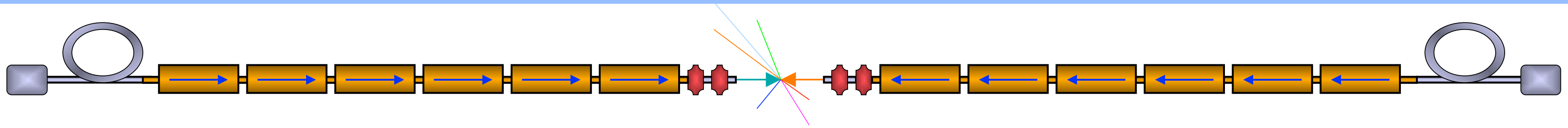
Electron-positron rings are **multi-pass** colliders limited by synchrotron radiation: **LEP, FCC-ee, CEPC**

Hence **proton rings** are energy frontier: **LHC, FCC-hh, SppC**



$$\Delta E \propto \left(\frac{E}{m}\right)^4 \frac{1}{R}$$

Electron-positron linear colliders avoid synchrotron radiation, but **single pass: SLC, ILC, CLIC**
Typically cost proportional to energy and power proportional to luminosity,



Novel approach: **muon collider** (the first of its kind)
Large mass suppresses synchrotron radiation => **multi-pass**
Fundamental particle requires less energy than protons
But lifetime at rest only 2.2 μs
Proportional to energy

Motivation and Goal

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

New strong interest:

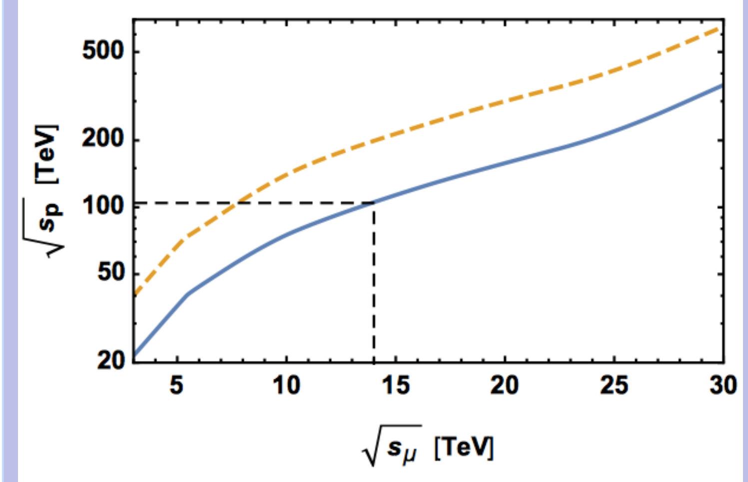
- Focus on **high energy** with **high luminosity**
  - 10+ TeV
  - potential initial energy stage (e.g. 3 TeV)
- **Technology** and **design advances**

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

Luminosity goal
(Similar to L(E_{CM} > 0.99 $E_{CM,0}$) CLIC at 3 TeV)
4×10^{35} cm^{-2}s^{-1} at 14 TeV

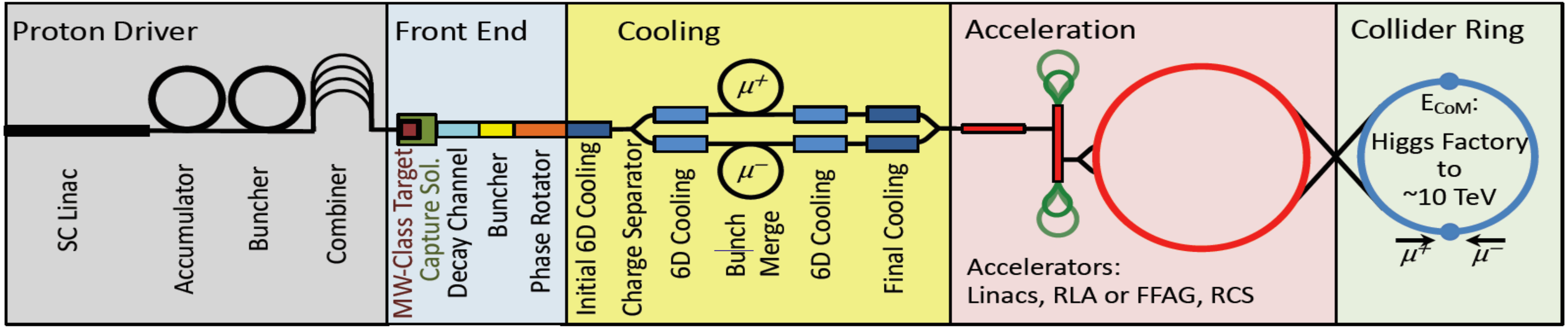
$$L \gtrsim \frac{5\,\text{years}}{\text{time}} \left(\frac{\sqrt{s_\mu}}{10\,\text{TeV}} \right)^2 2 \cdot 10^{35} \text{cm}^{-2}\text{s}^{-1}$$

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

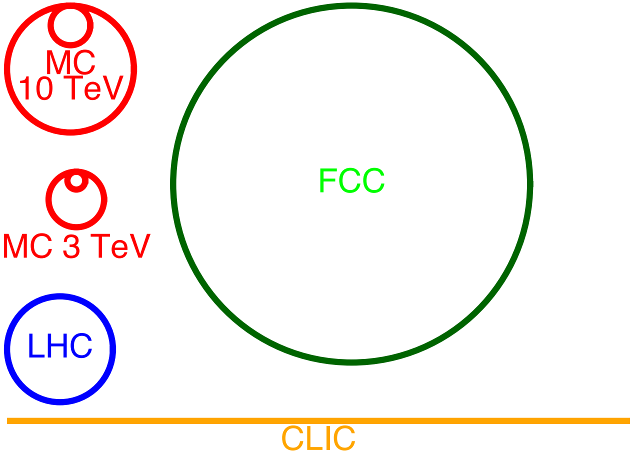
Protons produce pions which decay into muons
muons are captured

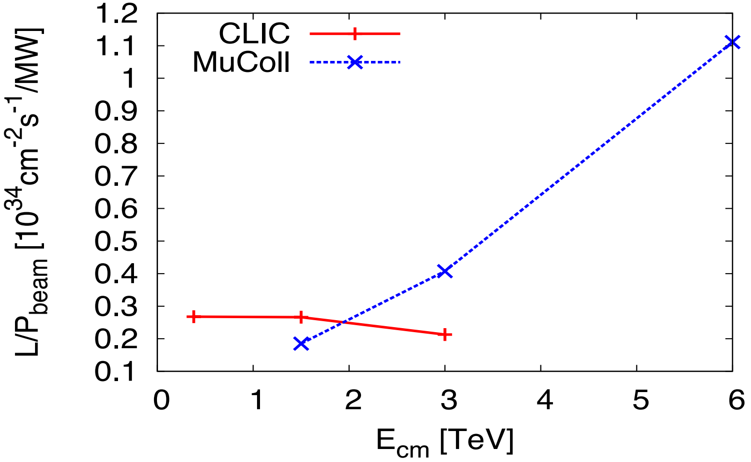
Ionisation cooling of muon in matter

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**

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	

Accelerator R&D Roadmap

International MUON Collider Collaboration

On CERN Council request Laboratory Directors Group developed
Accelerator R&D Roadmap

- global community participated, a **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;

Allows to make **informed decisions**

Council asked for implementation plan

- **do not yet have the resources of the reduced scenario**

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

http://arxiv.org/abs/2201.07895

Label	Begin	End	Description	Aspirational [FTEy]	Aspirational [kCHF]	Minimal [FTEy]	Minimal [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

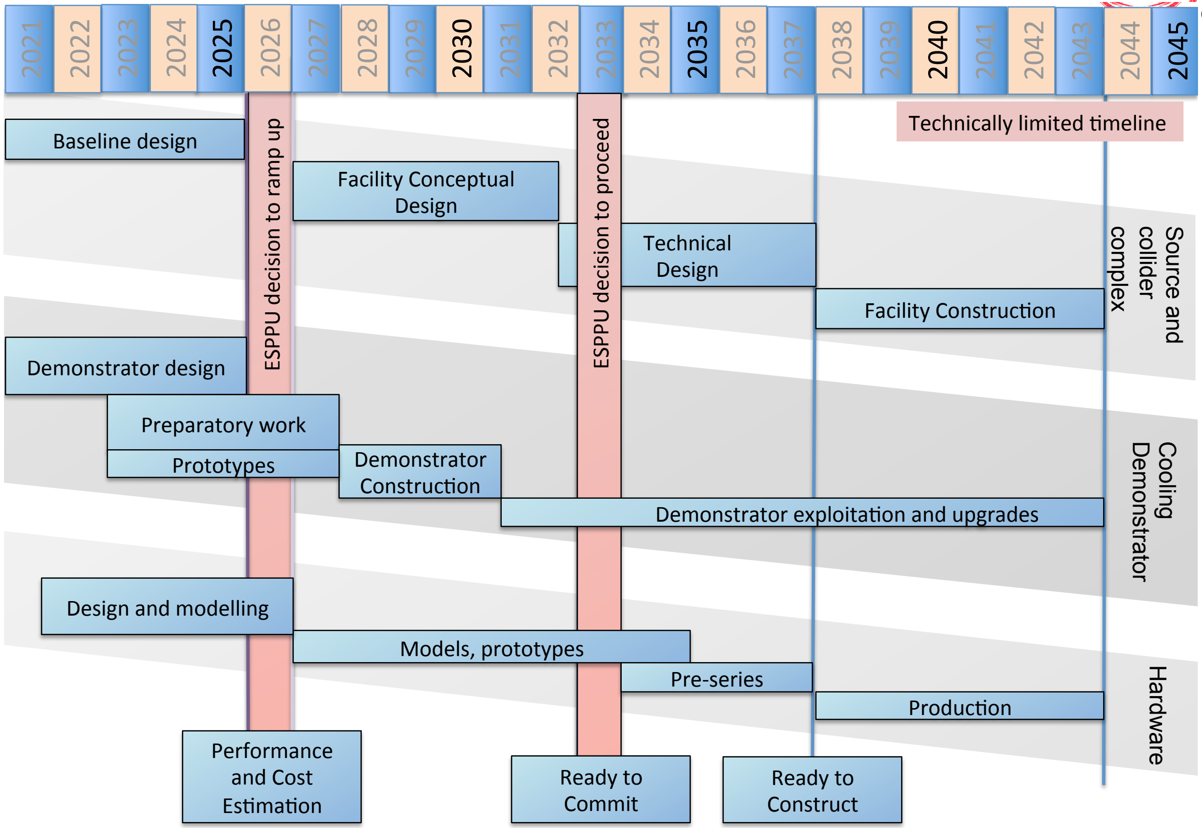
Table 5.5: The resource requirements for the two scenarios. The personnel estimate is given in full-time equivalent years and the material in kCHF. It should be noted that the personnel contains a significant number of PhD students. Material budgets do not include budget for travel, personal IT equipment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

Timeline

Muon collider important in the long term

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

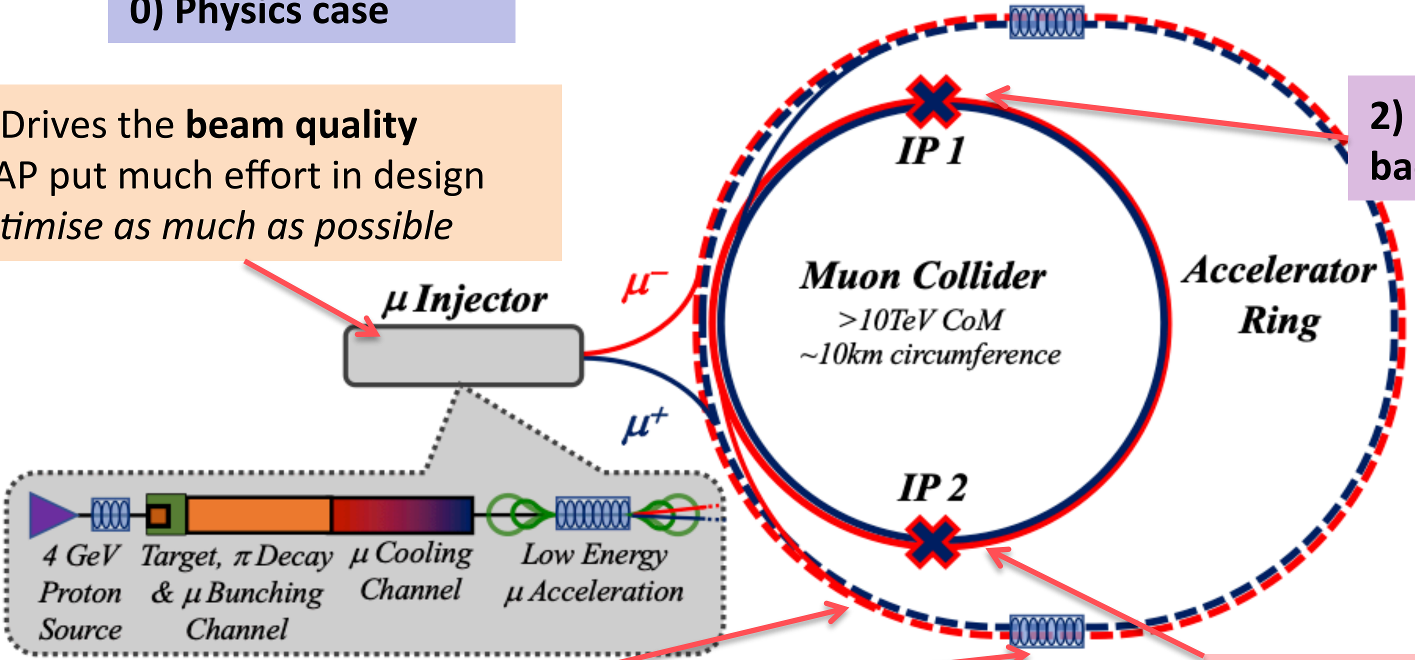
- e.g. in Europe if higgs factory built elsewhere
- **sufficient funding required now**
- very **strong ramp-up required** after 2026
- fast-track project might require some compromises on initial scope and performance
  - 3 TeV?



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**

Physics Studies

Details on physics case, detector and accelerator can be found in

- Snowmass white papers https://indico.cern.ch/event/1130036/
- EPJC report in preparation

Used tentative detector performance specifications in form of DELPHES card

- based on FCC-hh and CLIC performances, including masks against beam induced background (BIB)
- Please find the card here: https://muoncollider.web.cern.ch/node/14

M. Selvaggi, W. Riegler, U. Schnoor, A. Sailer, D. Lucchesi, N. Pastrone, M. Pierini, F. Maltoni, A. Wulzer et al.

Initial detector simulation studies at 1.5 and 3 TeV indicate that this is a **good model**

Now moving to 10 TeV

D. Lucchesi et al.

If you are interested to contribute please contact me or the responsible deputies:

Andrea Wulzer (physics) and **Donatella Lucchesi (Detector and MDI)**

Muon Decay and Detector Background

At 10 TeV O(40 000 muons/m bunch crossing decay)

About 1/3 of energy in electrons and positrons:

Masks protect detectors from **background**

- **optimising 10 TeV design**

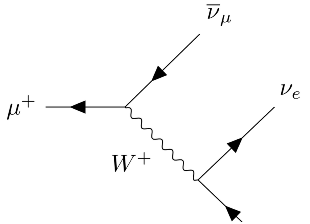
Other mitigation

- Timing (background mostly out of time
- Track direction (most background from mask)
- Detector design
- …

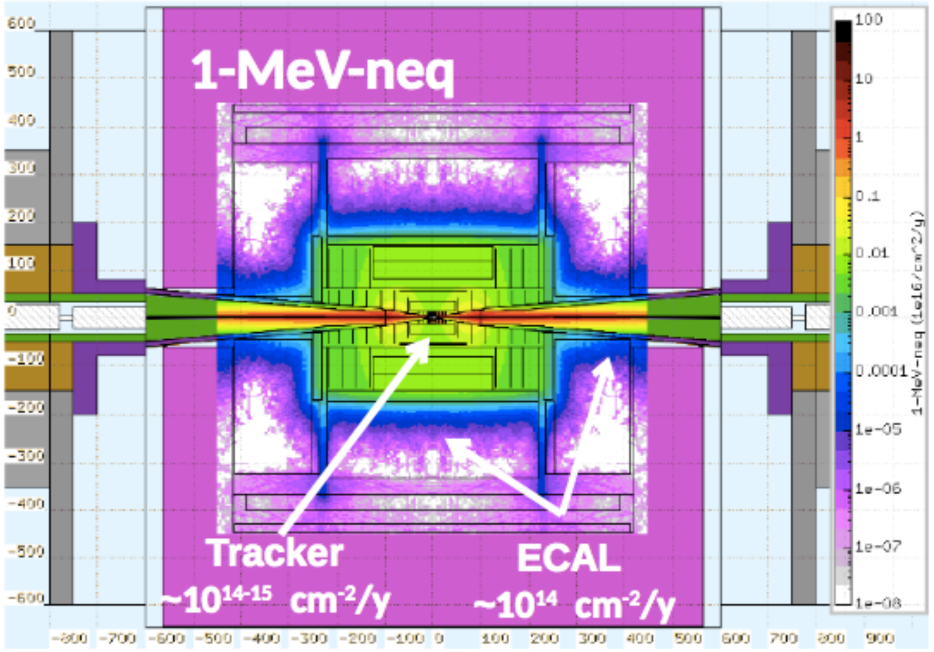
Other background from incoherent pairs is also studied (addition in GUINEA-PIG)

Detailed simulation studies at 1.5/3 TeV indicate DELPHES card is realistic

- studies indicate background does not increase significantly at 10 TeV (fewer decays/m)

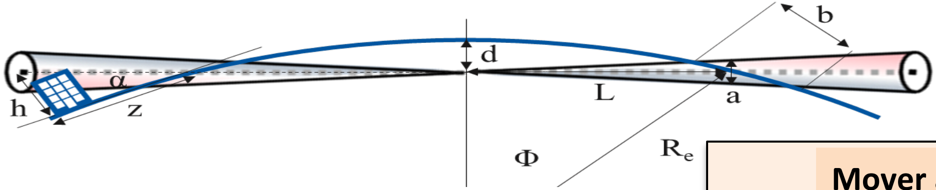


D. Lucchesi, A. Lechner, C Carli et al.

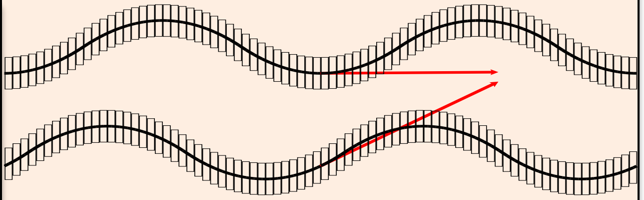


Neutrino Flux

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

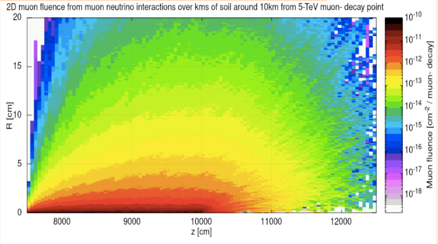


Mover and support system



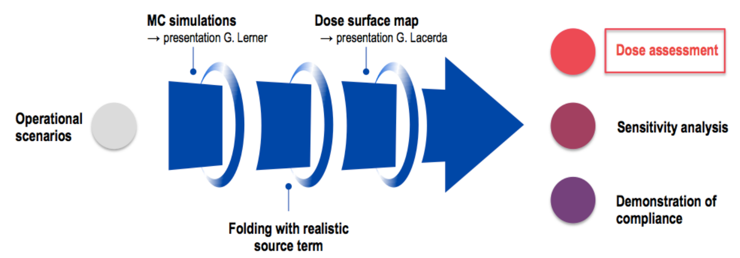
F. Bertinelli et al. (CERN, Riga)

FLUKA dose studies



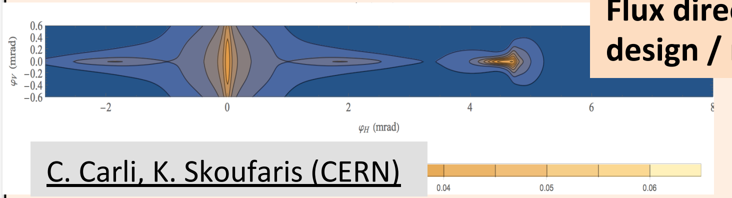
G. Lerner, D. Calzolari, A. Lechner, C. Ahdida

Conformity Verification Scheme



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

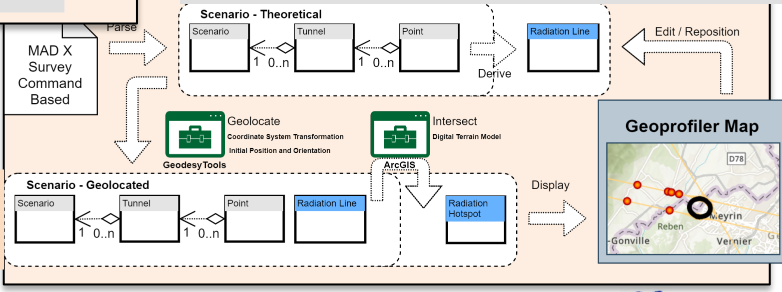
Flux direction map / lattice design / mover impact on beam



C. Carli, K. Skoufaris (CERN)

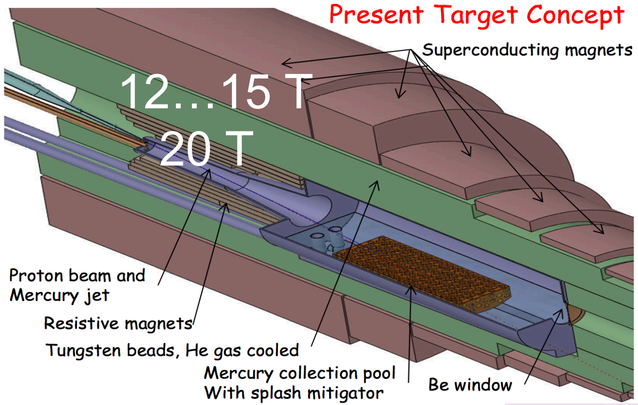
Mitigation: Site choice tool

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



Target

MAP target design, K. McDonald, et al.

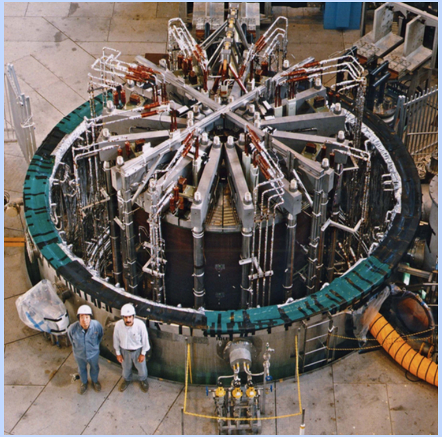


Two approaches:

- 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.

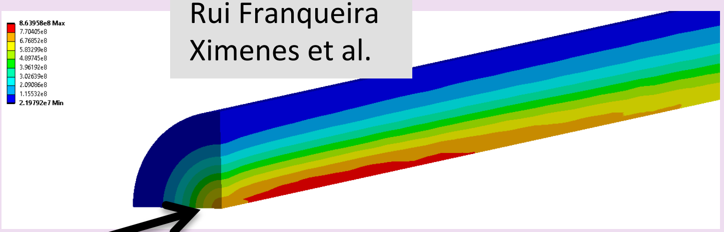


ITER Central Solenoid Model Coil
13 T in 1.7 m (LTS)

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.



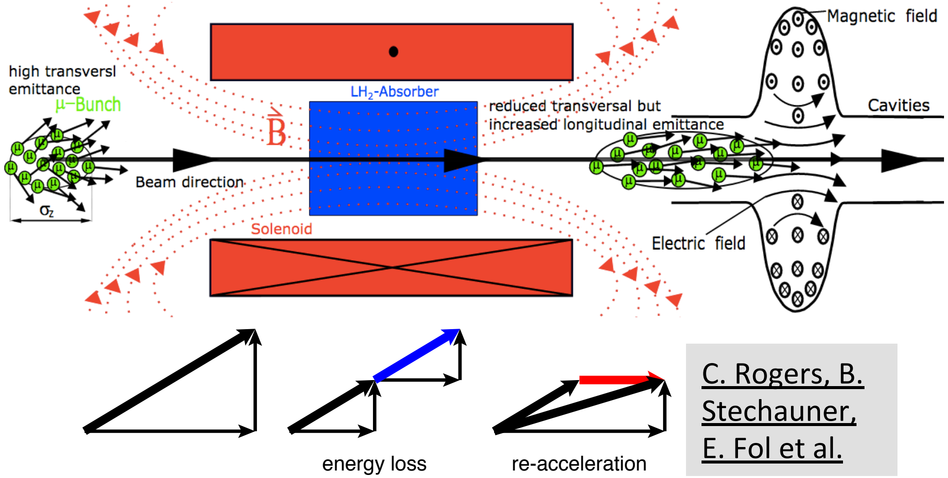
Proton beam

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

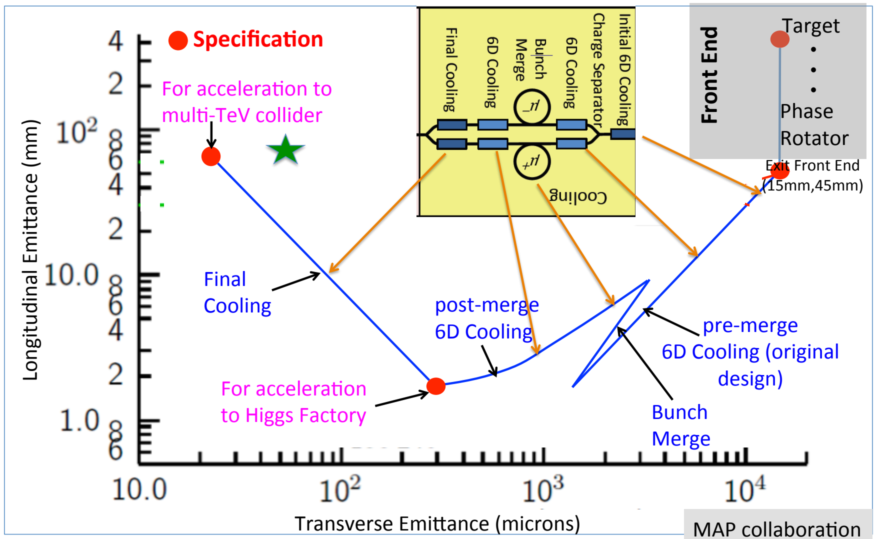
Muon Cooling



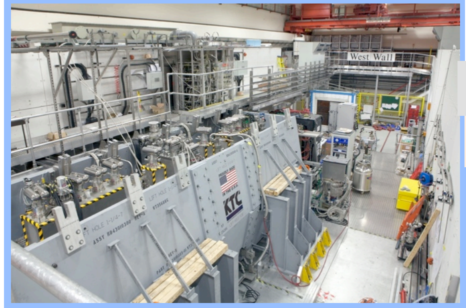
C. Rogers, B. Stechauner, E. Fol et al.

MAP designs almost achieve 10 TeV goal

- miss factor two for final cooling



MAP collaboration



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

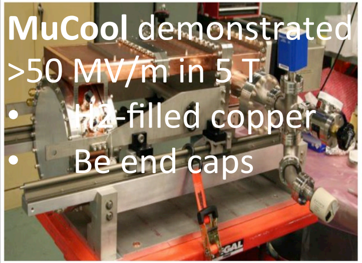
Integration/optimisation of overall cooling design
Integrating **improved technology**

C. Rogers et al.

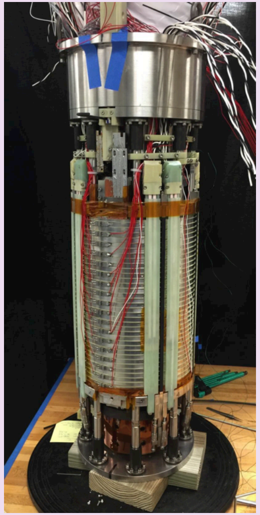
Cooling Cell Technology

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



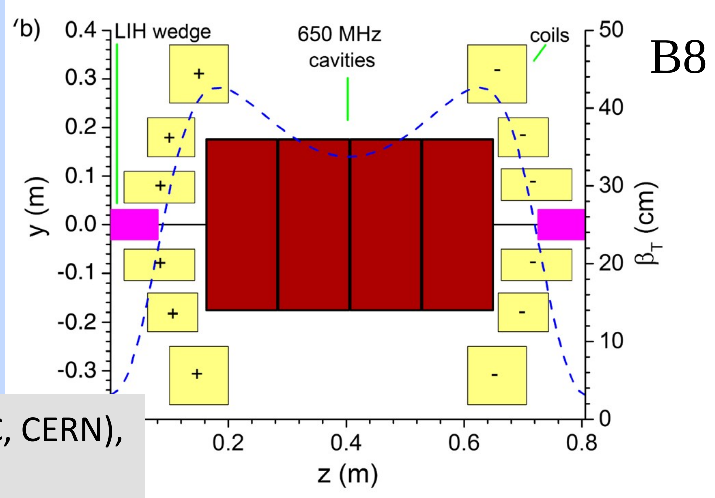
MAP demonstrated 30 T solenoid
- now magnets aim for 40+ T
- even more can be possible
- synergy with high-field research



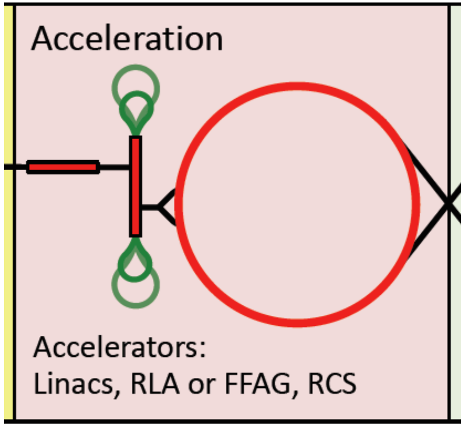
L. Bottura et al. INFN (Task Leader), CEA, CERN, LNCMI, PSI, SOTON, UNIGE and TWENTE, in collaboration with KEK and US-MDP

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)
Important cost and power consumption
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)

- Power converter with energy recovery

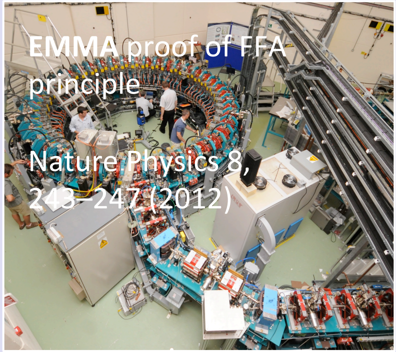
F. Boattini et al.

- RF with high transient beam loading

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

FNAL 1 kT/s HTS magnet

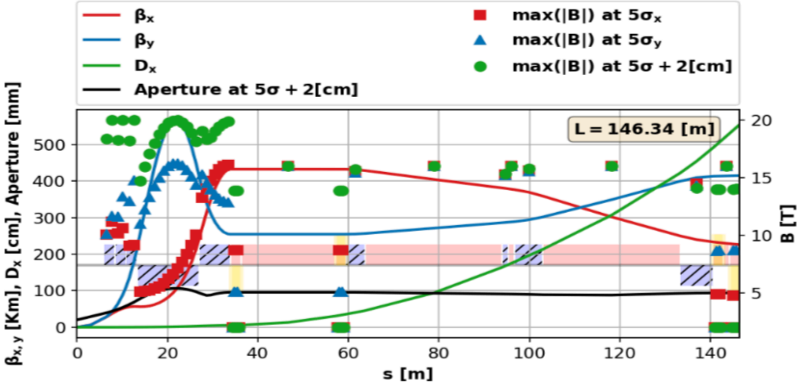
Alternative FFA



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

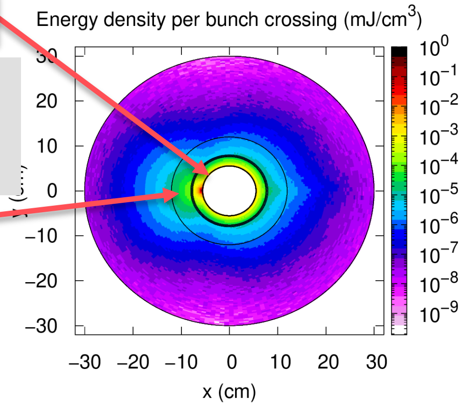


C. Carli, K. Skoufaris (CERN)

15 cm aperture for shielding to ensure magnet lifetime

Need stress managed magnet designs

INFN, Milano, Kyoto, CERN, profit from US



A. Lechner
D. Calzolari
(CERN)

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

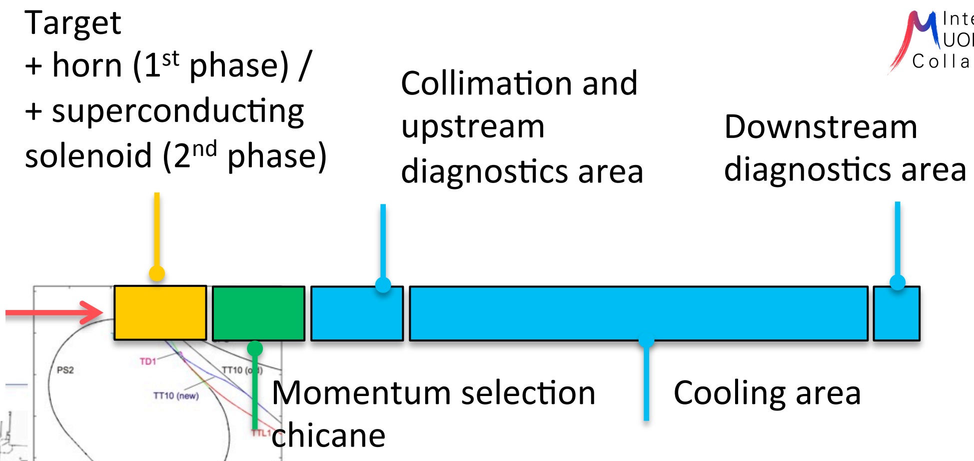
Demonstrator Facility Consideration

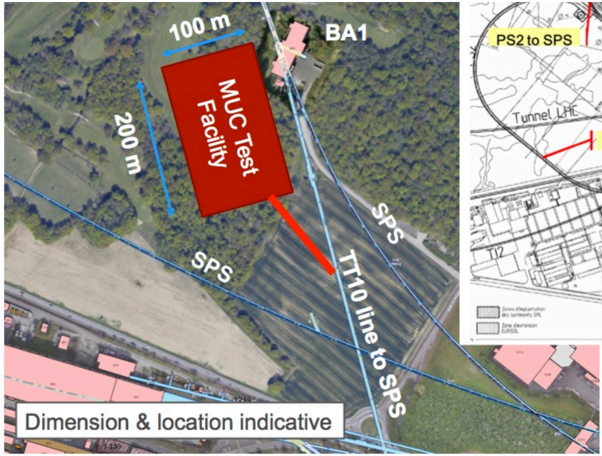
Planning **demonstrator** facility with muon production target and cooling stations

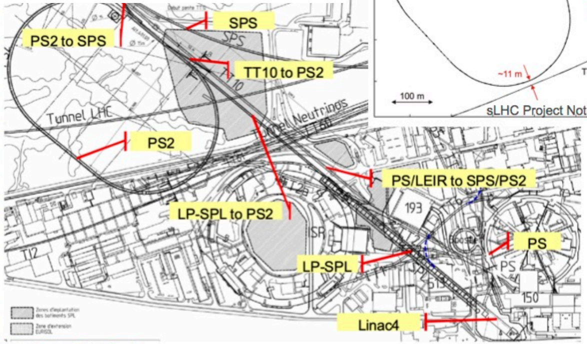
Suitable **site exists** on CERN land and can use **PS proton beam**

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

Other sites should be explored (FNAL?)

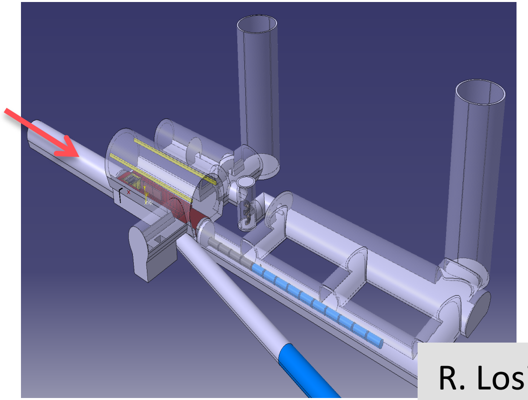






M. Benedikt, LHC Performance Workshop, Chamonix 2010

CERN-AB-2007-061



R. Losito et al.

Key Next Steps

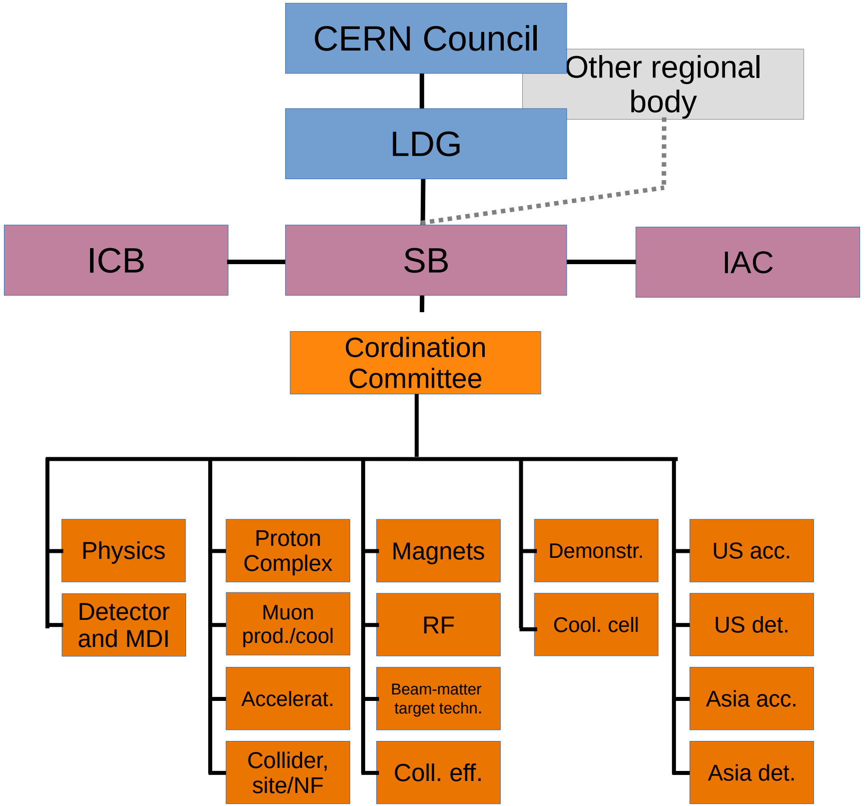
Formal organisation

- **Collaboration Board**
  - Chair to be elected October 11
- **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
  - member 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



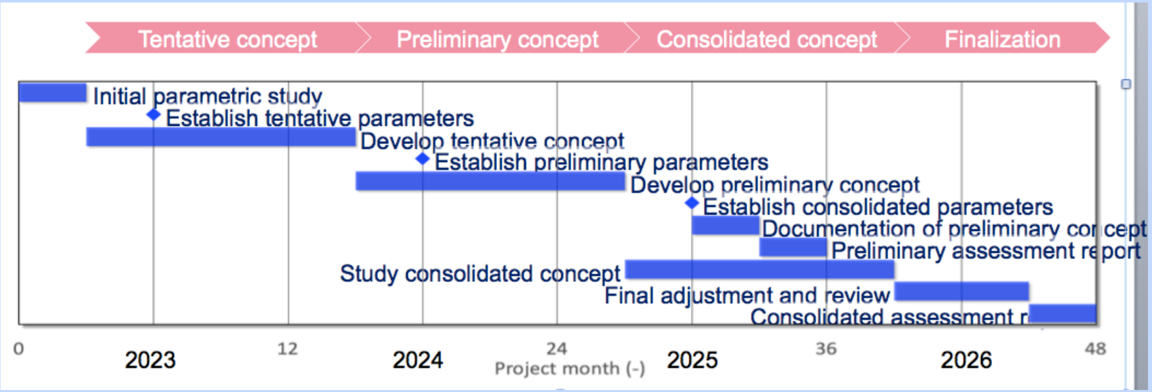
EU Design Study

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

January 2023 to December 2026

Approved late July, now preparing contract

EU contribution 3 MEUR, partners 4 MEUR, CERN



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 TECH call in 2024, to develop technologies

HORIZON-INFRA-2022-TECH-01-01:
Expected EU contribution: 5-10 MEUR
Total budget 110 MEUR
Type of Action: Research and Innovation Actions

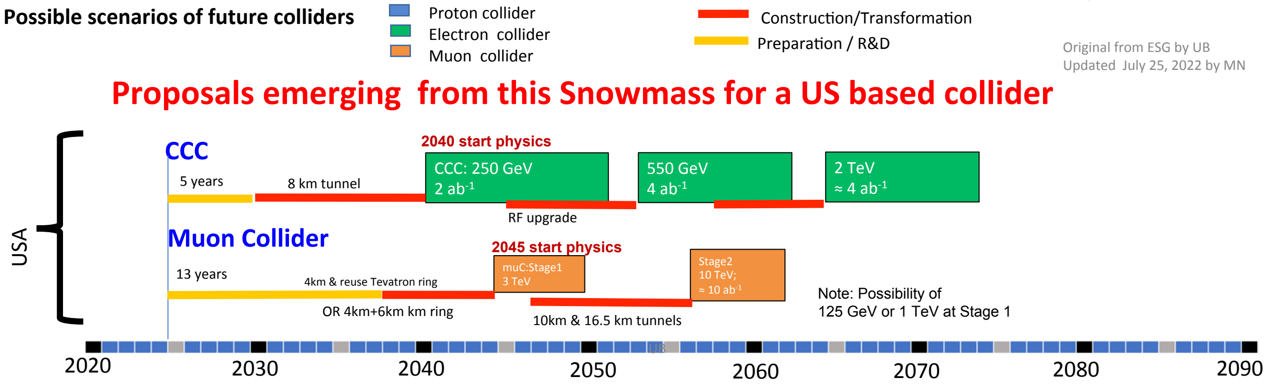
Snowmass

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 ILC/CCC [ie CCC used as an upgrade of ILC] 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

MoC and Design Study Partners

IEIO	**CERN**
FR	**CEA**
	CNRS-LNCMI
DE	DESY
	Technical University of Darmstadt
	University of Rostock
	KIT
IT	**INFN**
	University of Milano
	University of Padova
	University of Pavia
	University of Bologna
	ENEA
CH	***PSI***
	University of Geneva
BE	***Louvain***

UK	***STFC-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**
	BNL
China	***Sun Yat-sen University***
	IHEP
	Peking University
EST	***Tartu University***
LAT	***Riga Technical Univers.***
AU	***HEPHY***
	TU Wien
ES	***I3M***

CHART is contributing (and EPFL)
Informal contributions (US, Japan)

Note: *some MoC still being prcessed*

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** later this year
  - please let me know if you want to contribute

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
  - will consider other options later

- Started turning Roadmap into a workplan
- First important results are being obtained
- but still plenty of work remains
  - **increased R&D effort still required**
  - great opportunity to join, also for the physics and detector

- Collaboration meeting October 11-14 at CERN

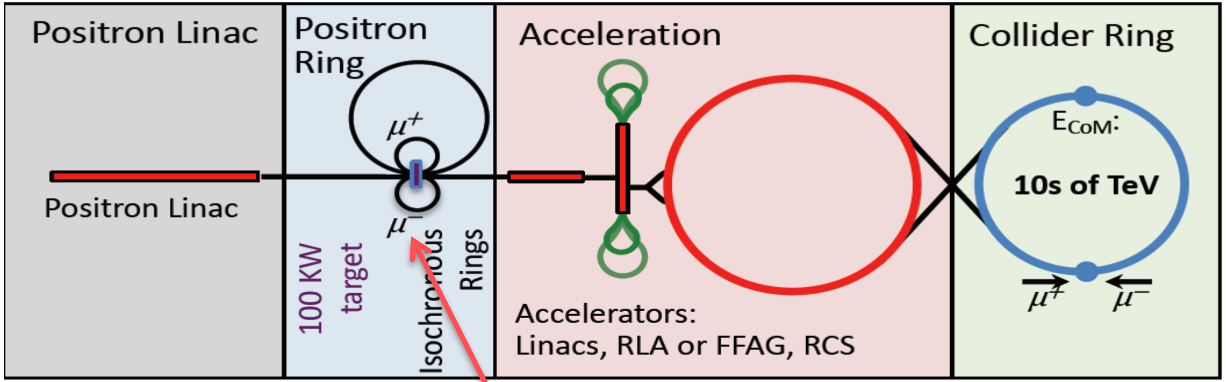
http://muoncollider.web.cern.ch

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

Reserve

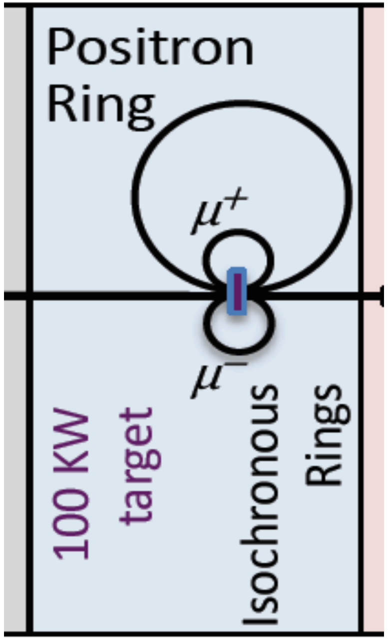
Alternatives: The LEMMA Scheme

LEMMA scheme (INFN) P. Raimondi et al.



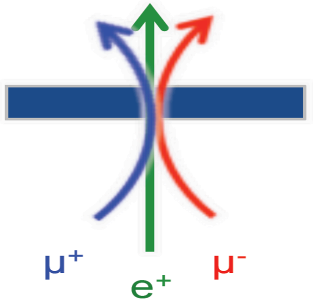
Note: New proposal by C. Curatolo and L. Serafini needs to be looked at

- Uses Bethe-Heitler production with electrons



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

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

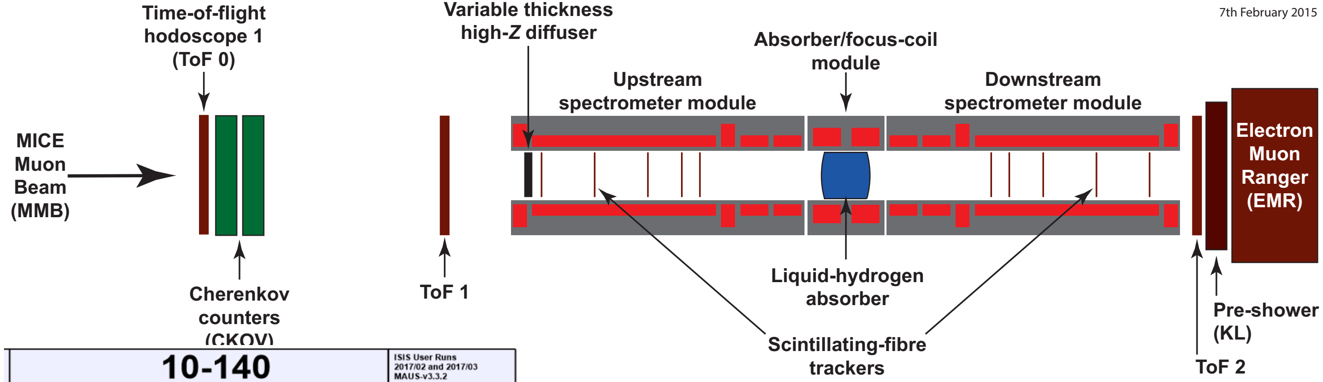


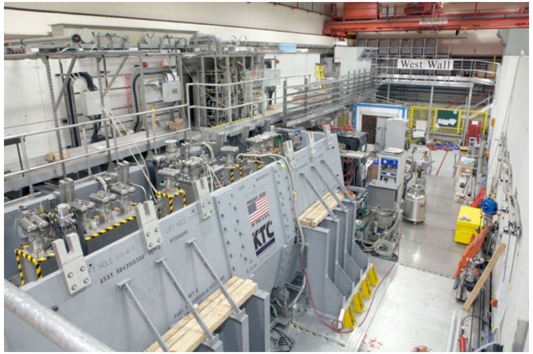
Excellent idea, but nature is cruel

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

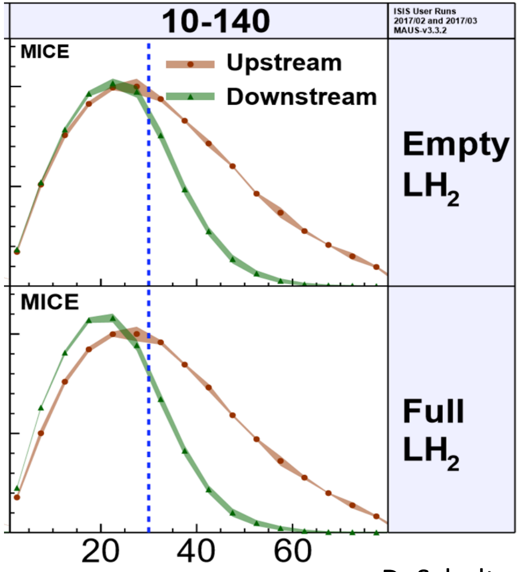
$\Rightarrow$ **Need same game changing invention**

MICE: Cooling Demonstration





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

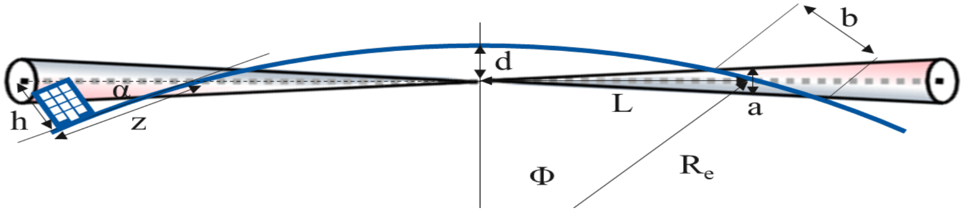
More complete experiment with higher statistics, more than one stage required

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

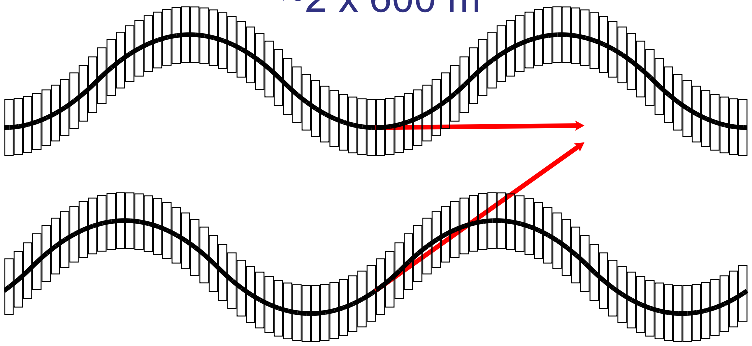
Neutrino Flux

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**

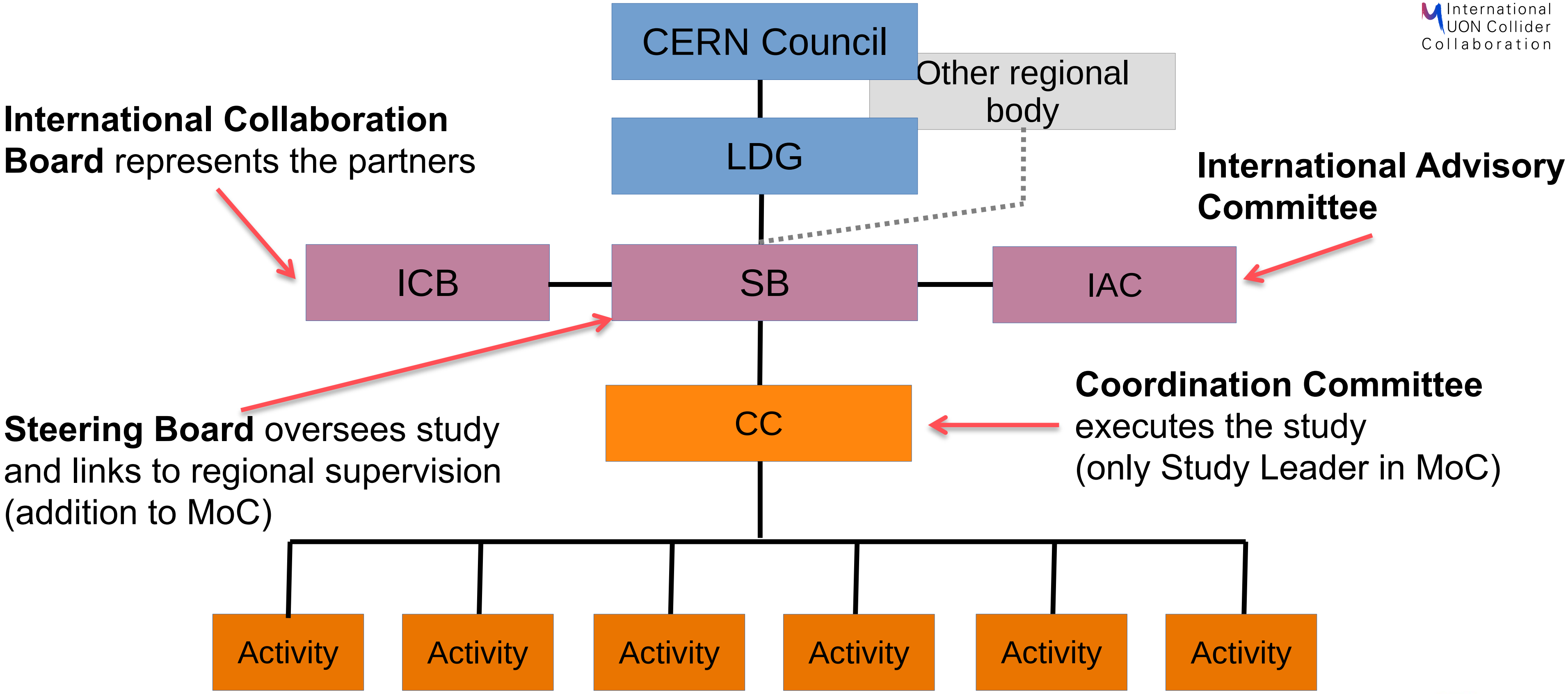


Need to study mover system, magnet, connections and impact on beam

Working on different approaches for experimental insertion

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

Organisation



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)

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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