Main Goals, Timeline, Collaboration
Status and Plans

D. Schulte
for the International Muon Collider Collaboration

SB, June 2023

Accelerator R&D Roadmap

International MUON Collider Collaboration

No insurmountable obstacle found for the muon collider

- but important need for R&D

Aim at **10+ TeV** and potential initial stage at **3 TeV**

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**

Interim report by end of 2023

Do not yet have the resources of the reduced scenario

- Will do as much as possible, following priorities and available expertise and resources
- Are approaching O(40 FTE)
- Efforts to increase resources

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		Minimal	
				[FTEy]	[kCHF]	[FTEy]	[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)

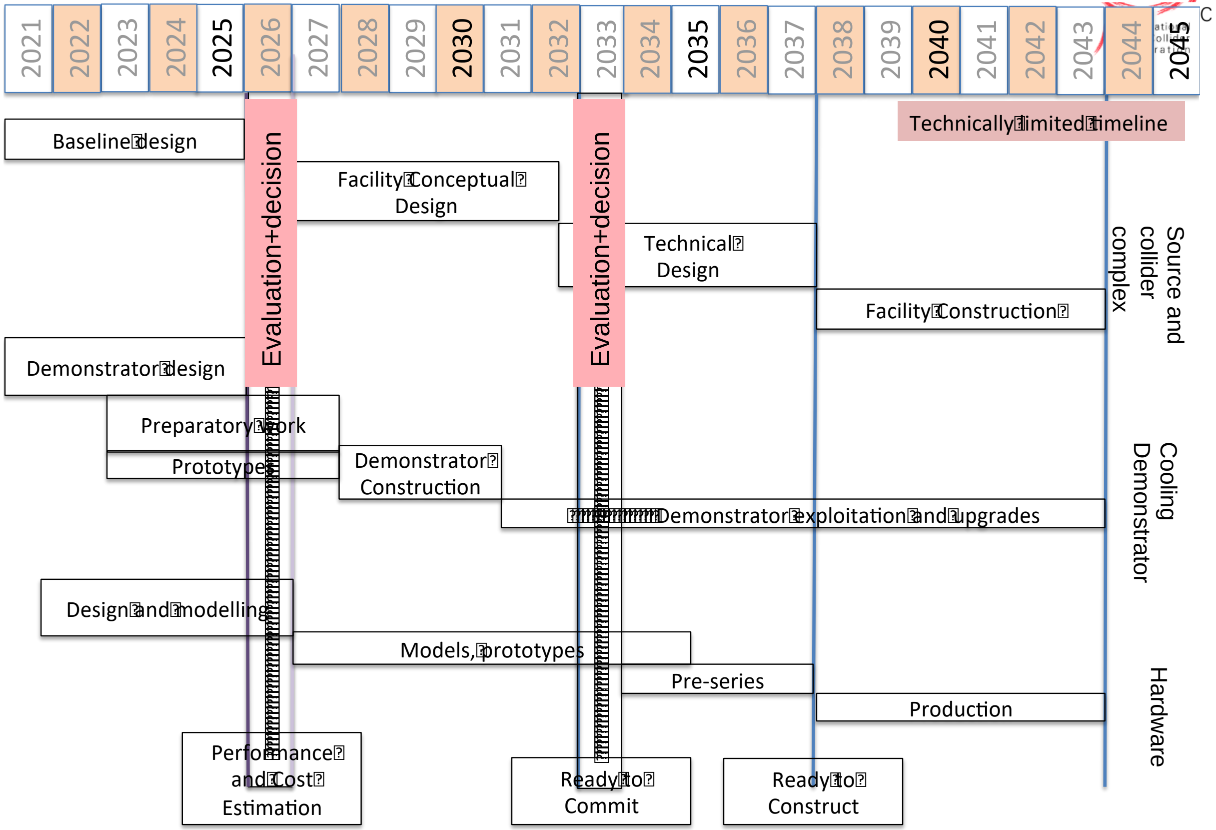
Muon collider important in the long term

Fastest track option with important ramp-up of resources to see if muon collider could come directly after HL-LHC

- Compromises in performance, e.g. 3 TeV

Needs to be revised but do not have enough information at this point for final plan

To be reviewed considering progress, funding and decisions



Roadmap Schedule

International MUON Collider Collaboration

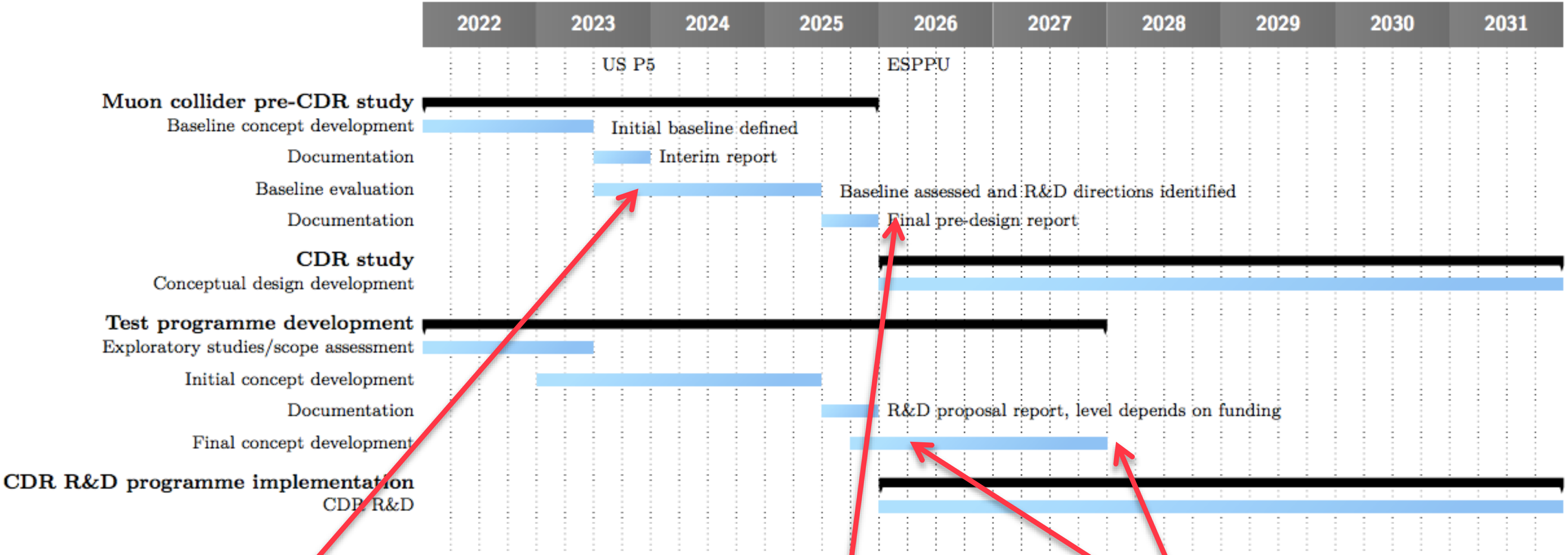


Fig. 5.4: Overall timeline for the R&D programme.

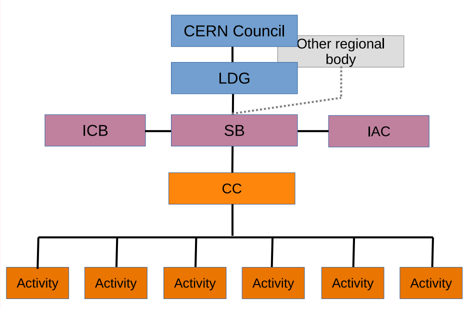
2023
Interim Report to gauge progress
Initial baseline defined

2025
Assessment Report

2025-2027
R&D plan will be refined

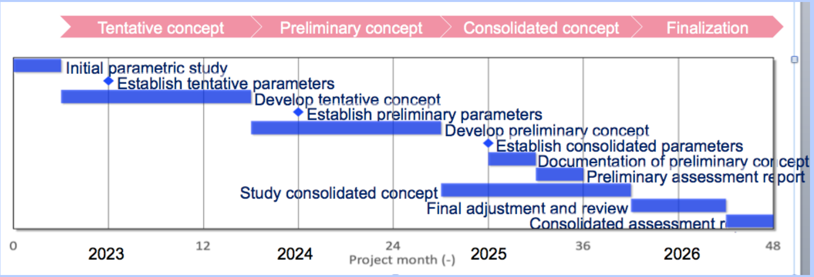
Muon Collider Community

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



50+ partner institutions
30+ already signed formal agreement

EU Design Study approved
(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, …**

TIARA wants magnet proposal

US Snowmass has **strong support**
- to contribute to R&D
- as a collider in the US

Lia appointed team to prepare P5 ask

Some first contacts with others

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
Mal	**Univ. of Malta**
BE	***Louvain***

UK	**RAL**
	UK Research and Innovation
	University of Lancaster
	University of Southampton
	University of Strathclyde
	University of Sussex
	Imperial College London
	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**
LAT	**Riga Technical Univers.**

US	**Iowa State University**
	Wisconsin-Madison
	Pittsburg University
	Old Dominion
	BNL
China	***Sun Yat-sen University***
	IHEP
	Peking University
EST	***Tartu University***
AU	**HEPHY**
	TU Wien
ES	**I3M**
	CIEMAT
	ICMAB
CH	**PSI**
	University of Geneva
	EPFL

KO	**KEU**
	Yonsei University
India	***CHEP***
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
	Tenessee

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

US P5 Ask

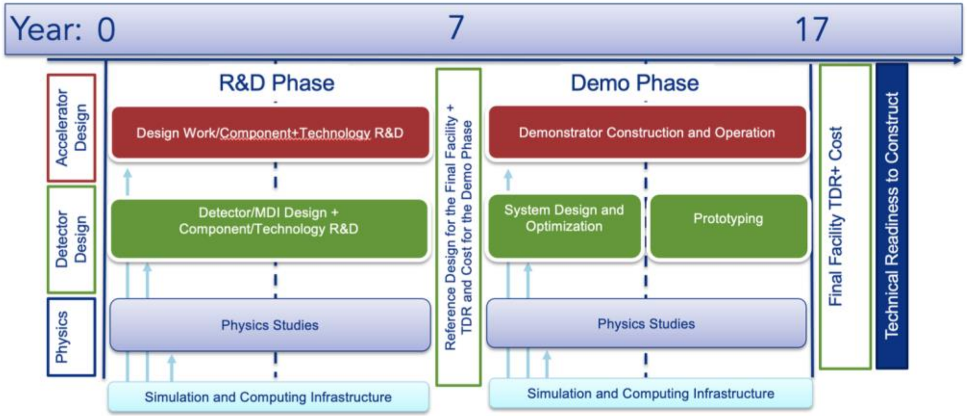
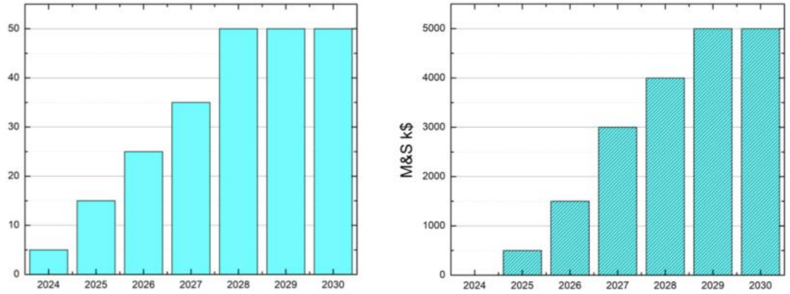


Figure 1: A sketch of the proposed muon collider R&D timeline, along with high-level activities, milestones, and deliverables.



: FTE and M&S profiles for accelerator R&D corresponding to the first phase of the
. We assume here that funding can start in 2024. The M&S is in FY23 dollars and
n is not included in these estimates.

S. Jindariani, D. Stratakis, Sridhara Dasu et al.
Goal is to contribute as much as Europe
Start of construction a bit later than in Roadmap
Will try to harmonise/define scenarios once US joins

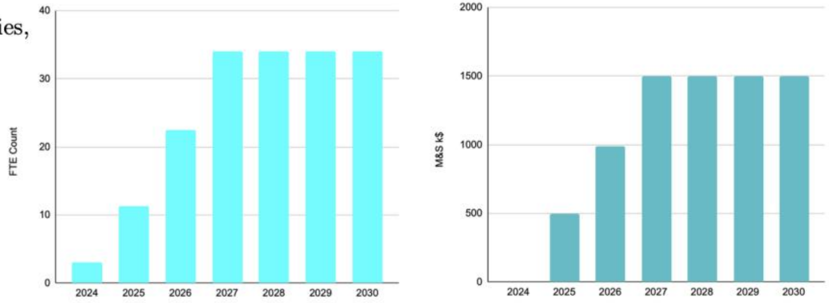
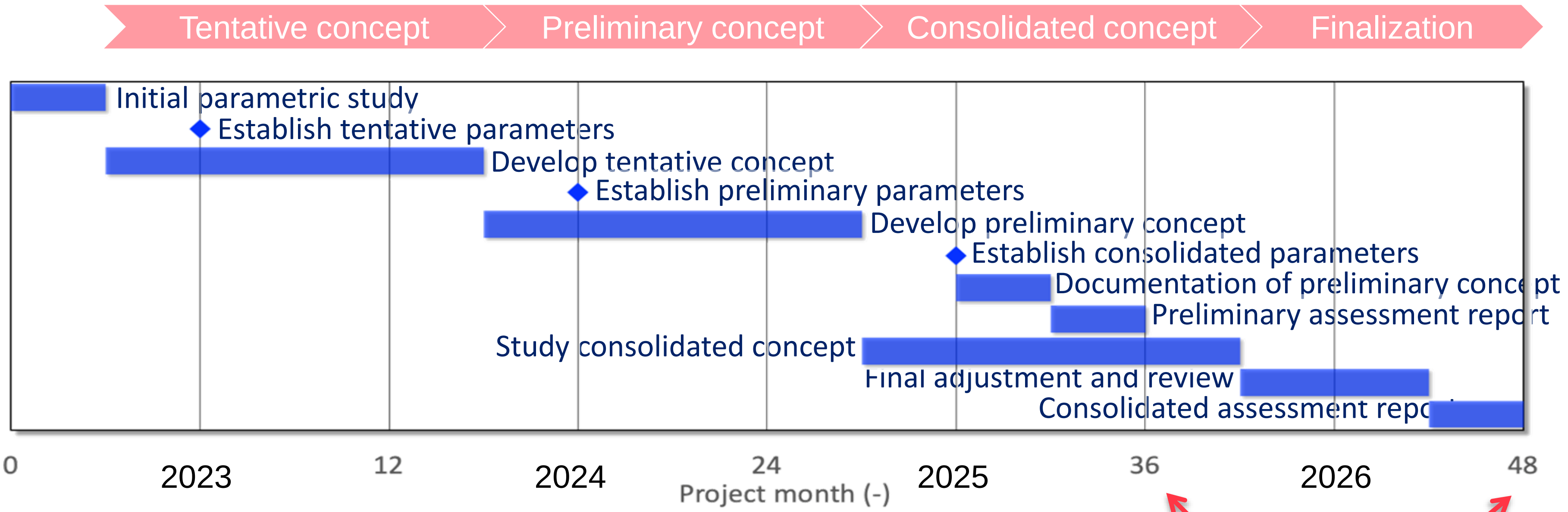


Figure 3: FTE and M&S profiles for detector R&D corresponding to the first phase of the program. We assume here that funding can start in 2024. The M&S is in FY23 dollars and escalation is not included in these estimates.

Total resources would approach Roadmap

- Some increase in Europe and Asia assumed
- 1-2 years delay
- But profile is different

EU Design Study Timeline



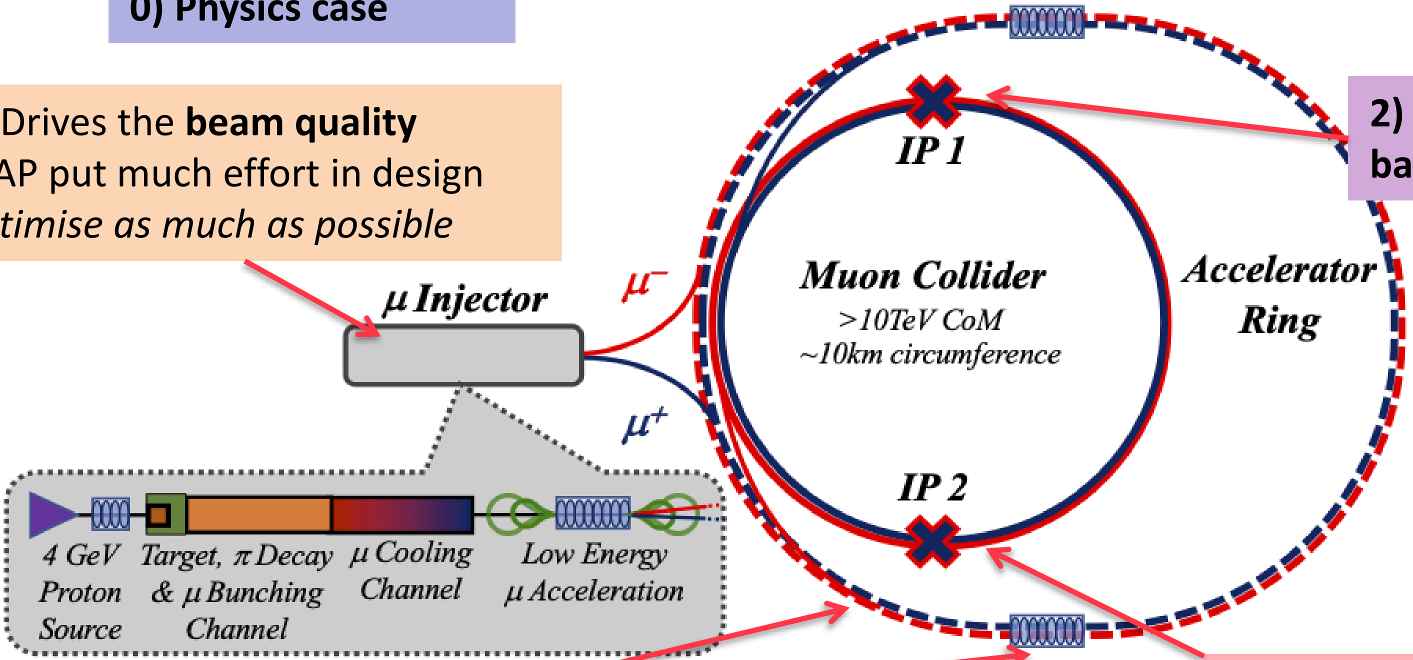
Next ESPPU ?

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**

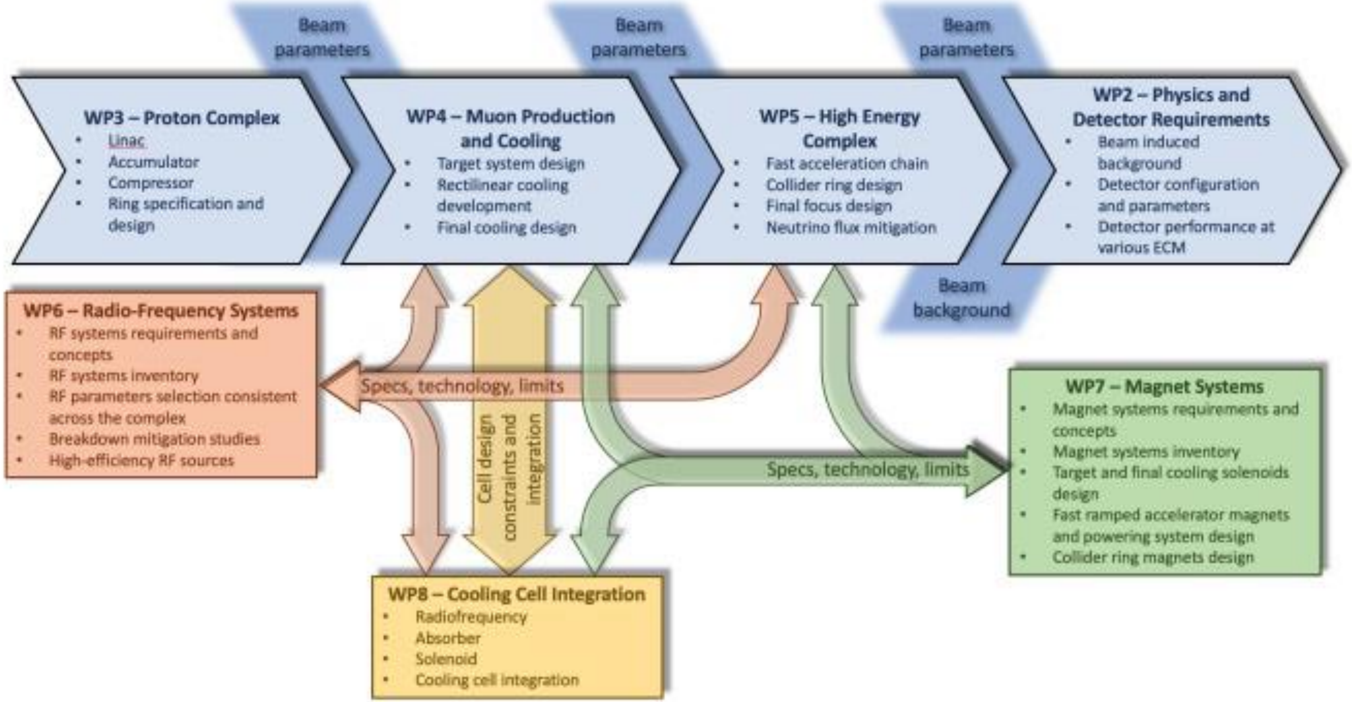
Current Work

Still lacking resources and several teams just getting into the subject, but already important results being obtained

Focus on most critical aspects

- Most pressing key issues and technologies
  - E.g. power in target, muon cooling design, acceleration, collider
- Installing integration loops
  - radial model of collider ring arc dipole, lattice design, cooling, shielding, magnet, vacuum, …
- Defining scope of demonstrator and R&D programme
- Preparation of test stand for RF in magnetic field
- Setting up magnet work with focus on HTS
- Exploring synergy
  - Technical
  - Physics
- Publications, outreach etc.

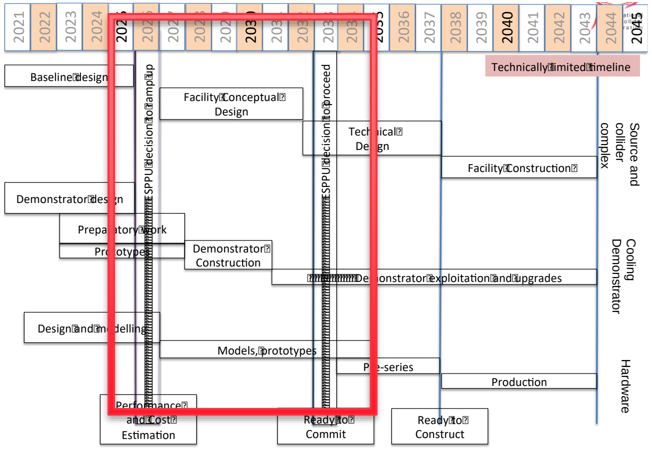
Current Work



CDR Phase, R&D and Demonstrator Facility

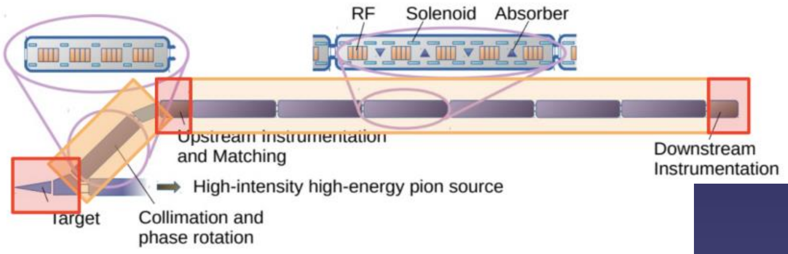
Broad R&D programme required and can be distributed world-wide

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

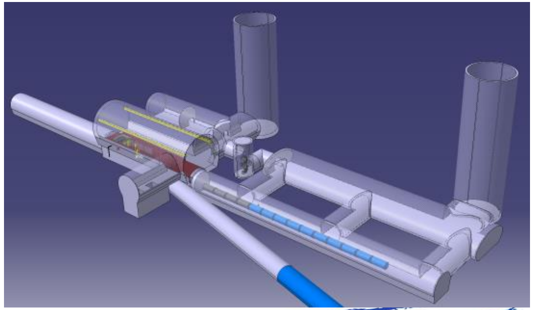


Integrated cooling demonstrator is a key facility

- 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

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

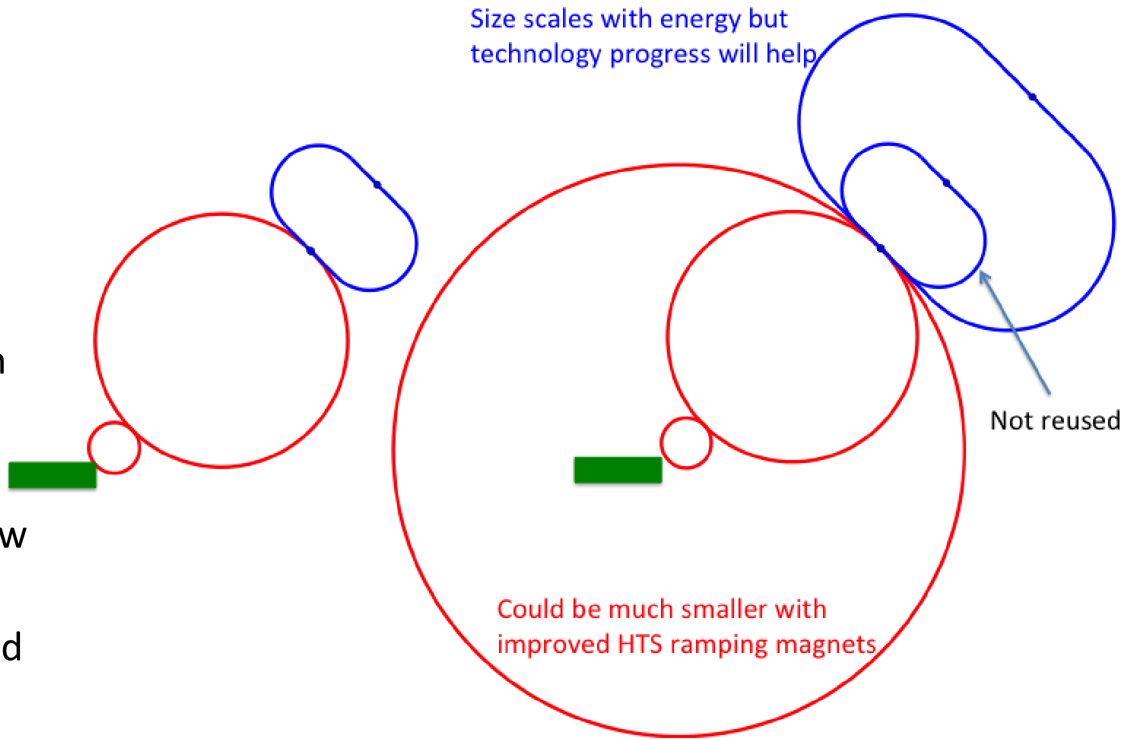
Staging

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

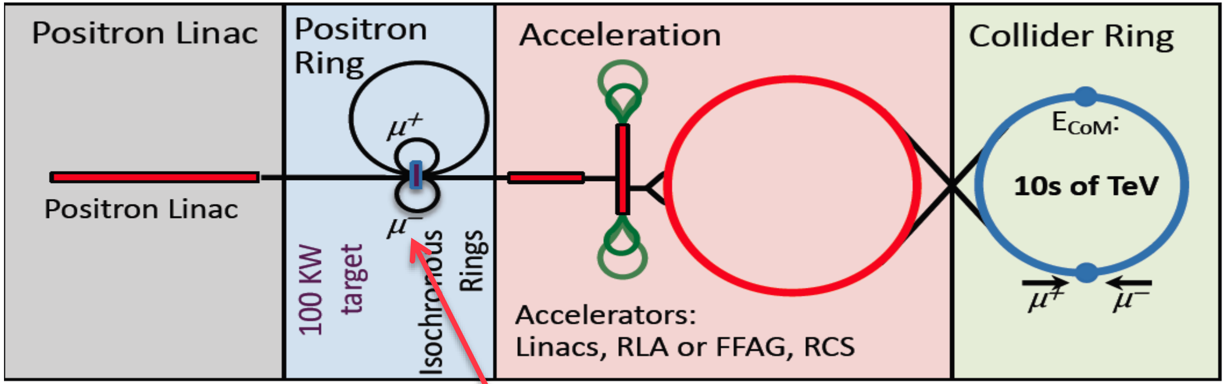
Upgrade adds one more accelerator and new collider ring

- only first collider ring is not being reused



Alternatives: The LEMMA Scheme

LEMMA scheme (INFN) P. Raimondi et al.



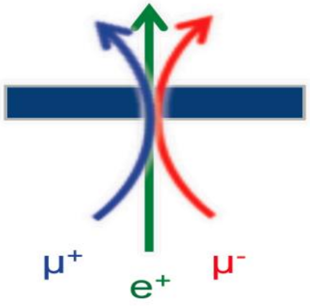
Note: New proposal by C. Curatolo and L. Serafini needs to be looked at

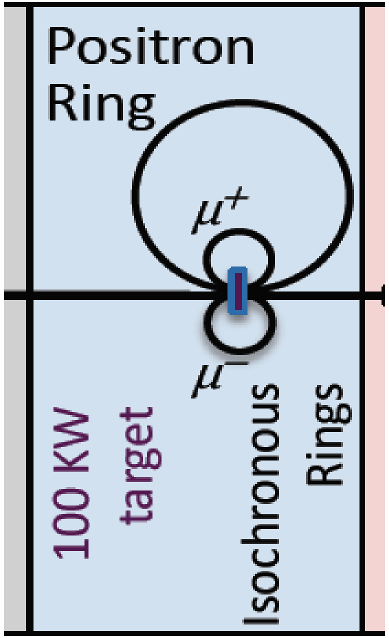
- Uses Bethe-Heitler production with electrons

45 GeV positrons to produce muon pairs

Accumulate muons from several passages

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



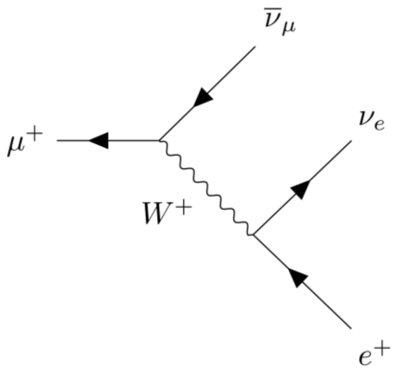


Excellent idea, but nature is cruel

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.

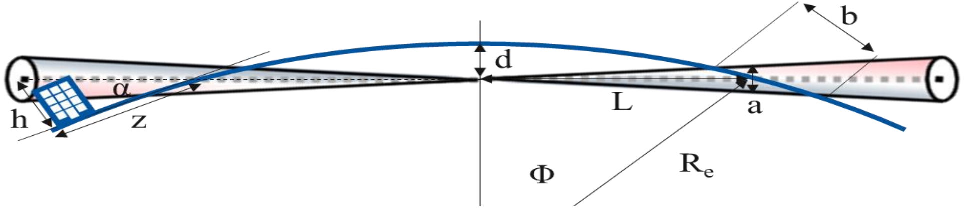
Neutrino flux to have negligible impact on environment

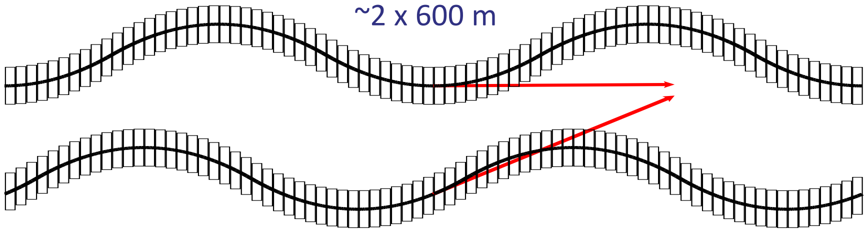
- want to be **negligible** (same level as LHC)
- opening cone decreases, cross section and shower energy increase with energy

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

Mechanical system with 15cm stroke, 1% vertical bending

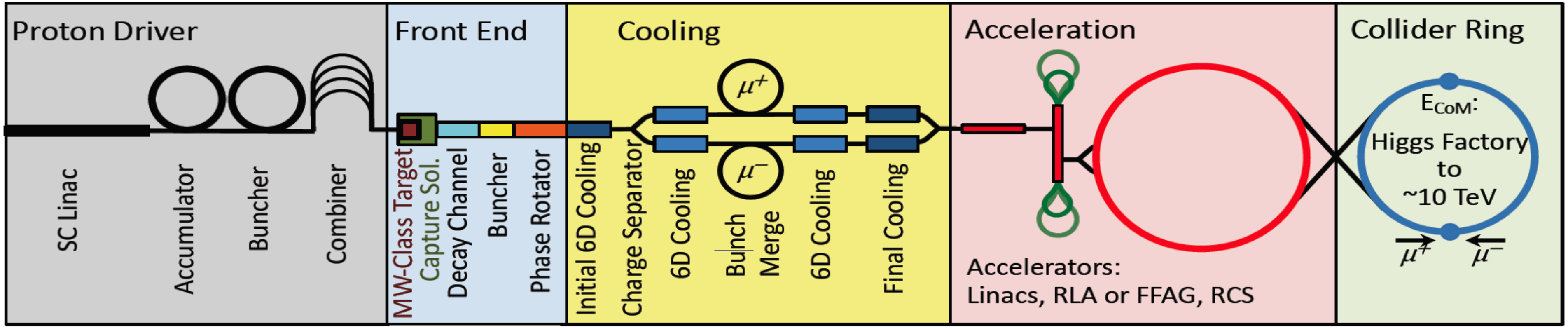
Length of pattern to be optimised for minimal impact on beam





Key Challenges

International
UON Collider
Collaboration



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

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

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.

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 in 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
  - …

Initial Target Parameters

International MUON Collider

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	

US Snowmass

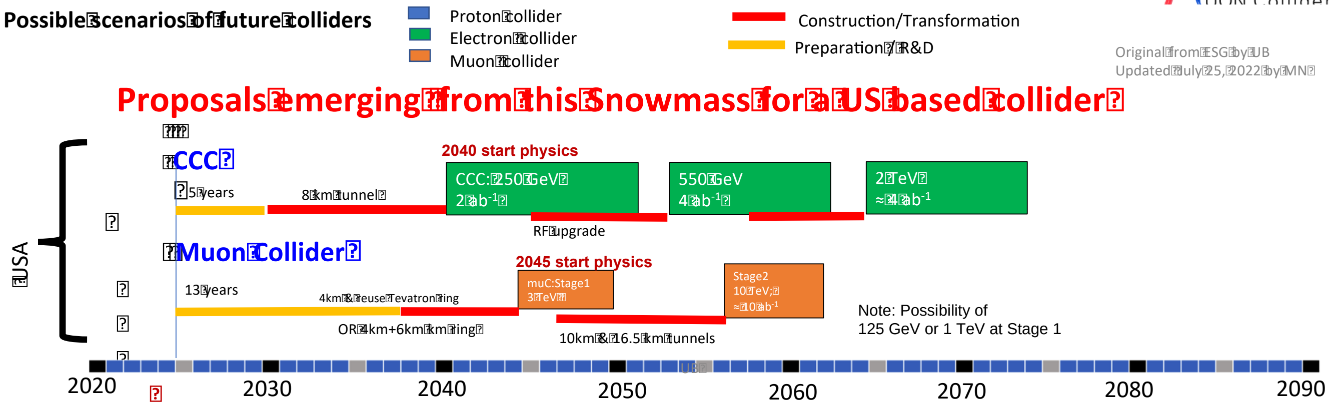
Strong interest in the US community in muon collider

- 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.

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

Thomas Roser et al

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