International
MUON Collider
Collaboration

iFAST

CERN

Muon Collider

D. Schulte
for the International Muon Collider Collaboration

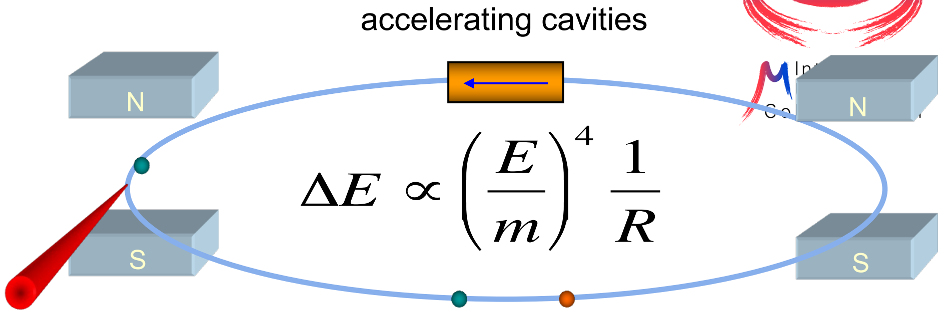
This project has received funding from the European Union's Horizon 2020
Research and Innovation programme under GA No 101004730.

muon4future
May 2023

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**



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 (MAP, now very strong interest again), experimental programme in UK (MICE) and alternatives studies by INFN (LEMMA)

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

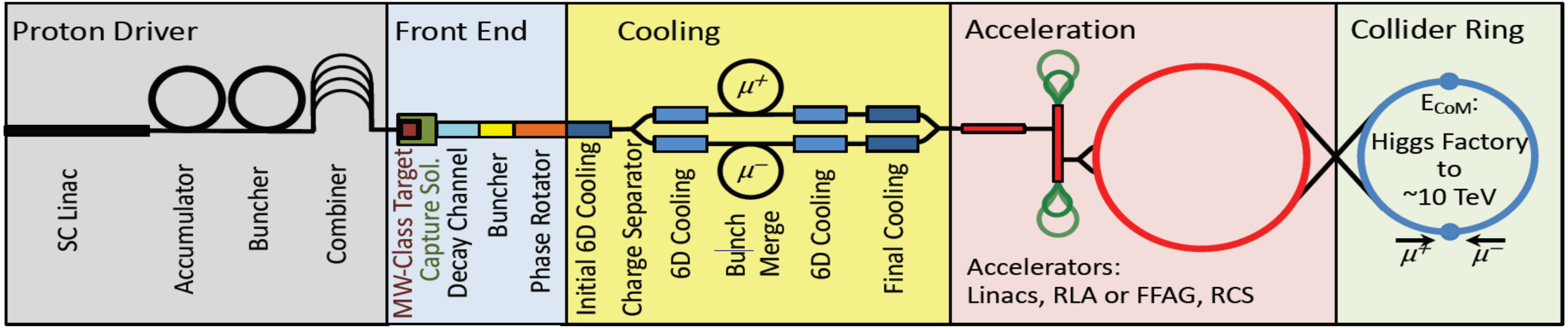
- review did not find any showstoppers

Goal is

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

Muon Collider Overview

Would be easy if the muons did not decay
Lifetime is $\tau = \gamma \times 2.2\ \mu s$



Short, intense proton bunch

Protons produce pions which decay into muons
muons are captured

Ionisation cooling of muon in matter

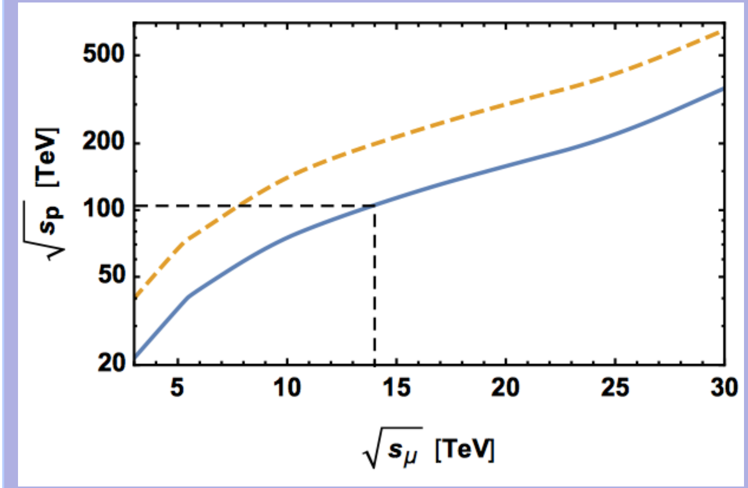
Acceleration to collision energy

Collision

Physics Goals

Leptons make the full energy available for the production of new particles
Protons only a fraction

Discovery reach
10-14 TeV lepton collisions are comparable to 100-200 TeV proton collisions for production of heavy particle pairs



Need more luminosity at higher energies as production cross section decreases

Luminosity goal
(Similar to L(E_{CM} > 0.99 $E_{CM,0}$) CLIC at 3 TeV)
$4x10^{35}$ $cm^{-2}s^{-1}$ at 14 TeV

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

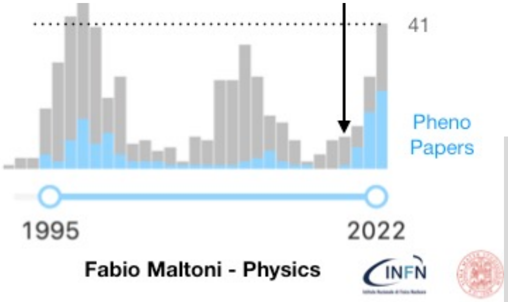
Yields constant number of events in the s-channel

$\sqrt{s}$	$\int \mathcal{L}dt$
3 TeV	1 ab^{-1}
10 TeV	10 ab^{-1}
14 TeV	20 ab^{-1}

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

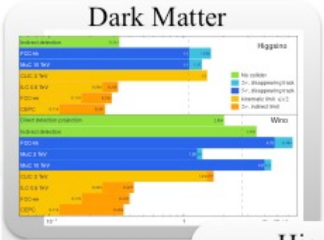
International MUON Collider Collaboration

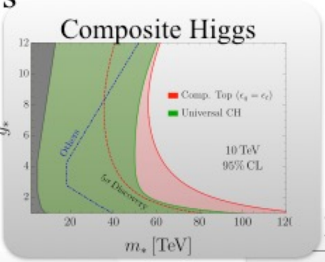
A. Wulzer, F. Maltoni, P. Meade et al.

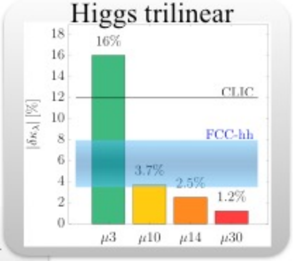
O(150) authors, 15 editors, 100 papers

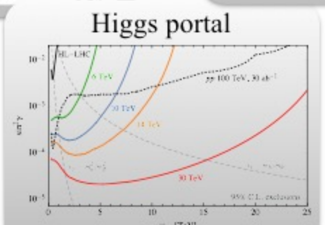
Selected summary plots, from Snowmass21 reports:

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









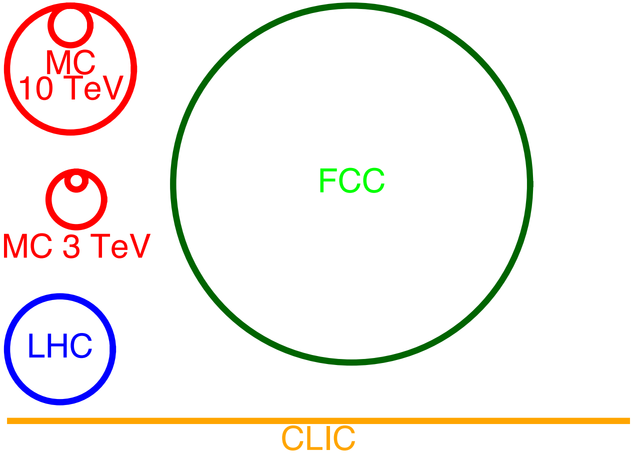
Higgs couplings

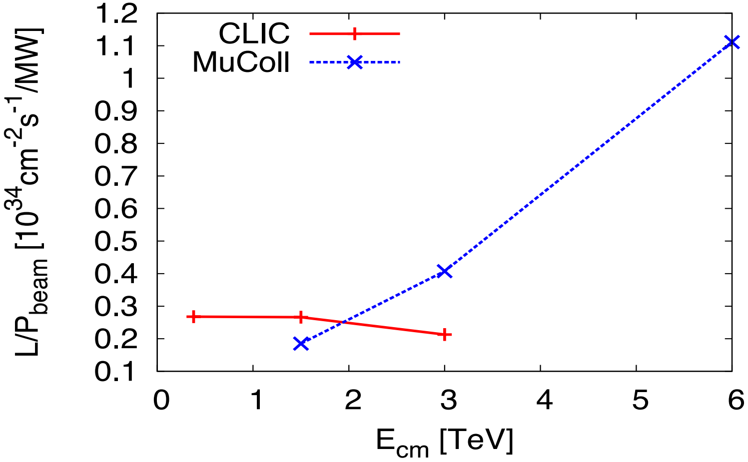
	HL-LHC	HL-LHC +10 TeV	HL-LHC +10 TeV + ee
κ_W	1.7	0.1	0.1
κ_Z	1.5	0.4	0.1
κ_g	2.3	0.7	0.6
κ_γ	1.9	0.8	0.8
$\kappa_{Z\gamma}$	10	7.2	7.1
κ_c	-	2.3	1.1
κ_b	3.6	0.4	0.4
κ_μ	4.6	3.4	3.2
κ_τ	1.9	0.6	0.4
κ_t^*	3.3	3.1	3.1

* No input used for μ collider

Strong US involvement starting with **Muon Smasher's Guide** and in **Muon Collider Forum**

Cost and 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

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.

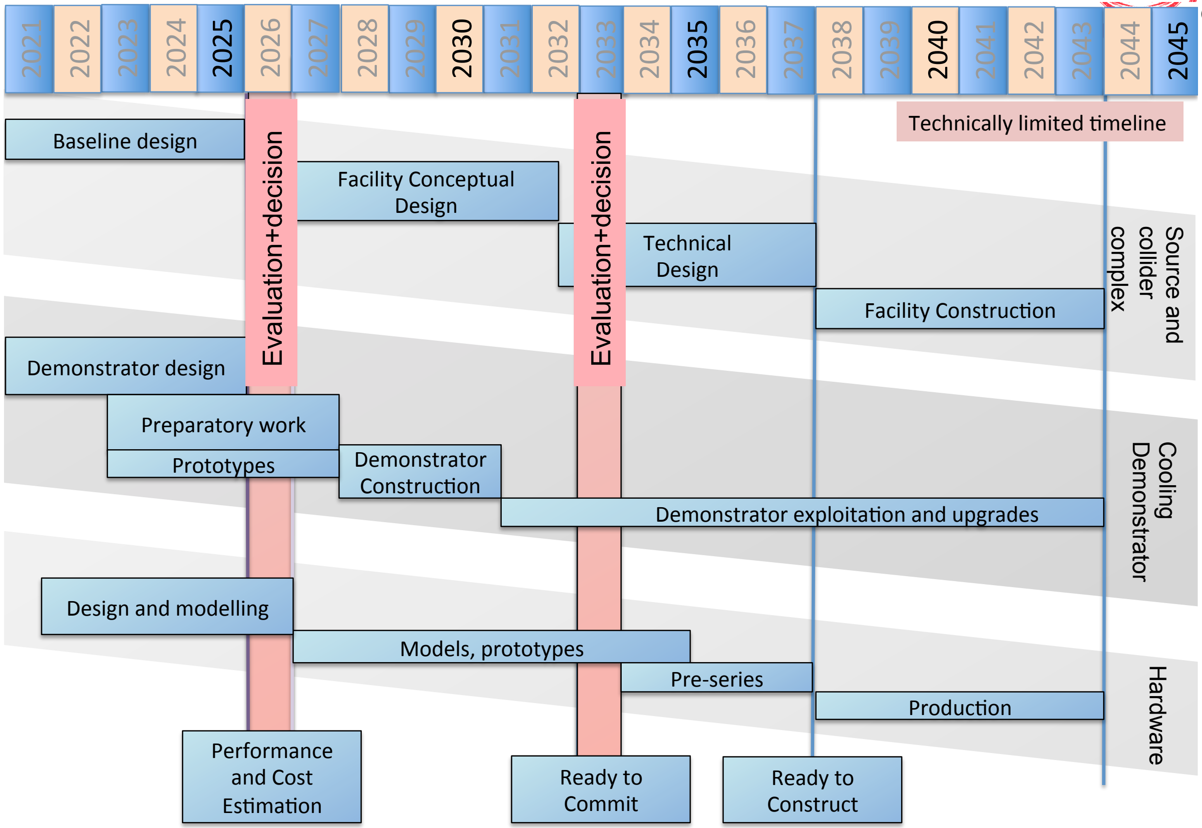
Technically Limited Timeline (From Roadmap)

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

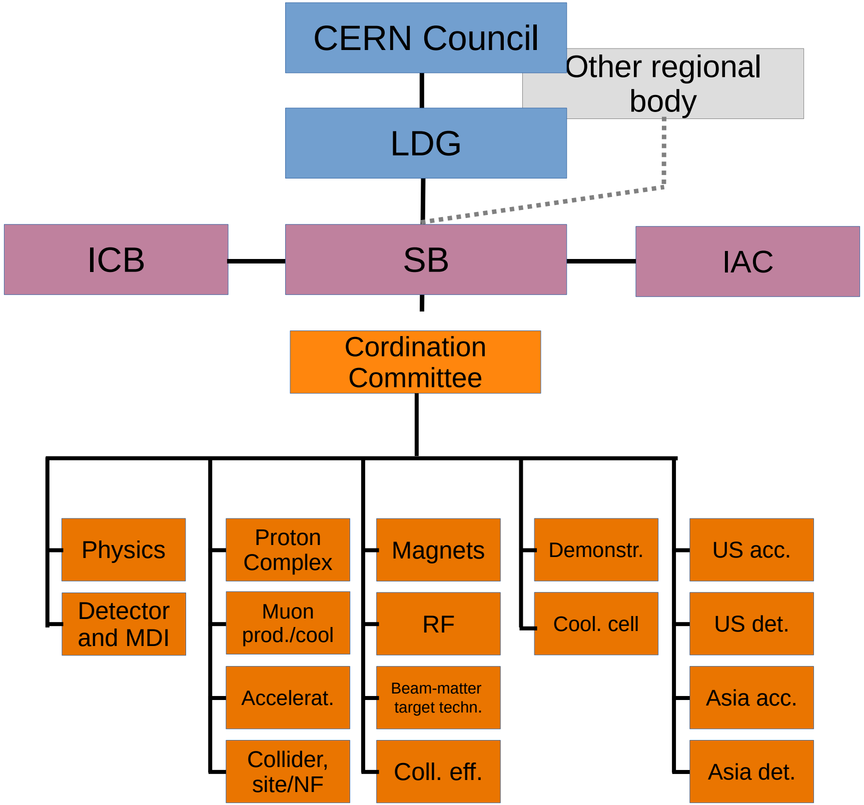


Organisation

- **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

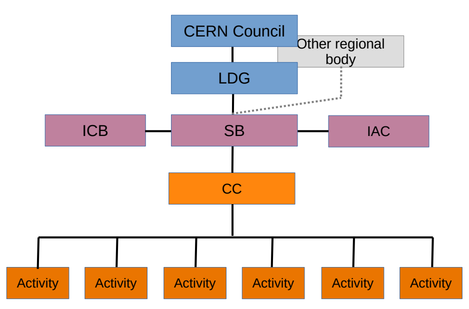
UK	**RAL**
	UK Research and Innovation
	University of Lancaster
	University of Southampton
	University of Strathclyde
	University of Sussex
	Imperial College
	Royal Holloway
	University of Huddersfield
	University of Oxford
	University of Warwick
	University of Durham
SE	**ESS**
	University of Uppsala
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

Muon Collider Community

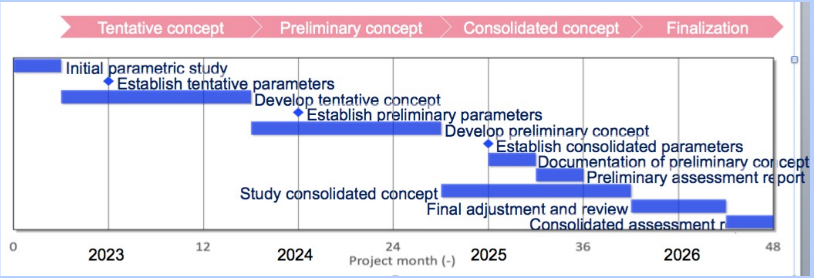
Formed **collaboration** to implement and R&D Roadmap for CERN Council



50+ partner institutions
30+ already signed formal agreement

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

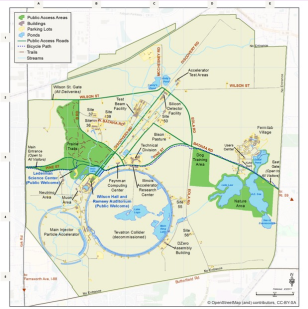
(EU+Switzerland+UK and partners)



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

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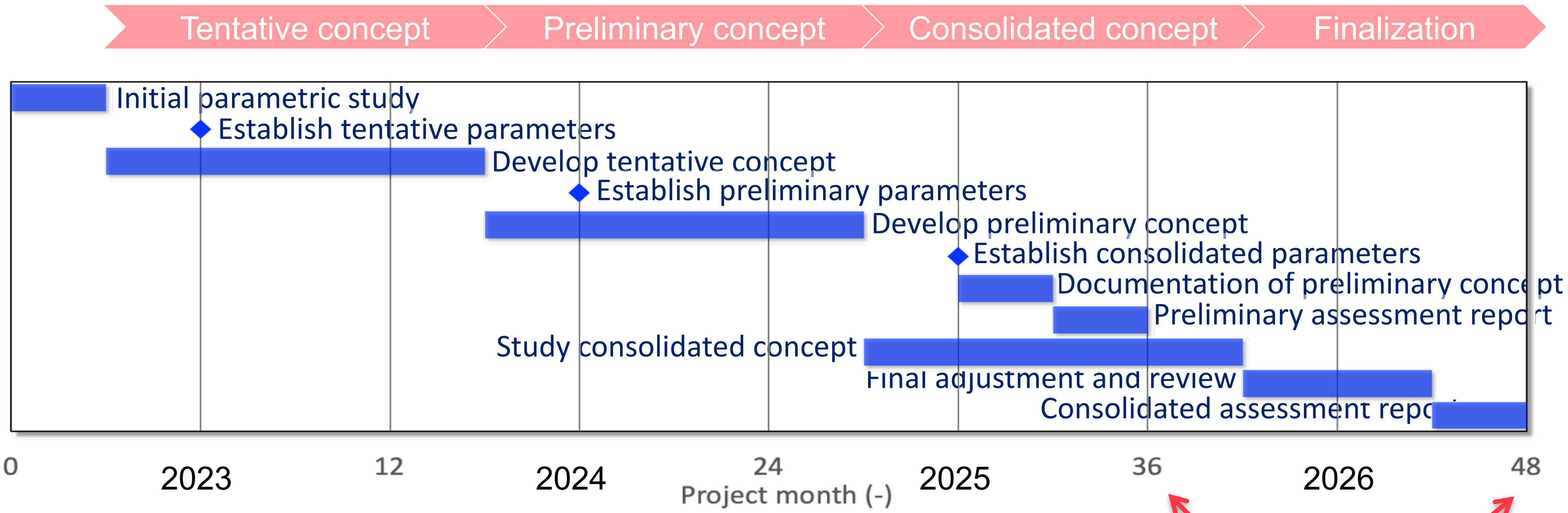


Next ESPPU ?

Representative of overall workplan

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

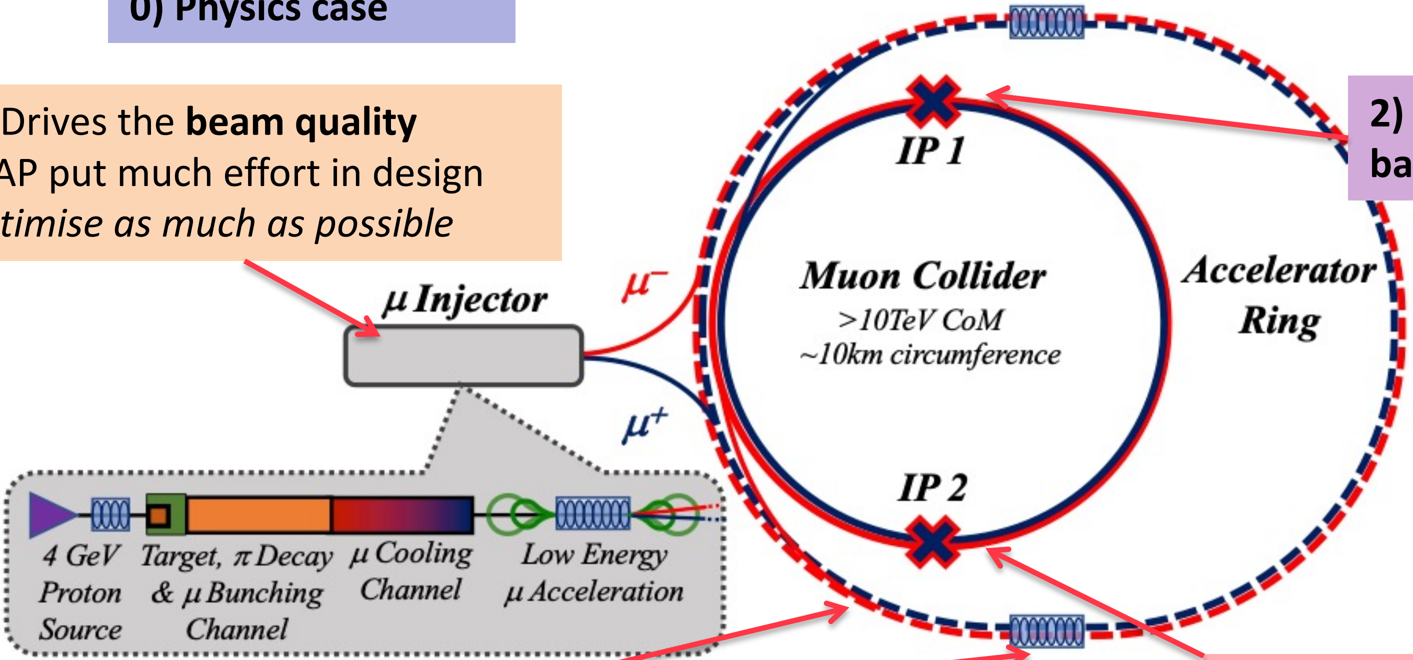
- Tentative parameters based on MAP study, might add margins
- Achieve goal in 5 years
- FCC-hh to operate for 25 years
- Aim to have two detectors

Parameter	Unit	3 TeV	10 TeV	14 TeV	CLIC at 3 TeV
L	10^{34} $\text{cm}^{-2}\text{s}^{-1}$	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	

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

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)

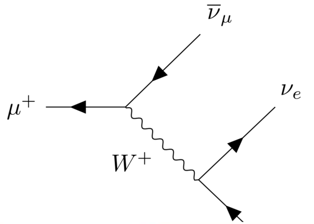
Studies at 1.5 <and 3 TeV with concept based on CLIC detector

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

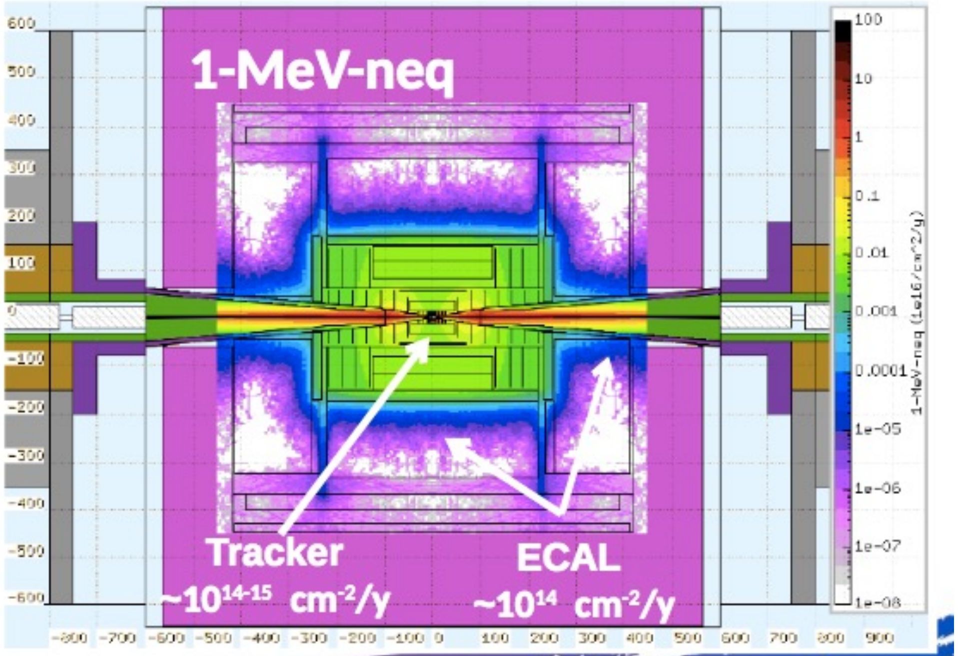
Studies with **beam-induced background** in progress

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

Concept for **10 TeV** in progress

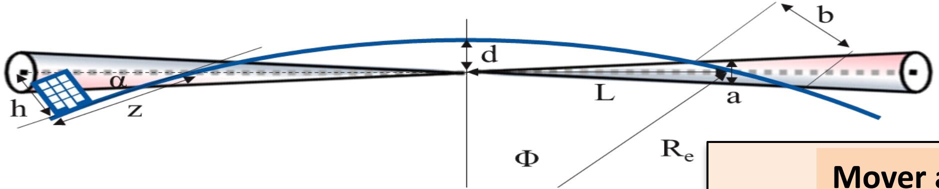


Detector team
O(69) authors, O(150 signatories)

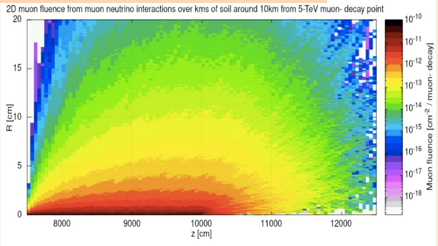


Neutrino Flux

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

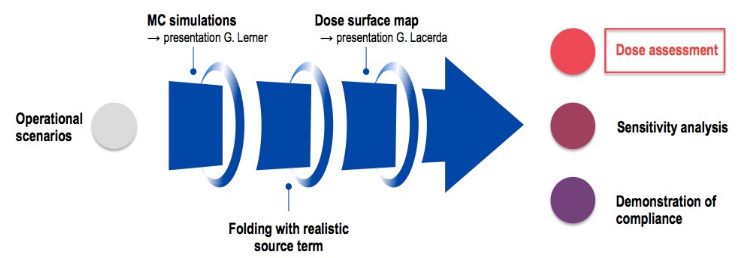


FLUKA dose studies



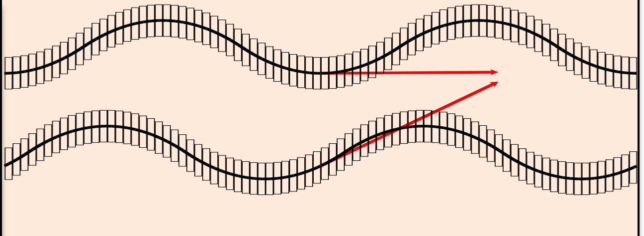
G. Lerner, D. Calzolari, A. Lechner, C. Ahdida

Conformity Verification Scheme



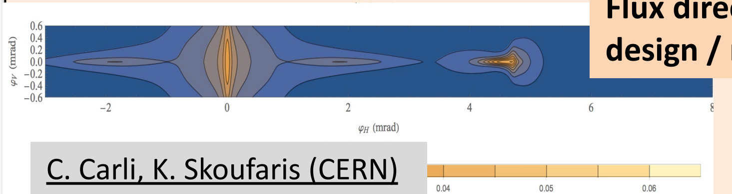
C. Ahdida, P. Vojtyla, M. Widorski, H. Vincke

Mover and support system



F. Bertinelli et al. (CERN, Riga)

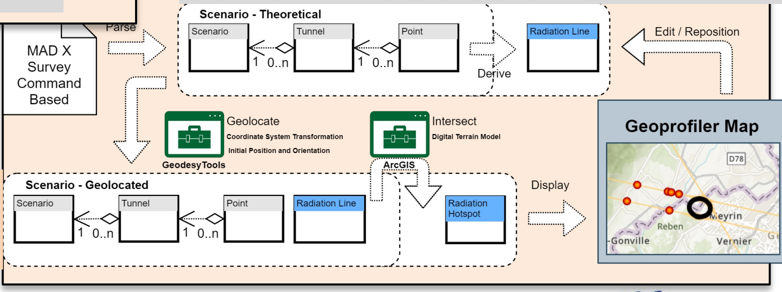
Flux direction map / lattice design / mover impact on beam



C. Carli, K. Skoufaris (CERN)

Mitigation: Site choice tool

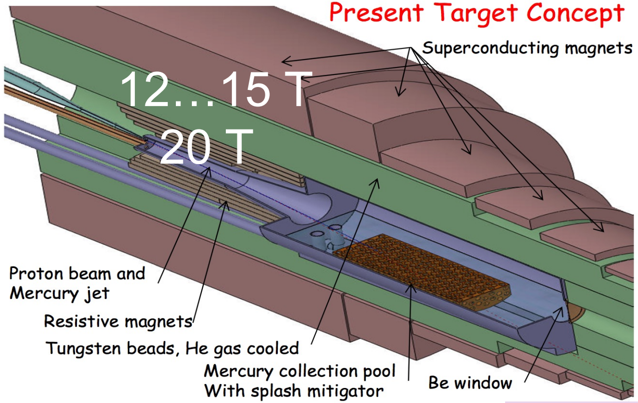
G. Lacerda, Y. Robert, N. Guilhaudin (CERN)



Protons and Target

International MUON Collider Collaboration

MAP target design, K. McDonald, et al.

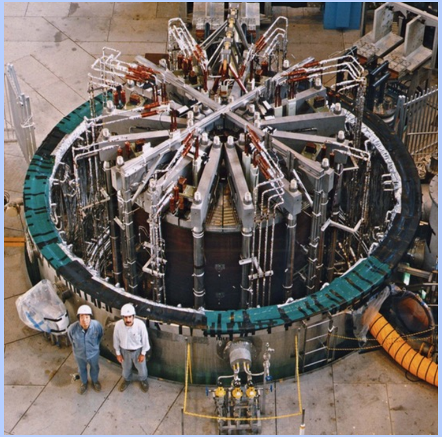


Large bore, high field solenoid

Nb_3Sn or HTS

Similar to ITER

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



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

2 MW proton beam is OK

Bunching challenge will be addressed by ESS experts

N. Milas et al. (ESS, Uppsala)

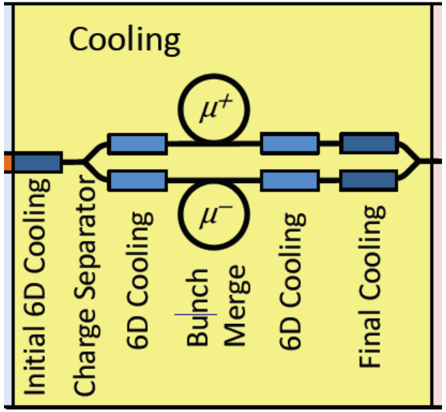
Rui Franqueira Ximenes et al.

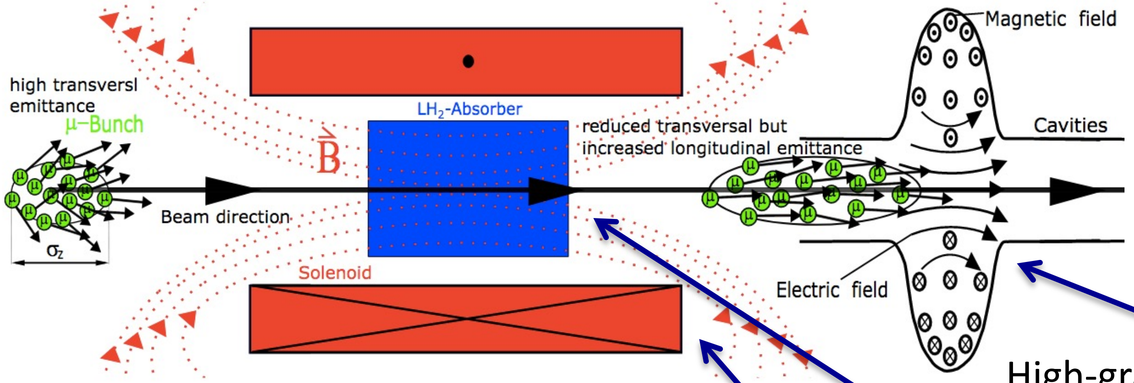
Operation at 2000 °C to maximise stress resistance

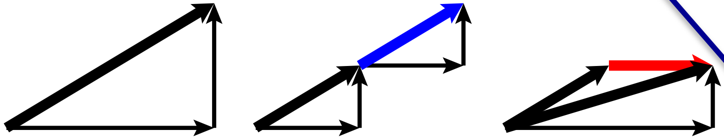
Shock and power in target:
Simulations of graphite target indicate 2 MW could be acceptable

STFC will also study alternatives

Muon Cooling Principle





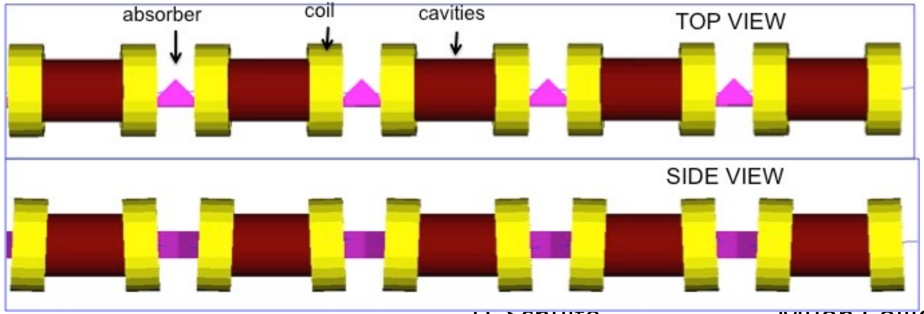


High-gradient normal-conducting cavities

Robust absorbers

High-field, superconducting solenoid

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



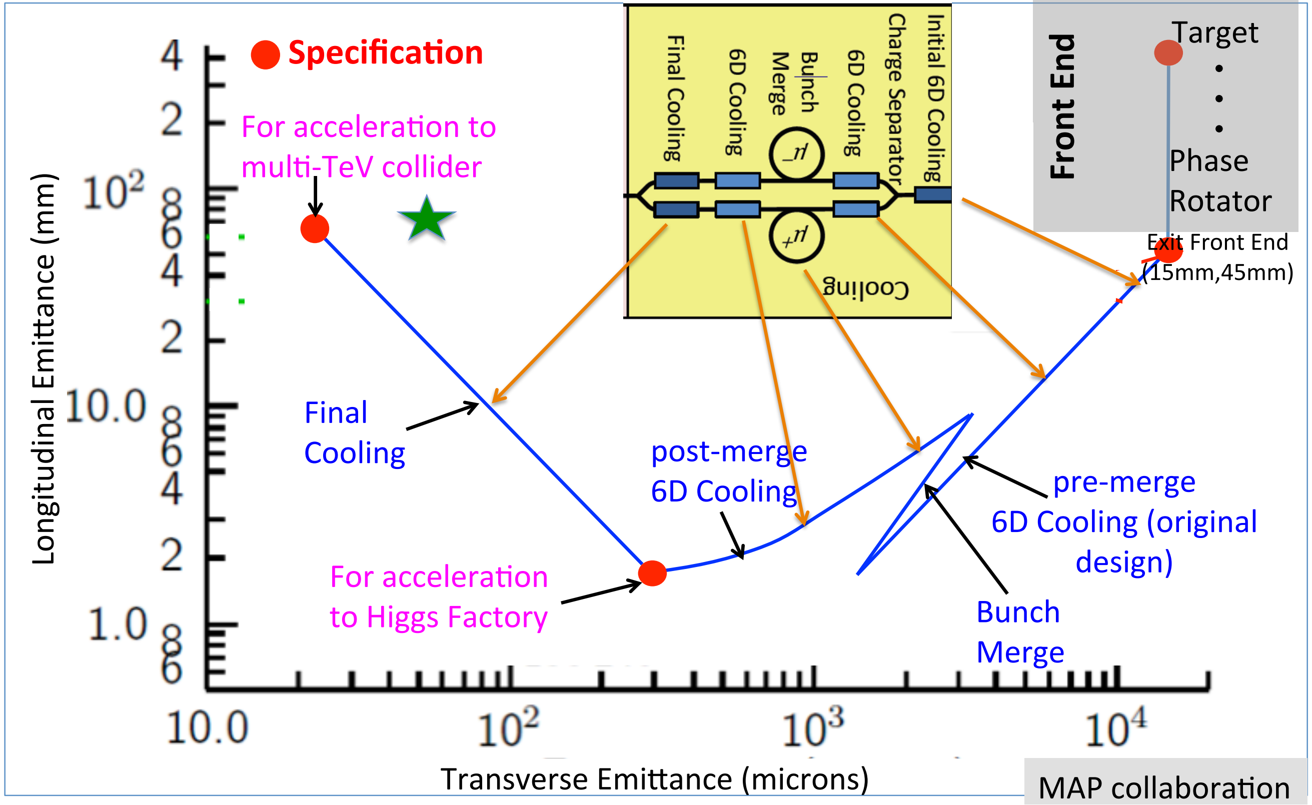
Muon Cooling Performance

Complex system with several stages

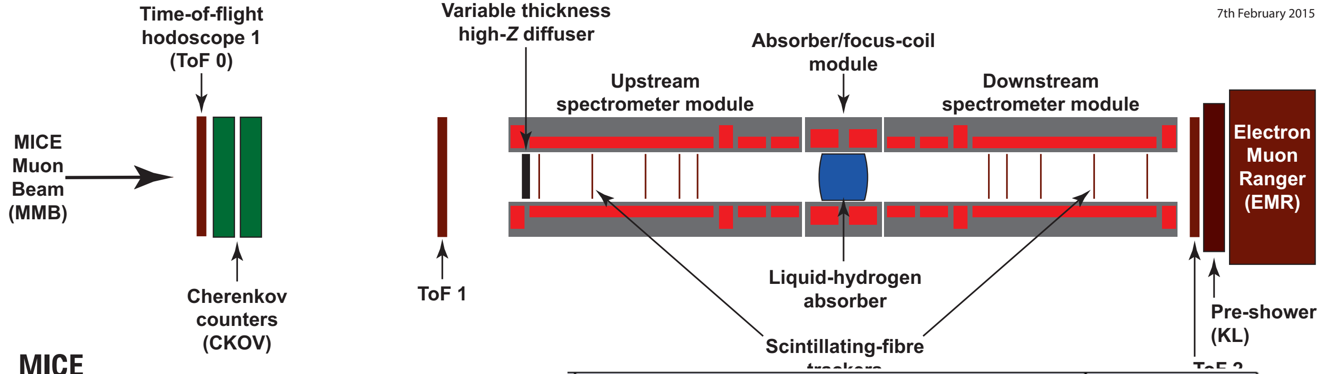
Substantial effort by MAP

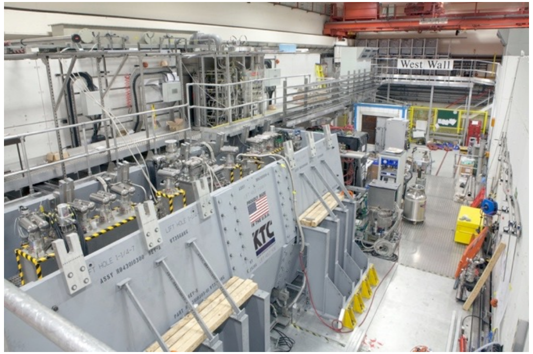
Concept using already achieved performances comes close to target

Will optimise the design based on realistic target performances



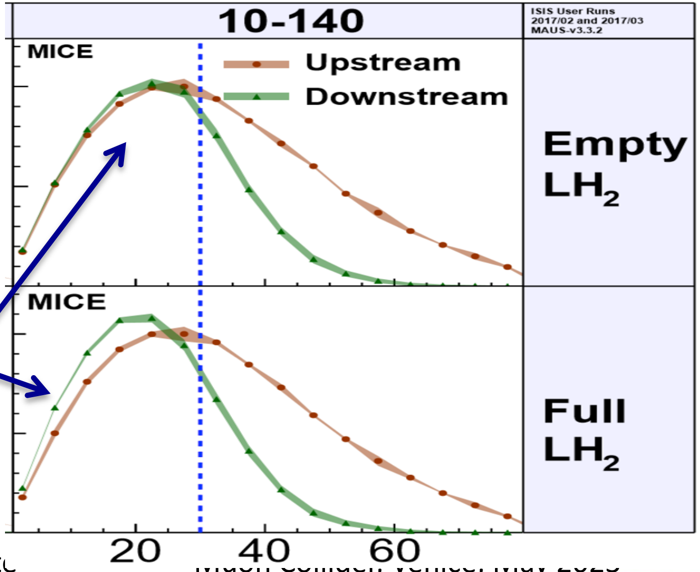
MICE: Cooling Demonstration





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

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



More particles at smaller amplitude after absorber is put in place

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

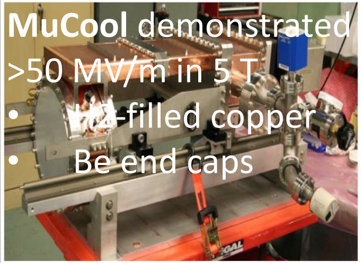
Integration of magnets, RF, absorbers, vacuum is engineering challenge

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

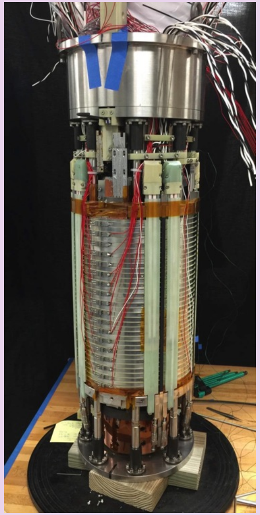


MuCool demonstrated >50 MV/m in 5 T

- H_2-filled copper
- Be end caps

Assessment of realistic goal for highest field solenoids

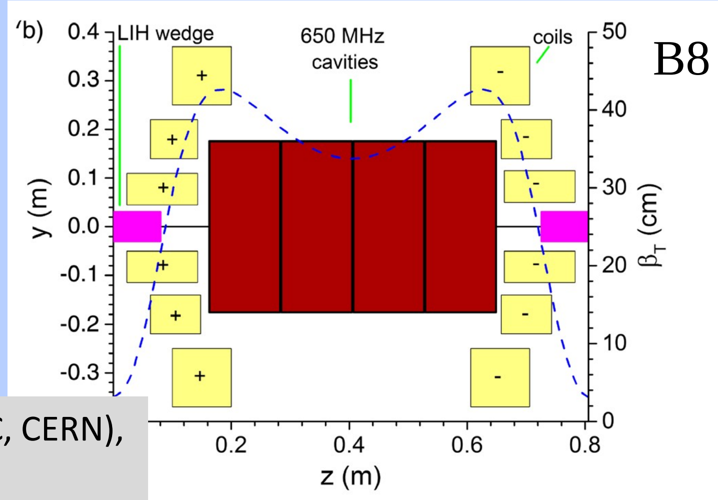
- MAP demonstrated 30 T
- now magnets aim for 40+ T
- even more can be possible



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

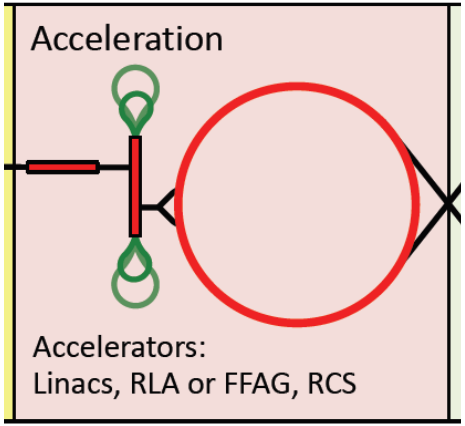
Will develop example **cooling cell integration**

- 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)

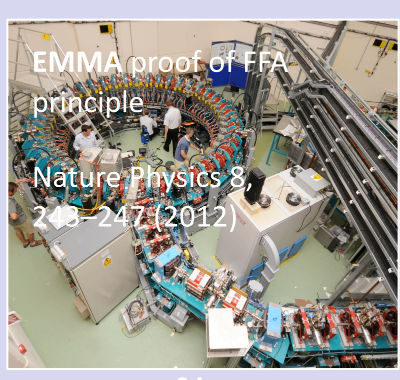
F. Boattini et al.

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

- Alternative FFA

S. Machida et al. (RAL)

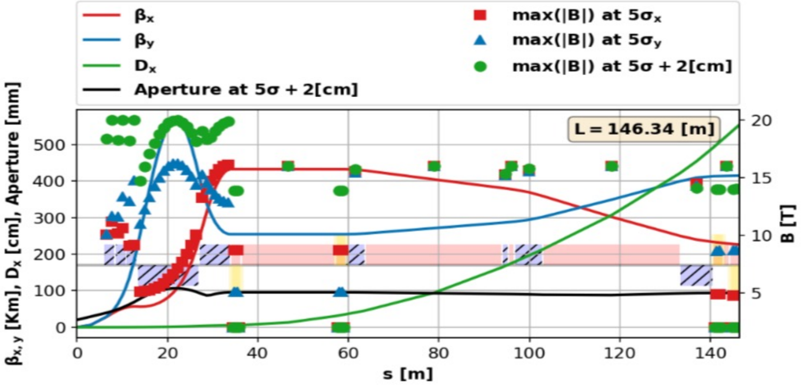
FNAL 300 T/s HTS magnet



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



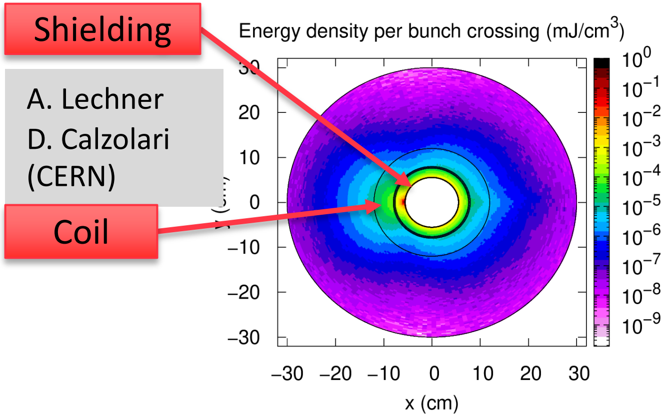
C. Carli, K. Skoufaris (CERN)

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

CDR Phase

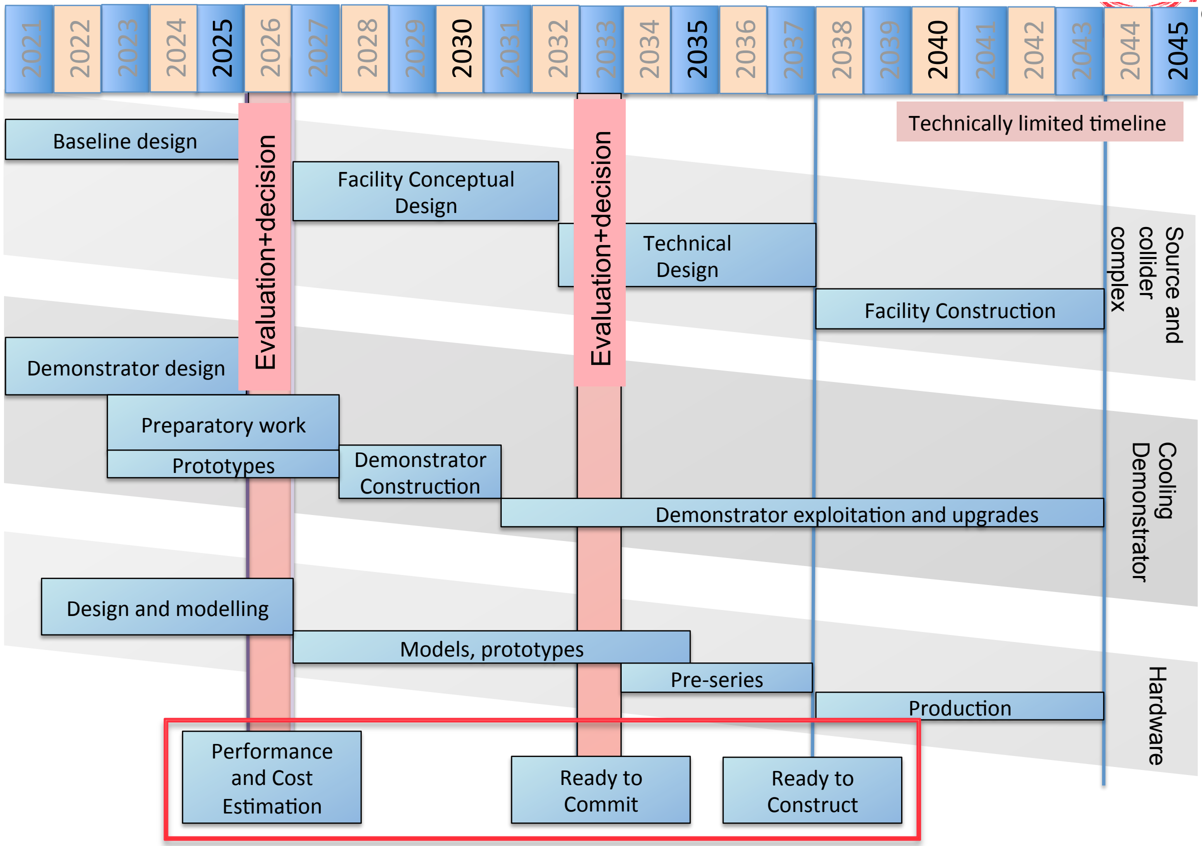
Fastest option based on European strategy processes
- To see if it could be next project after HL-LHC, if required

Accept compromises
- Lower energy (3 TeV?)
- Performance (tbd)

Requires more funding now and large increase after 2026

Will adjust to ongoing strategic developments
- Will include other regional options

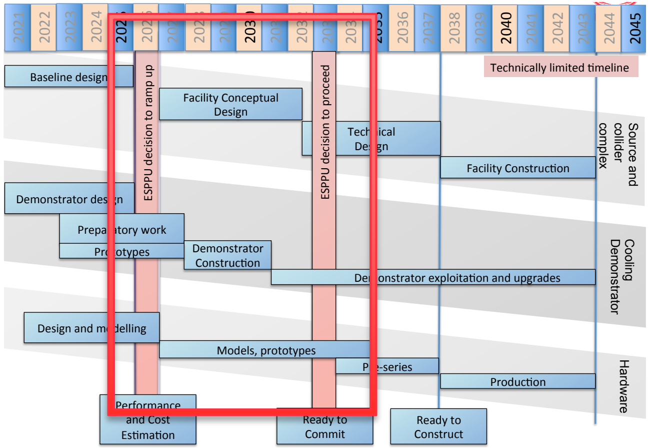
To be reviewed considering progress, funding and decisions



R&D and Demonstrator Facility

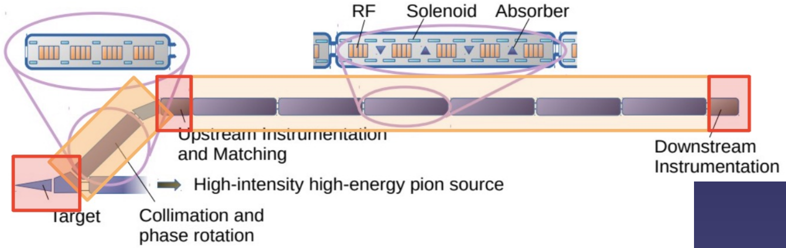
Broad R&D programme required and can be distributed world-wide

- Models and prototypes
  - Magnets, Target, RF systems, Absorbers, …
- CDR development
- Integrated tests, also with beam



Integrated cooling demonstrator is a key facility

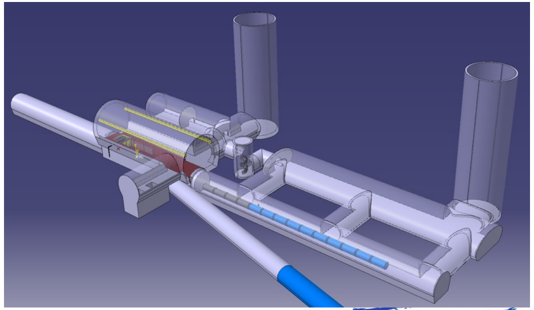
- look for an existing proton beam with significant power



C. Rogers, R. Losito, et al.

Different sites are being considered

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



Could be used to house physics facility

- Are trying to explore what are good options

US Snowmass

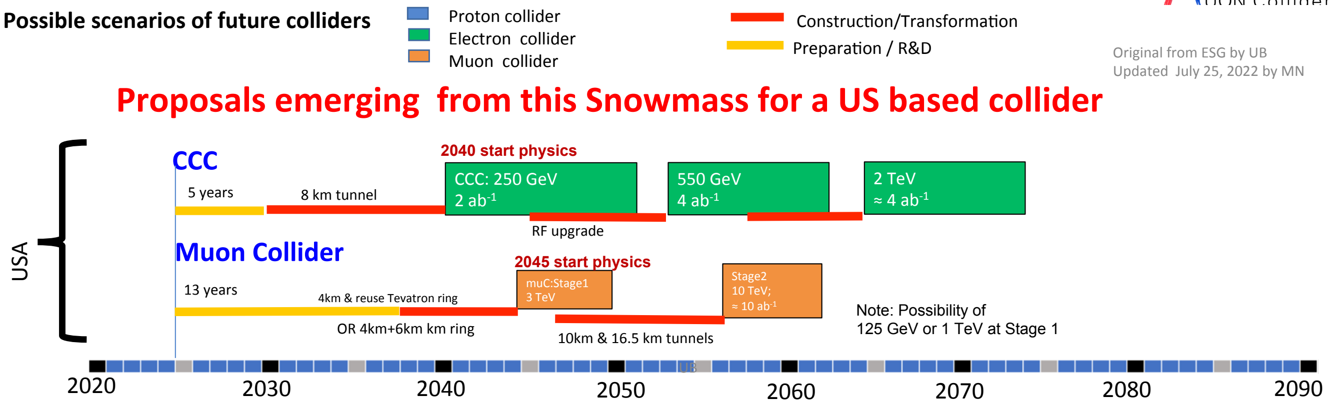
Strong interest in the US community in muon collider

- seen as an energy frontier machine
- decoupled from LC

US community wants funding for **R&D**

- **Goal: match European effort**

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

US Snowmass, cont.

International ...er ...n

Implementation Task Force

Muon Collider is a viable option for the HEP future

They made cost and power estimate for muon collider take it *cum grano salis*

Place MC in same risk tier as FCC-hh

Snowmass 2021

ITF's Look Beyond Higgs Factories

ITF Report – T.Roser, et al, arXiv:2208.06030

	CME (TeV)	Lumi per IP (10^34)	Years, pre-project R&D	Years to 1st Physics	Cost Range (2021 B$)	Electric Power (MW)
FCCee-0.24	0.24	8.5	0-2	13-18	12-18	290
ILC-0.25	0.25	2.7	0-2	<12	7-12	140
CLIC-0.38	0.38	2.3	0-2	13-18	7-12	110
HELEN-0.25	0.25	1.4	5-10	13-18	7-12	110
CCC-0.25	0.25	1.3	3-5	13-18	7-12	150
CERC(ERL)	0.24	78	5-10	19-24	12-30	90
CLIC-3	3	5.9	3-5	19-24	18-30	~550
ILC-3	3	6.1	5-10	19-24	18-30	~400
MC-3	3	2.3	>10	19-24	7-12	~230
MC-10-IMCC	10-14	20	>10	>25	12-18	*O*(300)
FCChh-100	100	30	>10	>25	30-50	~560
Collider-in-Sea	500	50	>10	>25	>80	»1000

Thomas Roser et al

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

Muon Collider Luminosity Scaling

Fundamental limitation

Requires emittance preservation and advanced lattice design

Applies to MAP scheme

$$\mathcal{L} \propto \gamma \langle B \rangle \sigma_\delta \frac{N_0}{\epsilon \epsilon_L} f_r N_0 \gamma$$

High energy

High field in collider ring

Large energy acceptance

Dense beam

High beam power

Luminosity per power increases with energy

Provided technologies can be made available

Constant current for required luminosity scaling

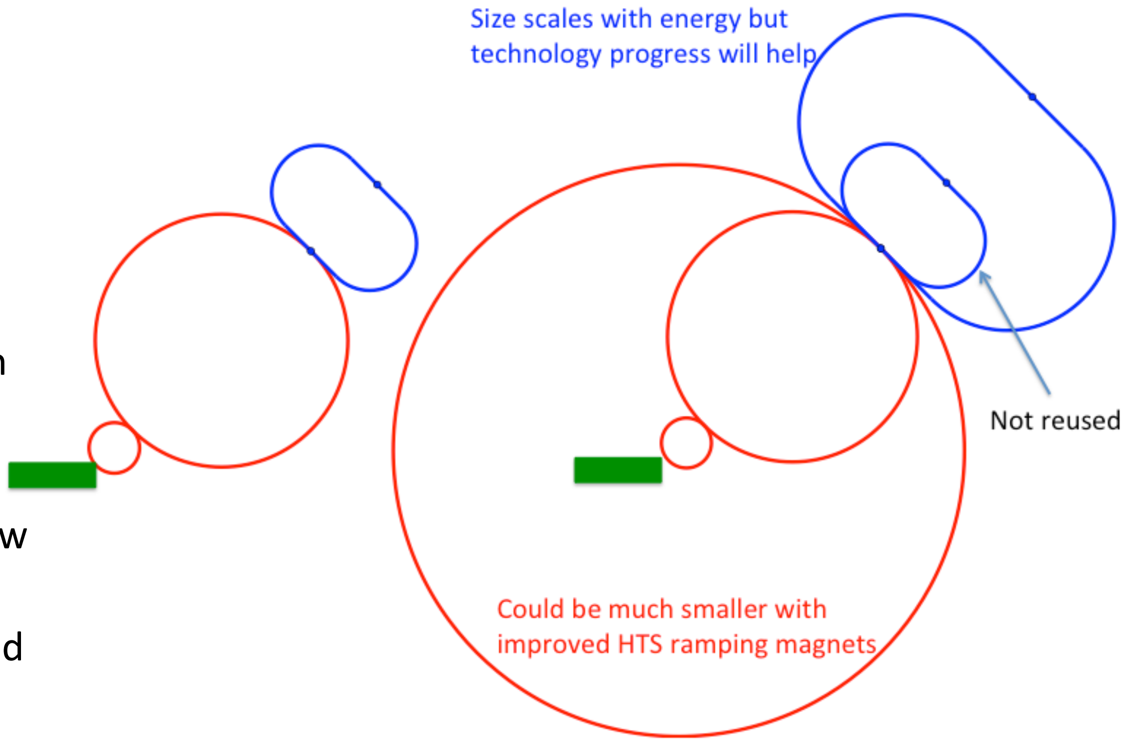
Staging

Ideally would like full energy right away, but staging could lead to faster implementation

- Substantially less cost for a first stage
- Can make technical compromises
  - e.g. 8 T NbTi magnets would increase collider ring from 4.5 to 6 km and reduce luminosity by 25%
- Timeline might be more consistent with human lifespan

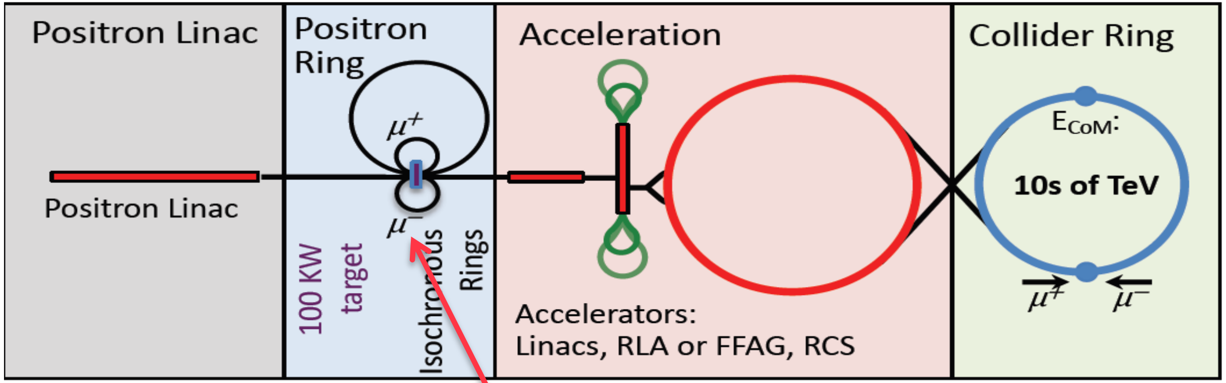
Upgrade adds one more accelerator and new collider ring

- only first collider ring is not being reused



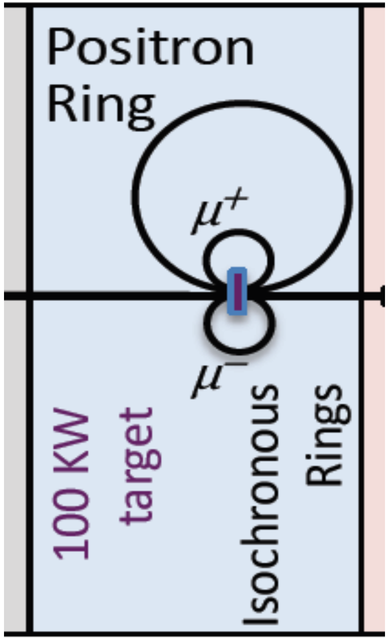
Alternatives: The LEMMA Scheme

LEMMA scheme (INFN) P. Raimondi et al.



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

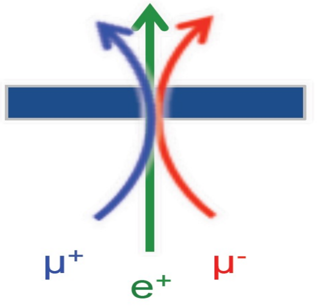
- Uses Bethe-Heitler production with electrons



45 GeV positrons to produce muon pairs

Accumulate muons from several passages

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

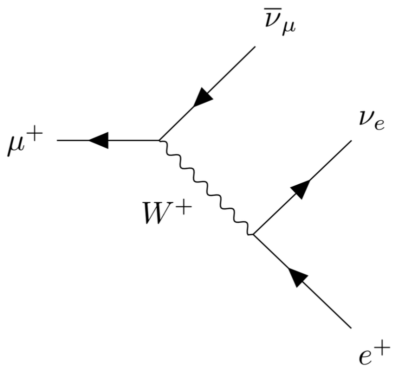


Excellent idea, but nature is cruel

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**

Muon Decay



About 1/3 of energy in electrons and positrons:

Experiments needs to be protected from **background** by masks

- simulations of 1.5, 3 and 10 TeV
- optimisation of masks and lattice design started
- first results look encouraging
- will be discussed at ICHEP

Collider ring magnets need to be shielded from losses

Losses elsewhere will also need to be considered but are less severe

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

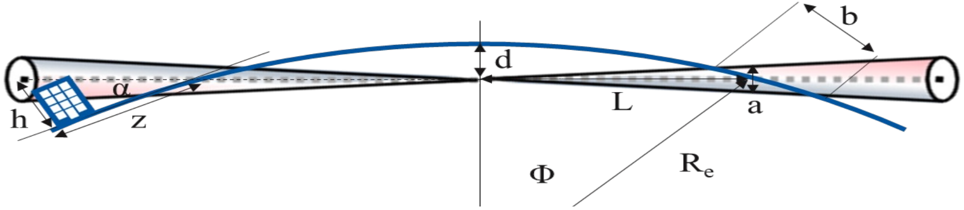
Neutrino flux to have negligible impact on environment

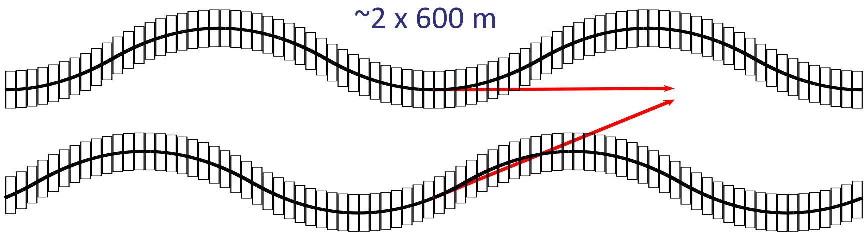
- want to be **negligible** (same level as LHC)
- opening cone decreases, cross section and shower energy increase with energy

Above about 3 TeV need to make beam point in different vertical directions

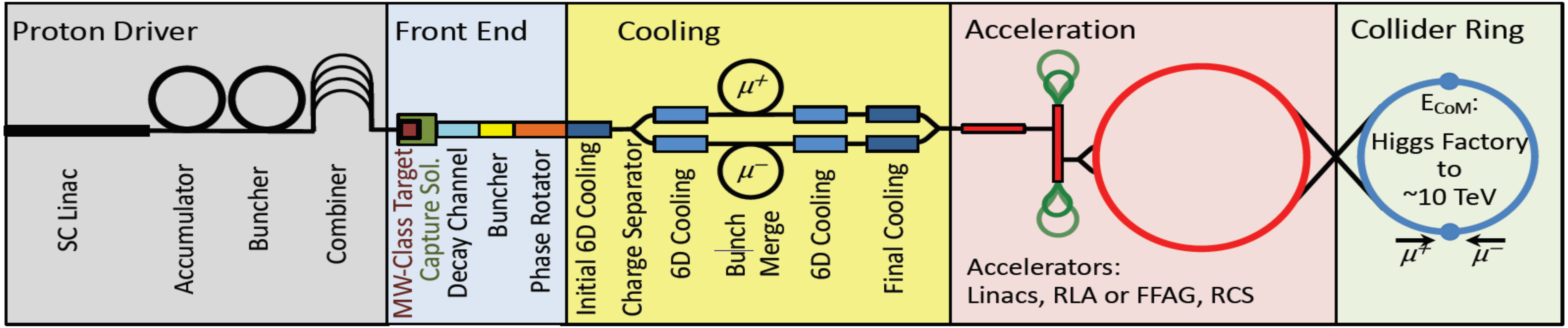
Mechanical system with 15cm stroke, 1% vertical bending

Length of pattern to be optimised for minimal impact on beam





Key Challenges



Proton complex
- Compressing protons to few bunches

Target
- Target
- Solenoid

Cooling channel
- Channel design
- Solenoids
- RF in magnetic field
- Absorbers
- Integration

RCS
- Beam dynamics
- Ramping magnets
- Power converter
- RF system

Collider ring
- Optics
- Magnets
- Neutrino flux
- Detector background

Neutrino Flux

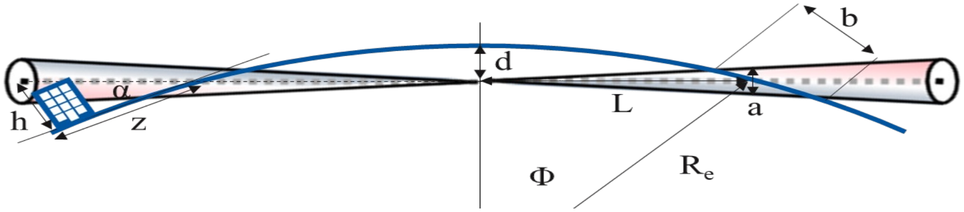
Dense neutrino flux cone can impact environment
Challenge scales with **E x L**

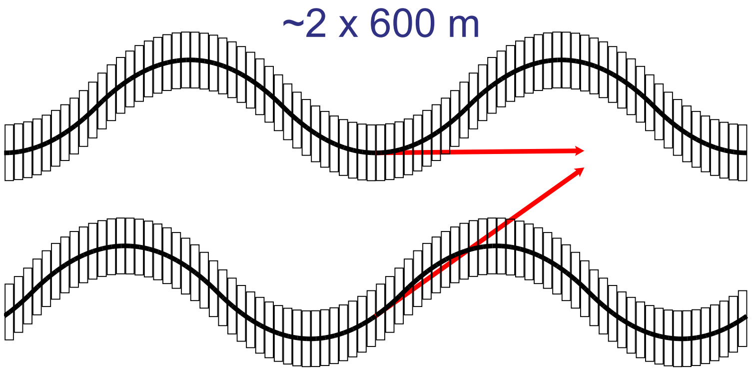
Goal is to reduce to negligible level, similar to LHC
- **3 TeV, 200 m deep tunnel is about OK**

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

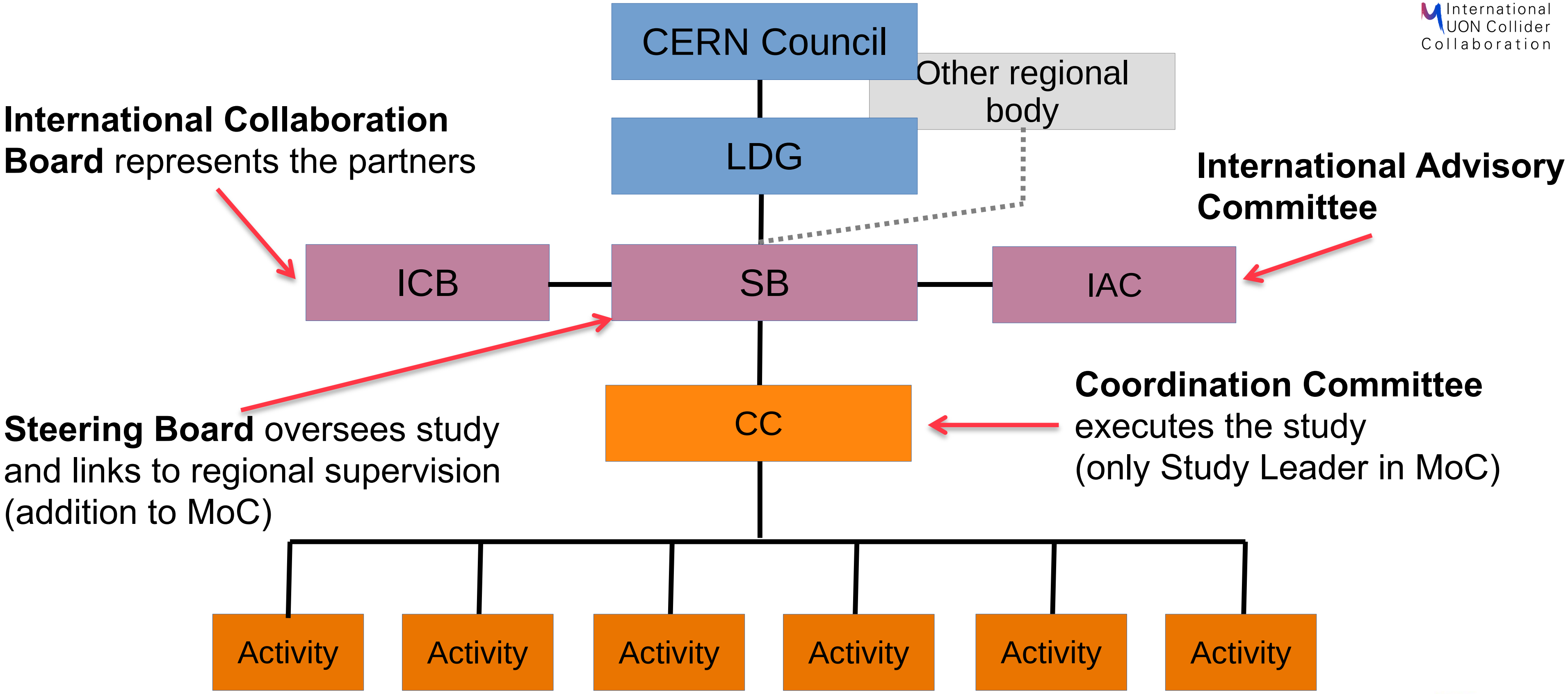
Working on different approaches for experimental insertion





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)

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

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.

R&D Plan

International MUON Collider Collaboration

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.

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

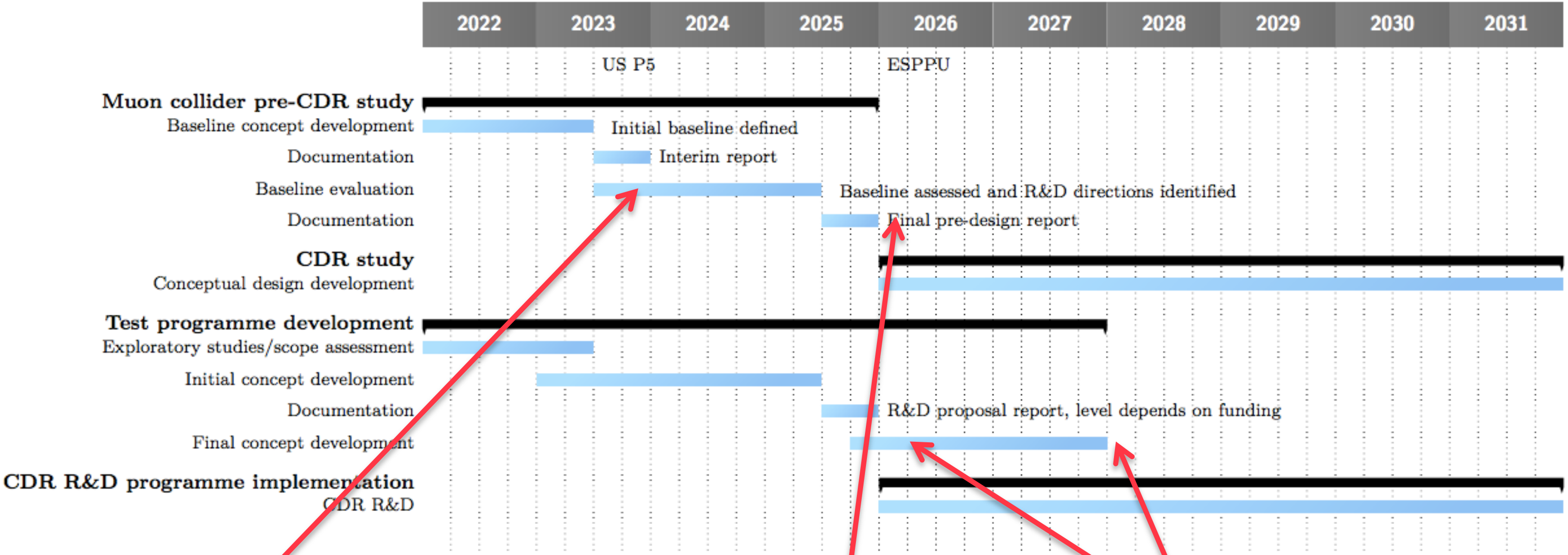


Fig. 5.4: Overall timeline for the R&D programme.

2023
Interim Report to gauge progress
Initial baseline defined

2025
Assessment Report

2025-2027
R&D plan will be refined

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

A strengthening on the physics and detector side is planned

Key Technologies

Magnets

- Superconducting solenoids for target and cooling profit from developments for society
  - target solenoid comparable to ITER central solenoid fusion
  - 6D cooling solenoids similar and wind power generators, motors
  - final cooling solenoids synergetic with high-field research, NMR
- Collider ring magnets
  - profit from developments for other colliders FCC-hh, stress-managed magnets
- Fast-ramping normal-conducting magnet system
  - HTS alternative, power converter

RF systems

- superconducting RF, normal-conducting RF, efficient klystrons

Target, cooling absorbers, windows, shielding

Neutrino mitigation mover system, cooling cell integration, …

Detector

Key Technologies, cont.

RF systems

- Normal-conducting cooling cavities in magnetic field
  - profit from CLIC work
- Superconducting accelerator RF
  - profit from ILC, …
- Efficient power sources
  - profit from CLIC work

Beam-matter interaction

- Proton target
- Cooling absorbers
- Shielding (accelerator and detector)

Mechanical system

- Neutrino flux mitigation system
- Muon cooling cell integration

Collaboration Vision

IMCC is an **international** collaboration and aims to

- Enlarge the collaboration
  - Physics interest in all regions, strong US contribution to the muon collider physics and detector, interest in Japan
  - First US university have joined collaboration, try to see how to move forward, also with labs
- Combine the R&D efforts for the design and its technologies
  - Critical contributions in all relevant fields the US
- Consider several sites for the collider
  - CERN would be one, FNAL and others should also be considered
  - A proposal with alternative sites is stronger for a single site
- Consider several sites for the demonstrators
  - E.g. Muon production and cooling demonstrator at CERN, FNAL, ESS, JPARC
  - e.g. RCS at ESRF or elsewhere
  - Target tests
  - …