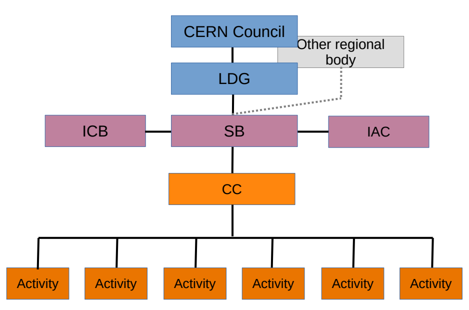
Muon Collider

D. Schulte and S. Stapnes
for the International Muon Collider Collaboration

LDG
November 2022

Muon Collider Community

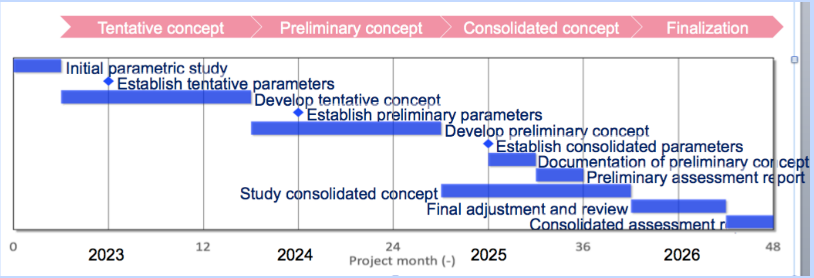
Formed **collaboration** to implement and R&D Roadmap for CERN Council



50+ partner institutions
30+ already signed formal agreement

EU Design Study approved this summer**,** 32 partners, O(3+4 MEUR)

(EU+Switzerland+UK and partners)



International
MUON Collider
Collaboration

Plan to apply in 2024 for
HORIZON-INFRA-2024-TECH
Goal: prepare experimental programme, e.g. **demonstrator, prototypes, …**

US Snowmass has **strong support**

- to contribute to R&D
- as a collider in the US

Now waiting for P5

From the Muon Collider report, ECFA, November 2022 by D.Schulte

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**

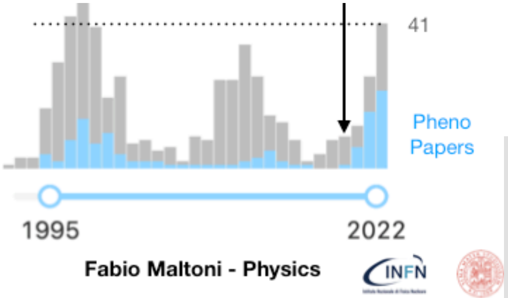
FI	**Tampere University**
US	**Iowa State University**
	Wisconsin-Madison
	Pittsburg University
	BNL
China	***Sun Yat-sen University***
	IHEP
	Peking University
EST	***Tartu University***
LAT	**Riga Technical Univers.**
AU	**HEPHY**
	TU Wien
ES	***I3M***
CH	**PSI**
	University of Geneva
	EPFL
BE	***Louvain***

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

Large US interest in Muon Colliders

From, e.g., Snowmass21 EF report draft:

"A 10-TeV scale muon collider with sufficient integrated luminosity provides an energy reach similar to that of a 100 TeV proton-proton collider. [...] muon and hadron colliders have similar reach and can significantly constrain scenarios motivated by the naturalness principle. [...] Multi-TeV muon colliders will have the benefit of excellent signal to background [...] One of the key measurements from the multi-TeV colliders is the one of the Higgs self-coupling to a precision of a few percent, and the scanning of the Higgs potential."



from F. Maltoni at IMCC Annual Meeting

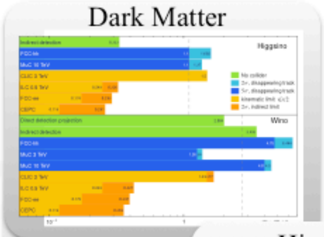
International UON Collider Collaboration

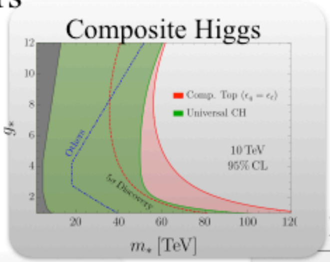
A. Wulzer, F. Maltoni, P. Meade et al.

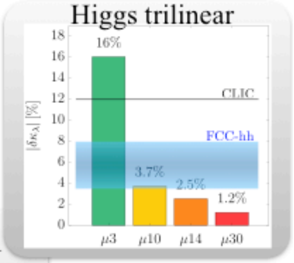
O(150) authors, 15 editors, 100 papers

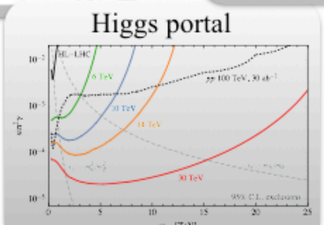
Selected summary plots, from Snowmass21 reports:

2 IMCC reports, plus Muon Collider Forum report. Total of 15 editors, ~150 authors, based on ~100 papers from 3 past years









Higgs couplings

	HL-LHC	HL-LHC +10 TeV	HL-LHC +10 TeV + ee
κ_W	1.7	0.1	0.1
κ_Z	1.5	0.4	0.1
κ_g	2.3	0.7	0.6
κ_γ	1.9	0.8	0.8
$\kappa_{Z\gamma}$	10	7.2	7.1
κ_c	-	2.3	1.1
κ_b	3.6	0.4	0.4
κ_μ	4.6	3.4	3.2
κ_τ	1.9	0.6	0.4
κ_t^*	3.3	3.1	3.1

* No input used for μ collider

Collaboration documents

Memorandum of Collaboration(MoC): Being signed by collaboration members (list shown earlier)

Memorandum on Cooperation
for the Muon Collider (MC) Study

THE INSTITUTES, LABORATORIES, UNIVERSITIES AND FUNDING AGENCIES AND OTHER SIGNATORIES OF THIS MEMORANDUM ON COOPERATION AND CERN AS THE HOST ORGANIZATION **("the Participants")**

Governance document: "Collaboration own" document, with updated description of the organisation, also taking into account being part of the European Accelerator R&D roadmap:

Governance Structure of the International Muon Collider Collaboration

D. Schulte, M. Lamont

June 27, 2022

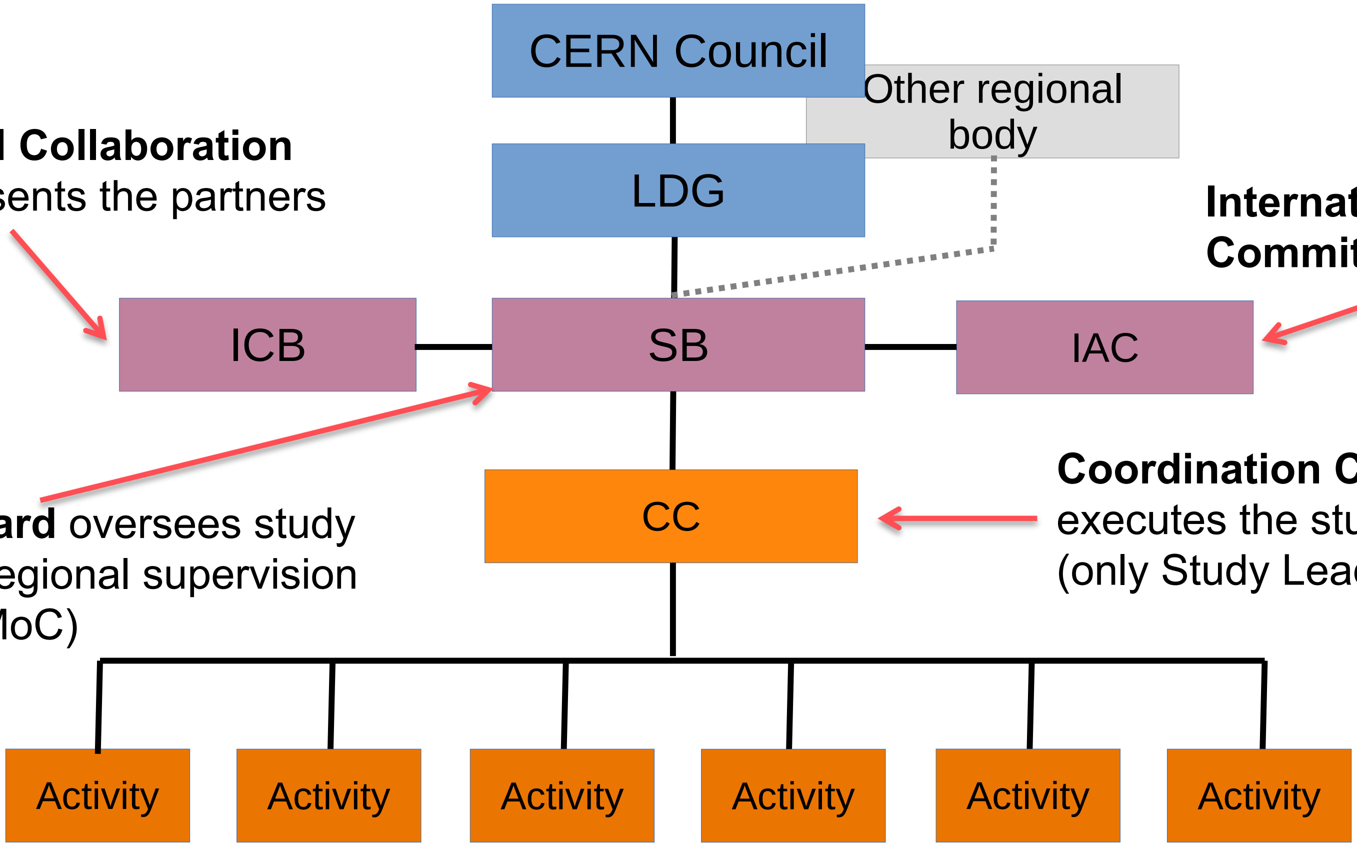
1 Preamble

The International Muon Collider Collaboration (IMCC) was initiated in 2020 following the recommendations of the update of the European Strategy for Particle Physics. A Memorandum of Cooperation (MoC) was drawn up; 20 institutes have already signed or are in the process of doing so. CERN shall act

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)

IMCC ICB#1

Tuesday 11 Oct 2022, 18:00 → 20:00 Europe/Zurich

30/7-018 - Kjell Johnsen Auditorium (CERN)

Videoconference | IMCC ICB#1 | Join | 30/7-018

International MUON Collider Collaboration

18:00 → 18:05 **Welcome** 5m

Speaker: Steinar Stapnes (CERN)

18:05 → 18:20 **ICB chair initial mandate** 15m

Speaker: Steinar Stapnes (CERN)

mandate.pdf | Muon_Collider_Gove... | MUON_ICB_Voting ri...

18:20 → 18:30 **Election procedure and electorate** 10m

- There are two candidates for the ICB chair election: Mohammad Eshraqi (ESS) and Nadia Pastrone (Torino).
- The election will be done electronically and can be launched after the ICB meeting. It can be kept open for a time to be decided, e.g. 24 hours.

Speaker: Steinar Stapnes (CERN)

Mamad-Eshraqi.pdf | Nadia-Pastrone.pdf

18:30 → 18:40 **Endorsement of Study Leader and Deputies** 10m

Speaker: Steinar Stapnes (CERN)

18:40 → 18:55 **Short report by Study Leader** 15m

Speaker: Daniel Schulte (CERN)

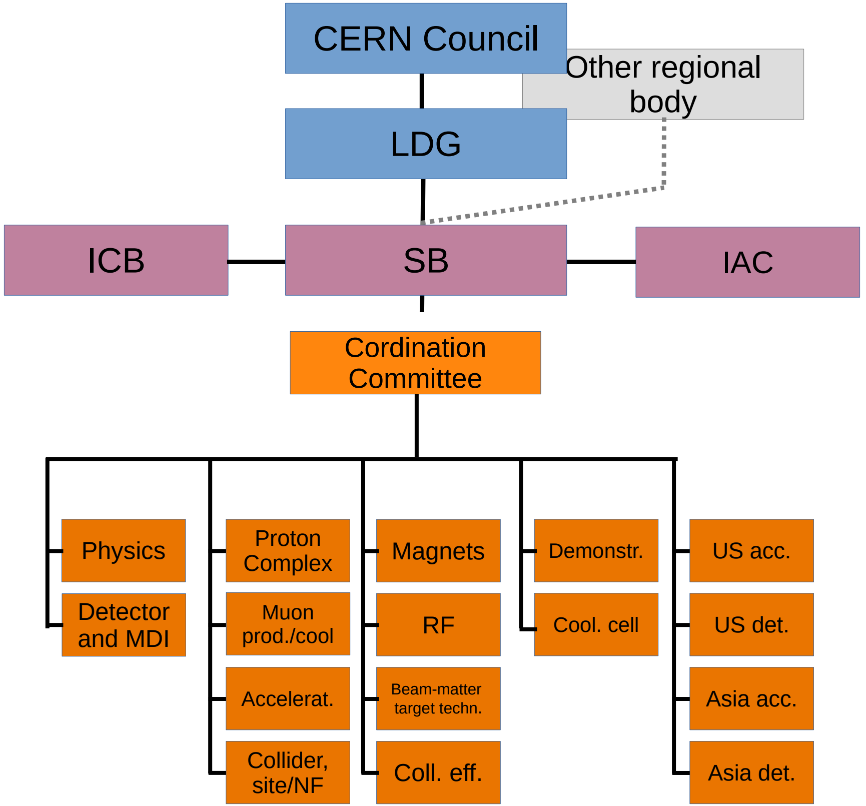
18:55 → 19:05 **Future appointments of Steering Board members and other committee matters** 10m

Speaker: Steinar Stapnes (CERN)

19:05 → 19:15 **Next meeting and AOB** 10m

Organisation

- **Collaboration Board (ICB)**
  - Elected chair: **Nadia Pastrone**
- **Steering Board (ISB)**
  - Chair **Steinar Stapnes**, CERN members: Mike Lamont, Gianluigi Arduini, +ICB representatives, SL and deputies
  - Started initial meetings between Steinar, Nadia, Daniel, ISB to be completed by next ICB
- **Coordination committee (CC)**
  - ICB endorsed
    - Study Leader Daniel Schulte
    - Deputies: Andrea Wulzer, Donatella Lucchesi, Chris Rogers
  - Members have been already working
  - Consider enlarging physics and detectors



Coordination Committee Members

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, Claude Marchand
Beam-matter int. target systems	Anton Lechner
Collective effects	Elias Metral
Cooling cell design	Lucio Rossi
Demonstrator	Roberto Losito

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

Points brought up in the ICB

- Next CB meeting linked to MuCol kick off (Spring 2023)
- Some important points to address/prepare for next ICB meeting:
  - Continue to include institutes according to rules to be defined (e.g. MoC, foreseen contributions, resources)
  - Work out/Clarify overlaps and co-existence between the collaboration structure overall and the MuCol project, from technical work to collaboration board/governing board and advisory group(s)
  - Complete the Steering Group (with representatives from collaboration and CERN)

Key points

- Good progress in building the organisational structures.
- Keep a focus on integration of groups not yet fully members of the collaboration, among them the US labs where this required more legal legwork and creativity

- Specifically for the muon collider: the Panel tasks are already largely covered by the collaboration bodies, but the SB – which include the collaboration management - can add value in particular in two areas:
  - In communication with the LDG including other panels. and other regions main FAs
  - And considering how a quite large demonstrator programme can be envisaged in next stage, again with key FAs

Coordination Panel Terms of Reference

- Oversee the development of a detailed execution plan for each R&D Theme, and coordinate the necessary work
- Have representation from all stakeholders, including (as appropriate) participating laboratories, institutes, and national communities
- Include representation from international partners, ensuring that a uniform picture for both European and international oversight bodies
- Act as a decision-making and prioritisation body within the approved scope of each R&D Theme, based on a consensus of stakeholders
- Where changes of objectives or scope, or prioritisation between objectives, are needed, submit recommendations and requests for comment to the LDG
- Ensure that decisions are made on a sound technical basis, drawing on the expertise of the collaborating projects and institutions, and setting up any subsidiary technical working groups that may be needed

Accelerator R&D Roadmap

International MUON Collider Collaboration

Full funding scenario deliverables by next ESPPU/other processes

- **Project Evaluation Report**
  - key performance, risk, cost and power drivers
  - site considerations (CERN and elsewhere)
- **R&D Plan**
  - describes a path towards the collider;
  - key element is **demonstrator concept**
- **Interim Report** (2023)

Allows to make **informed decisions**

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.

Current funding level allows only to address the most critical items

- making priorities based on risk and collaborator interest

Project Evaluation Report

The **Project Evaluation Report** for the next ESPPU will contain an assessment of whether the 10 TeV muon collider is a promising option and identify the required compromises to realise a 3 TeV option by around 2045. In particular the questions below would be addressed.

- What is a realistic luminosity target?
- What are the background conditions in the detector?
- Can one consider implementing such a collider at CERN or other sites, and can it have one or two detectors?
- What are the key performance specifications of the components and what is the maturity of the technologies?
- What are the cost drivers and what is the cost scale of such a collider?
- What are the power drivers and what is the power consumption scale of the collider?
- What are the key risks of the project?

Aspirational Timeline

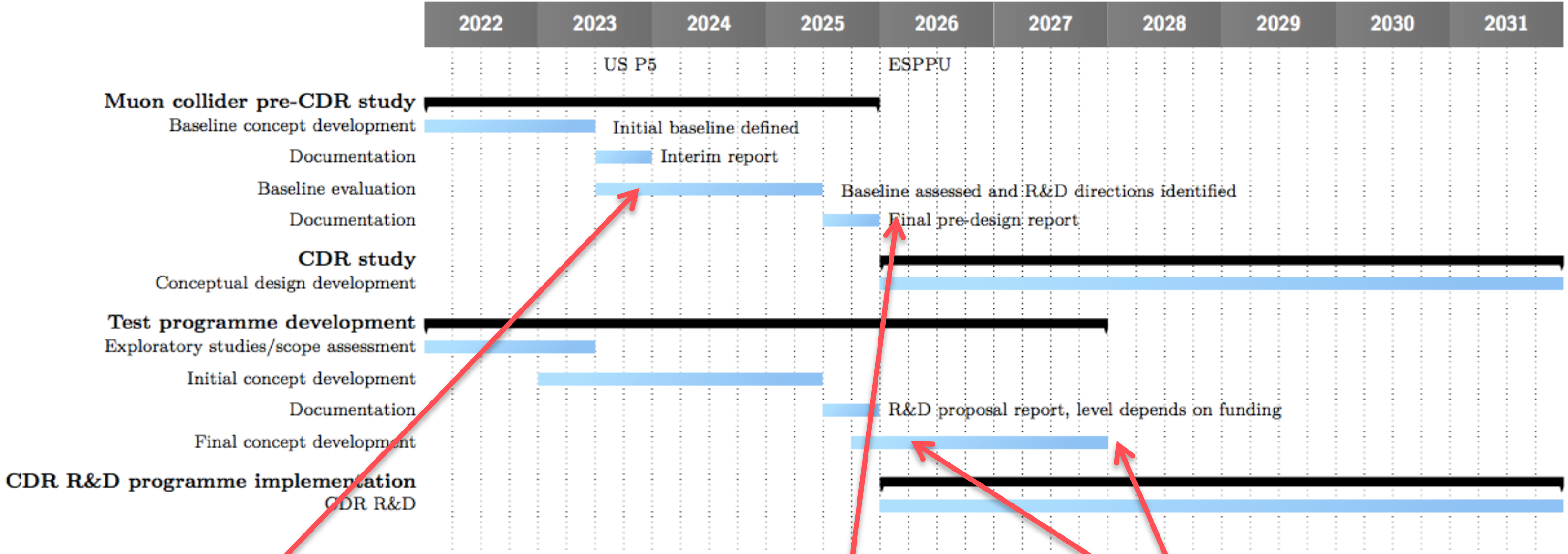


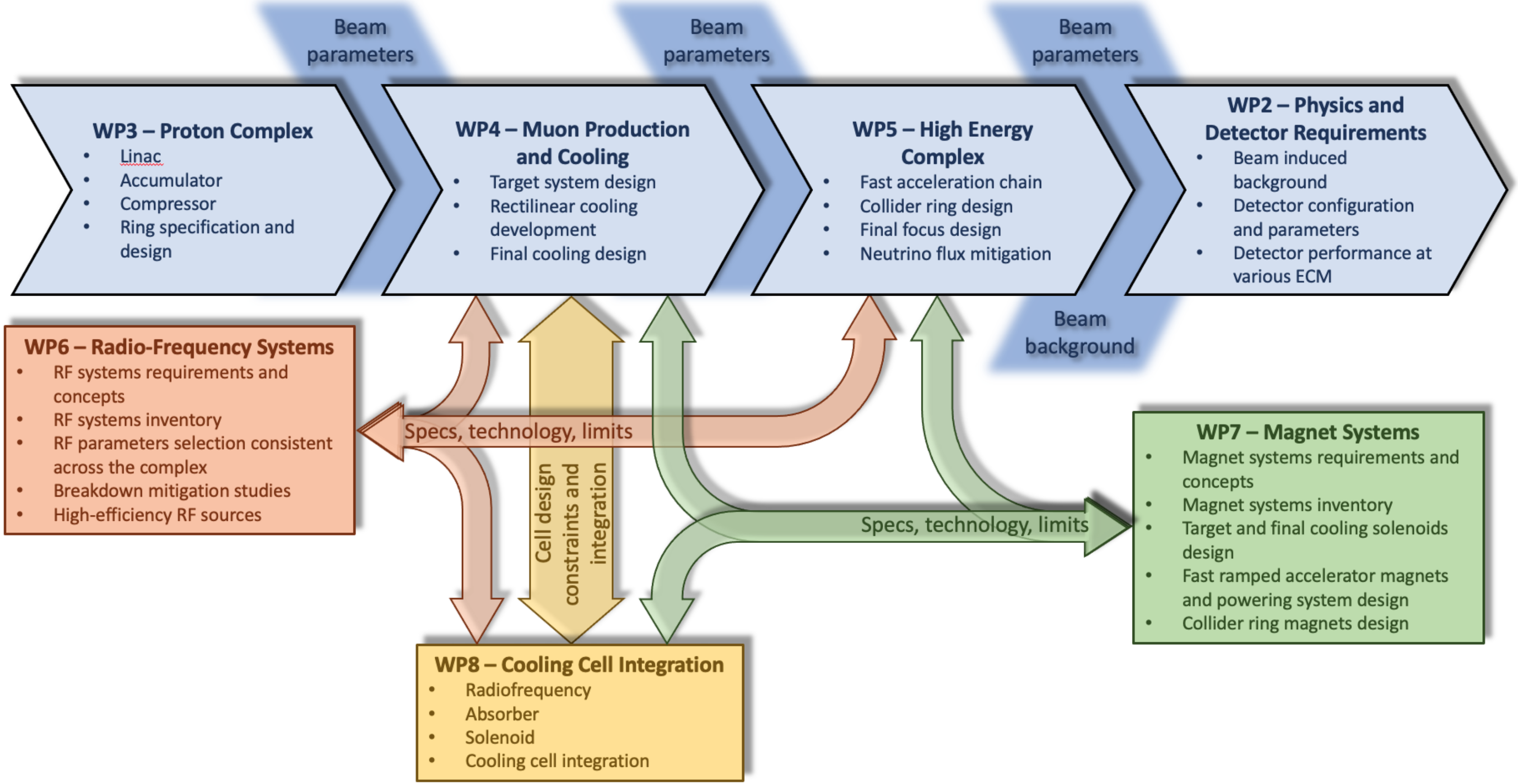
Fig. 5.4: Overall timeline for the R&D programme.

2023
Interim Report to gauge progress
Initial baseline defined

2025
Assessment Report

2025-2027
R&D plan will be refined

MuCol



Beam parameters
Beam parameters
Beam parameters
WP3 – Proton Complex
• Linac
• Accumulator
• Compressor
• Ring specification and design
WP4 – Muon Production and Cooling
• Target system design
• Rectilinear cooling development
• Final cooling design
WP5 – High Energy Complex
• Fast acceleration chain
• Collider ring design
• Final focus design
• Neutrino flux mitigation
WP2 – Physics and Detector Requirements
• Beam induced background
• Detector configuration and parameters
• Detector performance at various ECM
Beam background
WP6 – Radio-Frequency Systems
• RF systems requirements and concepts
• RF systems inventory
• RF parameters selection consistent across the complex
• Breakdown mitigation studies
• High-efficiency RF sources
Specs, technology, limits
Cell design constraints and integration
Specs, technology, limits
WP7 – Magnet Systems
• Magnet systems requirements and concepts
• Magnet systems inventory
• Target and final cooling solenoids design
• Fast ramped accelerator magnets and powering system design
• Collider ring magnets design
WP8 – Cooling Cell Integration
• Radiofrequency
• Absorber
• Solenoid
• Cooling cell integration

Reminder: Coordination Committee Members

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, **Claude Marchand**
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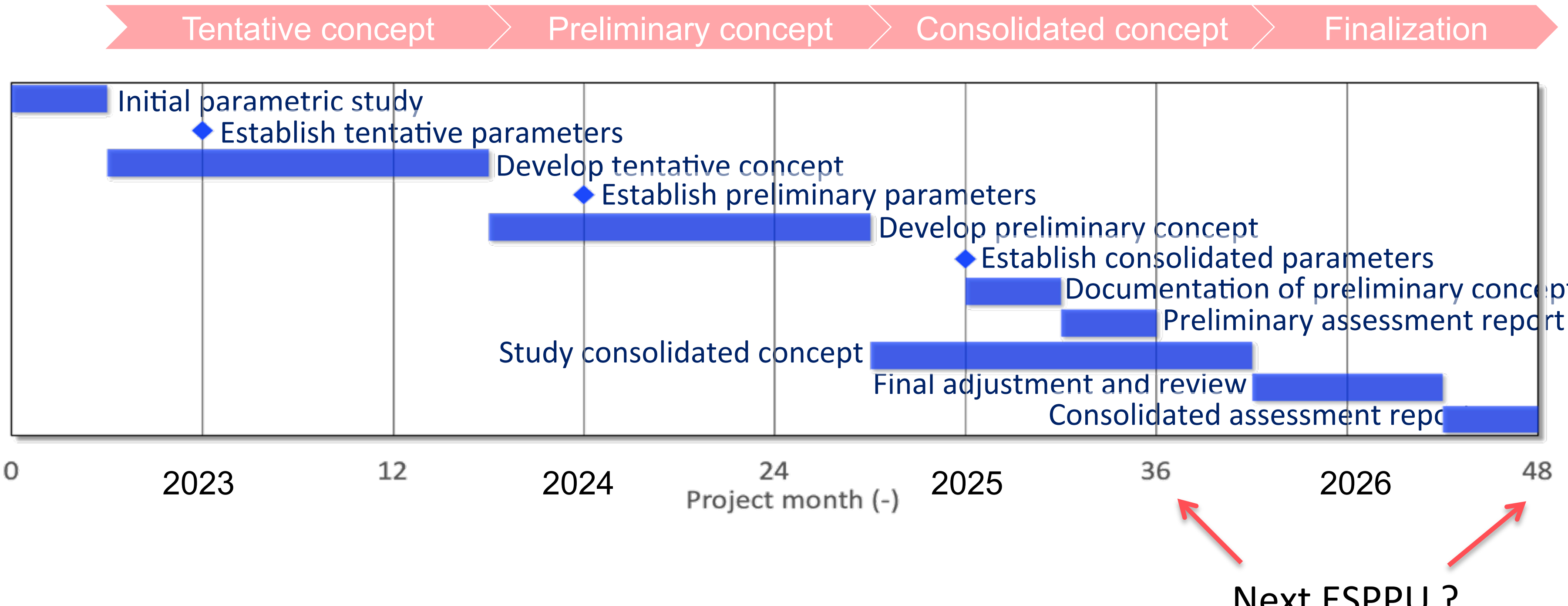
Collective effects	Elias Metral

Cooling cell design	**Lucio Rossi**
Demonstrator	Roberto Losito

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

The MuCol WP coordinators are CC members
essentially all activities are integrated in MuCol

EU Design Study Timeline



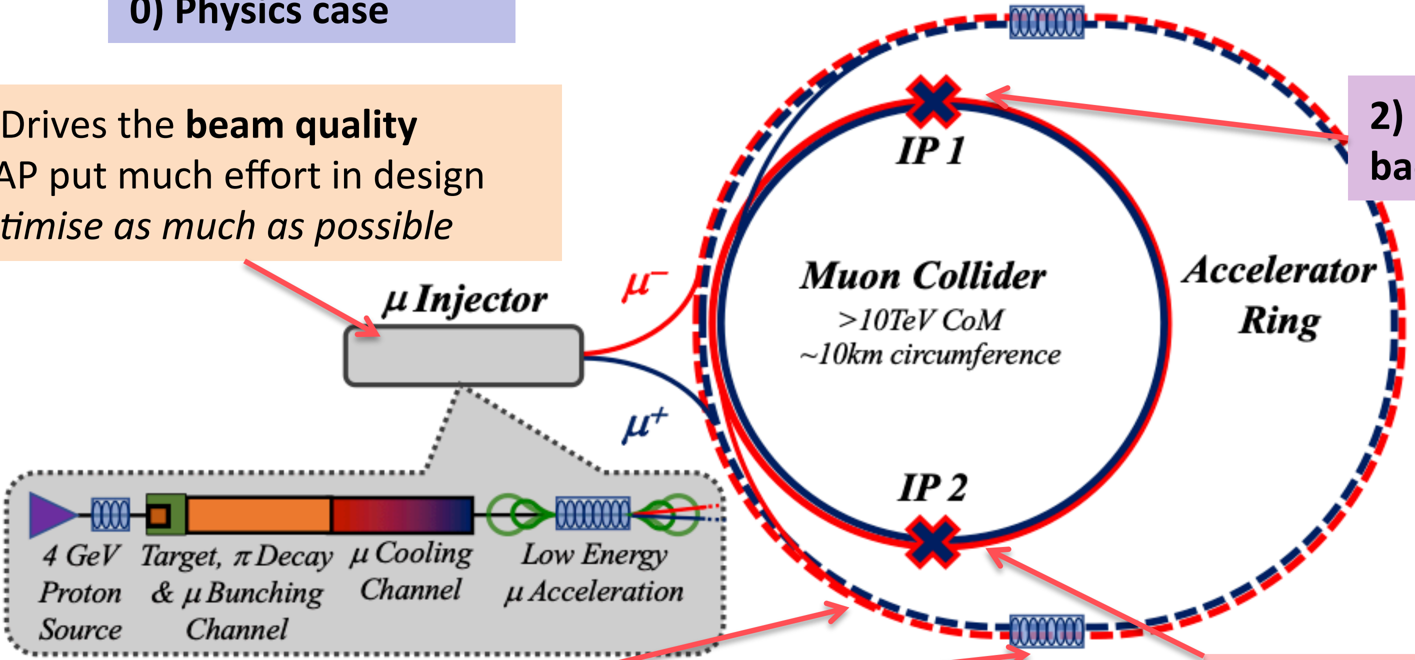
Representative of overall workplan

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**

Muon Decay and Detector Background

Muons decay produces electrons and positrons

- Loss per unit length almost independent of energy

Tools mostly ready to generate background

- tentative beamline and mask, FLUKA
- tentative beam-beam for muons (GUINEA-PIG)

Studies at 1.5 <and 3 TeV with concept based on CLIC detector

- **Radiation level in detector similar to HL-LHC**

Studies with **beam-induced background** in progress

- some channels are not affected by background
- some improvement required for other channels

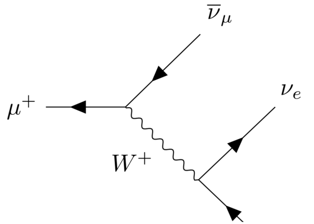
Concept for **10 TeV** in progress

UNIPD, with the participation of INFN, CEA, DESY, UOS, LIP, CERN, ISU, SYSU, UNIPV

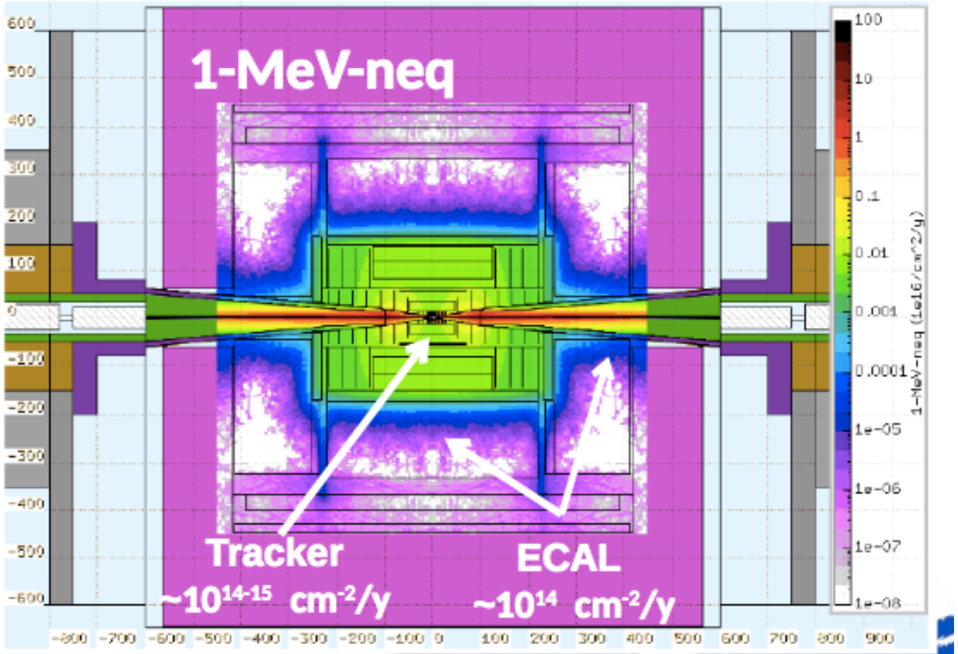
WP 2: Detector concept for 3 and 10+ TeV

WP 2: Reconstruction algorithm development

WP 2: Detector performance evaluation



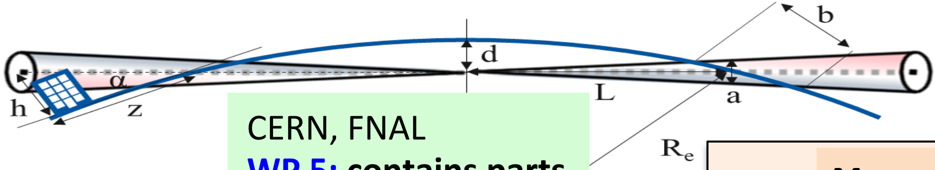
Detector team
O(69) authors, O(150 signatories)



International MUON Collider Collaboration

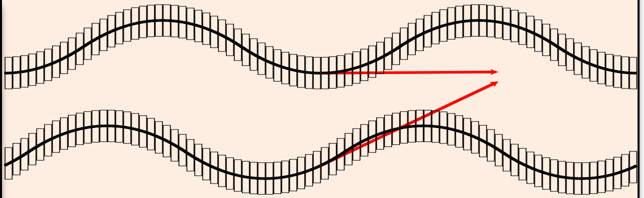
Neutrino Flux

Goal: **similar to LHC**: limit neutrino flux to have **negligible impact**, "fully optimised" (10% of MAP goal)
Verify performance of concept to be good for 14 TeV



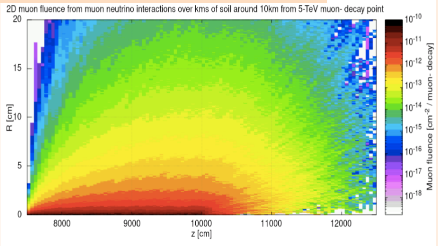
CERN, FNAL
WP 5: contains parts

Mover and support system



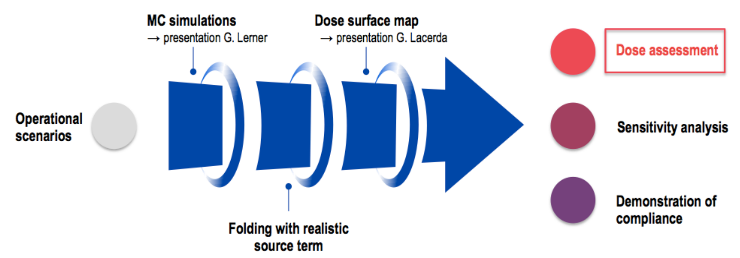
F. Bertinelli et al. (CERN, Riga)

FLUKA dose studies



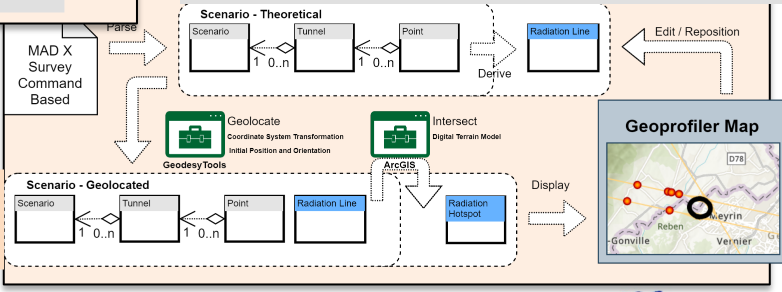
G. Lerner, D. Calzolari, A. Lechner, C. Ahdida

Conformity Verification Scheme

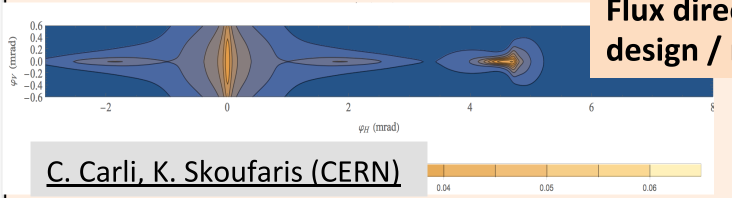


C. Ahdida, P. Vojtyla, M. Widorski, H. Vincke

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



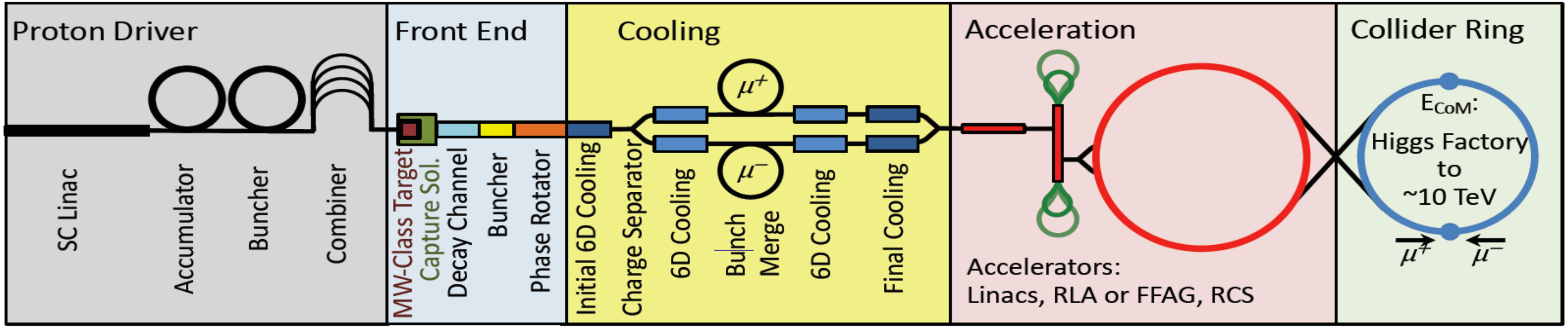
Flux direction map / lattice design / mover impact on beam



C. Carli, K. Skoufaris (CERN)

Mitigation: Site choice tool

Proton Complex



Need about 2 MW proton beam
400 kJ per pulse at 5 Hz

Complex system
Due to resources focus on bunching of beams

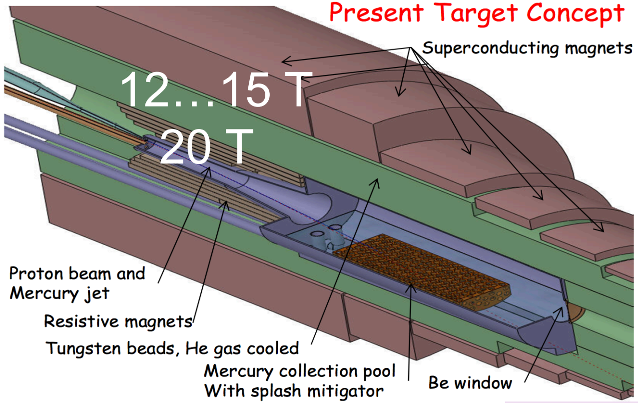
ESS, CERN, Uppsala
WP3: Compressor ring design (ESS)
- design

WP 3: Linac parameters (CERN)
- basic parameters

N. Milas et al. (ESS, Uppsala)

Target

MAP target design, K. McDonald, et al.



Two approaches:

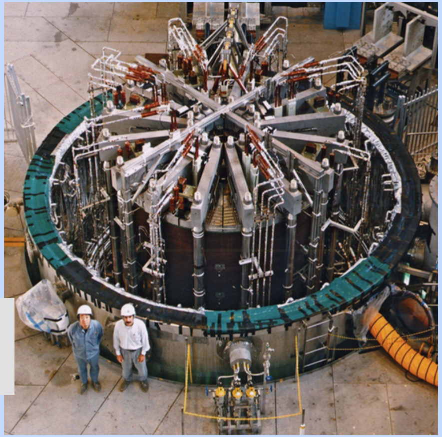
- 15 T LTS + 5 T resistive or 20 T HTS

Large aperture for shielding

WP 7: Solenoid target parameters
WP 4: Shielding needs and radiation

Synergy with ITER

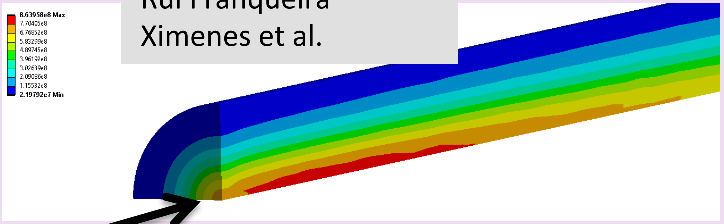
A. Lechner et al.
L. Bottura et al.



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

UKRI, Imperial, UWAR, CERN, INFN, UMIL, ENEA
WP4: Target design (CERN)
WP4: Shielding needs
WP7: Solenoid target parameters

Rui Franqueira Ximenes et al.

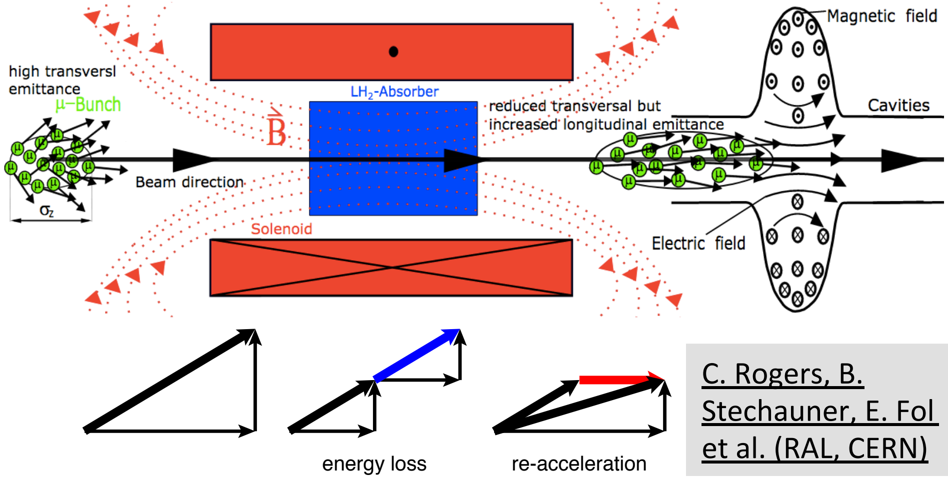


Proton beam

Operation at 2000 °C to maximise stress resistance

WP 4: Shock in target:
Simulations of **graphite target** indicate 2 MW could be acceptable
STFC will also study alternatives

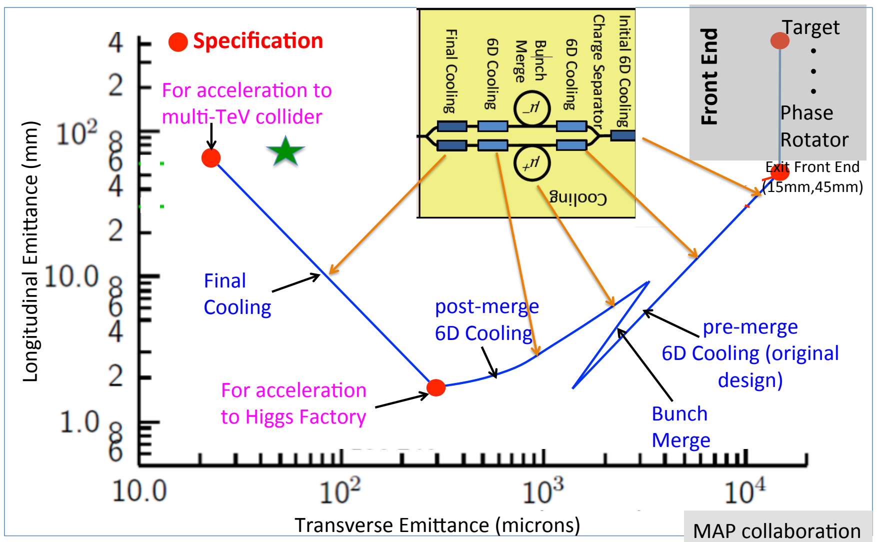
Muon Cooling



C. Rogers, B. Stechauner, E. Fol et al. (RAL, CERN)

MAP designs almost achieve 10 TeV goal

- miss factor two for final cooling



C. Rogers et al. (RAL, CERN)

UKRI, Imperial, UWAR, CERN, INFN, UMIL, ENEA, EPFL

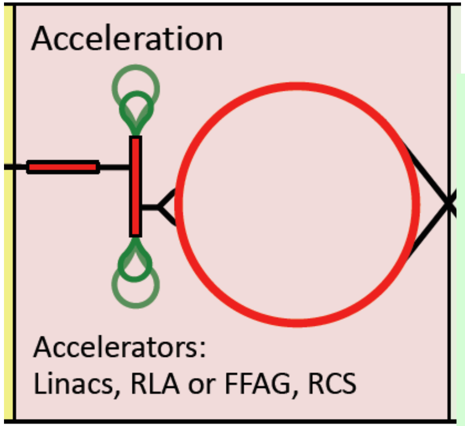
WP4: **Lattice design** (UKRI)

WP4: **Code development** (Imperial)

CHART: **Collective effects** (EPFL)

T. Pieloni et al. (EPFL, CERN)

Acceleration Complex



Core of baseline is sequence of pulsed synchrotron (0.4-11 ms)
Key cost and power driver, novel system

CEA, INFN, CERN, HUD, RHLU, BNL, LNCMI, Bologna, Darmstadt, Twente, Rostock, Milano, RAL

- **Integrated design of RCS**
  - **WP 5**: lattice with realistic hardware specifications
  - **WP 5**: collective effects
- **Concept of key components**
  - **WP 7**: Fast-ramping normal magnets
  - HTS alternative
  - **WP 7**: Efficient power converters
  - **WP 6**: RF with transient beam loading
- **WP 5:** Alternative FFA

A. Chance et al. (CEA)

E. Metral et al. (CERN)

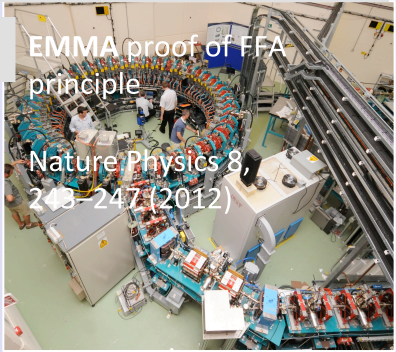
L. Bottura et al. (LNCMI, Darmstadt, Bologna, Twente)

F. Boattini et al.

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

S. Machida et al. (RAL)

FNAL 300 T/s HTS magnet

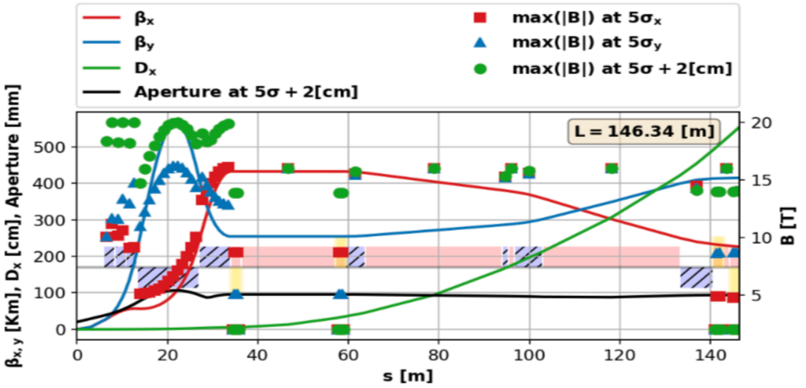


Collider Ring

MAP developed 4.5 km ring for 3 TeV with Nb_3Sn
- magnet specifications in the HL-LHC range

Work progressing on 10 km ring for **10 TeV collider ring**
- around 16 T Nb_3Sn or HTS dipoles
- final focus based on HTS

Need stress managed magnet designs



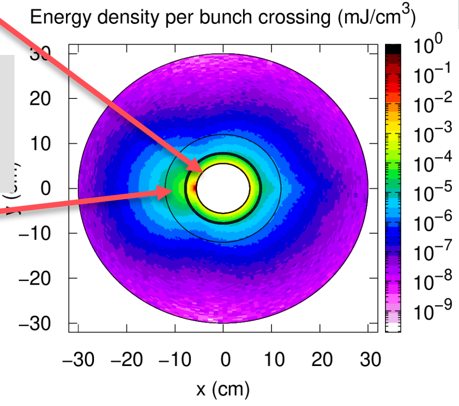
C. Carli, K. Skoufaris (CERN)

CERN, INFN, Milano, Kyoto, profit from US
WP 5: lattice design
WP 5: collective effects
WP 5: shielding
WP 7: collider magnets

Shielding

A. Lechner
D. Calzolari
(CERN)

Coil



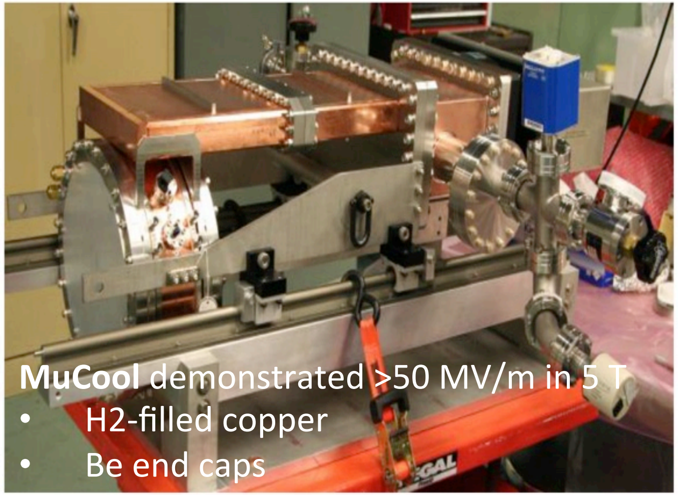
Field choice will be reviewed for cost
Example alternatives:
- a 6 km 3 TeV ring with **NbTi** at 8 T in arcs
- a 15 km 10 TeV ring with HL-LHC performances

RF Technology

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

High-energy RF system
- beamloading impact on beam
- efficiency
- robustness

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



CEA, INFN, UROS, ULA, Strathclyde, CERN
WP 6: Muon cooling RF design (CEA, INFN)
WP 6: Breakdown mitigation (CEA)
- **based on theoretical understanding**

WP 6: High-energy complex RF (Rostock)
WP 6: Efficient power sources (ULA)

Preparation of **new test stand**, but **needs funding**
- Test stand at CEA (700 MHz, ned funding)
- Test at other frequencies in the UK considered
- Use of CLIC breakdown experiment considered

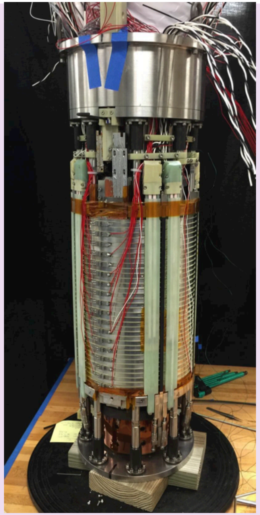
Magnet Technology

Target solenoid
- Large aperture high field, potential synergy with ITER

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

6D cooling solenoids
- Large aperture high field, potential synergy with power generators

Collider ring magnets
- Large aperture dipoles, quadrupoles etc.

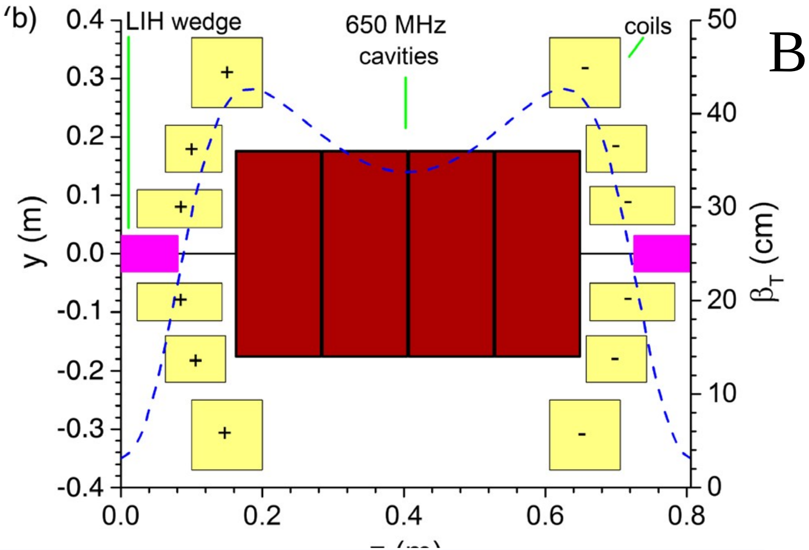


L. Bottura et al. INFN (Task Leader), CEA, CERN, LNCMI, PSI, SOTON, UNIGE and TWENTE, in collaboration with KEK and US-MDP

INFN, CERN, CEA, CNRS, KIT, PSI, SOTON, UNIBO, UNIGE, PSI, TUDa, TWENTE, in collaboration with KEK and US-MDP
WP 7: **Target capture and cooling magnets** (INFN)
WP 7: **Fast-ramping magnets** (CERN)
WP 7: **Collider ring magnets** (INFN)
For all: Develop realistic performance targets
Almost no budget for experiments

Cooling Cell Integration

International
UON Collider
Collaboration



B8

Cooling cell poses engineering challenges
Timely design and prototyping is essential for test facility
Use specific designs of components that are available in the very near future

Will develop **example cooling cell**

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

UMIL, INFN, UKRI, CERN, Imperial
WP 8: Absorbers and windows (CERN)
WP 8: RF system (INFN)
WP 8: Solenoids (Milano)
WP 8: Performance (UKRI)
WP 8: Cooling cell integration (Milano)

Demonstrator(s)

R&D efforts can be distributed over labs

- cooling demonstrator
- RF test stand
- module test stand
- …

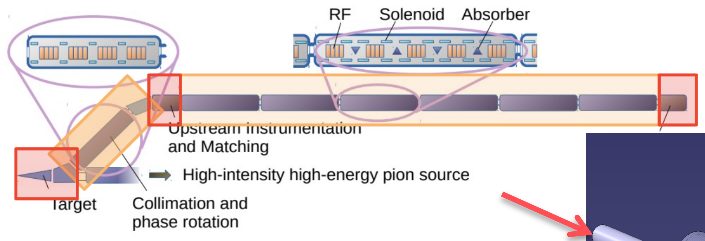
Could also have synergies

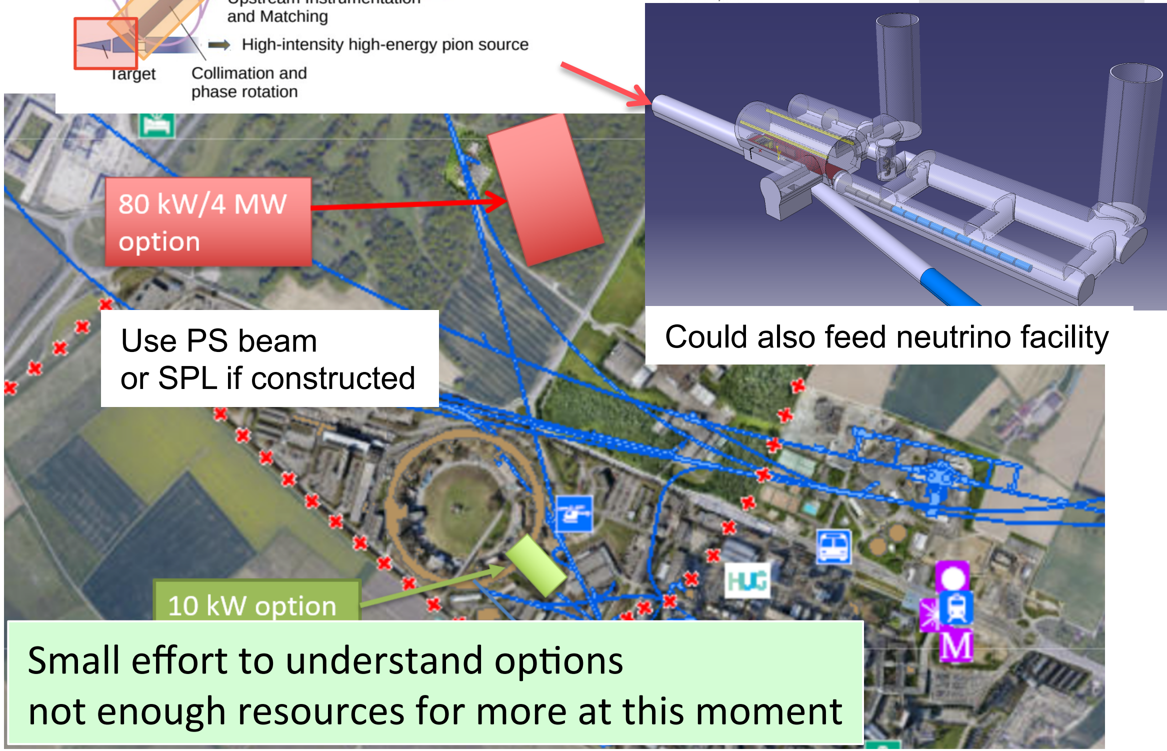
- booster for light sources (e.g. ESRF) or proton therapy?

For cooling demonstrator look for an existing proton beam with significant power

Different sites are being considered

- CERN, FNAL, ESS are being discussed
- J-PARC also interesting as option





Could also feed neutrino facility

Small effort to understand options
not enough resources for more at this moment

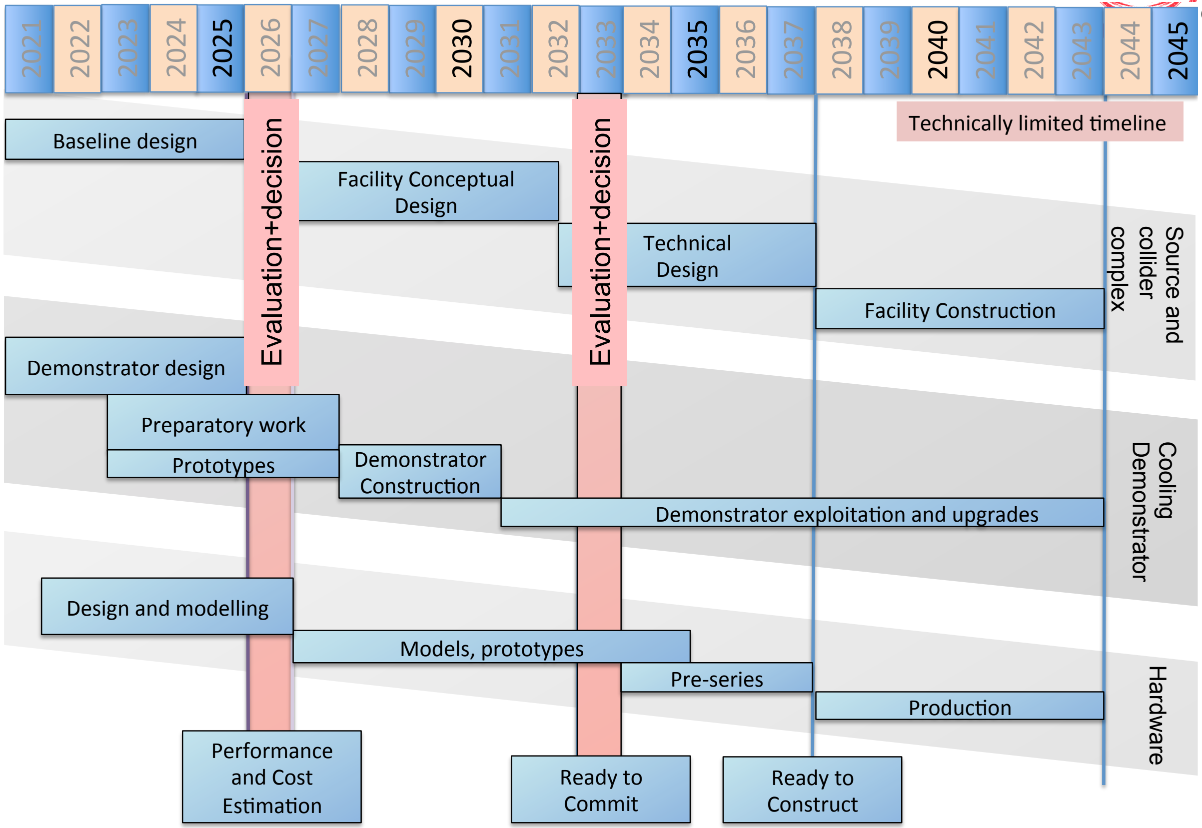
Technically Limited Timeline

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
- might require compromises on initial scope and performance
  - 3 TeV

To be reviewed considering progress, funding and decisions



US Snowmass

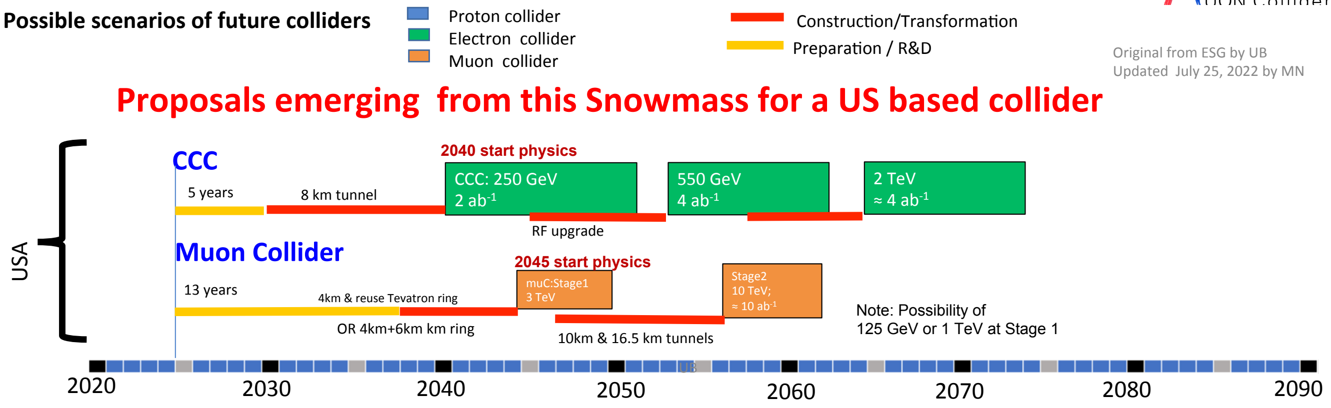
Strong interest in the US community in muon collider

- 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**

Implementation task force:
MC 10 cost range 12-18G$
MC 10 power O(300 MW)



- **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

What is missing?

Relevant gaps exist in the accelerator design

- Proton system: only compressor ring, simple parameters for linac, other systems missing
- Target area design: Beam transport, capture, bunching
- Muon cooling system: Quite limited for complex system, bunch combination design, alternatives
- Initial linac design: Not covered
- Accelerator and collider rings: Somewhat thin (e.g. operational considerations, tolerances)
- Demonstrator design: Focus is on cooling test module

What is missing?

Planned technology activities are mainly theoretical at this moment

More experimental effort is required, in particular

- RF test stand to validate cavities in magnetic field
- Magnet models in particular for HTS
- Power converter technology
- Absorbers and windows
- Target

Conclusion

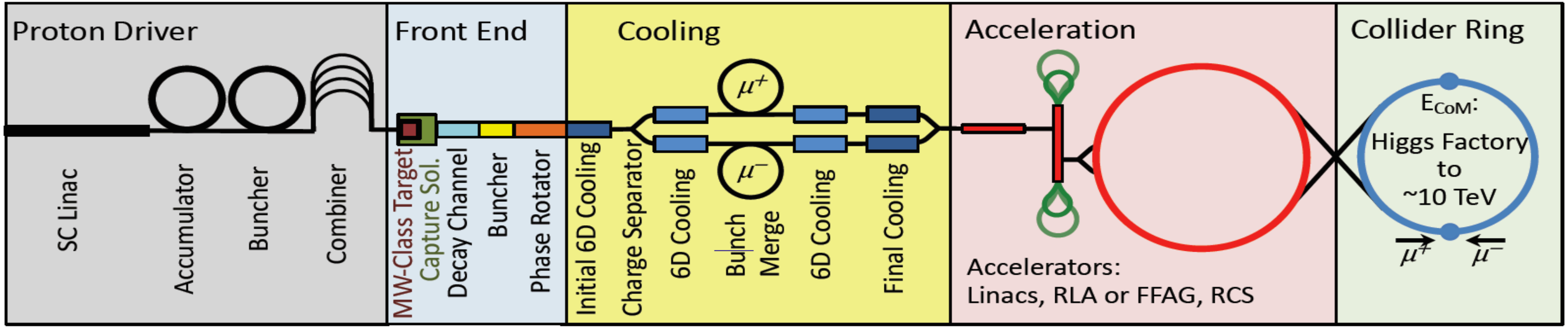
- Collaboration exists
  - expect to still increase
  - US P5 will play an important role
- Addressing key challenges
  - Very motivated team
  - Synergy with applications for society, e.g. HTS solenoids
  - More funding required for full results by next ESPPU
- Working on increasing resources
  - to provide project evaluation report
  - to provide R&D plan and demonstrator design
- Did not cover physics and (most of the) detector

http://muoncollider.web.cern.ch   Contact muon.collider.secretariat@cern.ch

Reserve

Collider Concept

Fully 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

Thanks to MAPS

Motivation and Goal

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

New strong interest in **high energy, high luminosity lepton collider**

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

Muon collider promises **sustainable** approach to the **energy frontier**

- limited power consumption, cost and land use

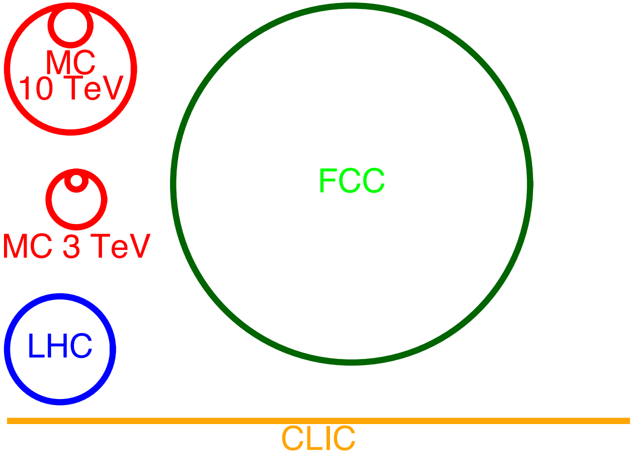
Technology and **design advances** in past years

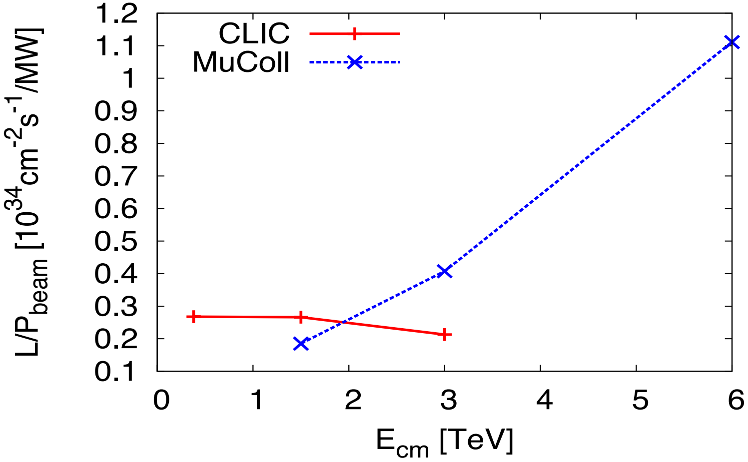
- review did not find any showstoppers

Goal is

- 10+ TeV collider
- potential initial energy stage (e.g. 3 TeV)
- higher energies to be explored later

Sustainability





CLIC is highest energy proposal with CDR

- No obvious way to further improve linear colliders (decades of R&D)
- Cost 18 GCHF, power approx. 500 MW

Rough rule of thumb:

- cost proportional to energy
- power proportional to luminosity

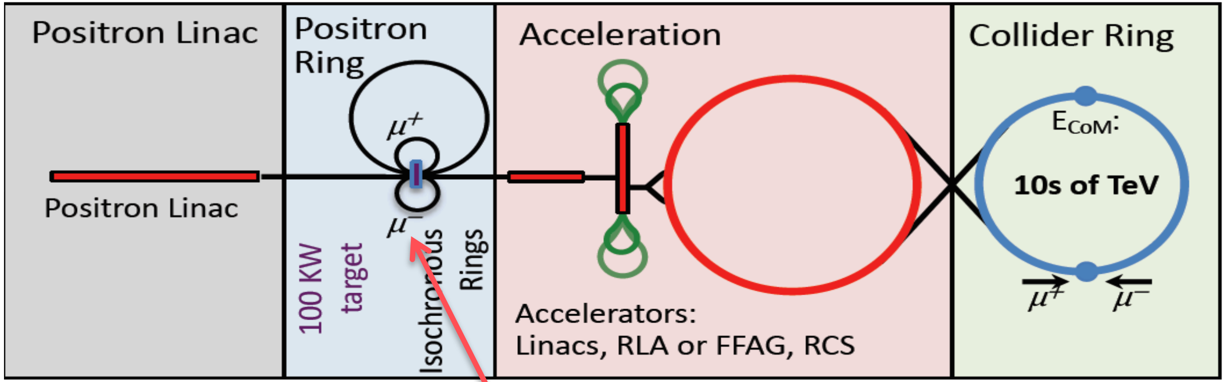
Muon Collider goals (10 TeV), challenging but reasonable:

- Much **more luminosity** than CLIC at 3 TeV **($L=20x10^{34}$, CLIC: $L=2x10^{34}/6x10^{34}$)**
- **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**

Alternatives: The LEMMA Scheme

LEMMA scheme (INFN) P. Raimondi et al.



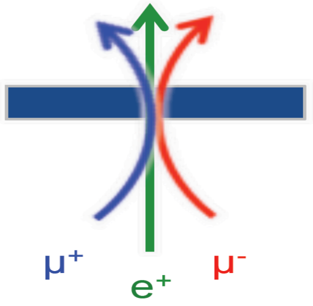
Note: New proposal by C. Curatolo and L. Serafini needs to be looked at

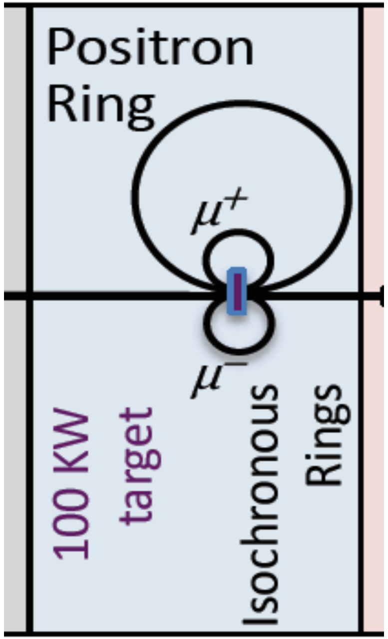
- Uses Bethe-Heitler production with electrons

45 GeV positrons to produce muon pairs

Accumulate muons from several passages

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



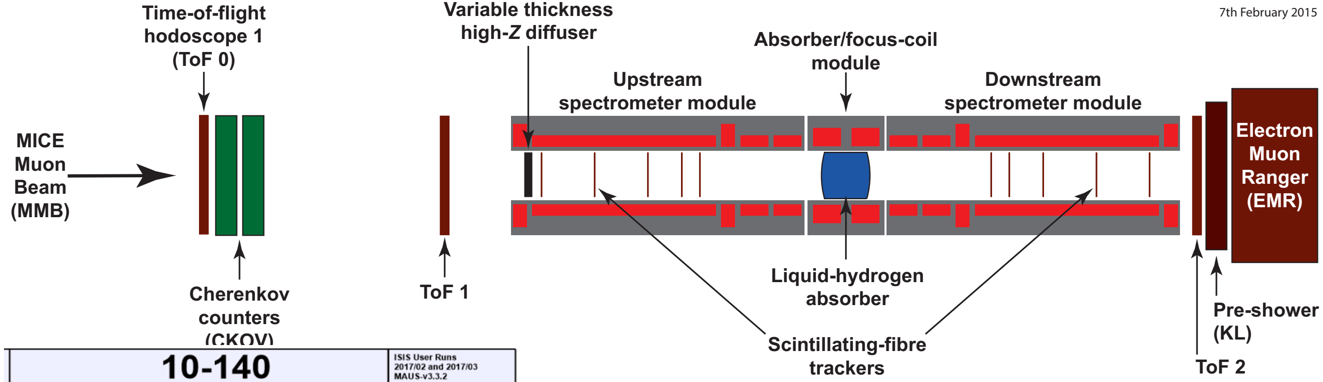


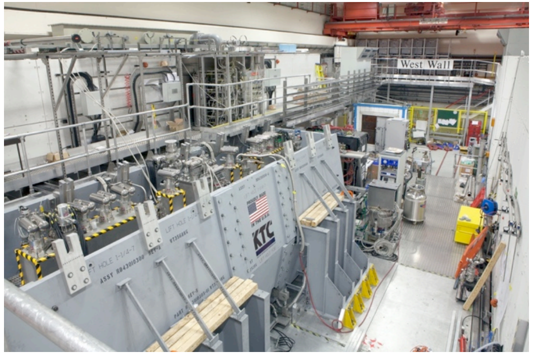
Excellent idea, but nature is cruel

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

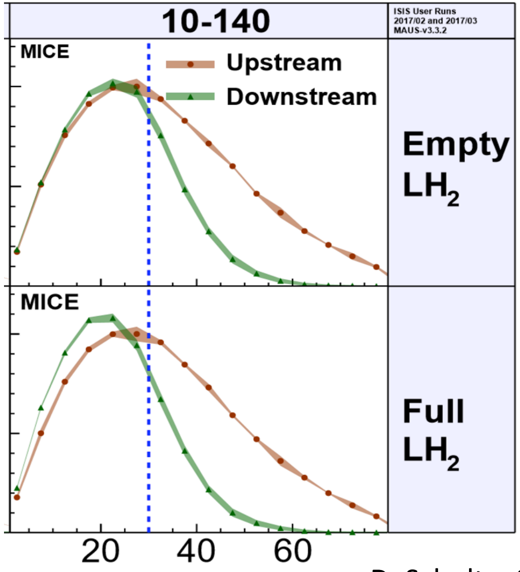
$\Rightarrow$ **Need same game changing invention**

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

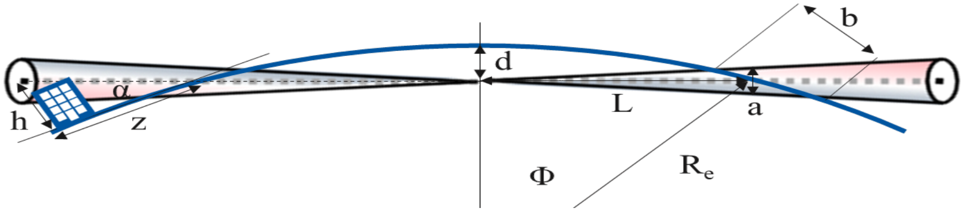
Integration of magnets, RF, absorbers, vacuum is engineering challenge

Neutrino Flux

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

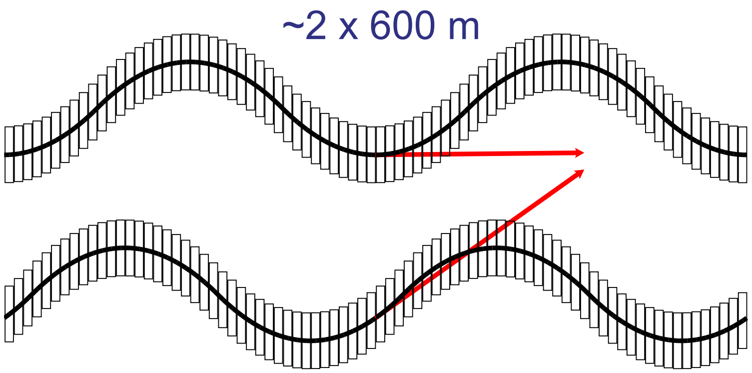
Goal is to reduce to negligible level, similar to LHC

- **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

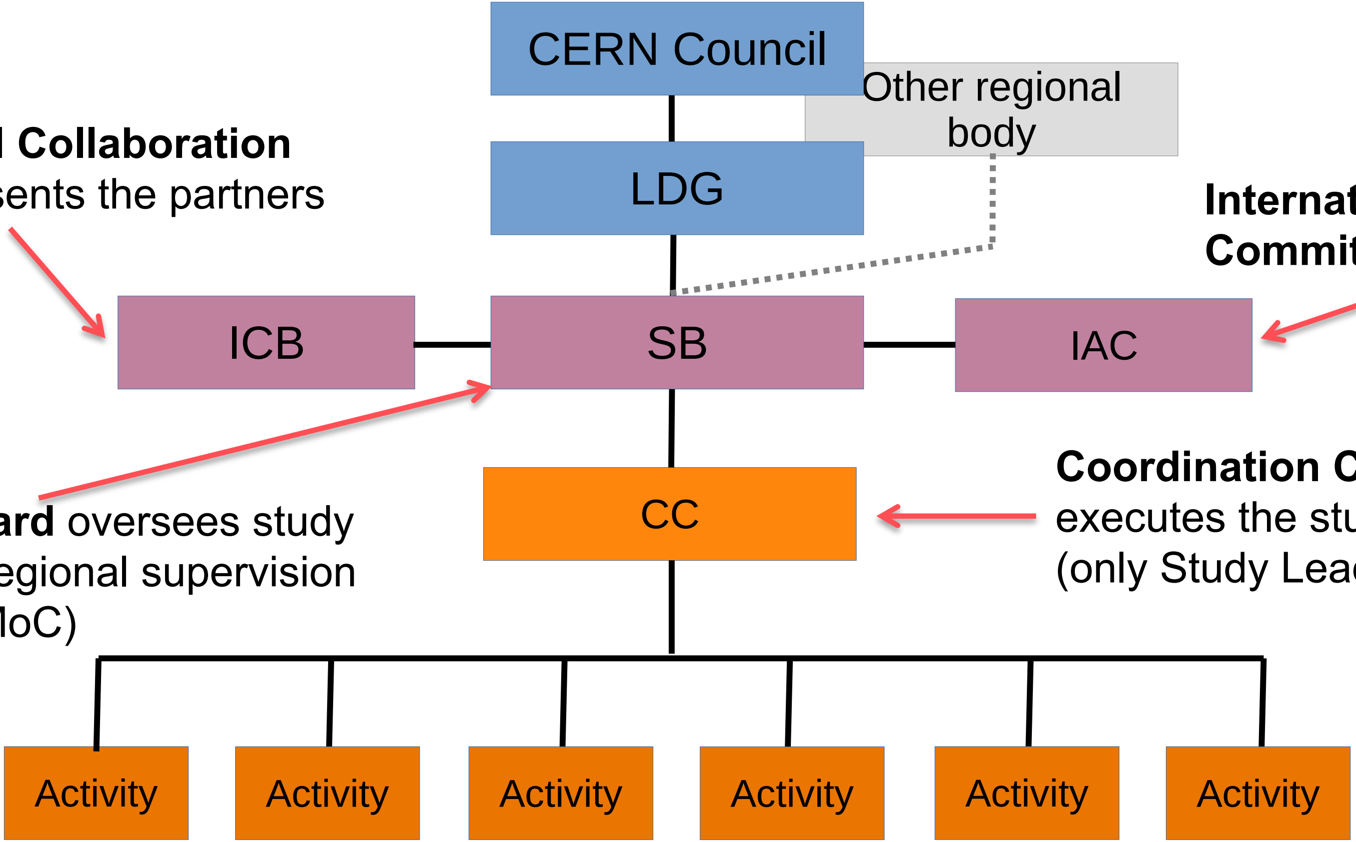
Working on different approaches for experimental insertion

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

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

R&D Plan

The R&D plan will describe the R&D path toward the collider, in particular during the CDR phase, and will comprise the elements below.

- An integrated concept of a muon cooling cell that will allow construction and testing of this key novel component.
- A concept of the facility to provide the muon beam to test the cells.
- An evaluation of whether this facility can be installed at CERN or another site.
- A description of other R&D efforts required during the CDR phase including other demonstrators.

This R&D plan will allow the community to understand the technically limited timeline for the muoncollider development after the next ESPPU.

Roadmap

In **aspirational scenario** can make **informed decisions**:

Three main deliverables are foreseen:

- a **Project Evaluation Report** for the next ESPPU will contain an assessment of whether the 10 TeV muon collider is a promising option and identify the required compromises to realise a 3 TeV option by 2045. In particular the questions below would be addressed.
    - What is a realistic luminosity target?
    - What are the background conditions in the detector?
    - Can one consider implementing such a collider at CERN or other sites, and can it have one or two detectors?
    - What are the key performance specifications of the components and what is the maturity of the technologies?
    - What are the cost drivers and what is the cost scale of such a collider?
    - What are the power drivers and what is the power consumption scale of the collider?
    - What are the key risks of the project?
- an **R&D Plan** that describes an R&D 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.

Minimal Scenario

Will allow **partially informed decisions**

- No conceptual design of neutrino flux and alignment system
- No alternative superconducting fast-ramping magnet system
- Several collider systems would (almost) not be covered, in particular
  - the linacs
  - the target complex
  - the proton complex
  - engineering considerations of the muon cooling cells
  - alternative designs for the final cooling system, acceleration, collider ring
- No RF test stand would be constructed for the muon cooling accelerating cavities
- No conceptual design of a muon cooling cell for the test programme
- No conceptual design of a muon cooling demonstrator facility
- No concept of RF power sources
- No tests/models to develop solenoid technology.

Schedule

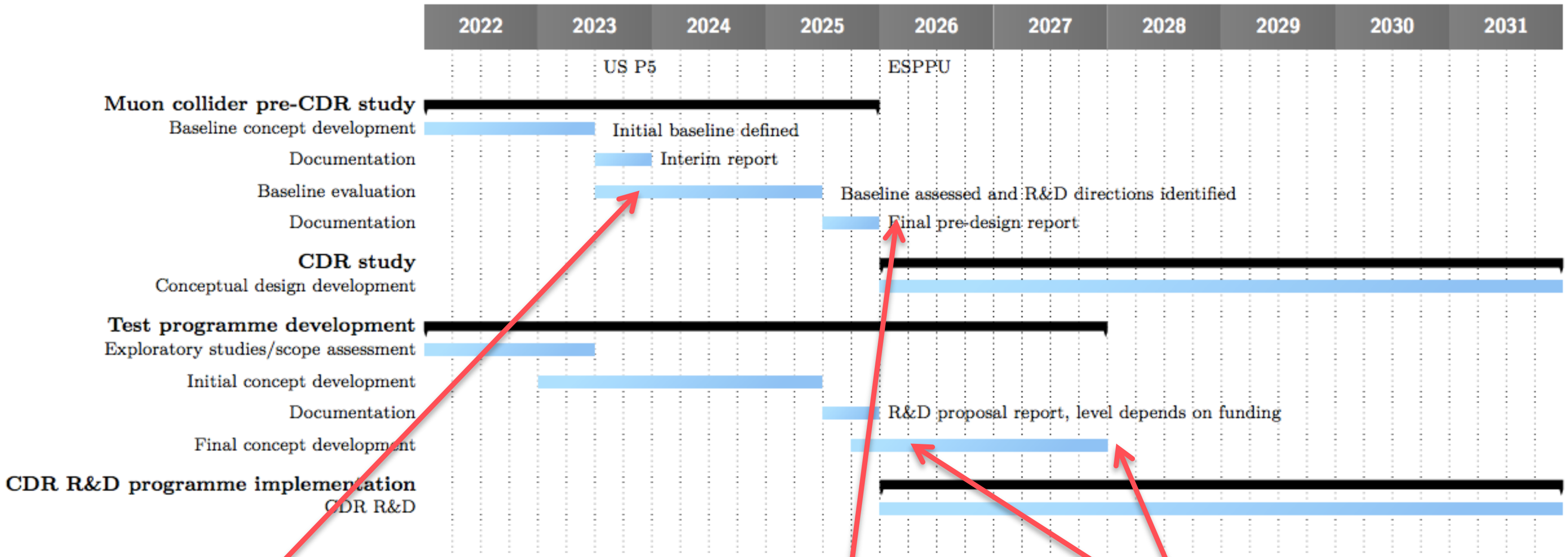


Fig. 5.4: Overall timeline for the R&D programme.

2023
Interim Report to gauge progress
Initial baseline defined

2025
Assessment Report

2025-2027
R&D plan will be refined

Motivation and Goal

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

International MUON Collider Collaboration

New strong interest:

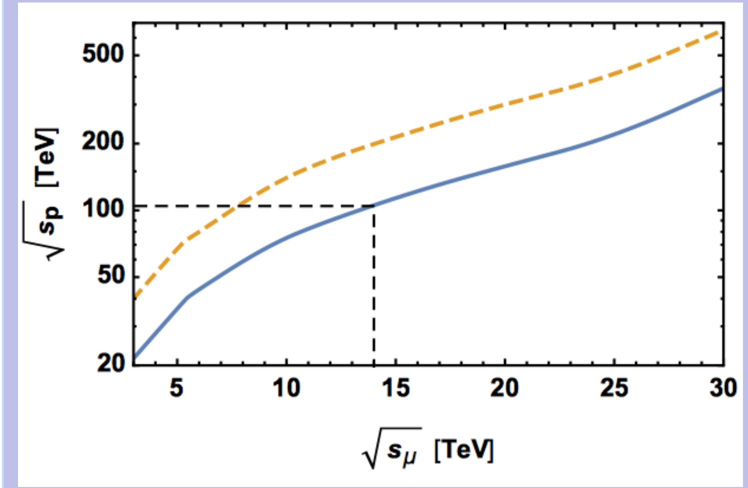
- Focus on **high energy** with **high luminosity**
  - 10+ TeV
  - potential initial energy stage (e.g. 3 TeV)
- **Technology** and **design advances**

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



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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

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**

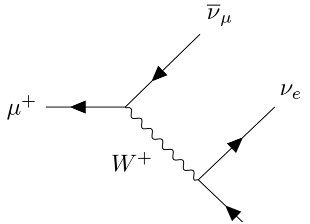
Other mitigation

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

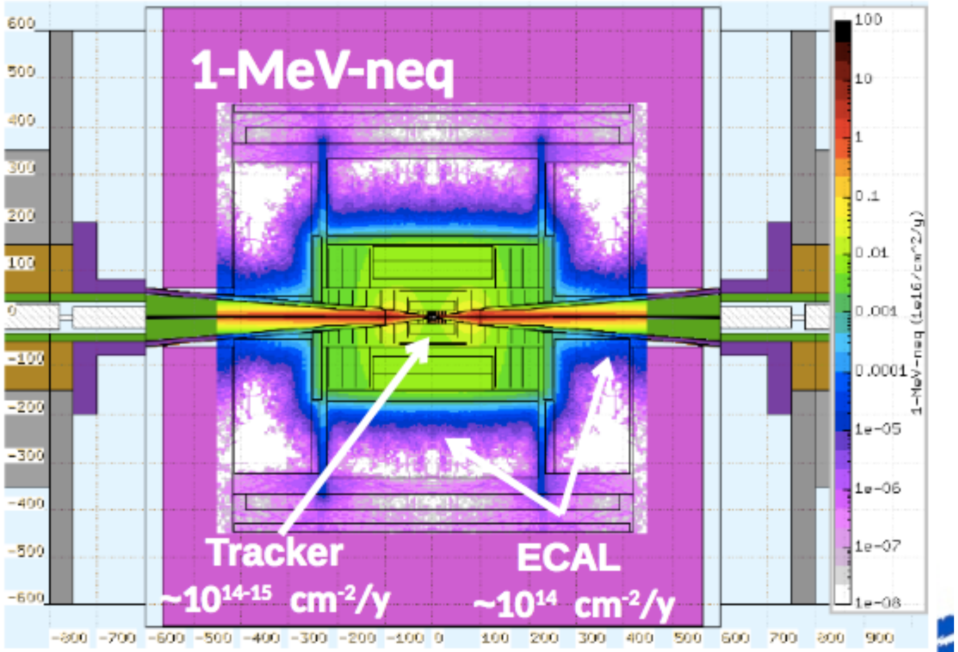
Other background from incoherent pairs is also studied (addition in GUINEA-PIG)

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.

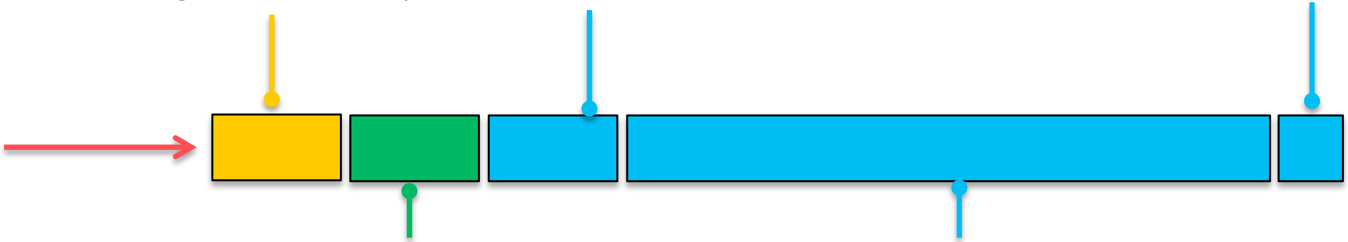


Test Facility Dimensions

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

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

Downstream diagnostics area, 5 m



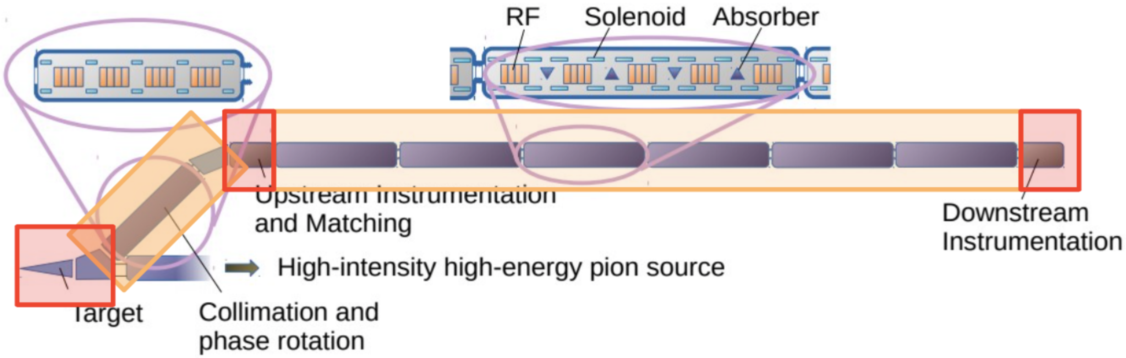
Momentum selection chicane, 10 m

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 also interesting as option

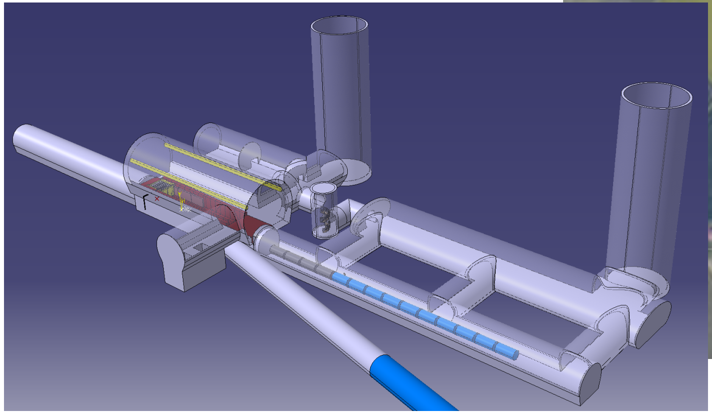


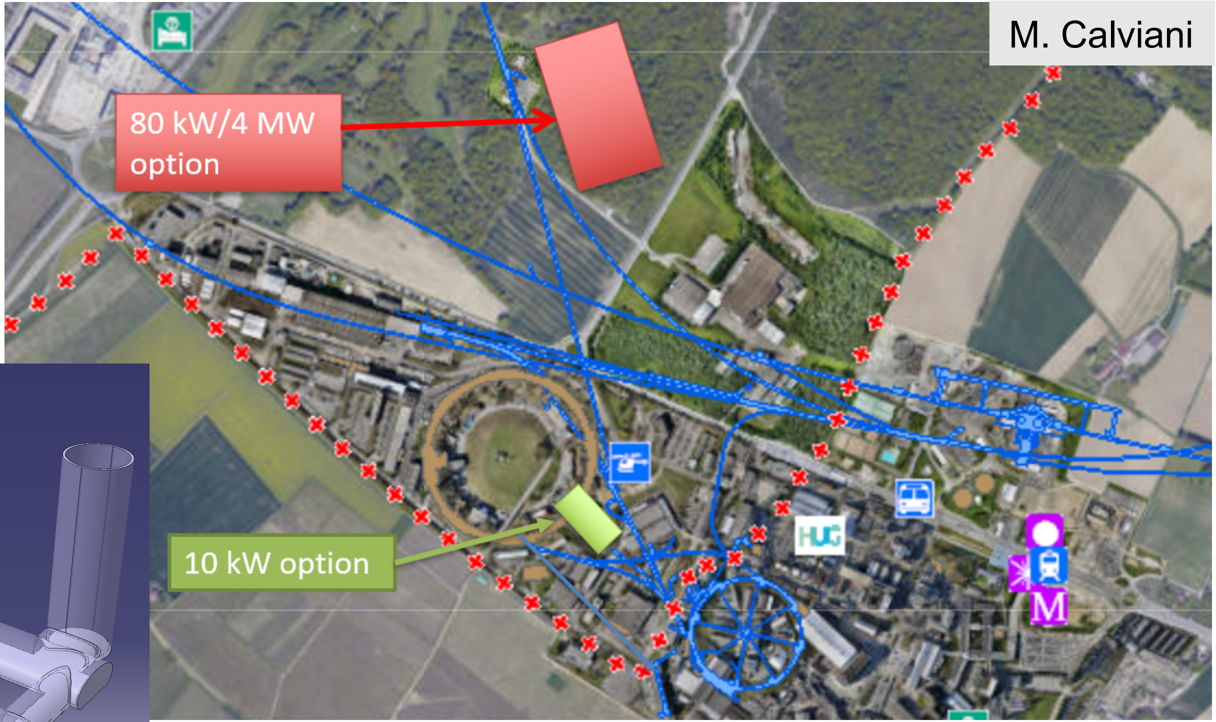
Possible CERN Locations

Consider nTOF-like beam from PS for cooling experiment:

- 1 pulse of 10^{13} p at 20 GeV per 1.2 s, i.e. 27 kW
- maybe O(100kW) possible

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





Workpackages

Proton complex (ESS, CERN, Uppsala)

- High-power linac (CERN)
- Compressor ring design (ESS)

Muon production and cooling complex (UKRI, Imperial, UWAR, CERN, INFN, UMIL, ENEA)

- Cooling system development (UKRI)
- Target system development (CERN)
- Code development (Imperial)