International Muon Collider Collaboration Status and Plans

with a personal view

Nadia Pastrone INFN TORINO

International MUON Collider Collaboration

Gruppi **INFN** in **RD_MUCOL:**

LNF PD RM1 MI TO TS BO MIB FE PV LNL RM3 BA NA LNS (GE)

Nuove attività legate allo sviluppo del disegno della facility

RD_MUCOL - Italia - Riunione di collaborazione

Pavia – 20 dicembre, 2022

Goals of the collaboration meeting

- ✓ Share our views and plan for next year and future in a nice environment
  ➔ Thanks to Pavia's group; Cristina, Ilaria, Chiara …
- ✓ Physics: where we are and what is needed to further studies ➔ identify benchmarks
- ✓ Accelerator technology: identify activities and define projects to present to INFN MAC
- ✓ Full simulation – Delphes ➔ design experiment @ 10 TeV and study different physics
- ✓ Detector R&D ➔ take active part to Detector Roadmap implementation
- ✓ Identify synergies for test facilities and demonstrator
- ✓ Next workshop/meeting/conferences

Preamble

International MUON Collider Collaboration

- ✓ Accelerator and Detector R&D Roadmaps under implementation plan

- ✓ Annual Meeting @ CERN October 11-14: https://indico.cern.ch/event/1175126/

- ✓ status&plan prepared for the Muon Collider Physics and Detector workshop @ FNAL Dec 15-16

  ➔ https://indico.fnal.gov/event/56615/:

  simulation tutorial
  interplay between Accelerator and Detector design
  physics: Higgs, DM, g-2…
  full simulation
  3 TeV ➔ 10 TeV
  full vs fast simulation ➔ Delphes
  pheno requirements
  synergies: MUIC, Mu2e, neutrinos, beam dump

Essentials

- ✓ the **international community** is working together and growing since 2018 – 5 years – mainly based on previous **U.S. MAP project** results, **MICE** in UK and **alternative studies** in Italy with **crucial contribution to demonstrate the physics potential and the measurements' feasibility**
- ✓ an **international collaboration** was established soon after the ESPPU recommendation, in July 2020
- ✓ Accelerator R&D Roadmap and Snowmass21, carried on in parallel, **strengthen the community**

➔ IMCC has the responsibility to steadily evolve into the most inclusive environment to deliver a multi-TeV muon collider design study, exploiting at best the international resources and synergies, to establish by the next strategies whether the investment into a full CDR and a demonstrator is scientifically justified to be chosen as the future feasible and viable option

- ✓ a **baseline scheme to design the 10 TeV facility is sketched out** and requires several further studies, setting the right priorities and R&D plans, engaging all the present and future participating institutes

multi-TeV Muon Collider

Input Document to EU Strategy Update – Dec 2018
"Muon Colliders," arXiv:1901.06150
by *CERN-WG on Muon Colliders*

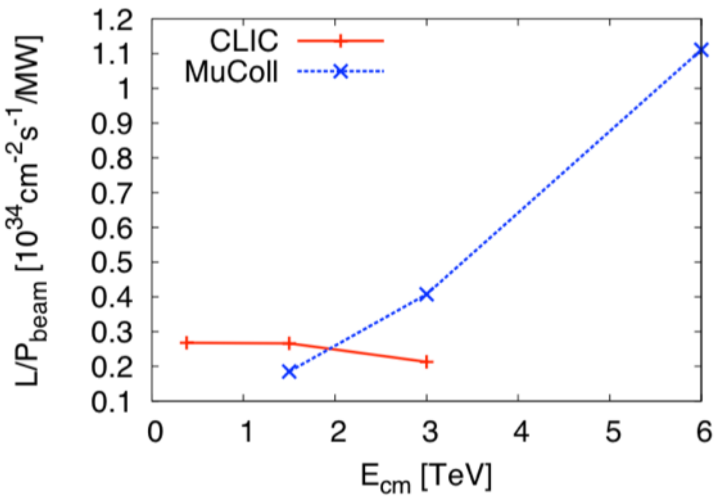
International MUON Collider Collaboration

European Strategy Update – June 19, 2020:

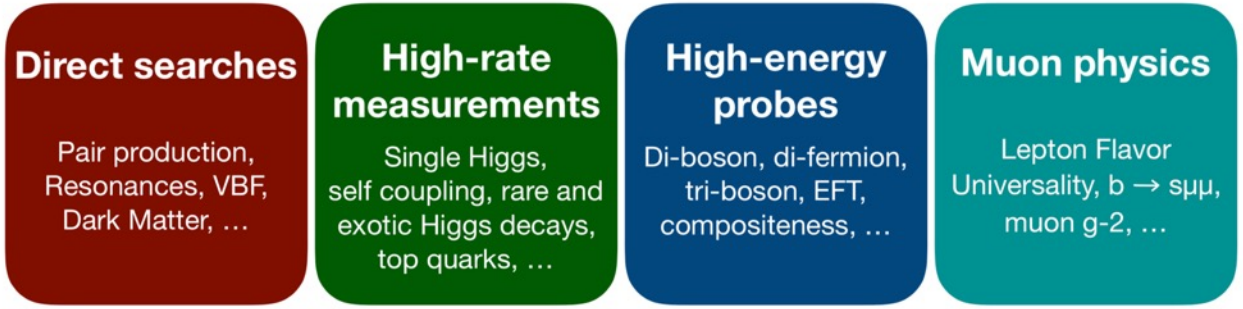
High-priority future initiatives [..]

In addition to the high field magnets the **accelerator R&D roadmap** could contain:

[..] an **international design study** for a **muon collider**, as it represents a **unique opportunity** to achieve a *multi-TeV energy domain beyond the reach of e^+e^- colliders*, and potentially within a *more compact circular tunnel* than for a hadron collider. The biggest challenge remains to produce an intense beam of cooled muons, but *novel ideas are being explored.*



A dream machine to probe unprecedented energy scales and many different directions at once!



nature physics

[Muon colliders to expand frontiers of particle physics]()

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

International Context

Project Leader:
Daniel Schulte

International MUON Collider Collaboration

- **Laboratory Directors' Group (LDG) initiated a muon collider collaboration July 2, 2020**
- **CERN Medium Term Plan** 2021-2025 - dedicated budget line – ~2MCHF/year
  mainly to cover machine up to MDI activities
- **International Design Study based at CERN → MoC signed by Funding Agencies and several Institutes**
  the project encompasses physics, machine, detector and Machine Detector Interface
- European LDG **Accelerator R&D Roadmap → implementation after Council Dec 2021**
  dedicated Muon Beams Panel - but also synergies in High field magnets, RF and ERL
- European ECFA **Detector R&D Roadmap → implementation after Council Dec 2021**
  Muon collider @ 10 TeV is one of the targeted facilities emerging from the EPPSU
- US Snowmass'21 Muon Collider Forum **since 2021 – Muon Collider Forum Report Sept 2022**
- Snowmass/P5 process in the US → **ready by Fall 2023**
- HORIZON-INFRA-2022-DEV-01-01 EU project **MuCol** under reevaluation after approval **July 2022**
  Research infrastructure concept development for design study → **supported by TIARA**

Collaboration Meeting of the Muon Collider Study @ CERN
October 11-14, 2022 https://indico.cern.ch/event/1175126/

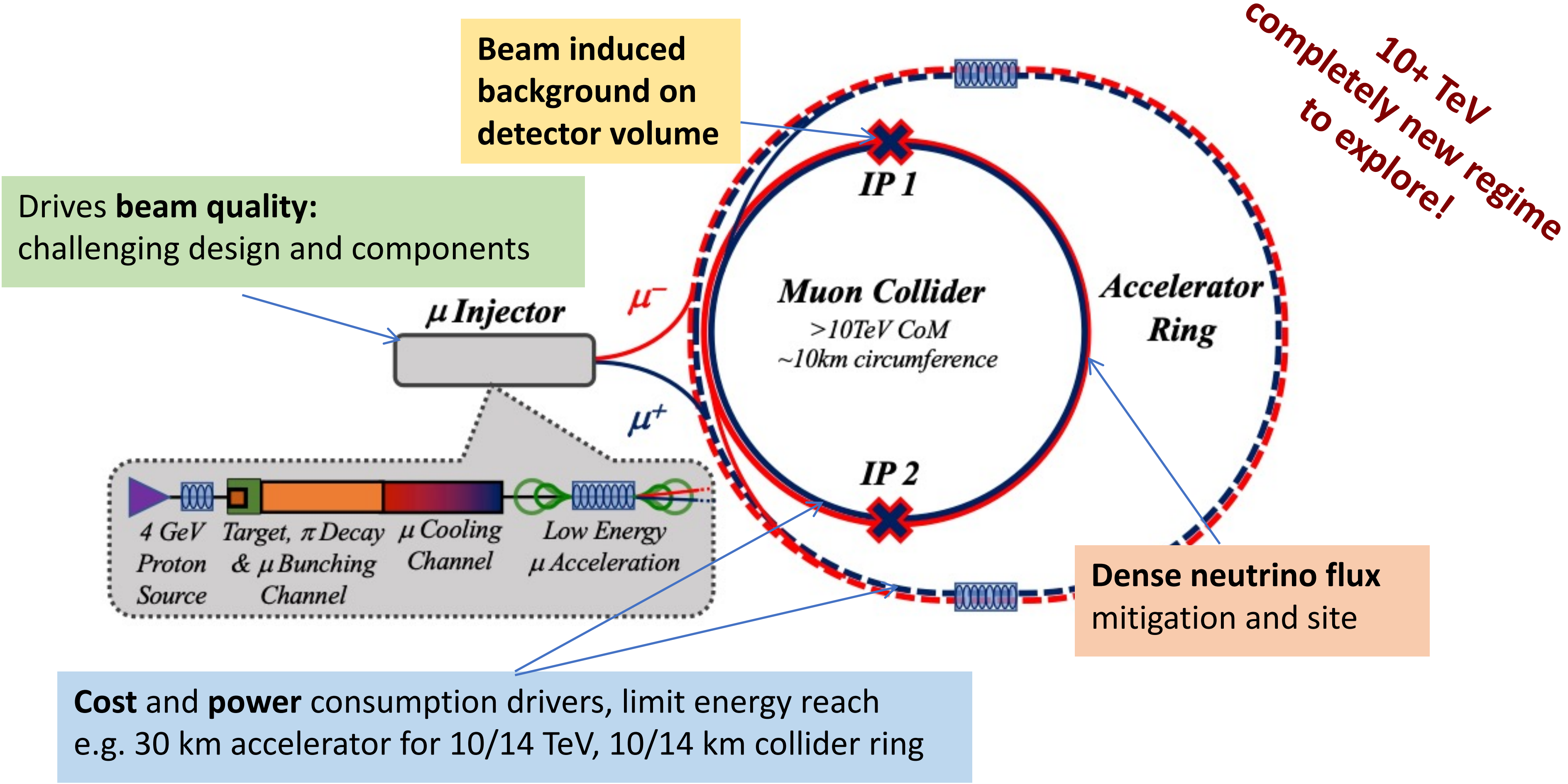
International Design Study facility

Proton driver production as baseline

- **Focus on two energy ranges:**

3 TeV technology ready for construction in 10-20 years

10+ TeV with more advanced technology



Key Challenge Areas

- **Physics potential** evaluation, including **detector concept and technologies to design experiments**

- Impact on the environment
  - **Neutrino flux mitigation** and its impact on the site (first concept exists)
  - **Machine Induced Background** impact the detector, and might limit physics

- **High-energy systems** after the cooling (acceleration, collision, ...)
  - Fast-ramping magnet systems
  - High-field magnets (in particular for 10+ TeV)
- **High-quality muon beam production**
  - Special RF and high peak power
  - Superconducting solenoids
  - Cooling string demonstration (cell engineering design, demonstrator design)

High energy complex requires known components
➔ synergies with other future colliders

- **Full accelerator chain**
  - e.g. proton complex with H- source, compressor ring ➔ test of target material

Roadmap Plan

Site
ν mitigation

MDI
Collider ring
Cooling
Proton complex
Beam dynamics

Magnets:
HF dipoles and solenoids
Fast ramping

NCRF – SCRF
RF Test stand

Cooling cell
Demonstrator

Target system
Integration

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

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Scenarios

Aspirational		Minimal	
[FTEy]	[kCHF]	[FTEy]	[kCHF]
445.9	11875	193	2445

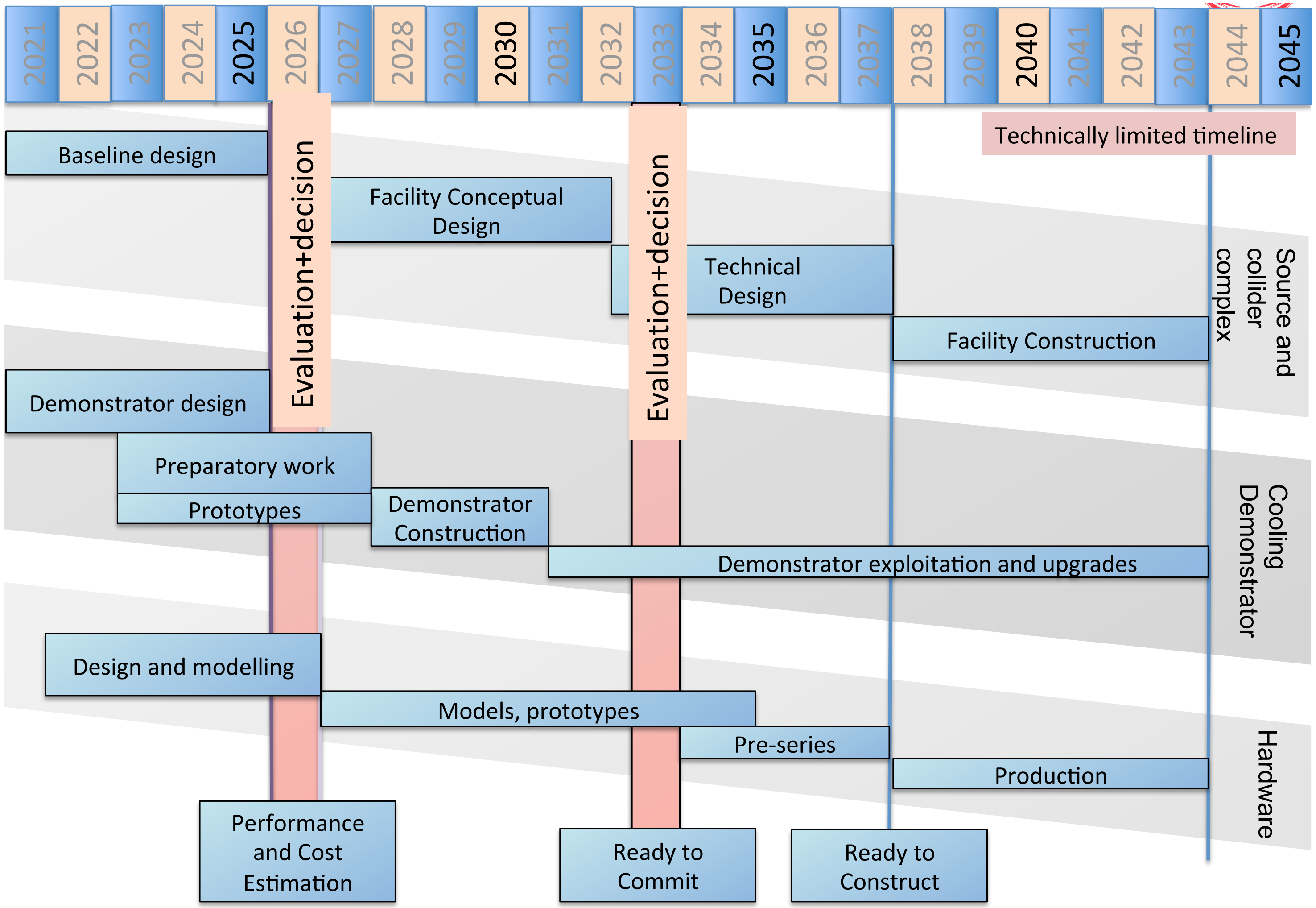
~70 Meu/5 years

Accelerator R&D Roadmap

Bright Muon Beams and Muon Colliders

Panel members: **D. Schulte**,(Chair), **M. Palmer** (Co-Chair), T. Arndt, A. Chancé, J. P. Delahaye, A.Faus-Golfe, S.Gilardoni, P.Lebrun, K.Long, E.Métral, N.Pastrone, L.Quettier, T.Raubenheimer, C.Rogers, M.Seidel, D.Stratakis, A.Yamamoto
Associated members: A. Grudiev, R. Losito, D. Lucchesi

International MUON Collider Collaboration



The panel has identified a development path that can address the major challenges and deliver a 3 TeV muon collider by 2045

https://arxiv.org/abs/2201.07895

Technically limited timeline

Long-term future: a multi-TeV collider

from Snowmass

- **For the next decade and beyond**
  - **2025-2030**:
    - Develop an initial design for a first stage TeV-scale Muon Collider in the US (pre-CDR)
    - Support critical detector R&D towards EF multi-TeV colliders
  - **2030-2035**: Demonstrate principal risk mitigation and deliver CDR for a first-stage TeV-scale Muon Collider
  - **After 2035**:
    - Demonstrate readiness to construct and deliver TDR for a first-stage TeV-scale Muon Collider
    - Ramp up funding support for detector R&D for EF multi-TeV colliders

https://arxiv.org/abs/2203.07256

https://arxiv.org/abs/2203.07964

https://arxiv.org/abs/2203.07224

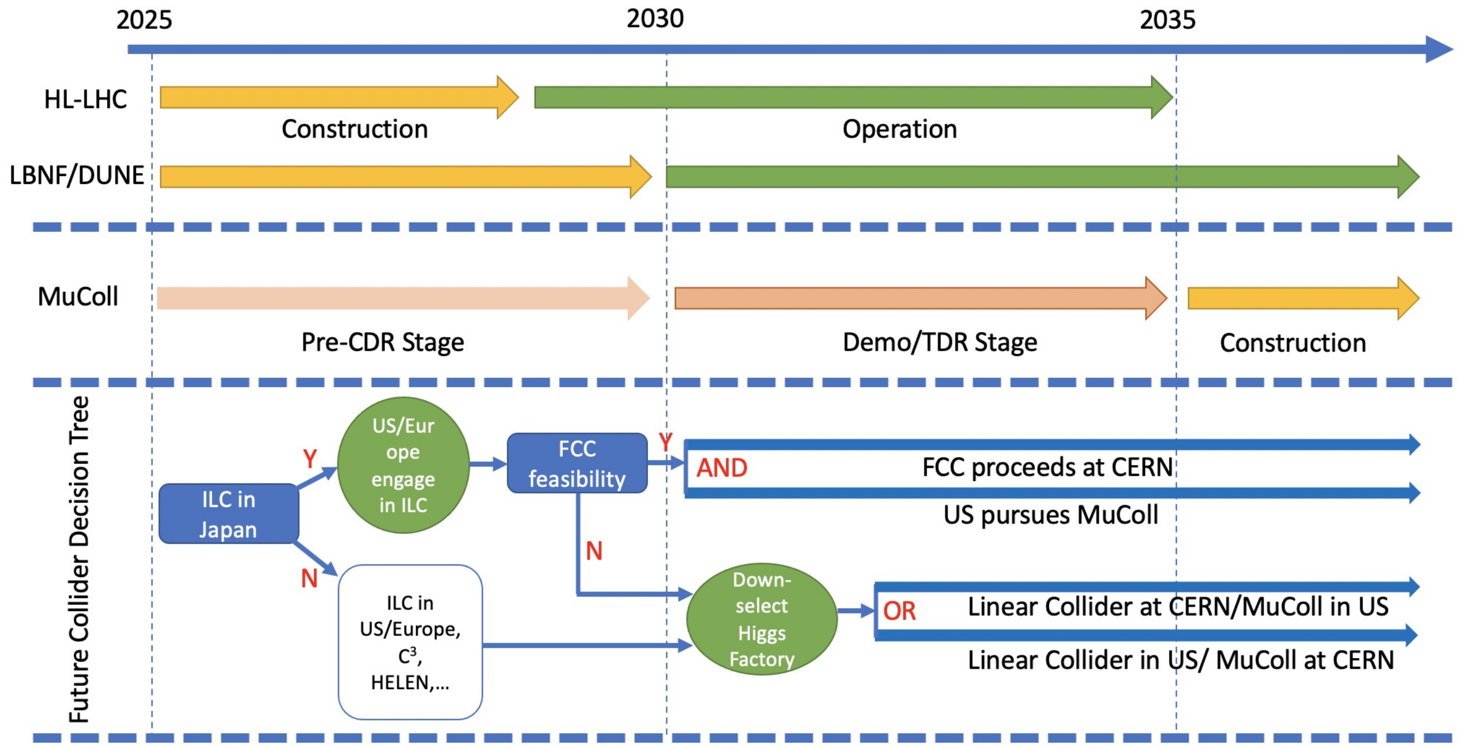
https://arxiv.org/abs/2203.08033

https://arxiv.org/abs/2203.07261

Muon Collider Forum Report

arXiv:2209.01318 [hep-ex]

Forum Conveners:
K.M. Black, S. Jindariani, D. Li, F. Maltoni, P. Meade, D. Stratakis



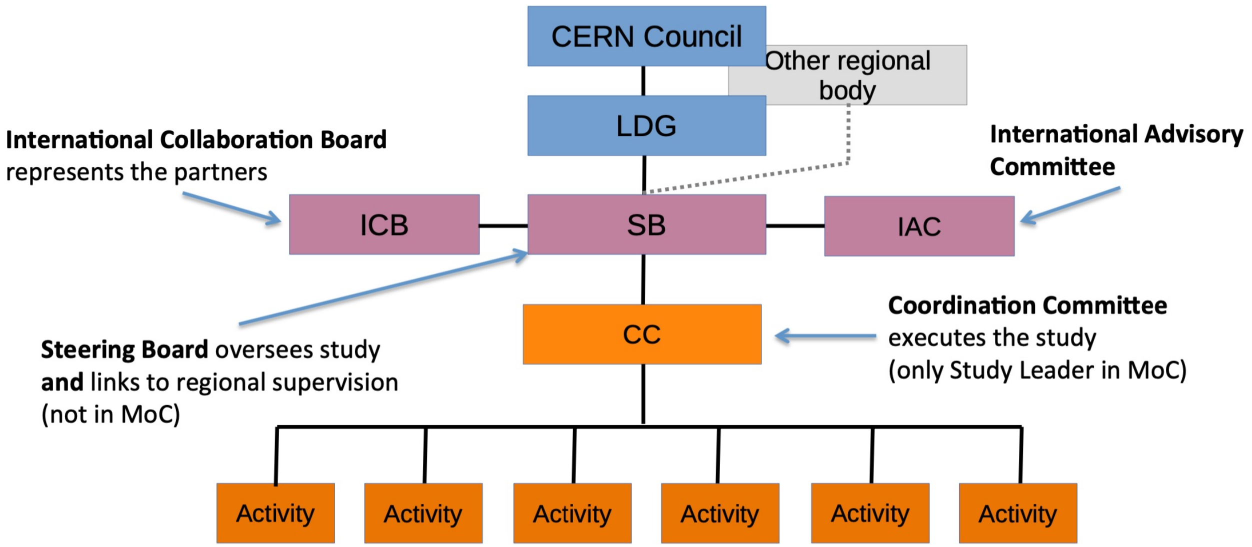
IMCC organization for Roadmap implementation

After the MoC a Governance Structure of the International Muon Collider Collaboration document by D. Schulte, M. Lamont

➔ implementation details including LDG/Council requests **STILL TO BE REFINED AND IMPROVED**

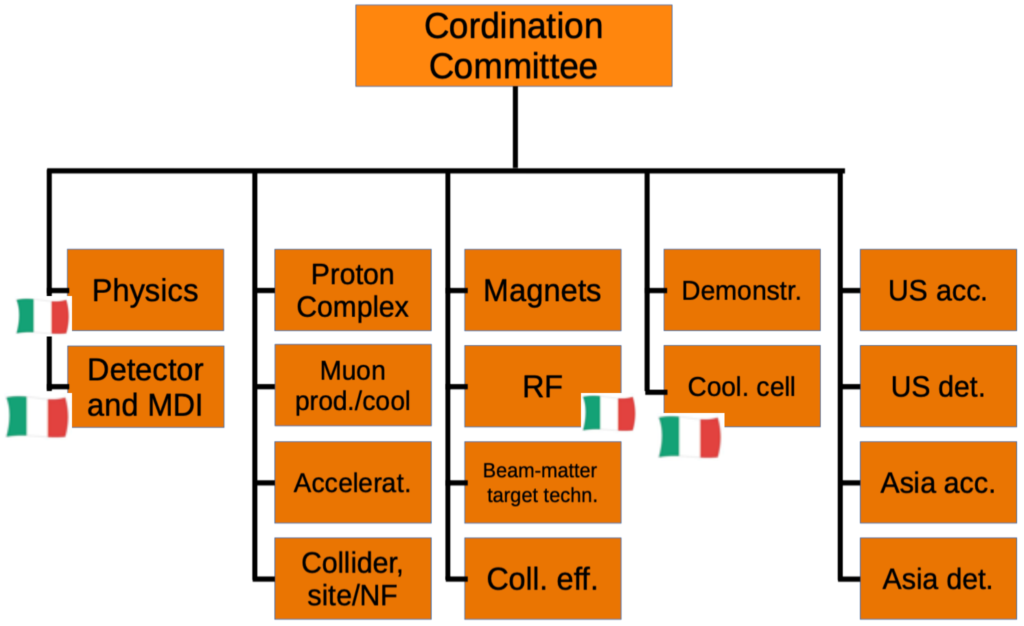
Proposed Governance

CERN is host organisation, can be transferred to other partner on request of CERN and with approval of ICB
Will review governance in 2024, US could join at that time



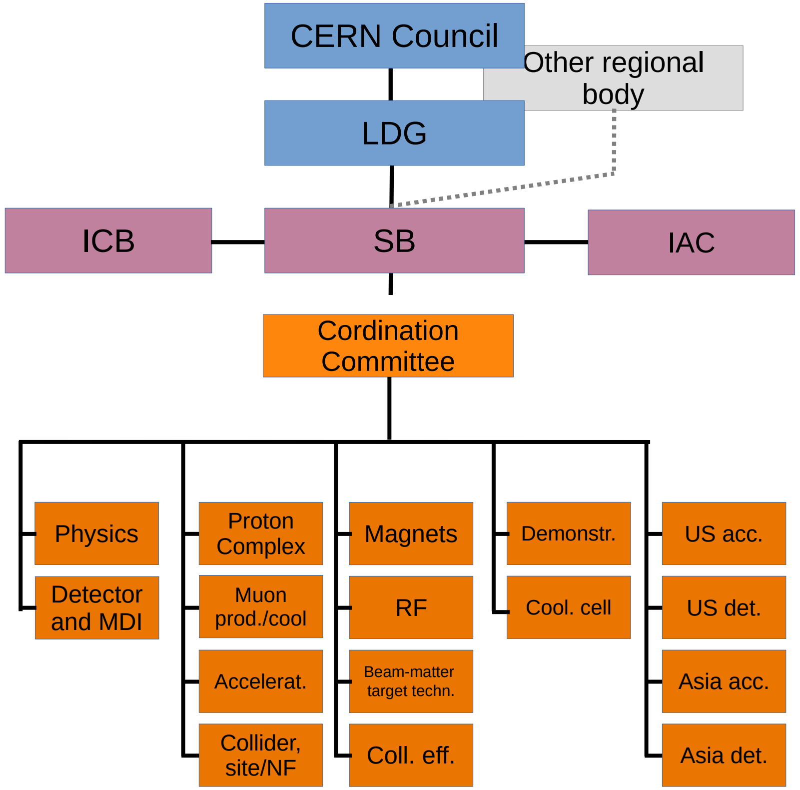
MoC signed by CERN CEA INFN STFC-RAL ESS IHEP and different universities in EU, US, China

Coordination Committee



IMCC organization names

- **Collaboration Board (ICB)**
  - Elected chair: **Nadia Pastrone**
- **Steering Board (SB)**
  - Chair **Steinar Stapnes**, CERN members: Mike Lamont, Gianluigi Arduini, + ICB representatives, ICB chair and SL and deputies
- **International Advisory Committee (IAC)** *still to be formed*
- **Coordination committee (CC)**
  - ICB endorsed:
    - Study Leader **Daniel Schulte**
    - Deputies: **Andrea Wulzer, Donatella Lucchesi, Chris Rogers**



Physics	Andrea Wulzer
Detector and MDI	Donatella Lucchesi

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

Cooling cell design	Lucio Rossi
Demonstrator	Roberto Losito

Magnets	Luca Bottura
RF cavities	Alexej Grudiev, Claude Marchand
Beam-matter interaction target systems	Anton Lechner
Collective effects	Elias Metral

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

IMCC web page: http://muoncollider.web.cern.ch

Plans, timeline ……

International MUON Collider Collaboration

2023 **IMCC Interim Report**	**Project Evaluation Report**	**R&D Plan**	**2025-26** **Consolidated concept**	**2026-27** **Next ESPPU**
2023 **P5 report**	**Strengthen International Collaboration**	**Design and R&D studies Plan**	**2026-2027** **Consolidated concept**	**2028** **Next Snowmass**

Current funding level and available resources allows only to address the most critical items
➔ more resources could be provided by R&D program both for detector and accelerator technologies at national, regional and international level

Crucial to:

- make convincing priorities
- explore and exploit synergies for technology R&D, test facilities physics/technology goals and application to other fields and society
- promote and take part to R&D programs in any continent
- **share a common view and nurture an open and enthusiastic global community**

…. and desiderata

2023 **IMCC Interim Report**	**Project Evaluation Report**	**R&D Plan**	**2025-26** **Consolidated concept**	**2026-27** **Next ESPPU**
2023 **P5 report**	**Strengthen International Collaboration**	**Design and R&D studies Plan**	**2026-2027** **Consolidated concept**	**2028** **Next Snowmass**

International MUON Collider Collaboration

- ✓ as the CERN WG during ESPPU, IMCC should steadily develop offering a common framework to the international community to work together
- ✓ IMCC organization and coordination structure should evolve in time and start to be adjusted as soon as the P5 process will be completed by Fall 2023

by the end of the next Strategy processes in ~2030,
the IMCC should be truly "all-inclusive" region-wise
with the US, Europe and Asia (Japan) as equal partners

A growing collaboration

http://map.fnal.gov/

U.S. Muon Accelerator Program (MAP)

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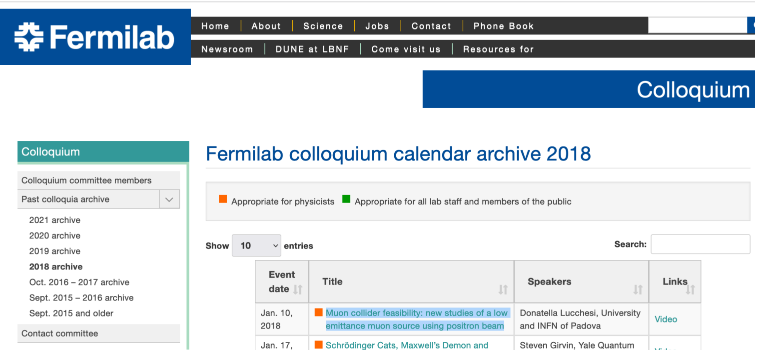
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Past colloquia archive
2021 archive
2020 archive
2019 archive
2018 archive
Oct. 2016 – 2017 archive
Sept. 2015 – 2016 archive
Sept. 2015 and older
Contact committee

Fermilab colloquium calendar archive 2018

Appropriate for physicists · Appropriate for all lab staff and members of the public

Show 10 entries   Search:

Event date	Title	Speakers	Links
Jan. 10, 2018	Muon collider feasibility: new studies of a low emittance muon source using positron beam	Donatella Lucchesi, University and INFN of Padova	Video
Jan. 17,	Schrödinger Cats, Maxwell's Demon and	Steven Girvin, Yale Quantum	

participants

Meeting	Participants
Padova July 2018	
CERN April 2019	56
CERN October 2019	85
Remote March 2020	165
Remote July 2020	272
Remote Community May-Oct 2021	153-113
CERN October 2022	187

www.symmetrymagazine.org

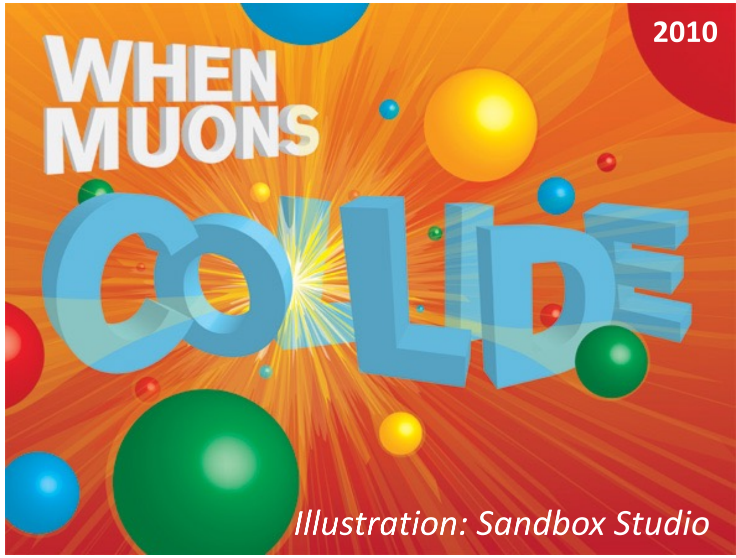
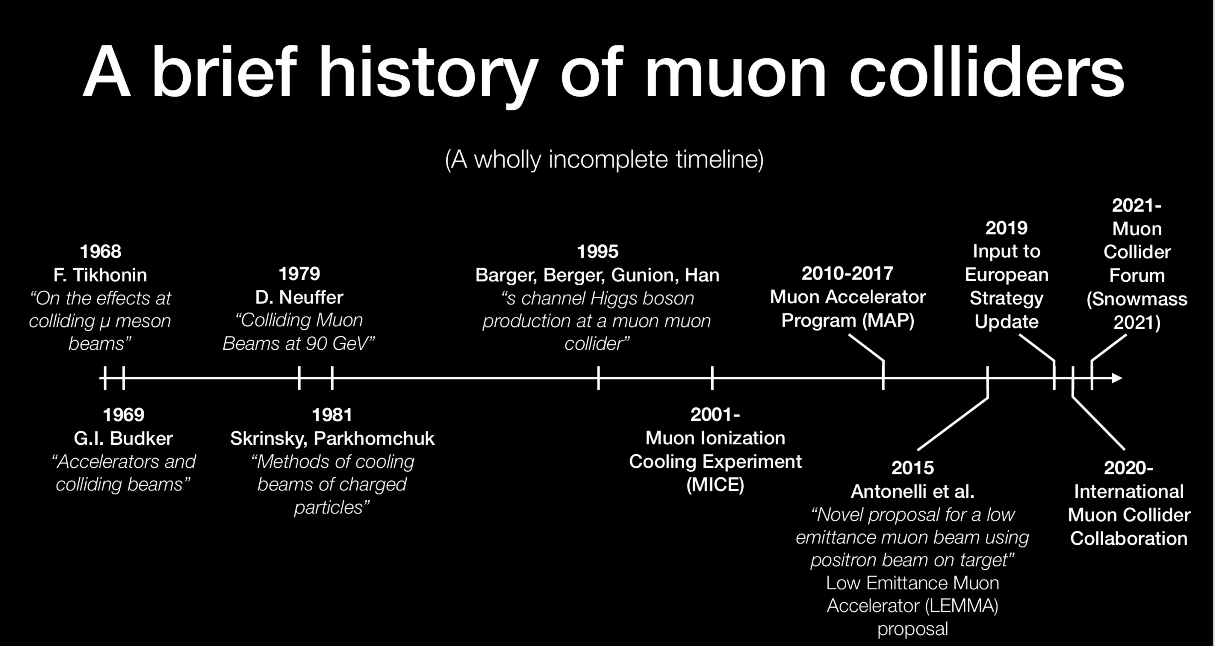
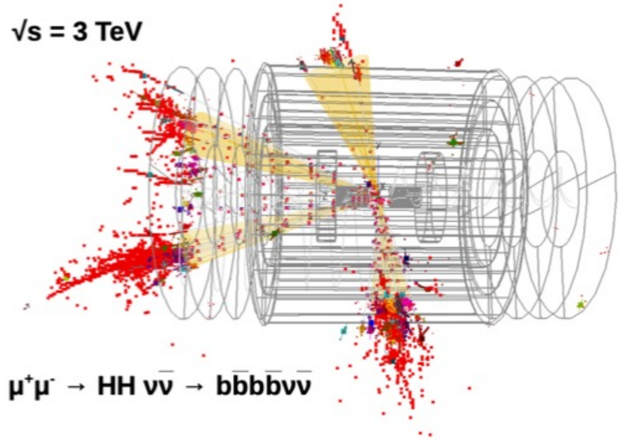


Illustration: Sandbox Studio



Looking forward to a bright future

International MUON Collider Collaboration



- New key technologies are developing or available
  ➔ Time scale is becoming realistic for a multi-TeV collider
- New Physics opportunities
  ➔ Higher energy – Higher luminosity
  ➔ Direct searches+precision – reach physics program

Advances in detector and accelerator pair with the opportunities of the physics case

Ready? *GO!*

extras

Rapid response program

AGENDA IN PREPARATION
MORE INFO TOMORROW (?)

Muon Collider Workshop: Feb 27, 2023 - Mar 10, 2023

Application deadline is: *Dec 22, 2022*

Coordinators: Nathaniel Craig, Sergo Jindariani, Federico Meloni, Isobel Ojalvo, and Andrea Wulzer

High-energy muon colliders have recently emerged as compelling candidates for the next phase of exploration in fundamental physics. Blurring the dichotomy between energy and precision, they are poised to address many of the questions stemming from the discovery of the Higgs boson and meaningfully continue the pursuit of physics at shorter distances. The unparalleled efficiency and compact footprint of high-energy muon colliders offer considerable advantages, while their development would necessarily advance particle physics at both the intensity and energy frontiers.

This rapid response program will bring together theorists, experimentalists, and accelerator physicists with the ultimate goal of charting a collaborative international path for a muon collider. Focal points of the program include coordinating efforts among international collaborations; developing the physics case for a demonstrator facility; assessing the central needs and opportunities for theory, experiment, and accelerator physics; and building bridges to the broader particle physics community.

https://www.kitp.ucsb.edu/activities/muoncollider-m23

Anagrafica RD_MUCOL

International MUON Collider Collaboration

TOTALE: 111 PERSONE - 19.6 FTE

SEZIONE	SIGLA	PERSONA	TOT (incl synergies)	RD_MUCOL	MuCol	I.FAST	AIDAinnova
			%FTE	%FTE	%FTE	%FTE	%FTE

BA (16 PERSONE - 2.5 FTE)
BO (8 PERSONE - 1.25 FTE)
FE (3 PERSONE - 0.4 FTE)
LNF (8 PERSONE - 1.1 FTE)
LNL (6 PERSONE - 0.45 FTE)
LNS (3 PERSONE - 0.45 FTE)
MI (9 PERSONE - 1.5 FTE)
MIB (3 PERSONE - 0.3 FTE)

NA (3 PERSONE - 0.3 FTE)
PD (15 PERSONE - 3.6 FTE)
PV (9 PERSONE - 2.1 FTE)
RM1 (8 PERSONE - 2.85 FTE)
RM3 (5 PERSONE - 0.4 FTE)
TO (13 PERSONE - 2 FTE)
TS (2 PERSONE - 0.4 FTE)

GE will appear on MuCol EU project: 0.3 FTE

Key Challenge Areas

International MUON Collider Collaboration

- **Physics potential** evaluation, including **detector concept and technologies**

- Impact on the environment
  - **Neutrino flux mitigation** and its impact on the site (first concept exists)
  - **Machine Induced Background** impact the detector, and might limit physics

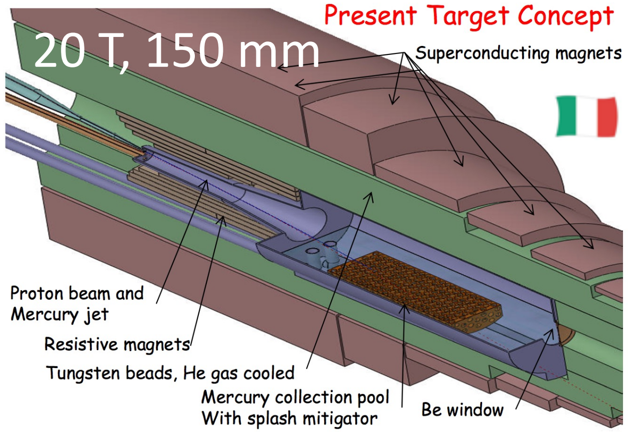
- **High-energy systems** after the cooling (acceleration, collision, ...)
  - Fast-ramping magnet systems **NEW!!**
  - High-field magnets (in particular for 10+ TeV) **NEW!!**

- **High-quality muon beam production NEW!!**
  - Special RF and high peak power
  - Superconducting solenoids
  - Cooling string demonstration (cell engineering design, demonstrator design)

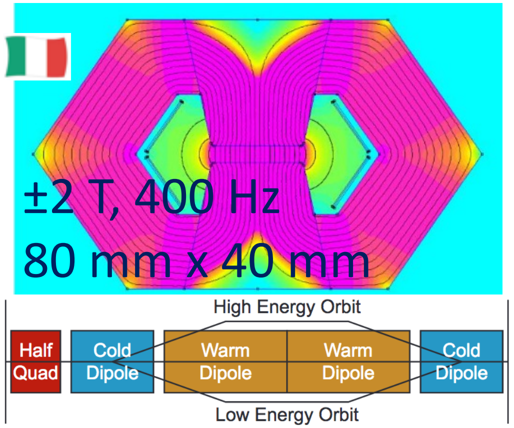
High energy complex requires known components
➔ synergies with other future colliders

- **Full accelerator chain**
  - e.g. proton complex with H- source, compressor ring ➔ test of target material

Magnet Demands @ Muon Collider



High-field and large aperture target solenoid with heavy shielding to withstand heat (100 kW/m) and radiation loads



Combination of DC SC magnets (10 T) and AC resistive magnets (± 2T)

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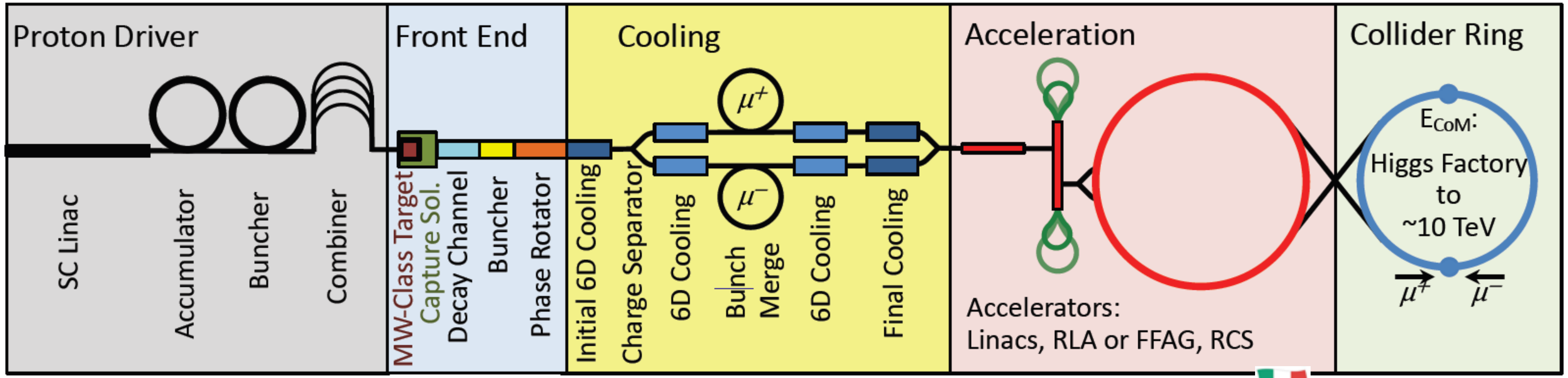
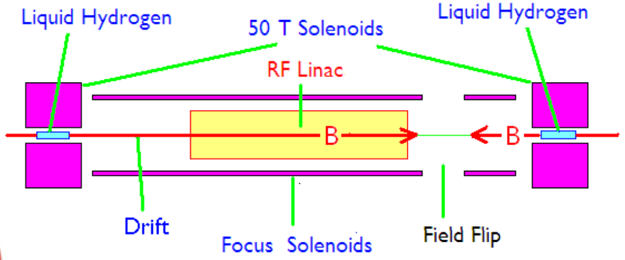
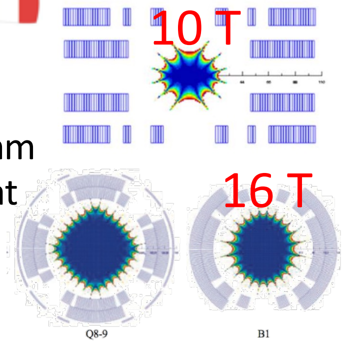


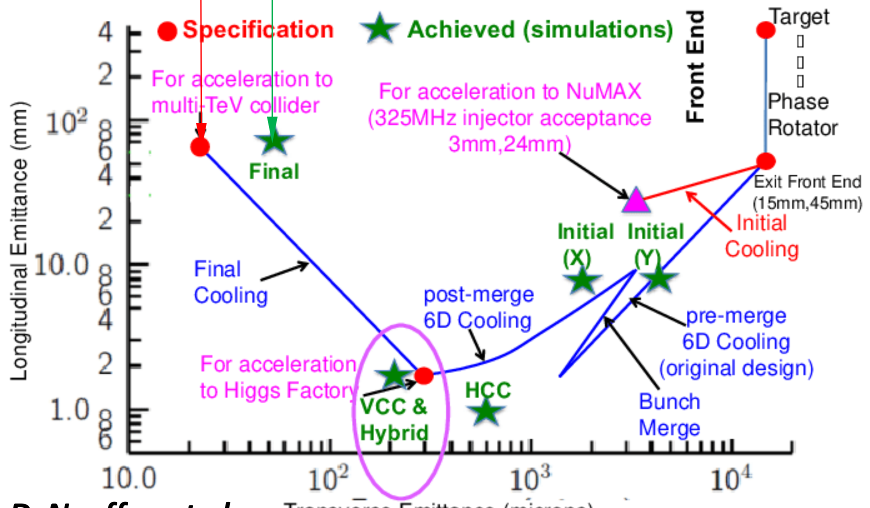
Ultra-high-field solenoids (40...60 T) to achieve desired muon beam cooling



Open midplane or large dipoles and quadrupoles in the range of 10...16 T, bore in excess of 150 mm to allow for shielding against heat (500 W/m) and radiation loads

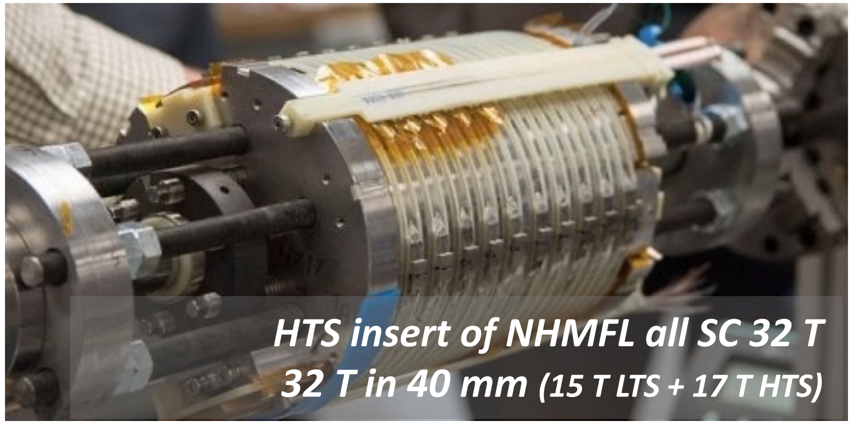


Cooling solenoids



D. Neuffer, et al.

***A field of 40 T (minimum), up to 60 T (target) is needed* to meet emittance specification at the end of the cooling stage**



Present state of the art is the 32T all-SC solenoid in operation at NHMFL.

Novel technology is required (NI/PI) for compact, UHF solenoids operating without (or minimal) helium

Solenoids for a muon collider need to be compact (reduce cost), mechanically strong (withstand extraordinary e.m. forces) and well protected against quench (large stored energy)

Targeted R&D is required to address these challenges