International MUON Collider Collaboration

CERN

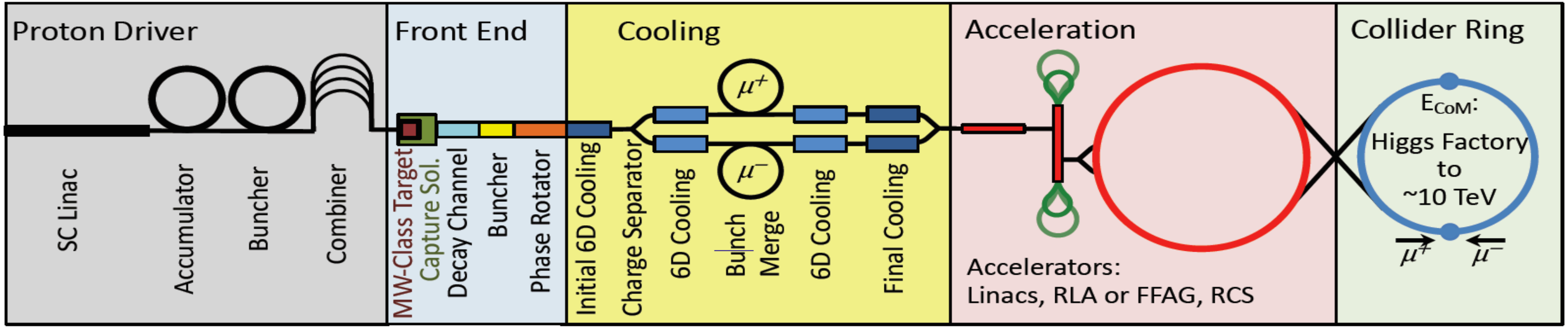
Muon Collider

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

ECFA
November 2022

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

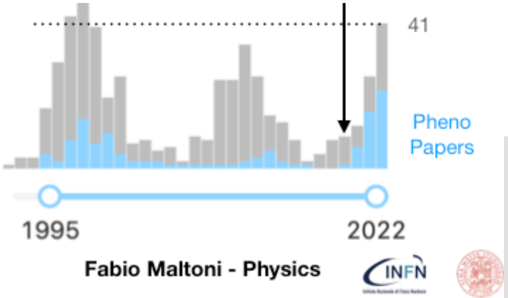
Goal is

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

A new 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

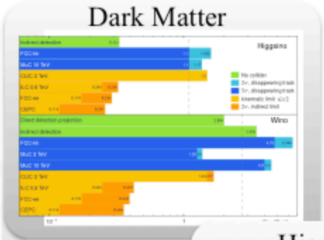
International
UON Collider
Collaboration

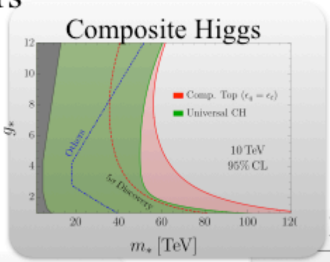
A. Wulzer, F. Maltoni, P. Meade et al.

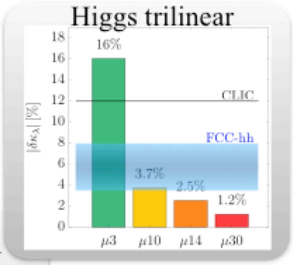
O(150) authors, 15 editors, 100 papers

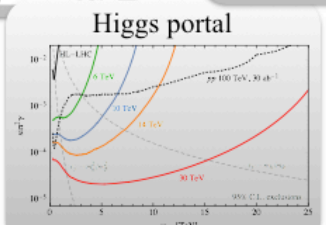
Selected summary plots, from Snowmass21 reports:

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







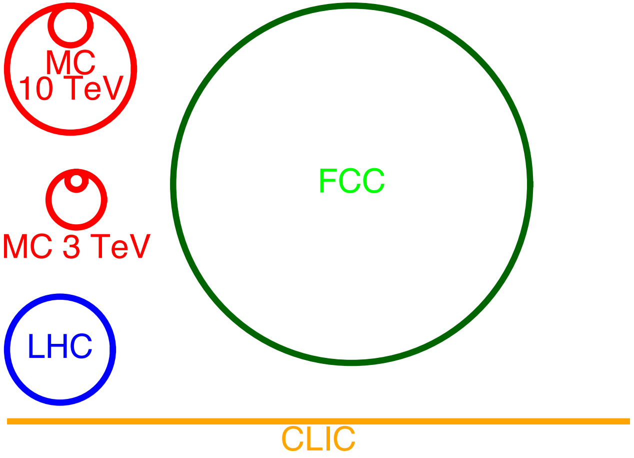


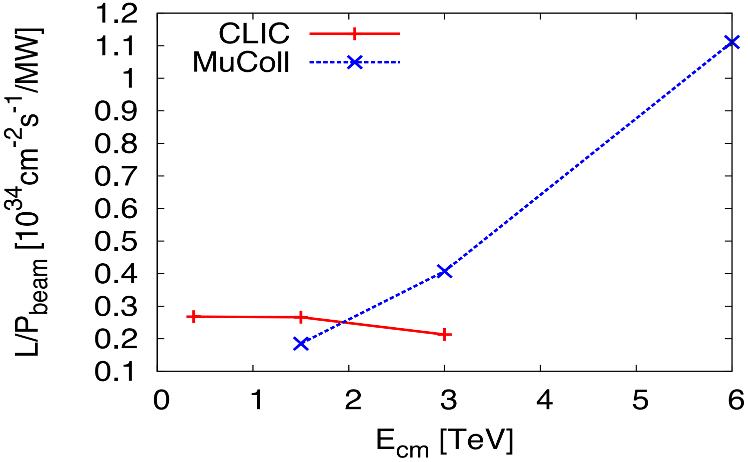
Higgs couplings

	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

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

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

Accelerator R&D Roadmap

International MUON Collider Collaboration

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

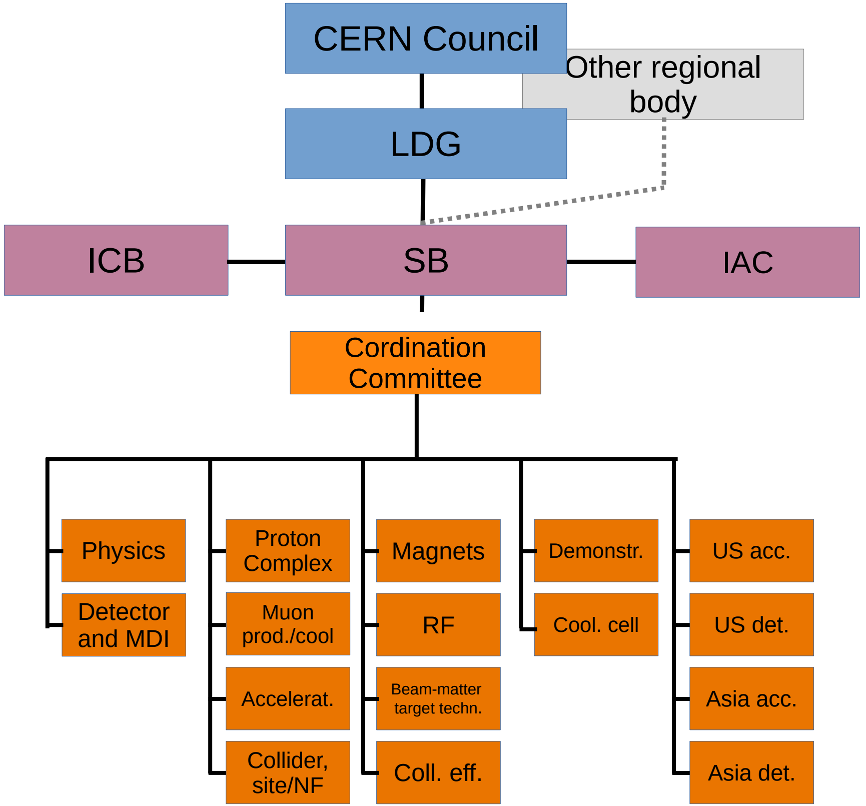
Table 5.5: The resource requirements for the two scenarios. The personnel estimate is given in full-time equivalent years and the material in kCHF. It should be noted that the personnel contains a significant number of PhD students. Material budgets do not include budget for travel, personal IT equipment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

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



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

Reminder: Coordination Committee Members

Physics	Andrea Wulzer
Detector and MDI	Donatella Lucchesi

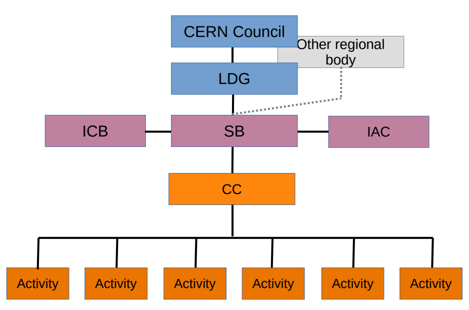
Protons	Natalia Milas
Muon production and cooling	Chris Rogers
Muon acceleration	Antoine Chance
Collider	Christian Carli

Magnets	Luca Bottura
RF	Alexej Grudiev, Claude Marchand
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

Muon Collider Community

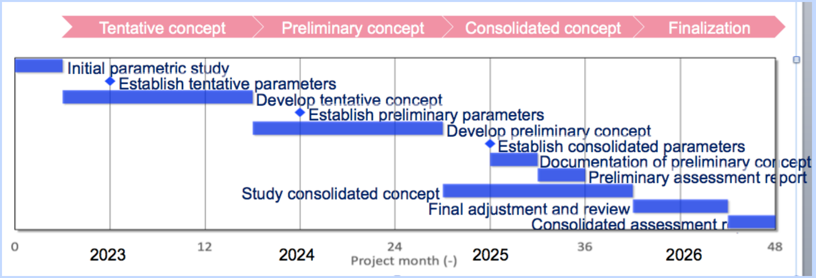
Formed **collaboration** to implement and R&D Roadmap for CERN Council



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)



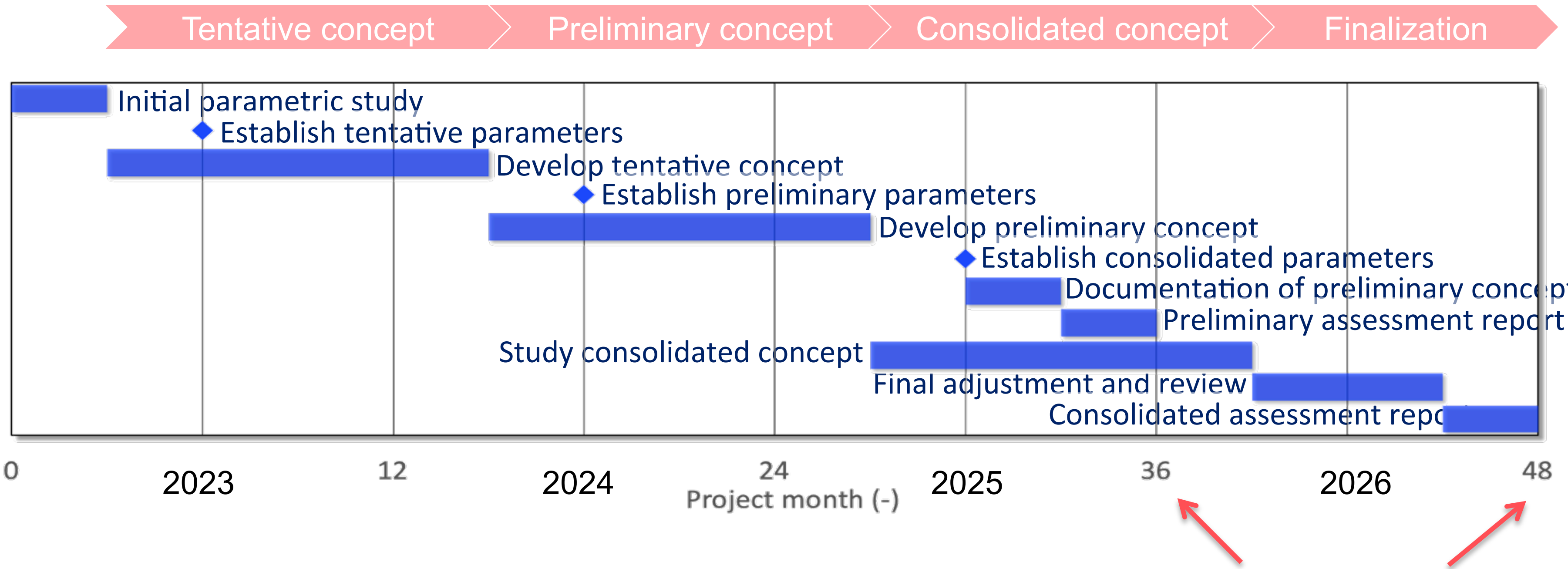
Plan to apply in 2024 for **HORIZON-INFRA-2024-TECH**
Goal: prepare experimental programme, e.g. **demonstrator, prototypes, …**

US Snowmass has **strong support**

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

Now waiting for P5

EU Design Study Timeline



Next ESPPU ?

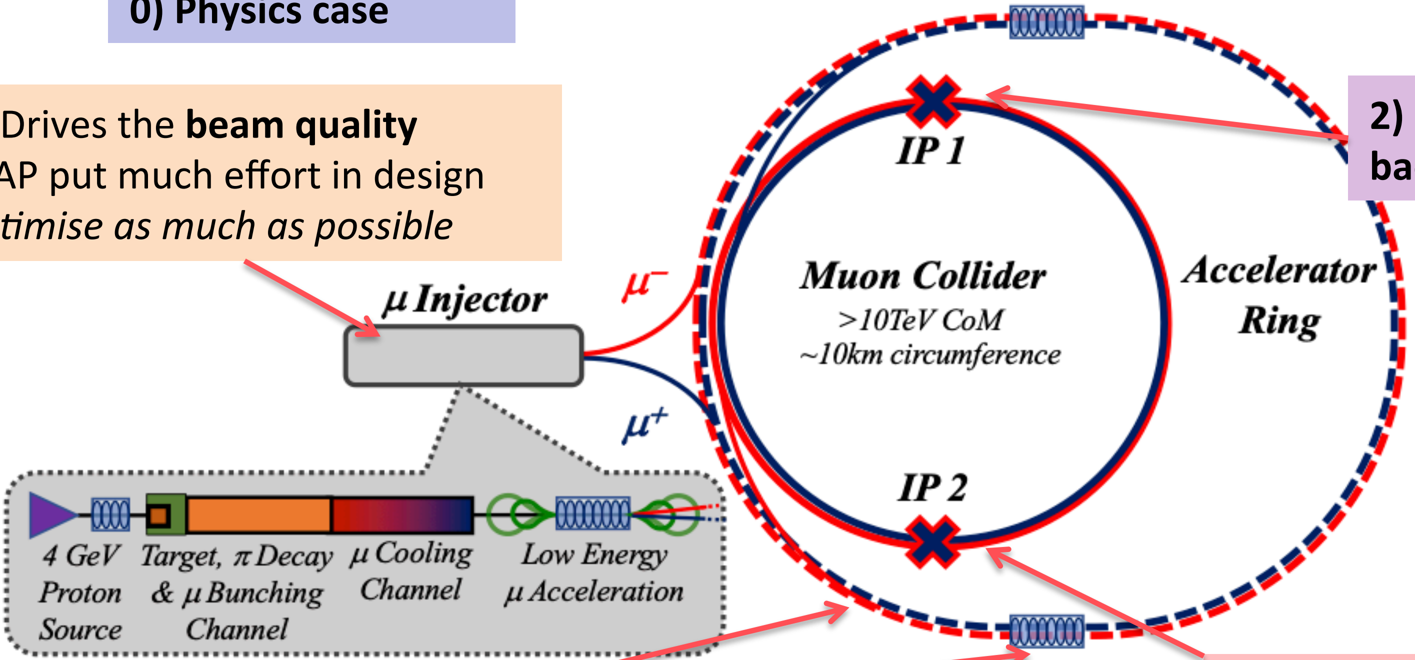
Representative of overall workplan

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)

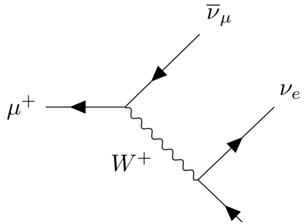
Studies at 1.5 <and 3 TeV with concept based on CLIC detector

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

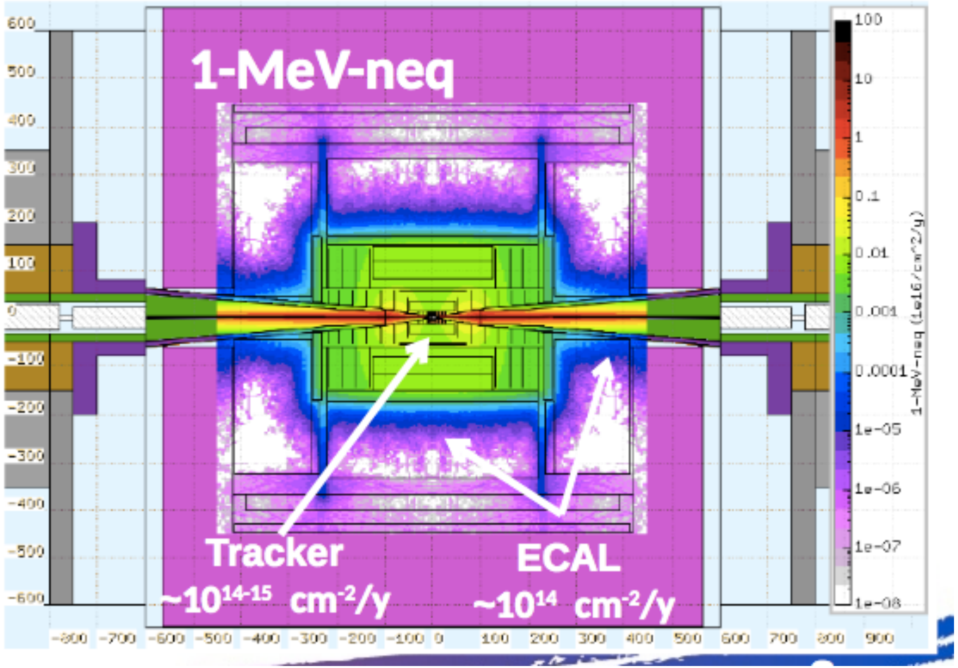
Studies with **beam-induced background** in progress

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

Concept for **10 TeV** in progress

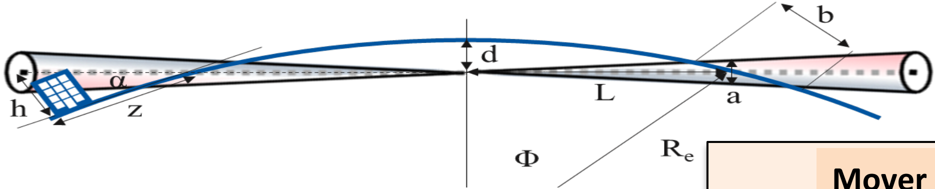


Detector team
O(69) authors, O(150 signatories)



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



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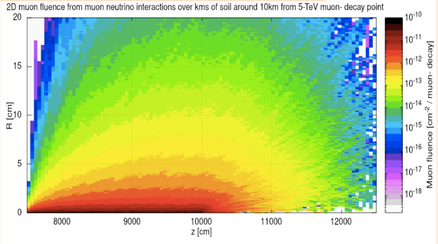
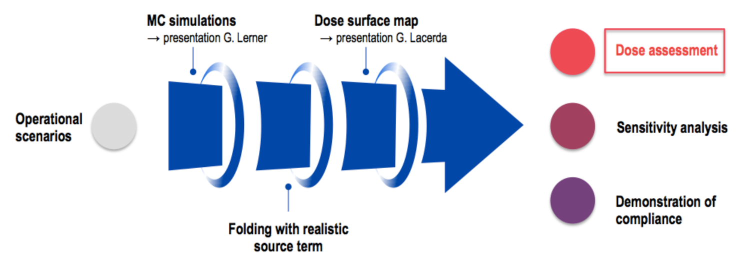
FLUKA dose studies



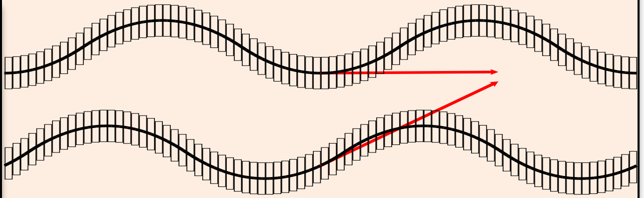
G. Lerner, D. Calzolari, A. Lechner, C. Ahdida

Conformity Verification Scheme



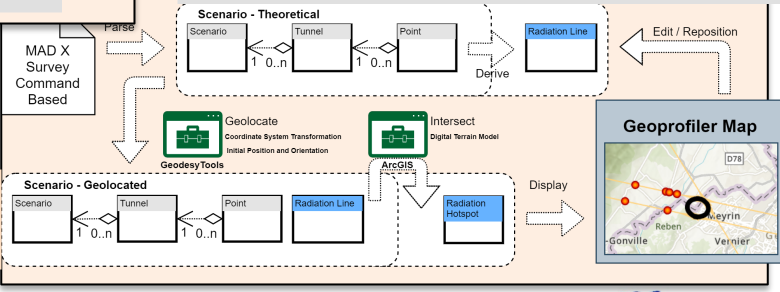
C. Ahdida, P. Vojtyla, M. Widorski, H. Vincke

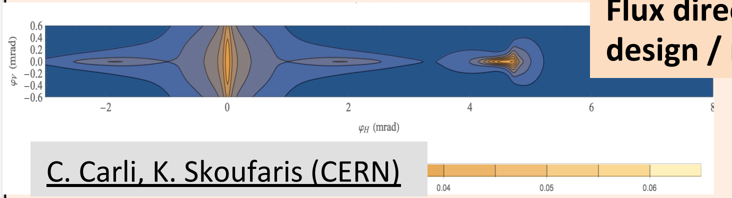
Mover and support system



F. Bertinelli et al. (CERN, Riga)

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





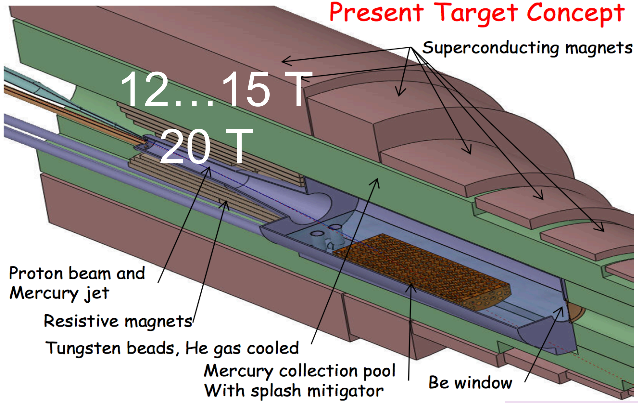
C. Carli, K. Skoufaris (CERN)

Flux direction map / lattice design / mover impact on beam

Mitigation: Site choice tool

Target

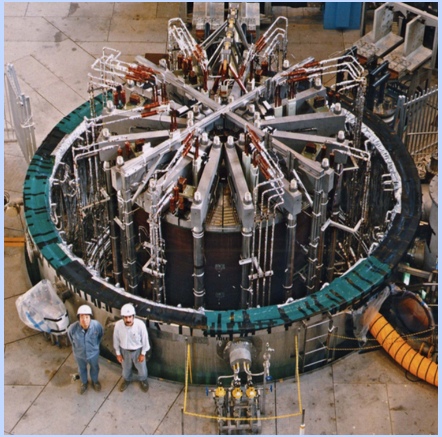
MAP target design, K. McDonald, et al.



Large bore, high field solenoid

Nb_3Sn or HTS

Similar to ITER



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

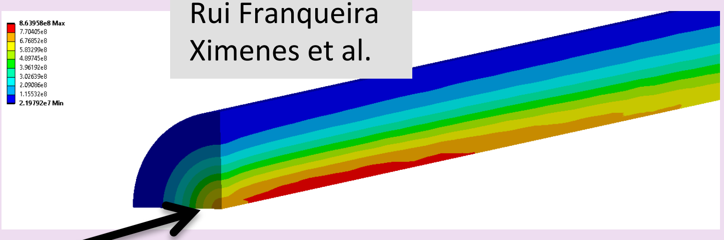
A. Lechner et al.
L. Bottura et al.

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.



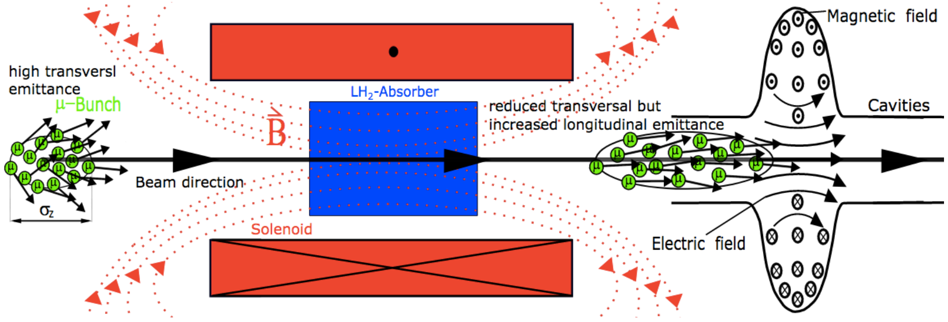
Proton beam

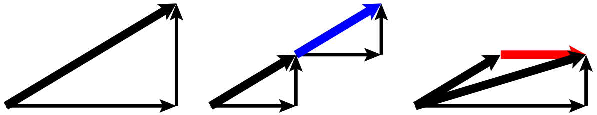
Operation at 2000 °C to maximise stress resistance

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

STFC will also study alternatives

Muon Cooling

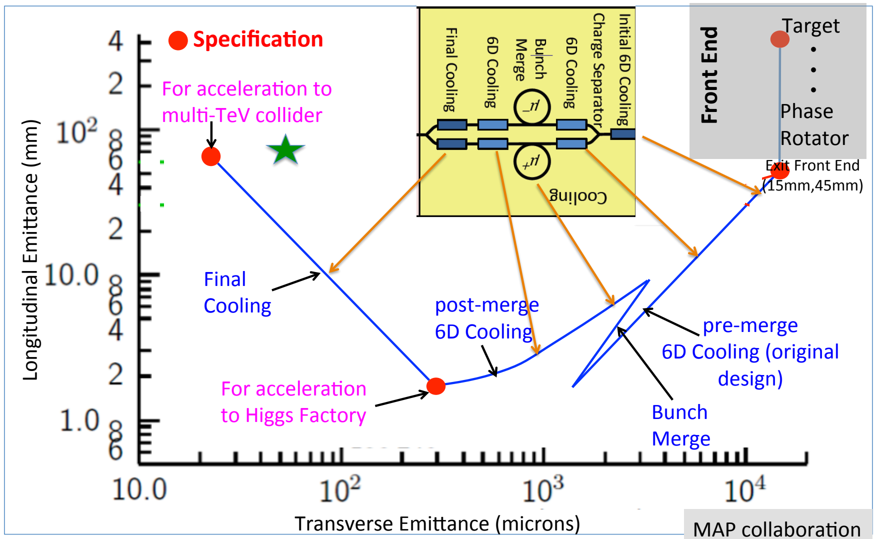




C. Rogers, B. Stechauner, E. Fol et al. (RAL, CERN)

MAP designs almost achieve 10 TeV goal

- miss factor two for final cooling

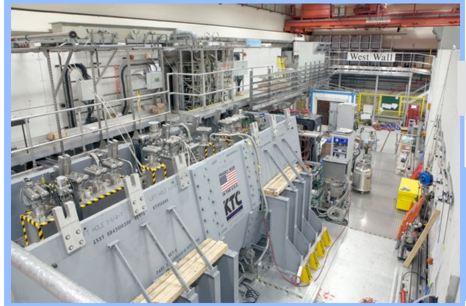


MAP collaboration

Integration/optimisation of design
Integrating **improved technologies**
Collective effects

C. Rogers et al. (RAL, CERN)

T. Pieloni et al. (EPFL, CERN)



MICE Collaboration

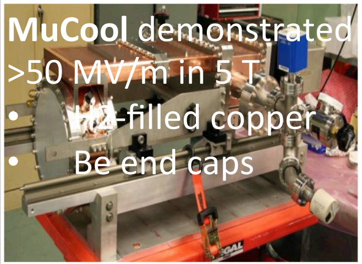
Nature vol. 578, p. 53-59 (2020)

Principle demonstrated with no RF
Use of data for benchmarking is still ongoing

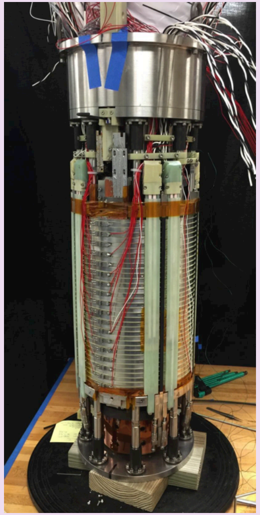
Cooling Cell Technology

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

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

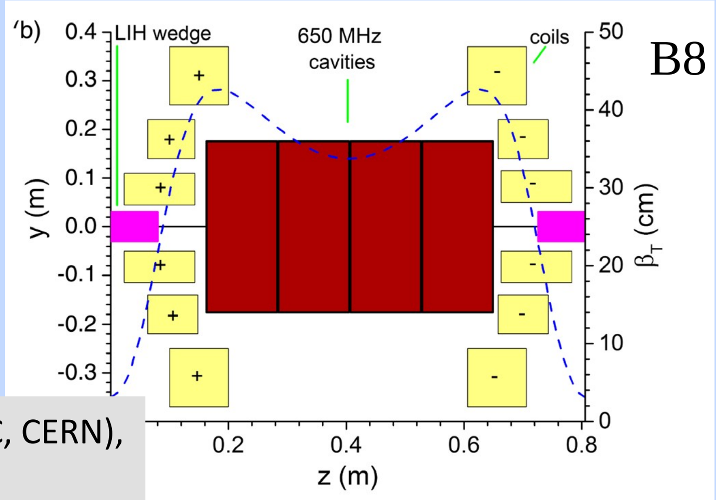


Assessment of realistic goal for highest field solenoids
- MAP demonstrated 30 T
- now magnets aim for 40+ T
- even more can be possible



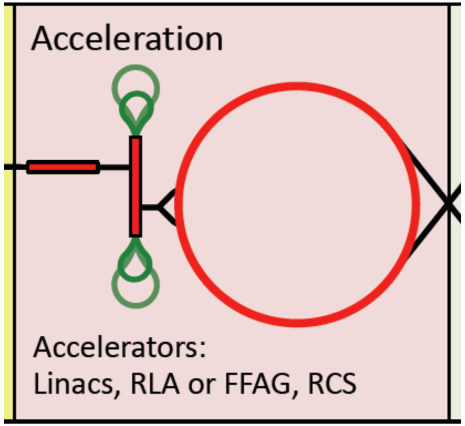
L. Bottura et al. INFN (Task Leader), CEA, CERN, LNCMI, PSI, SOTON, UNIGE and TWENTE, in collaboration with KEK and US-MDP

Will develop example **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



Core of baseline is sequence of pulsed synchrotron (0.4-11 ms)
Important cost and power consumption

Started

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

A. Chance et al. (CEA)

E. Metral et al. (CERN)

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

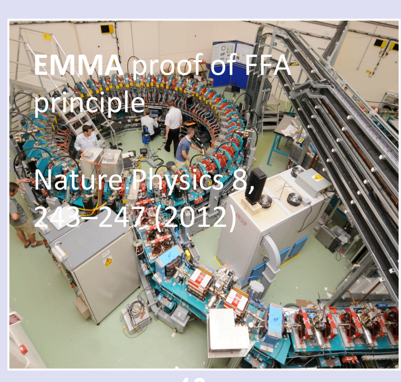
F. Boattini et al.

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

FNAL 300 T/s HTS magnet

- Alternative FFA

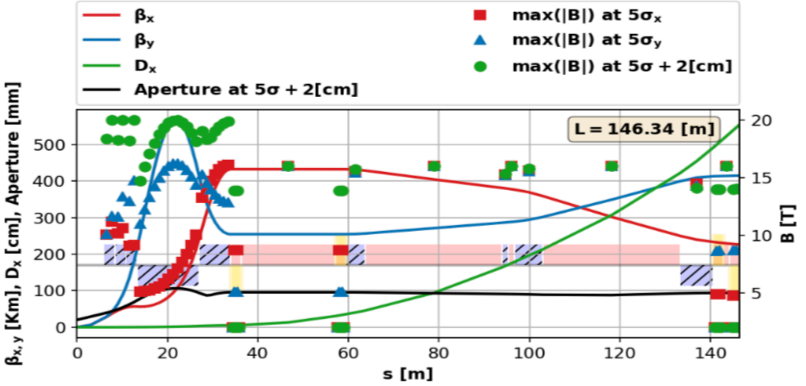
S. Machida et al. (RAL)



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

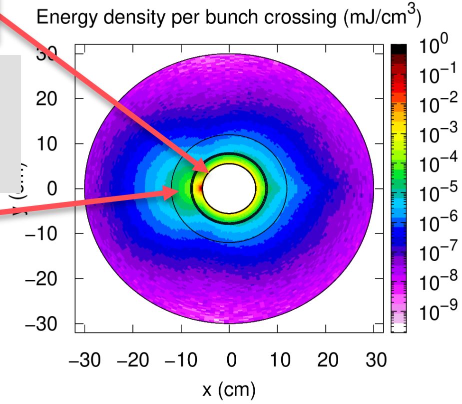


C. Carli, K. Skoufaris (CERN)

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(s)

International MUON Collider Collaboration

R&D efforts can be distributed over labs

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

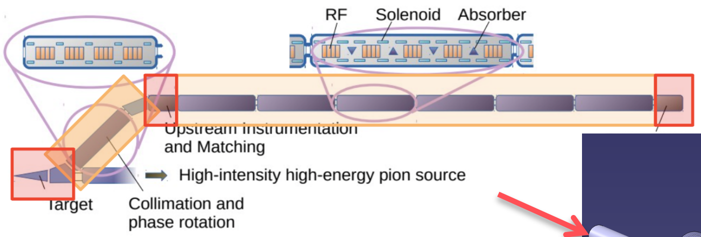
Could also have synergies

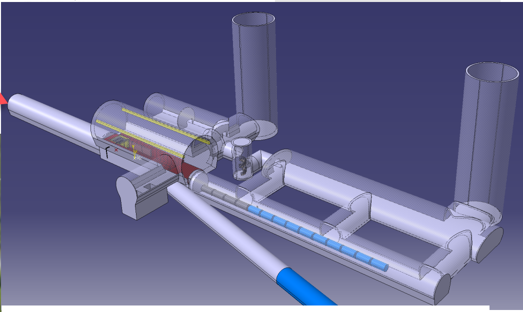
- booster for light sources (e.g. ESRF) or proton therapy?

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

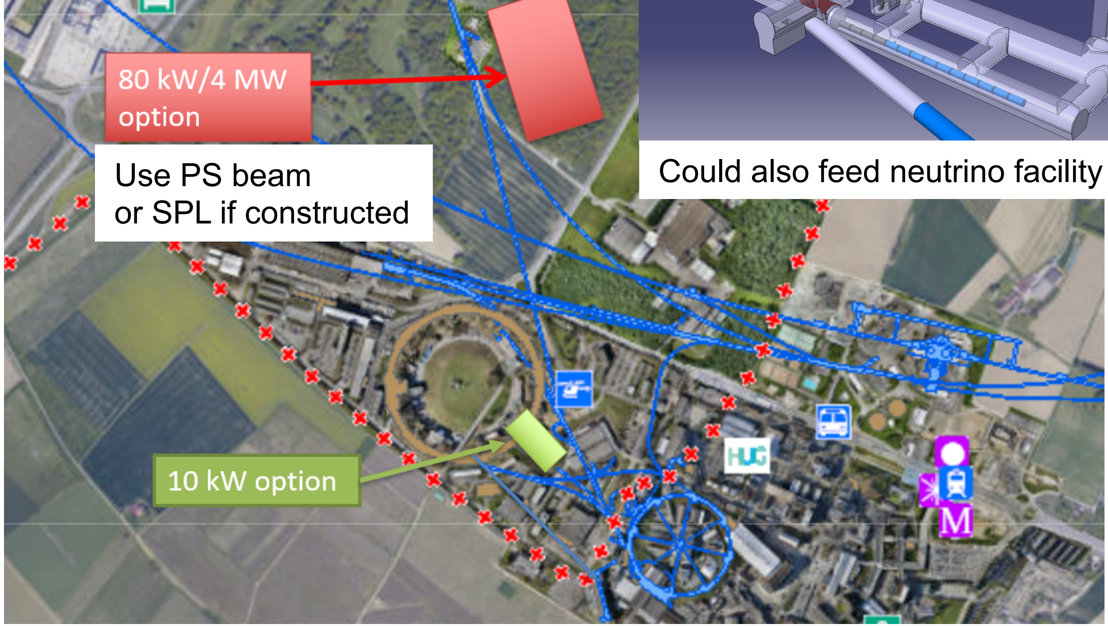
Different sites are being considered

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





Could also feed neutrino facility



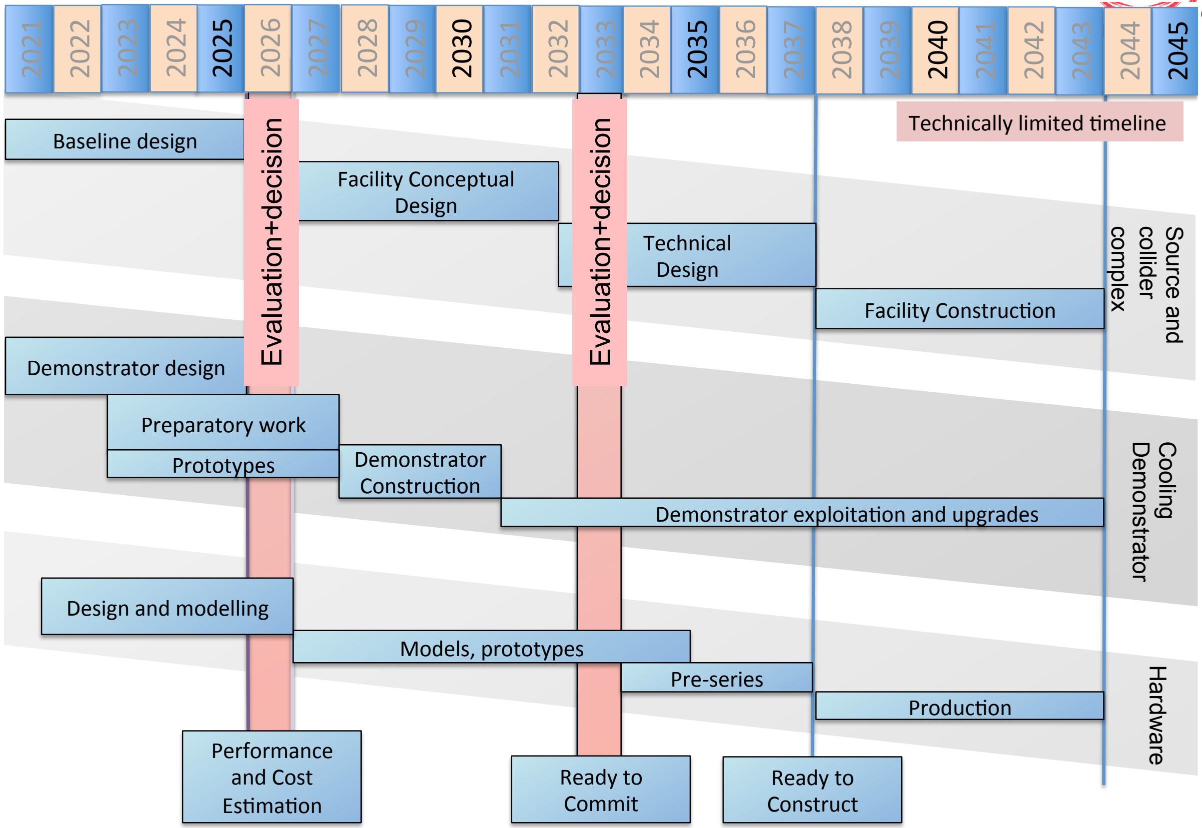
Technically Limited Timeline

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

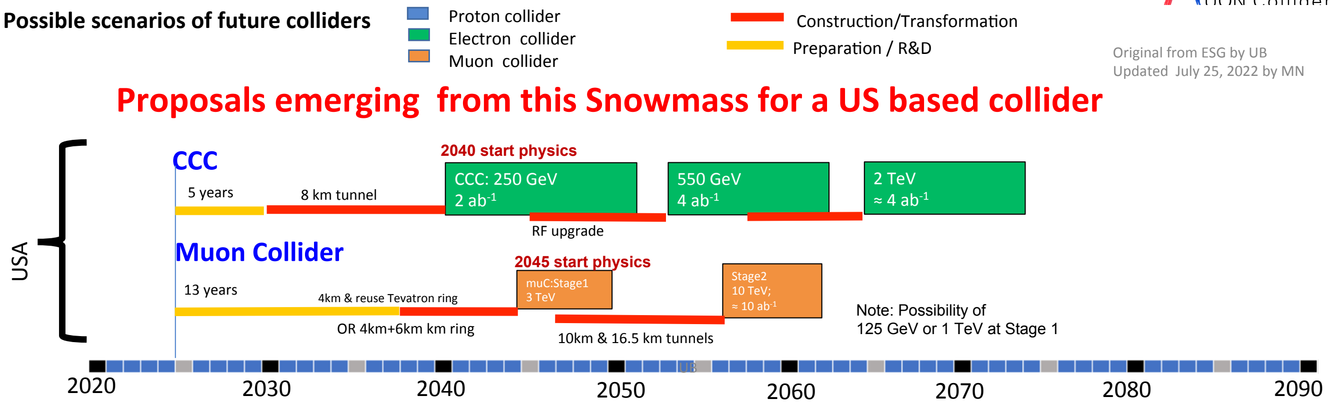
Strong interest in the US community in muon collider

- 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

Conclusion

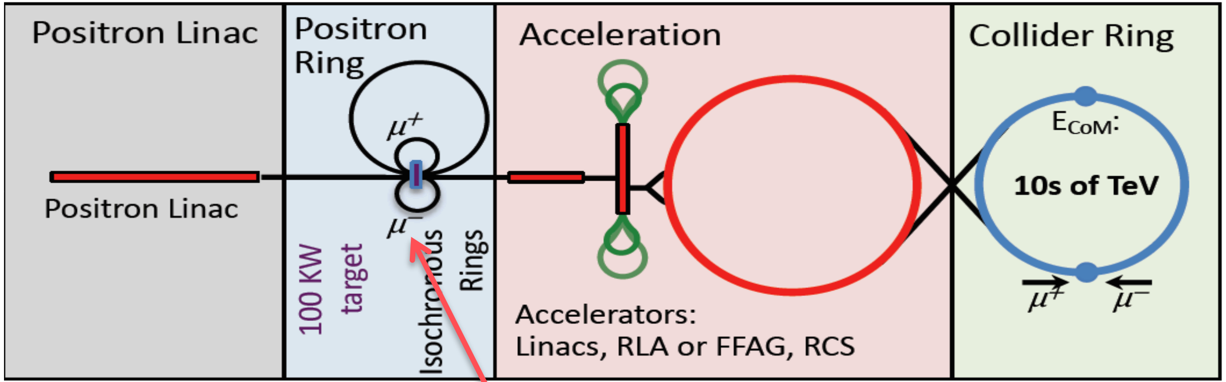
- Muon collider is unique opportunity for high-energy, high-luminosity lepton collider
  - but less mature than other options
- Currently two different options considered
  - goal of 10+ TeV, potential 3 TeV intermediate stage explored
- Collaboration exists
  - expect to still increase
  - US P5 will 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

http://muoncollider.web.cern.ch To join contact muon.collider.secretariat@cern.ch

Reserve

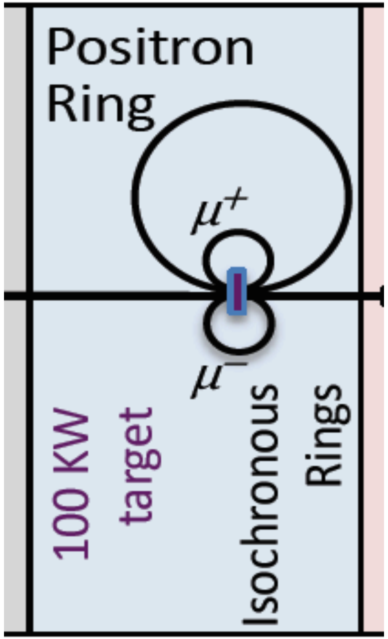
Alternatives: The LEMMA Scheme

LEMMA scheme (INFN) P. Raimondi et al.



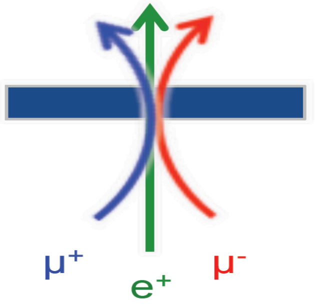
Note: New proposal by C. Curatolo and L. Serafini needs to be looked at

- Uses Bethe-Heitler production with electrons



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

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

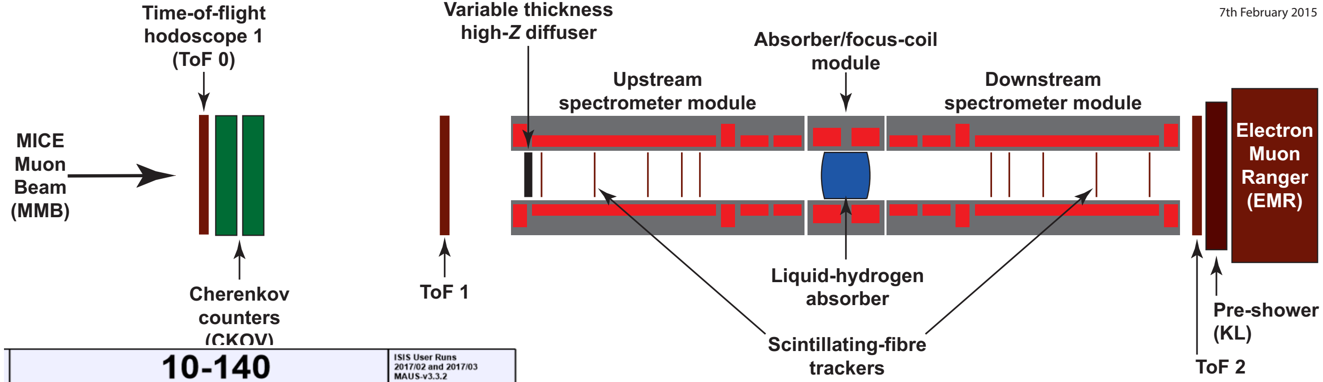


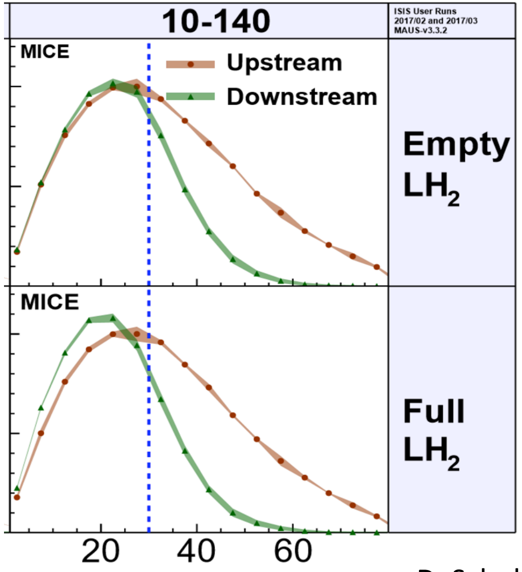
Excellent idea, but nature is cruel

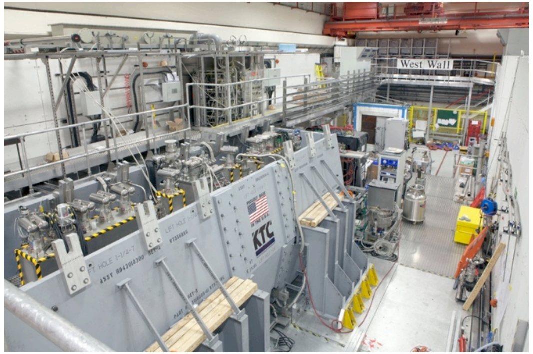
Detailed estimates of fundamental limits show that we require a very large positron bunch charge to reach the same luminosity as the proton-based scheme

$\Rightarrow$ **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

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

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

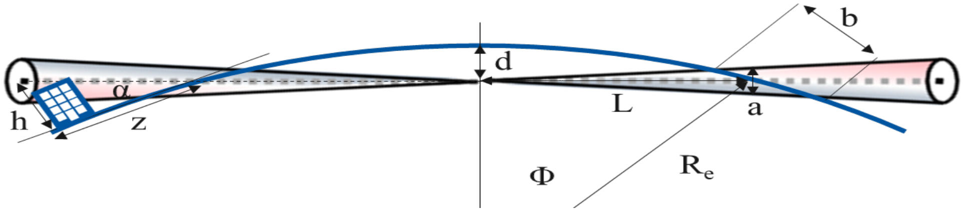
WEPOPT053

Neutrino Flux

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

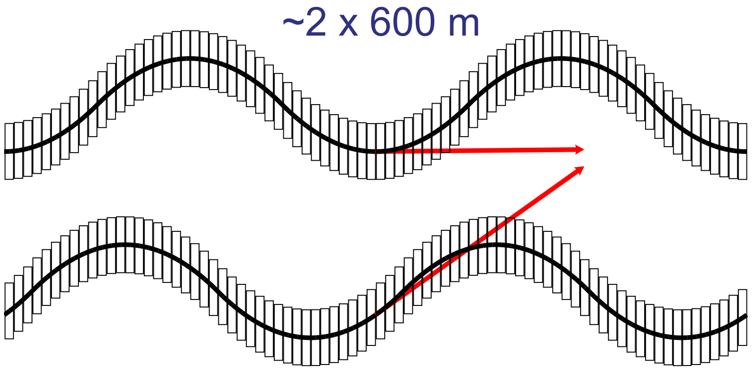
Goal is to reduce to negligible level, similar to LHC

- **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

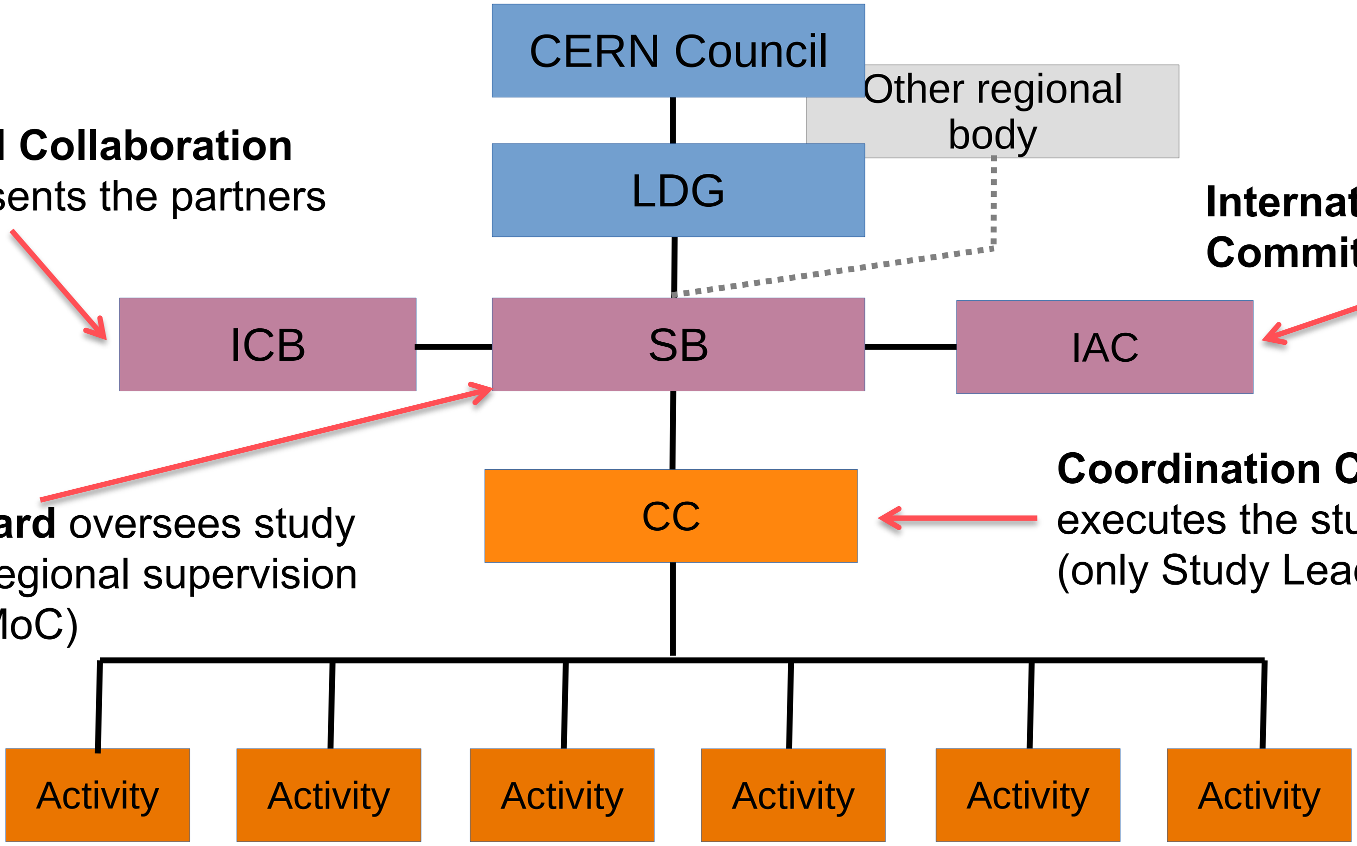
Working on different approaches for experimental insertion

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

International MUON Collider

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

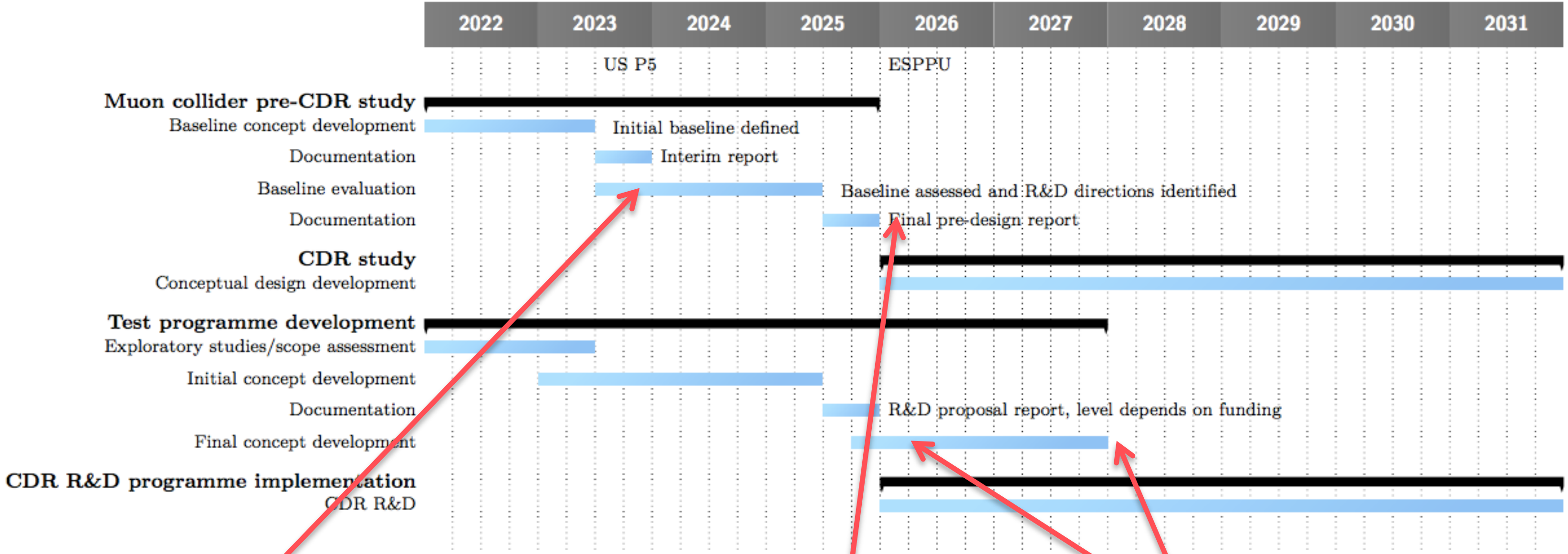


Fig. 5.4: Overall timeline for the R&D programme.

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

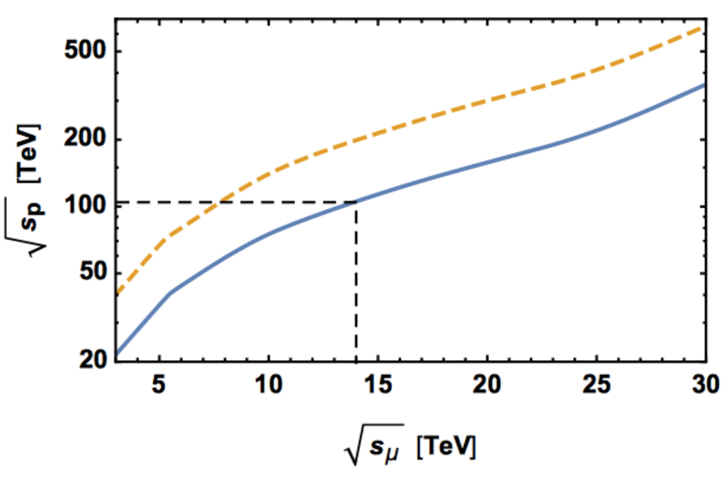
(Similar to $L(E_{CM} > 0.99\, E_{CM,0})$ CLIC at 3 TeV)

$4\times10^{35}\ cm^{-2}s^{-1}$ at 14 TeV

$$L \gtrsim \frac{5\,\text{years}}{\text{time}} \left(\frac{\sqrt{s_\mu}}{10\,\text{TeV}}\right)^2 2\cdot10^{35}\text{cm}^{-2}\text{s}^{-1}$$

Discovery reach

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



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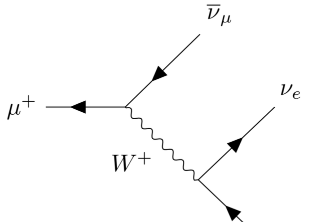
Reuse of **existing infrastructure**, e.g. **LHC tunnel** to house accelerator

Muon Decay and Detector Background

International MUON Collider Collaboration

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

About 1/3 of energy in electrons and positrons:



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

Masks protect detectors from **background**

- **optimising 10 TeV design**

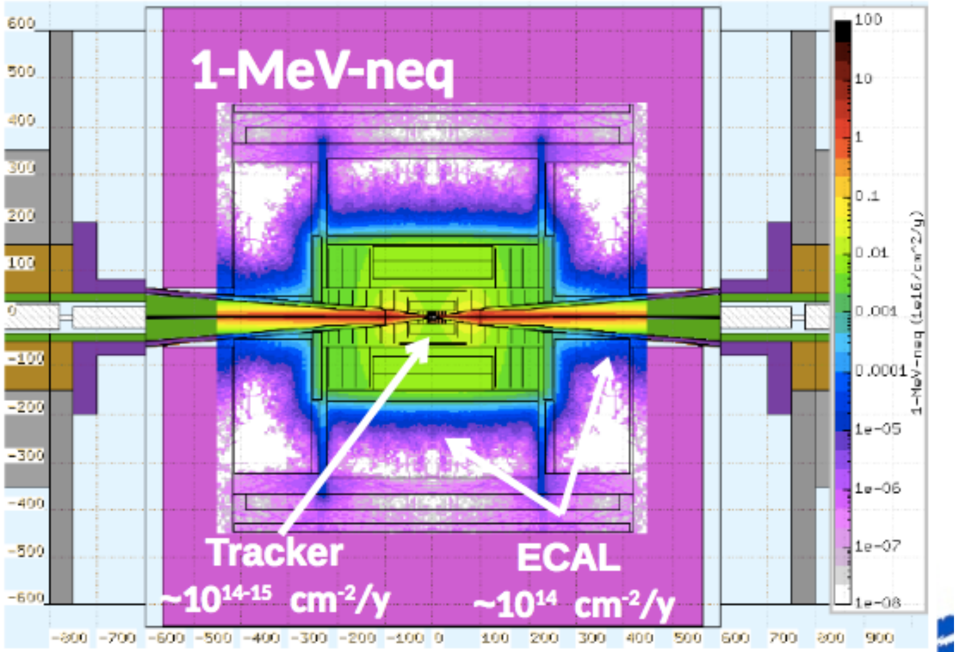
Other mitigation

- 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)

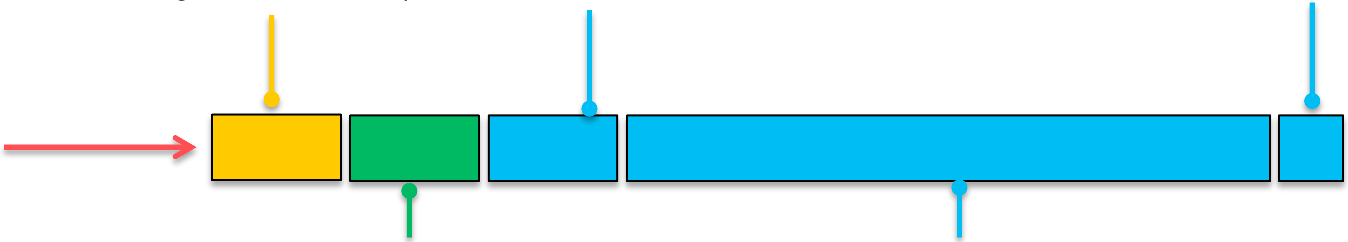


Test Facility Dimensions

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

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

Downstream diagnostics area, 5 m



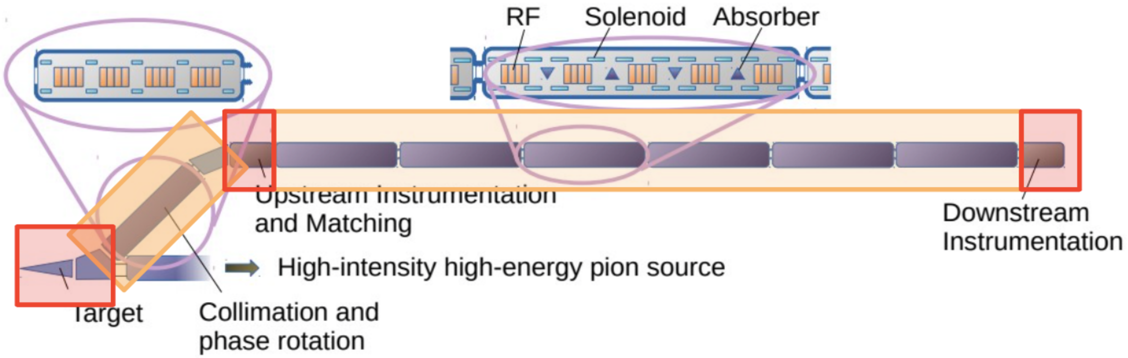
Momentum selection chicane, 10 m

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