Discussione su EU Strategy on Particle Physics @ Torino

17 ottobre 2024

multi-TeV Muon Collider

Stato collaborazione e progetto internazionale
Aggiornamento attività INFN in corso e future – sinergie

Nicola Amapane - Nadia Pastrone

Gruppi **INFN** *in* ***RD_MUCOL @ CSN1*** **121 persone/30.2 FTE**

RD_MUCOL @ CSN1 – ESPP_A_MUCOL @ GE – UE-MUCOL – UE-I_FAST

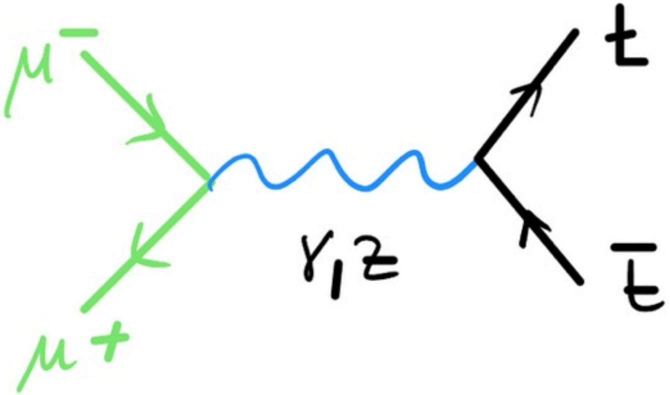
BA BO FE FI GE MI MIB LNF LNL LNS NA PD PI PV RM1 RM3 TO TS

Physics, Detector R&D, MDI, Crystals/Targets, Accelerator Activities

HORIZON-INFRA-2022-DEV-01-01

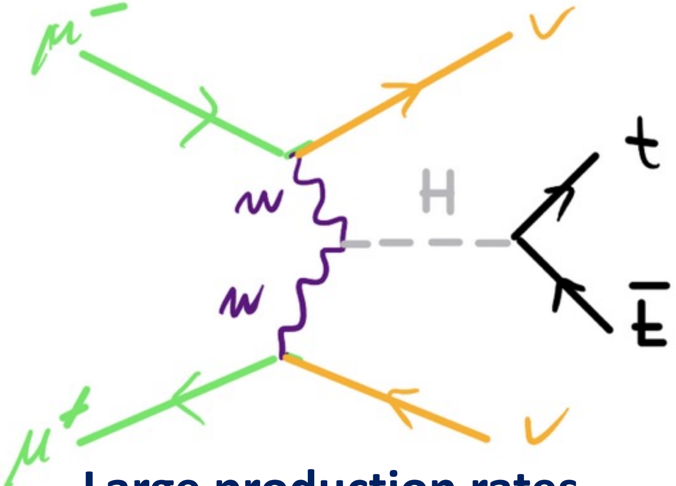
multi-TeV Muon Collider: two colliders in one!

International
MUON Collider
Collaboration



$$\sigma_s \sim \frac{1}{s}$$

Energetic final states
(either heavy or very boosted)



$$\sigma_s \sim \frac{1}{M^2} log^n \frac{s}{M}$$

Large production rates,
SM coupling measurements
Discovery light and weakly interacting

Fabio Maltoni "Physics Overview" Annual Meeting IMCC

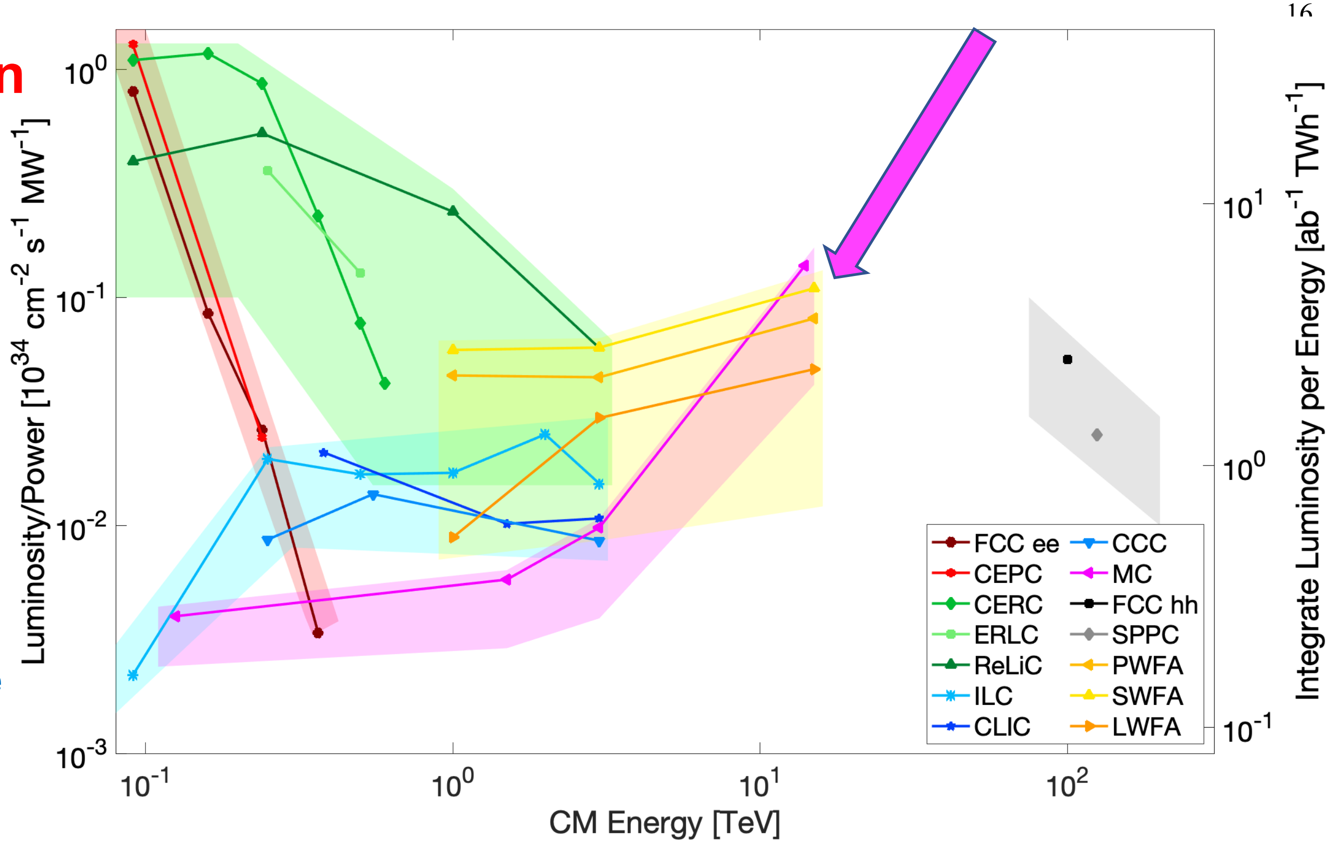
Strong and crucial synergies to design the machine and the experiment
to reach the physics goals with energy and luminosity allowing % precision measurements
➔ **Physics benchmarks steer machine parameters and experiment design**

Energy efficiency of present and future colliders

Thomas Roser et al., Report of the Snowmass 2021 Collider Implementation Task Force, Aug 2022

Luminosity per power consumption

- Figure-of-merit Peak Luminosity (per IP) per Input Power and Integrated Luminosity per TWh.
- Luminosity is per IP and integrated luminosity assumes 10^7 sec/year
- Data points are provided to the ITF by proponents of the respective machine
- The bands around the data points reflect approximate power consumption uncertainty for the different collider concepts.



The effective energy reach of hadron colliders (LHC, HE-LHC and FCC-hh) is approximately a factor of seven lower than that of a lepton collider operating at the same energy per beam

US P5 – International partnership

International
MUON Collider
Collaboration

Stability of the program requires implementing the framework
for our international partnerships!

Parallel to the R&D for a Higgs factory,
the US R&D effort should develop a 10 TeV pCM collider (design and technology), ….

The US should participate in the International Muon Collider Collaboration (IMCC) and take a leading role in defining a reference design.
We note that there are many synergies between muon and proton colliders, especially in the area of development of **high-field magnets**. R&D efforts in the next 5-year timescale will define the scope of test facilities for later in the decade, paving the way for initiating **demonstrator facilities within a 10-year timescale** (Recommendation 6).

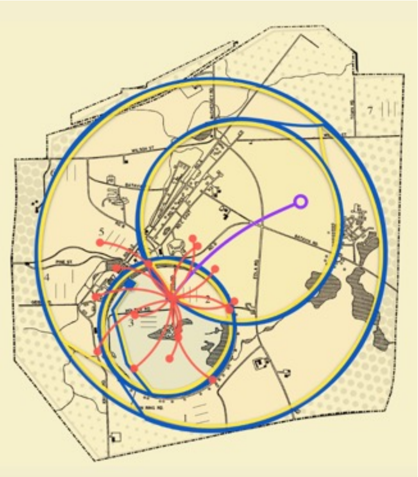
BCG vaccination for cattle pp. 1410 & 1433
Steps toward regulating indoor air quality p. 1418
Landfills emit methane persistently p. 1499

Science

$15
29 MARCH 2024
science.org

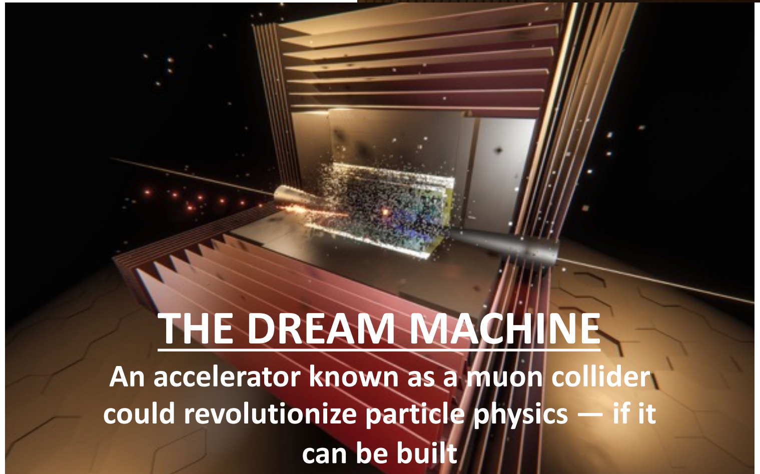
AAAS

A radical new particle accelerator concept emerges. Call it physicists'
MUON SHOT
p. 1405



INAUGURAL US MUON COLLIDER COMMUNITY MEETING

FNAL – August 9, 2024



THE DREAM MACHINE
An accelerator known as a muon collider could revolutionize particle physics — if it can be built

Motivation for a multi-TeV Muon Collider

International
MUON Collider
Collaboration

Towards a muon collider,
Eur. Phys. J. C 83 (2023) 864

Strong interest in **high-energy, high-luminosity lepton collider**
- combines **precision physics** and **discovery reach**
- application of hadron collider technology to a lepton collider

Muon collider promises **sustainable** approach to the **energy frontier**
- limited power consumption, cost and land use ➔ **site evaluation and reuse of existing tunnels**

Technology and **design advances** in past years
- reviews of the muon collider concept in Europe and US found **no insurmountable obstacle**
- **identified required R&D**, documented in accelerator R&D Roadmap
- first parameters' report submitted October 2023

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

NEW OPTION: initial 10 TeV stage at reduced luminosity

Interim report https://arxiv.org/abs/2407.12450

Strong support by P5 Report @ December 2023

NEW
European Strategy
for Particle Physics Update

Input documents
due by
March 31 2025

Council approval expected
June 2026

Key Challenges of the facility

Proton driver production
Baseline @ International Design Study

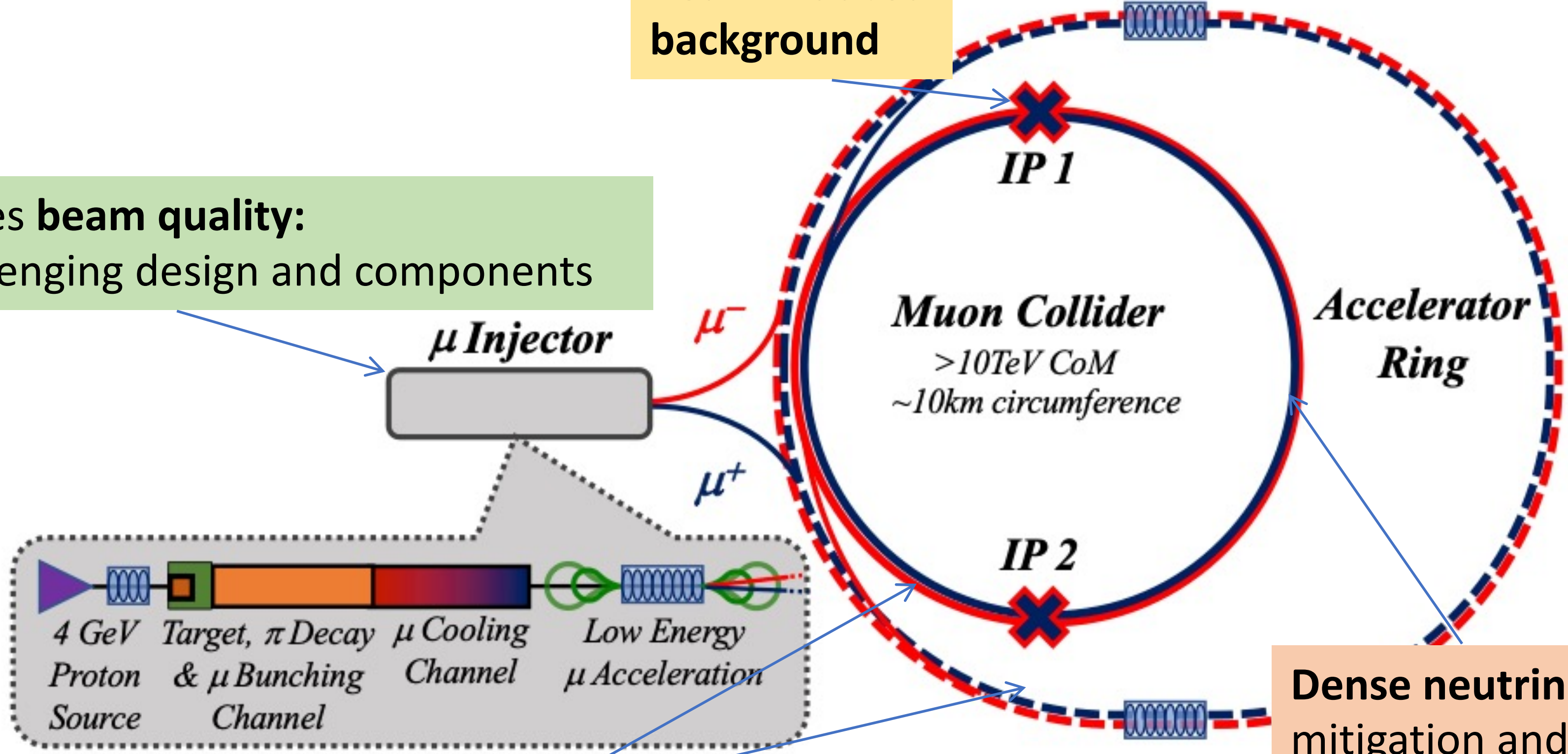
10+ TeV
completely new
regime
to explore!

$\mathcal{L} = (E_{CM}/10\text{TeV})^2 \times 10\ \text{ab}^{-1}$

@ 3 TeV	~	1 ab^{-1}	5 years
@ 10 TeV	~	10 ab^{-1}	5 years
@ 14 TeV	~	20 ab^{-1}	5 years

Beam induced background

Drives **beam quality:**
challenging design and components



Dense neutrino flux
mitigation and site

Cost and **power** consumption drivers, limit energy reach
e.g. 30 km accelerator for 10/14 TeV, 10/14 km collider ring

Muon Collider Forum Report

Accelerator R&D Roadmap

Bright Muon Beams and Muon Colliders

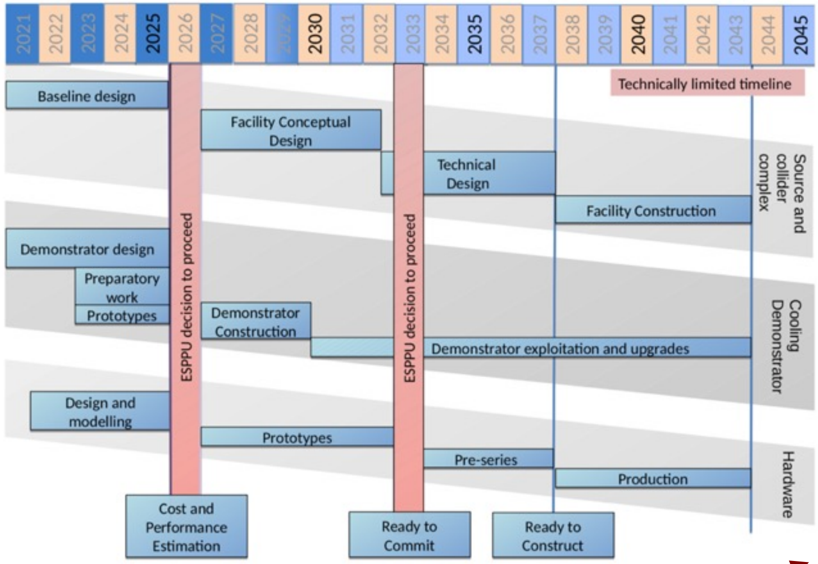
Panel members: **D. Schulte**,(Chair), M. Palmer (Co-Chair), T. Arndt, A. Chancé, J. P. Delahaye, A.Faus-Golfe, S.Gilardoni, P.Lebrun, K.Long, E.Métral, **N.Pastrone**, L.Quettier, T.Raubenheimer, C.Rogers, M.Seidel, D.Stratakis, A.Yamamoto
Associated members: A. Grudiev, R. Losito, **D. Lucchesi**

presented to CERN Council in December 2021

published https://arxiv.org/abs/2201.07895

now under implementation by LDG + Council…

Technically limited timeline



Development path
to deliver a
3 TeV muon collider by 2045

Roadmap Plan

MDI

Dipoles/solenoids
High field
(Nb3Sn, HTS?)

RF cavities
SC e NC

Cooling cell
Demonstrator

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

Scenarios

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

~70 Meu/5 years

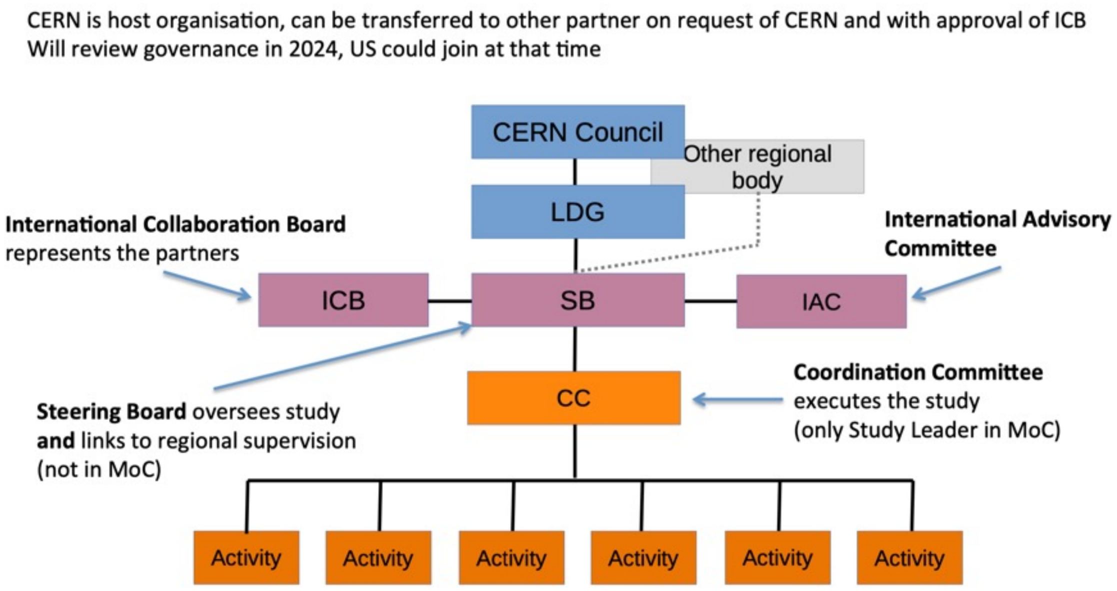
Not yet available the resources of the reduced scenario

Facing priorities with O(40 FTE)

Efforts to increase resources

IMCC Organization after the Roadmap

- Study Leader **Daniel Schulte**
  - Deputies: **Andrea Wulzer, Donatella Lucchesi, Chris Rogers**



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

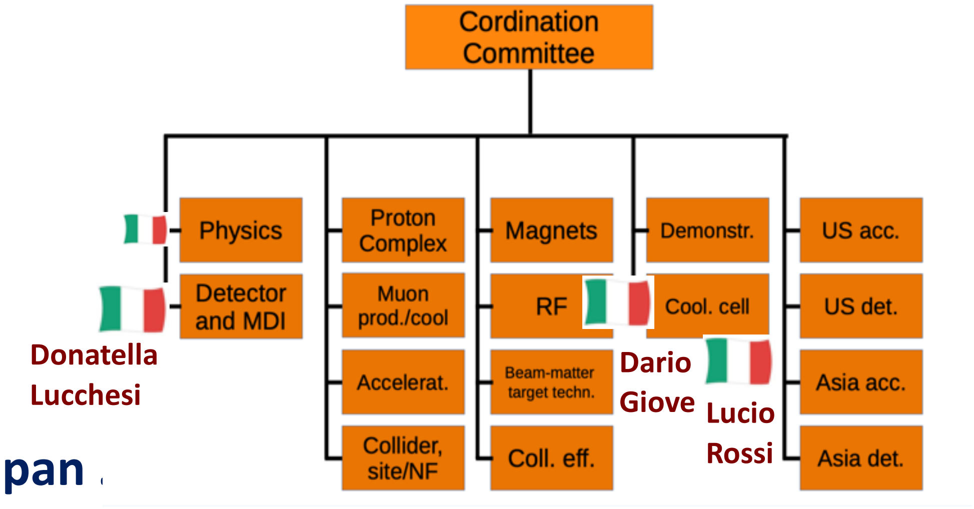
MoC signed by CERN CEA INFN STFC-RAL ESS IHEP and different universities in EU, US, China

19 countries: CERN, IT, US, UK, FR, DE, CH, ES……
CHINA, KOREA, INDIA….. Interest from Japan .

80 institutes

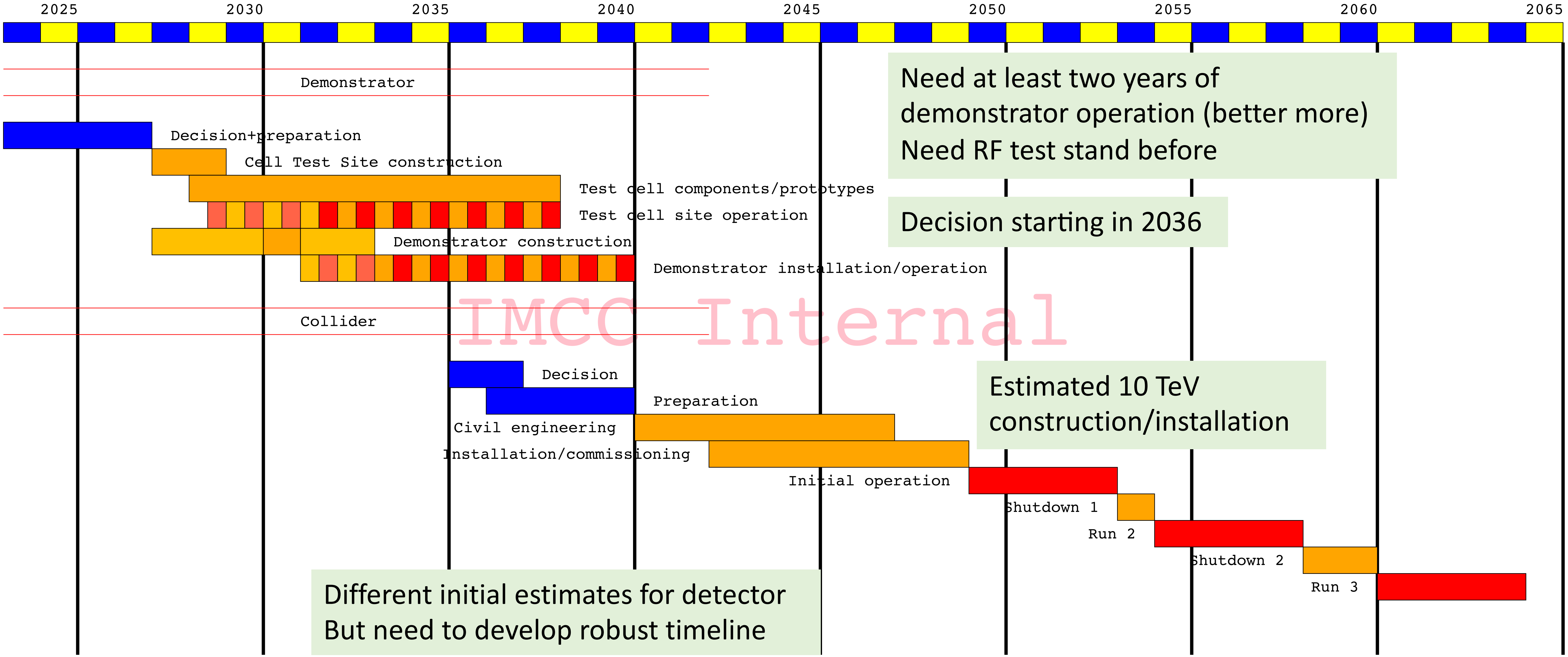
- **Collaboration Board (ICB)**
  - Elected chair : **Nadia Pastrone**
- **Steering Board (SB)**
  - Chair **Steinar Stapnes**,
  - CERN members: Mike Lamont, Gianluigi Arduini,
  Dave Newbold (STFC), Pierre Vedrine (CEA)
  Beate Heinemann (DESY)
  ICB chair and SL and deputies
- **International Advisory Committee (IAC)**
  - Chair **Ursula Bassler (IN2P3)**

Coordination Committee



Tentative Timeline (Fast-track 10 TeV)

Only a basis to start the discussion, will be reviewed this year



Need at least two years of demonstrator operation (better more)
Need RF test stand before

Decision starting in 2036

Estimated 10 TeV construction/installation

Different initial estimates for detector
But need to develop robust timeline

Time-critical Developments

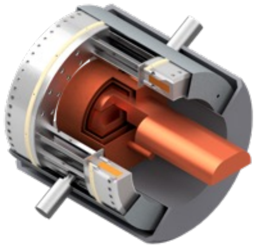
Identified three main technologies that can limit the timeline

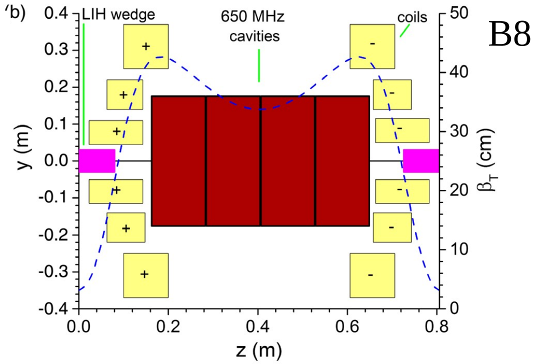
Muon cooling technology

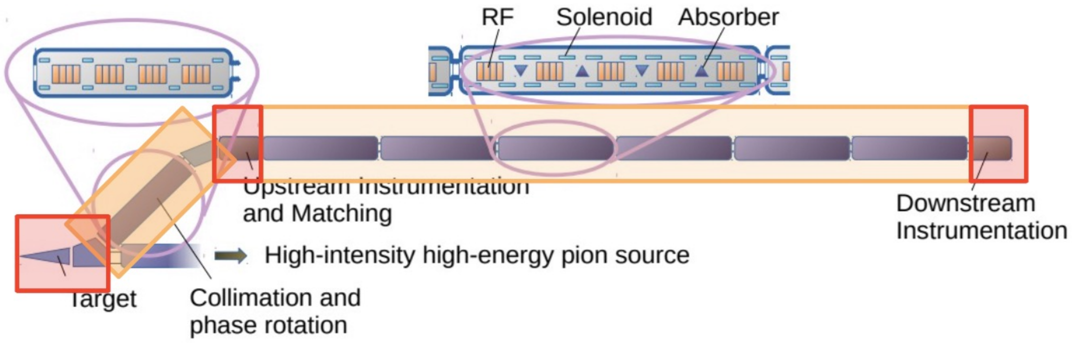
- **RF test stand** to test cavities in magnetic field
- **Muon cooling cell** test infrastructure
- **Demonstrator**
  - Muon beam production and cooling in several cells

Magnet technology

- HTS solenoids
- Collider ring magnets with Nb3Sn or HTS







Crucial studies

Physics simulations

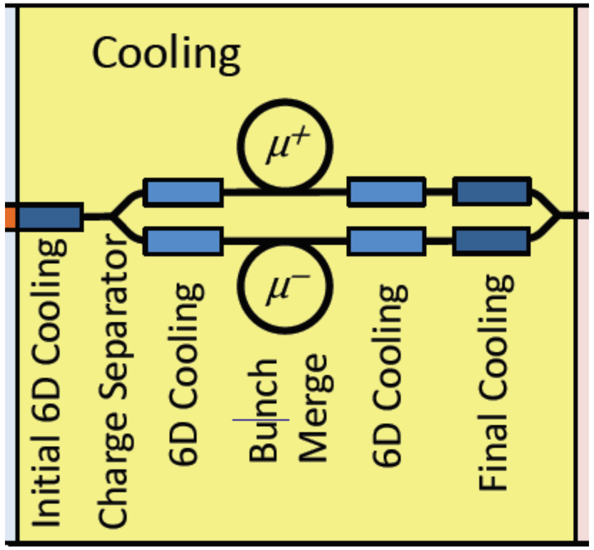
- **Physics potential**
- **Detector performances**

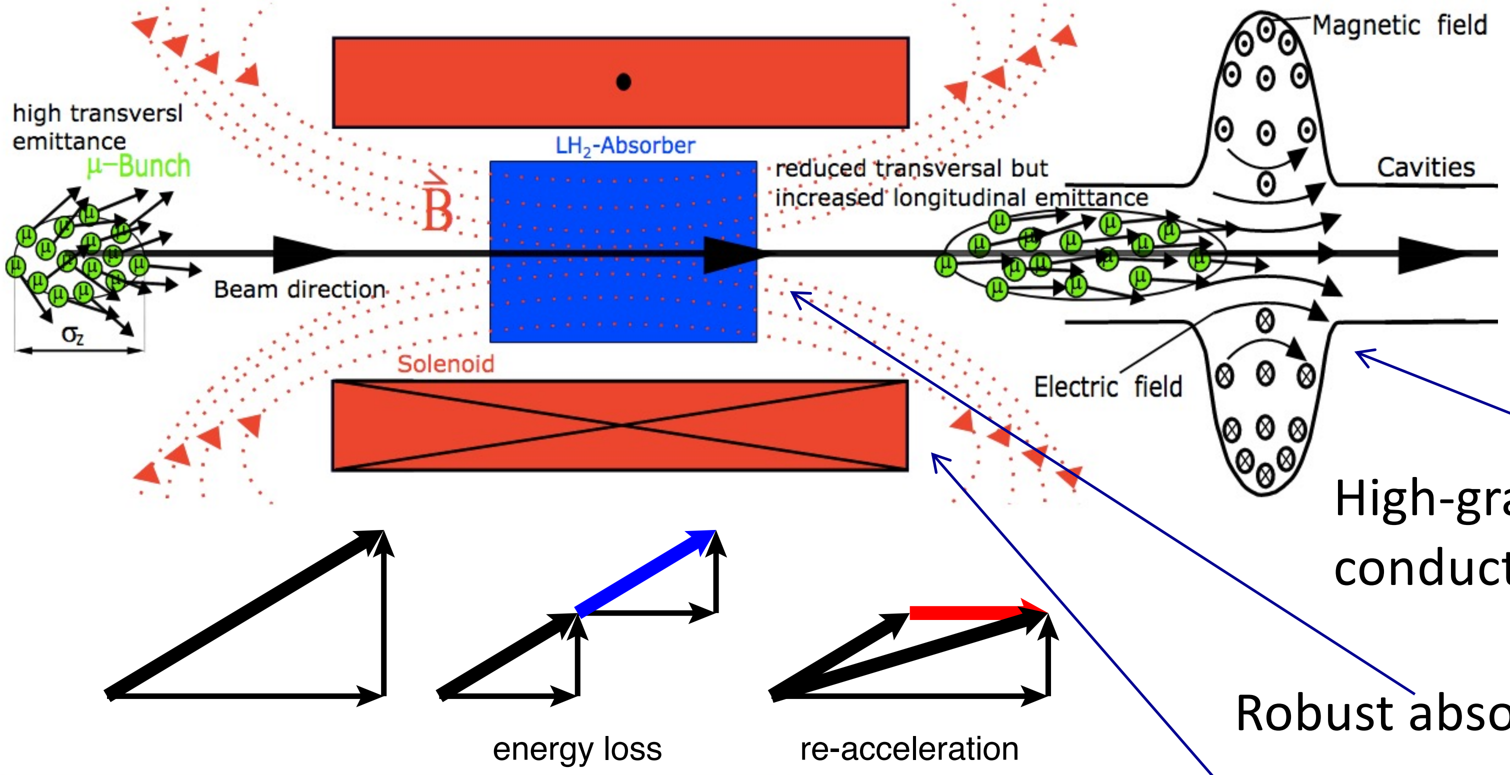
Important Developments

Detector technology and design

- Can do the important physics with near-term technology
- But available time will allow to improve further and exploit AI, MI and new technologies

Muon Cooling Principle

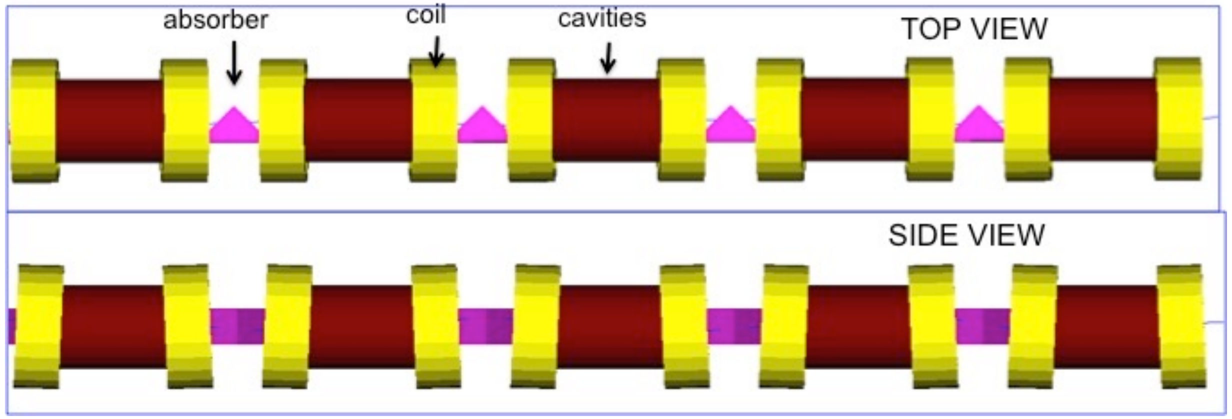




High-gradient normal-conducting cavities

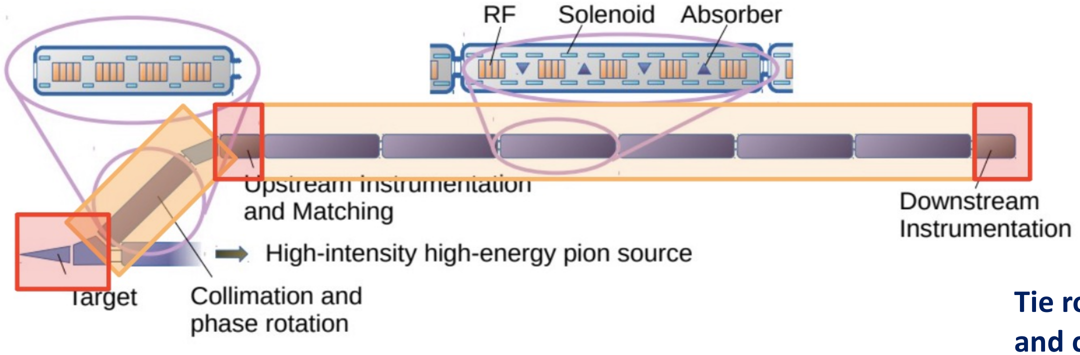
Robust absorbers

High-field, superconducting solenoid

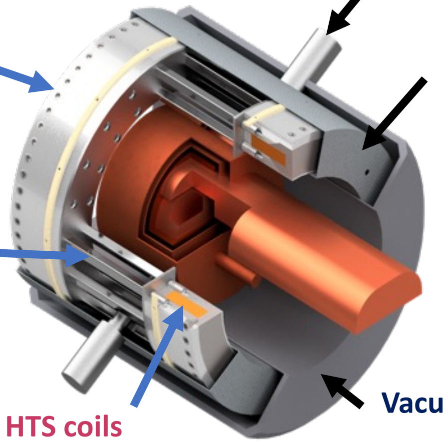


Principle has been demonstrated in MICE
Nature vol. 578, p. 53-59 (2020)

RF @ cooling cells: INFN studies and tests



with cryostat


Two stage cryocooler

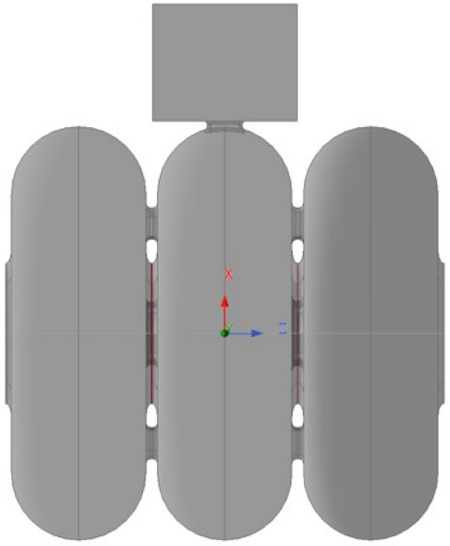
Coil support structure

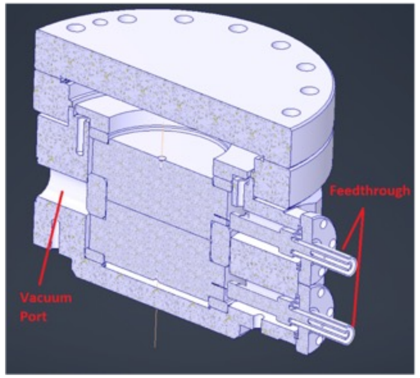
Thermal shield

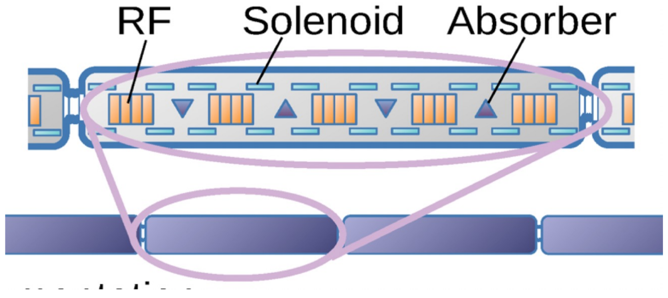
Tie rods for repulsion and compression forces

Vacuum vessel

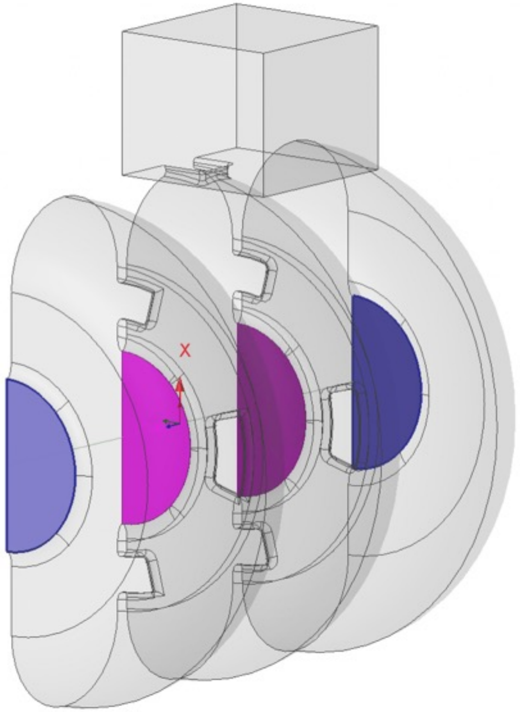
HTS coils





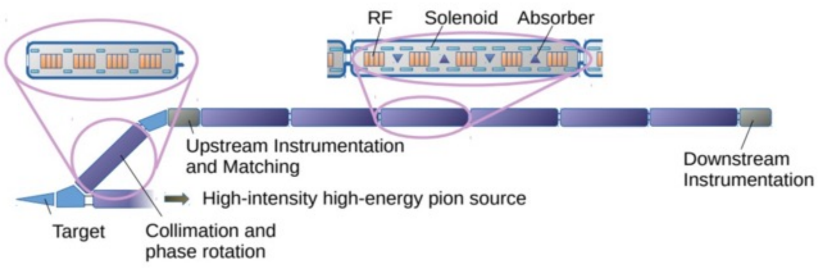


3 cells RF preliminary structure



MI-LASA: Dario Giove et al.
INFN-TO: Paolo Mereu
Carlo Mingioni - Marco Nenni
PoliTO: Lorenzo Peroni Martina Scapin

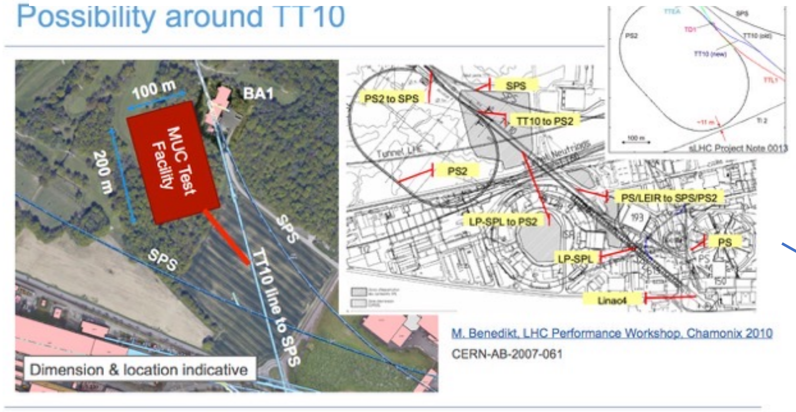
Demonstrator Facility: a crucial step forward!



Planning **demonstrator** facility with muon production target and cooling stations

Suitable **site exists** on CERN land and can use **PS proton beam**

- could combine with **NuStorm** or other option

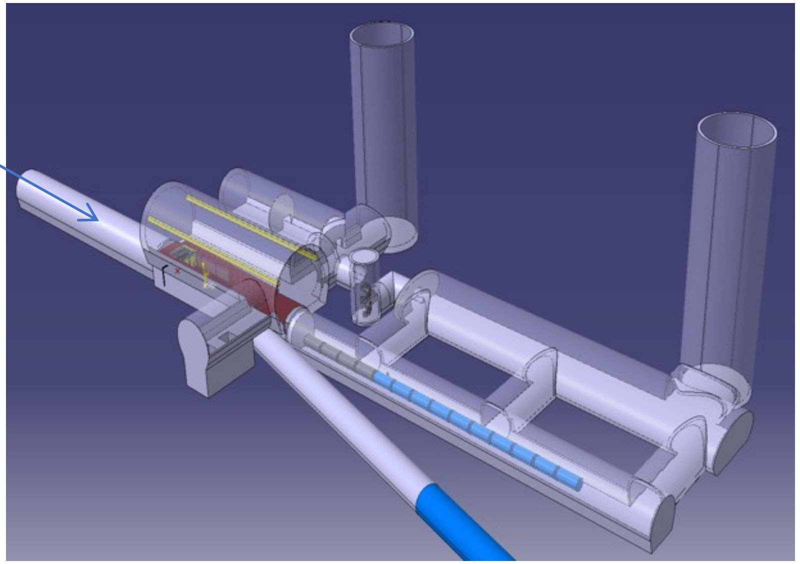

Possibility around TT10

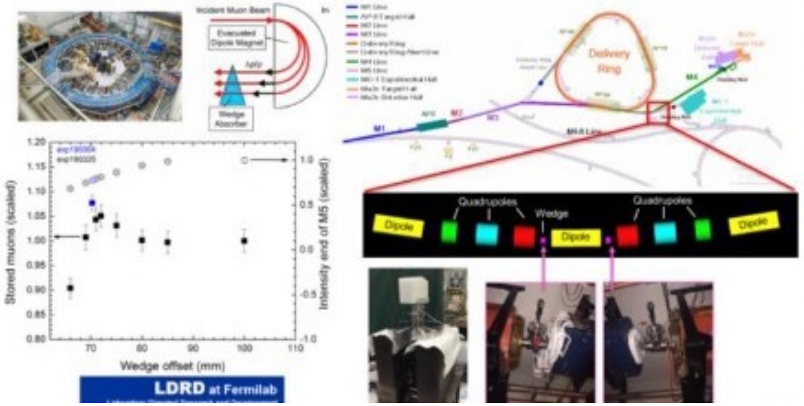
Dimension & location indicative

M. Benedikt, LHC Performance Workshop, Chamonix 2010

CERN-AB-2007-061

@ CERN





@ FNAL

International Muon Collider Collaboration: Demonstrator Workshop

@ FNAL October 30 – November 1, 2024

The constraint & the challenge to design and operate an experiment

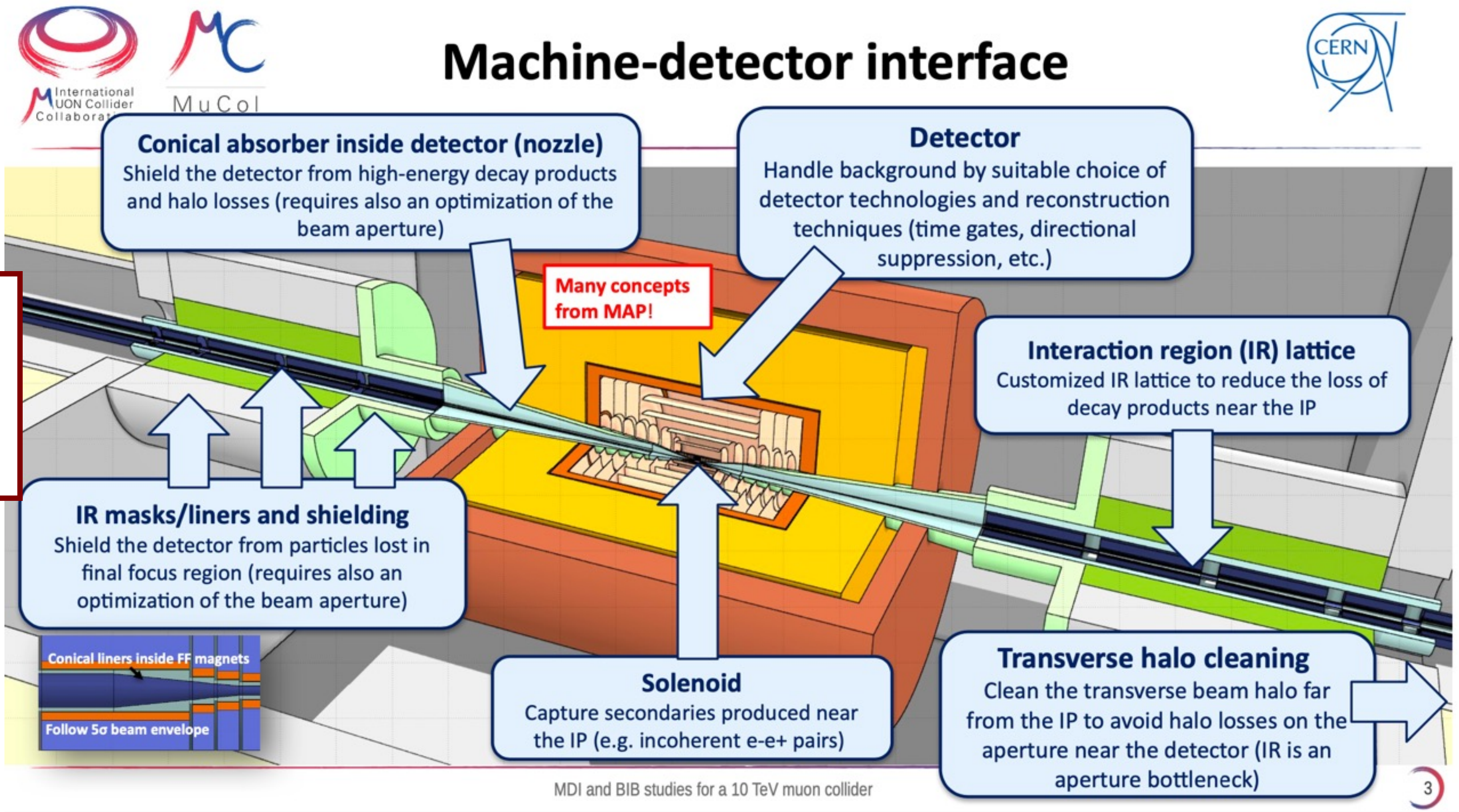
Machine Detector Interface - beam-induced background

Background is a significant driver for MDI design - background sources:

- **Muon decay**
- Beam halo losses and Beam-beam (mainly incoherent e-/e+ pair production)

The machine elements, MDI and interaction region must be properly designed and optimized @ each collider energy

CERN-PD-TO-TS
INFN-TO: Nazar Bartosik et al.



Machine-detector interface

Conical absorber inside detector (nozzle)
Shield the detector from high-energy decay products and halo losses (requires also an optimization of the beam aperture)

Detector
Handle background by suitable choice of detector technologies and reconstruction techniques (time gates, directional suppression, etc.)

Many concepts from MAP!

Interaction region (IR) lattice
Customized IR lattice to reduce the loss of decay products near the IP

IR masks/liners and shielding
Shield the detector from particles lost in final focus region (requires also an optimization of the beam aperture)

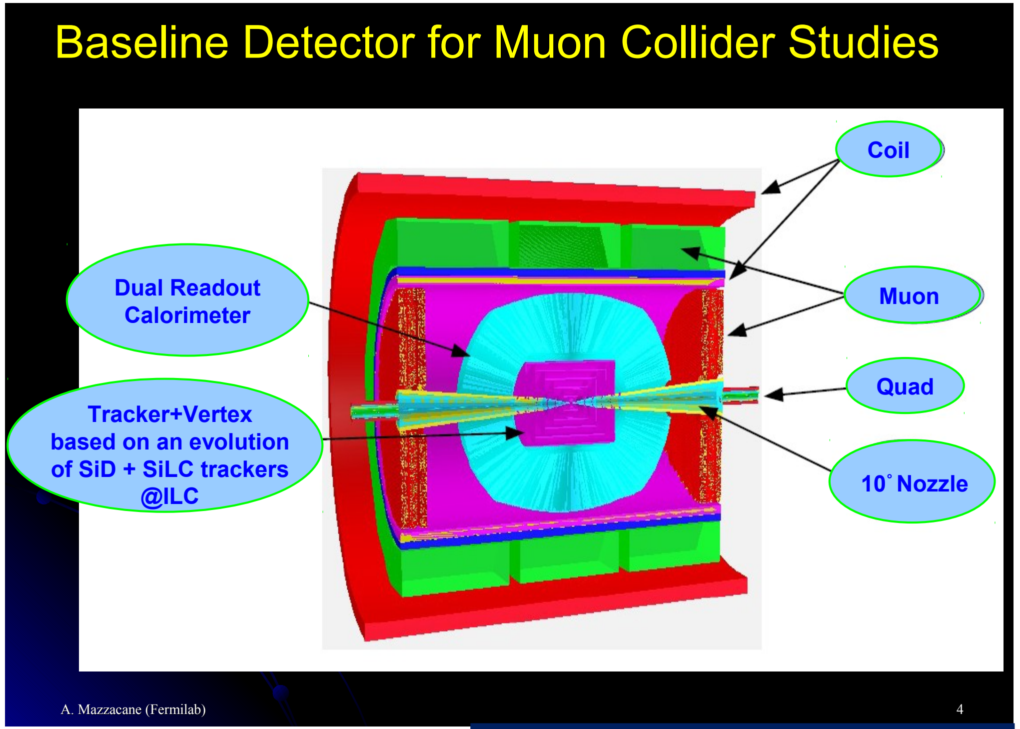
Solenoid
Capture secondaries produced near the IP (e.g. incoherent e-e+ pairs)

Transverse halo cleaning
Clean the transverse beam halo far from the IP to avoid halo losses on the aperture near the detector (IR is an aperture bottleneck)

[Workshop](#) @ CERN 11 – 12 March 2024
[Workshop](#) @ CERN 25 – 26 June 2024

Daniele Calzolari – CERN &UniPD

Experiment design evolution

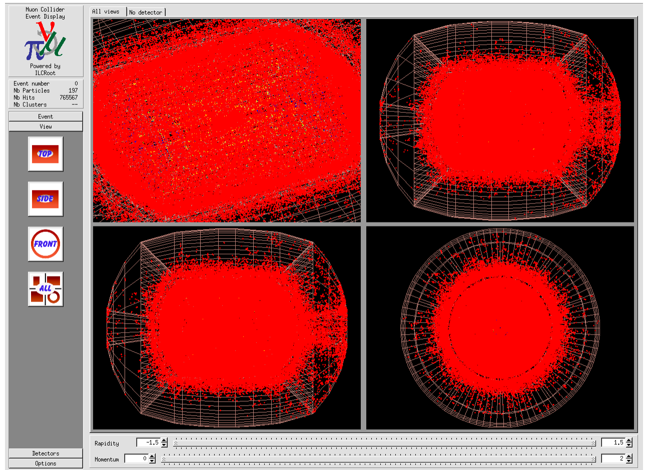


Baseline Detector for Muon Collider Studies

A. Mazzacane (Fermilab) 4

Anna Mazzacane – FNAL – MAP

No cuts: all hits

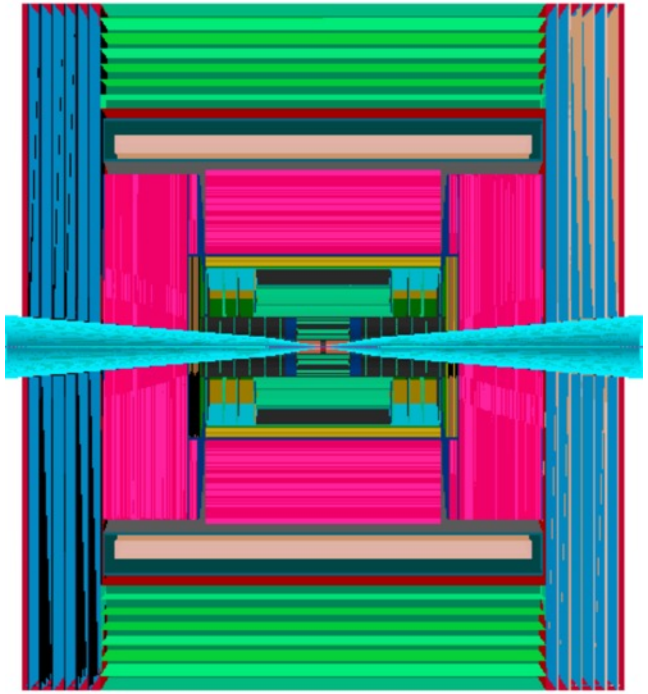


Muon Collider simulation:
MAP package
Background @ √s=125 GeV

Nikolai V. Mokhov – FNAL – MAP

Background (MARS simulation)
from muon decays and interaction with machine elements included

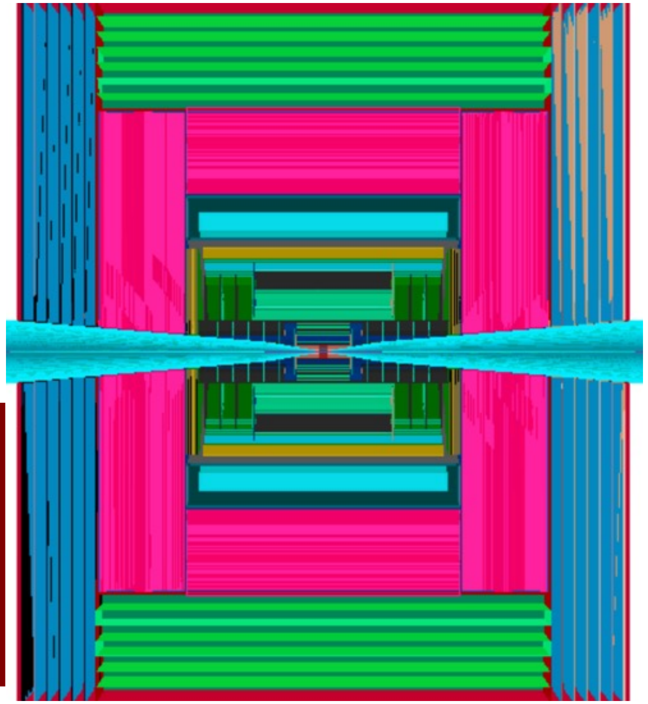
MuColl_v1 @ 3 TeV



Donatella Lucchesi et al. – IMCC

INFN-TO: Nazar Bartosik et al.

MUSIC design @ 10 TeV



New detector concepts:
MUSIC and **MAIA**
moving the solenoid inside the calorimeters

Crucial full simulation studies for
Detector performance for low- and high-momentum ..

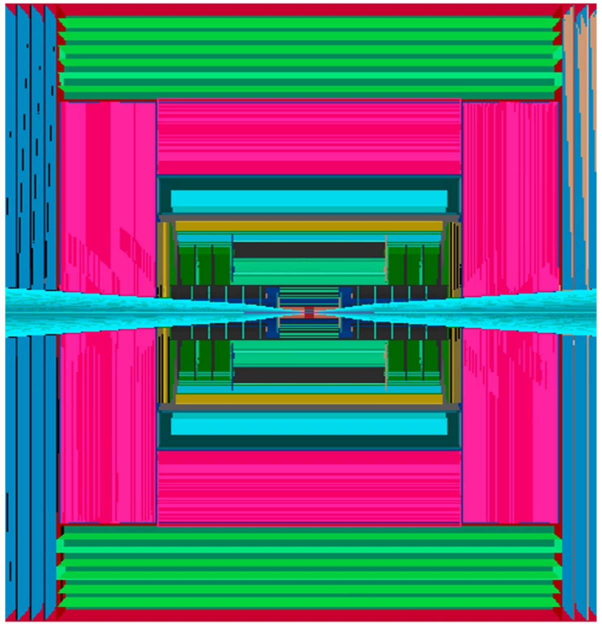
Massimo Casarsa et al.

Detector concepts for 10 TeV collisions

Two detector concepts are currently under development with different layouts

PbF$_2$-crystal electromagnetic calorimeter (inside the solenoid)

Si-W electromagnetic calorimeter (ouside the solenoid)



superconducting solenoid (B = 5 T)

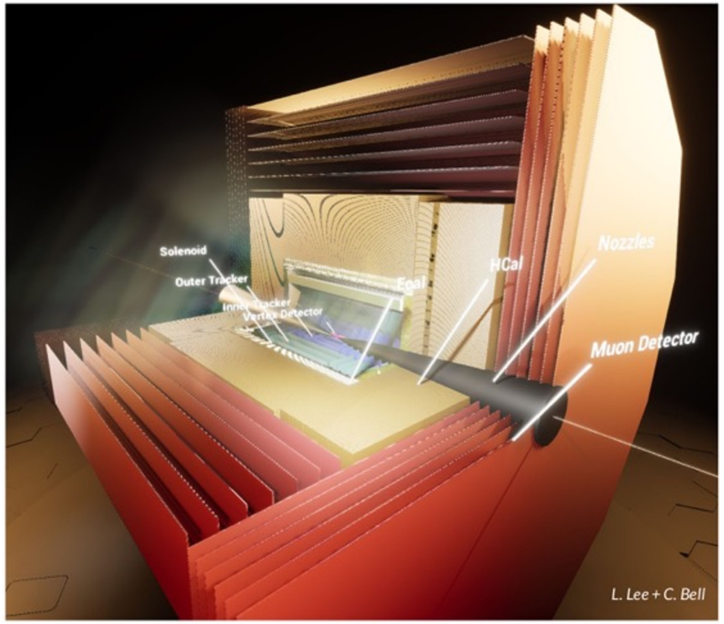
full silicon tracking system

tungsten shielding nozzles

Fe-scintillator hadronic calorimeter (serves as B field return yoke)

muon detectors

ALEPH-like detector



L. Lee + C. Bell

ATLAS-like detector

INFN-TO:
Nazar Bartosik
Nadia Pastrone et al.

Massimo Casarsa et al.
ICHEP 2024

key features being optimized:
tracker radius and layout, magnetic field intensity, calorimeter depth, forward muons

Full simulation and reconstruction software available on github.com/MuonColliderSoft
derived from CLIC's iLCSoft
(transition to the Key4hep framework in progress)

Experiment design requirements @ 10 TeV

BA, LNF, RM1, PI, PV, PD, TO, TS

Aim at **10+ TeV** and potential initial stage at **3 TeV**
NEW OPTION: initial 10 TeV stage at reduced luminosity
Interim report https://arxiv.org/abs/2407.12450

Strong interest in developing:

- 4D vertex and tracker sensors
- new calorimeters 4D or 5D ideas
- sustainable muon detector
- front-end electronics with on-board intelligence
- powerful reconstruction algorithm
- AI simulation and analysis tool

Promising Technologies and R&D Directions for the Future Muon Collider Detectors

INFN-TO:
Nazar Bartosik
Nadia Pastrone et al.

Detector technology R&D and design ==>>> DRD

- we can do the important physics with technology being implemented for HL-LHC upgrades or follow-ups
- available time will allow to improve further and exploit synergies and new emerging technologies

"Strong planning and appropriate investments in Research and Development (R&D) in relevant technologies are essential for the full potential, in terms of novel capabilities and discoveries, to be realised" ESPPU 2020

On-going R&D on tracking sensors – DRD3

	Vertex Detector	Inner Tracker	Outer Tracker
Cell type	pixels	macropixels	microstrips
Cell Size	$25\,\mu m \times 25\,\mu m$	$50\,\mu m \times 1\,mm$	$50\,\mu m \times 10\,mm$
Sensor Thickness	$50\,\mu m$	$100\,\mu m$	$100\,\mu m$
Time Resolution	30 ps	60 ps	60 ps
Spatial Resolution	$5\,\mu m \times 5\,\mu m$	$7\,\mu m \times 90\,\mu m$	$7\,\mu m \times 90\,\mu m$

INFN-TO:
Nazar Bartosik
Marco Ferrero
Valentina Sola
Cacilia Hanna
Anna Rita Altamura
et al.

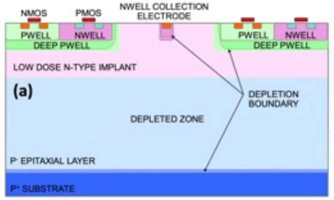
International MUON Collider Collaboration

Silicon LGAD sensors for 4D tracking up to very high fluence:

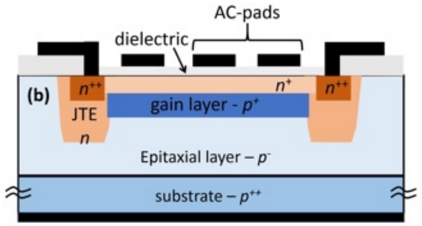
[V. Sola et al., Nucl. Instrum. Meth. A 1040 (2022) 167232](https://doi.org/10.1016/j.nima.2022.167232).

Sinergy with timing sensors development for HL-LHC

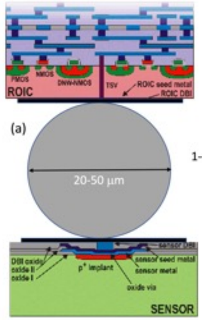
Promising technologies



Monolithic devices (CMOS):
Good timing and spacial resolution, but radiation hardness to be improved



Low Gain Avalanche Detectors (LGAD):
Large and fast signal (20-30 ps resolution), moderate radiation hardness



Hybrid small pixel devices:
No gain but fast timing (20-30 ps resolution) and good position resolution. Intrinsically radiation hard

NEW In Padova synergy with ALICE developments both on detector sensors DMAPS and infrastructures

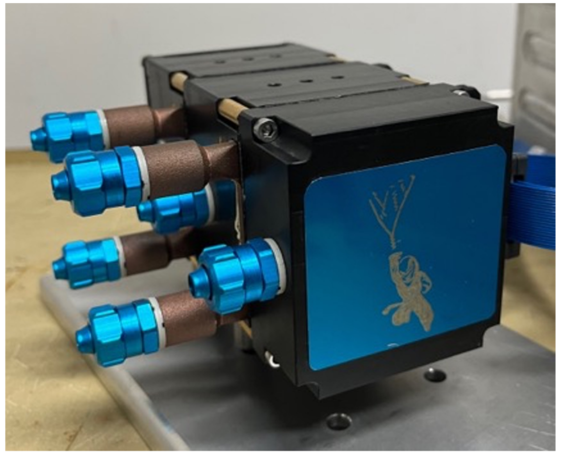
Project funded also by an EU ERC Consolidator Grant

On-going R&D in e.m. calorimeters – DRD6

Crilin, *JINST* **17** P09033

Crilin – CRystal calorImeter with Longitudinal InformatioN –

semi-homogeneous electromagnetic calorimeter based on **Lead Fluoride Crystals** (PbF_2) matrices where each crystal is readout by 2 series of 2 UV-extended surface mount **SiPMs**



2-layer 3x3-crystal Crilin prototype

High-density crystal:
need for increased layer numbers with space constraints

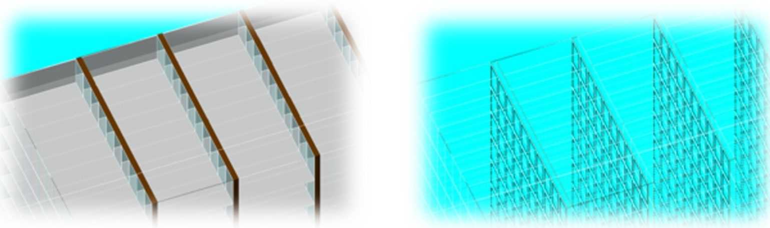
Speed response:
Cherenkov crystals, ensuring accurate and timely particle detection

Semi-homogeneous:
strategically between homogeneous and sampling calorimeters
→ able to exploit the strengths of both kinds

Flexibility:
able to modulate energy deposition for each cell and adjust crystal size

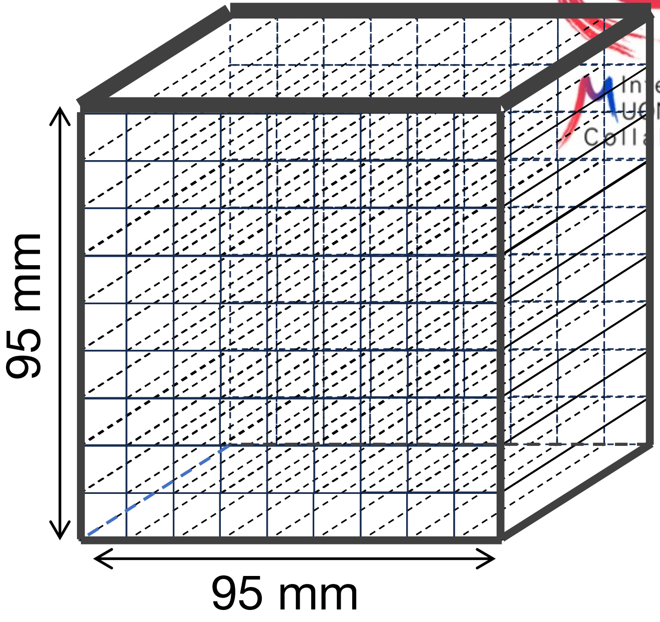
Compactness:
Unlike segmented or high granularity calorimeters it can optimize energy detection while staying compact

total ionising dose: ~1 kGy/year (100 krad)
total neutron fluence: 10^{14} n_{1MeVeq} /cm^2 / year



Crilin Module Prototype
9x9 crystals/layer – 5 layers

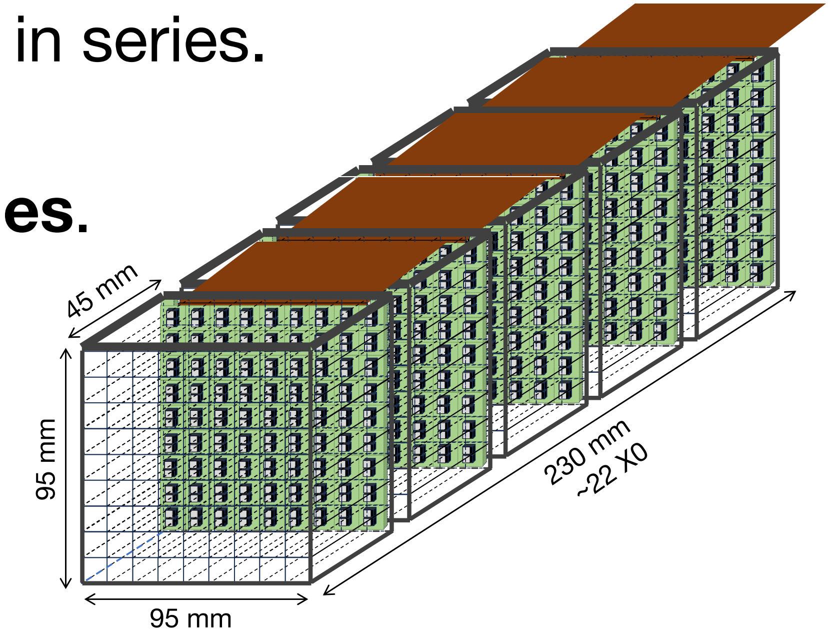
Ivano Sarra et al.
ICHEP 2024

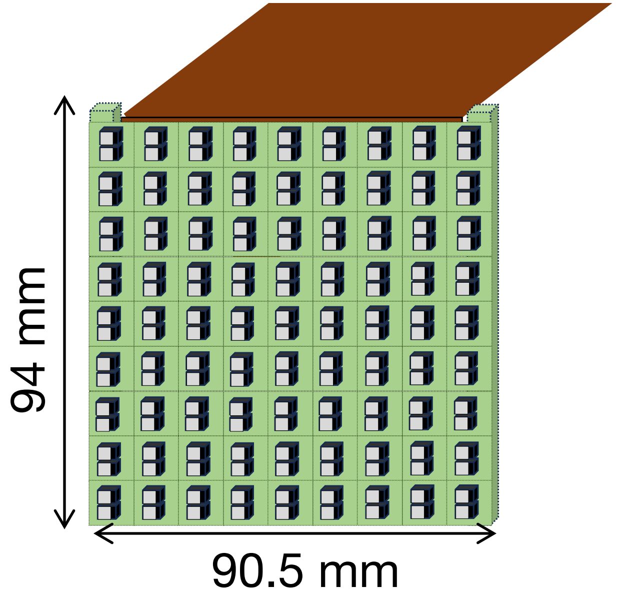


1. **Aluminum matrix to hold the crystals**:
   1. 50-100 µm thickness between crystals
   2. Thicker (~ 2mm) in the external envelope with microchannels for cooling
2. **Kapton strip for polarization and output signal**:
   1. Handles polarization and output signals for each channel of two SiPMs in series.
3. **Connectors at the back of the 5 assembled modules.**

DRD6-WP3 from 2025

Expanding to a 9x9 x5(layers) configuration
with a target of 2 M_R – 22 X_0.





On-going R&D in hadronic calorimeters – DRD6 - BA

MPGD-based hadronic calorimeter, Nucl. Instrum.Meth. A 1047 (2023) 167731

MPGD-HCAL

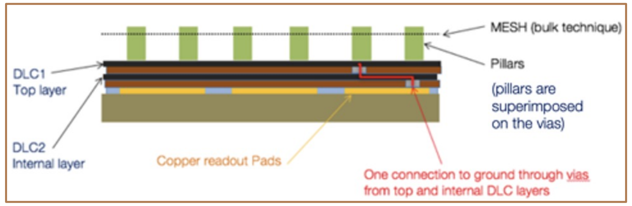
based on **resistive Micro-Pattern Gaseous Detectors** as **readout layers for a sampling hadronic calorimeter**

MPGD features:

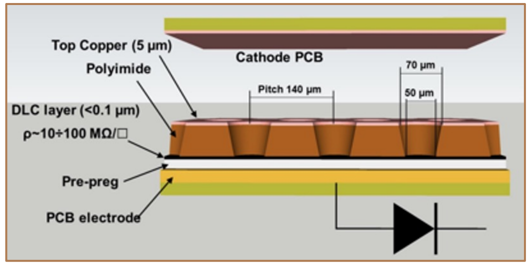
- **cost-effectiveness** for large area instrumentation
- radiation hardness up to several **C/cm²**
- **discharge rate** not impeding operations
- rate capability O (**MHz/cm²**)
- high granularity
- time resolution of **few ns**

one of the goals of such R&D is to choose the best technology for calorimetry @ Muon Collider

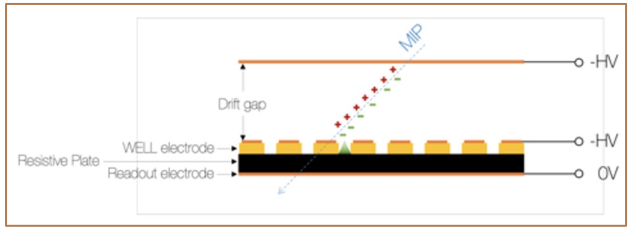
Micromegas (MM)



µRWELL



RPWELL



Past work:

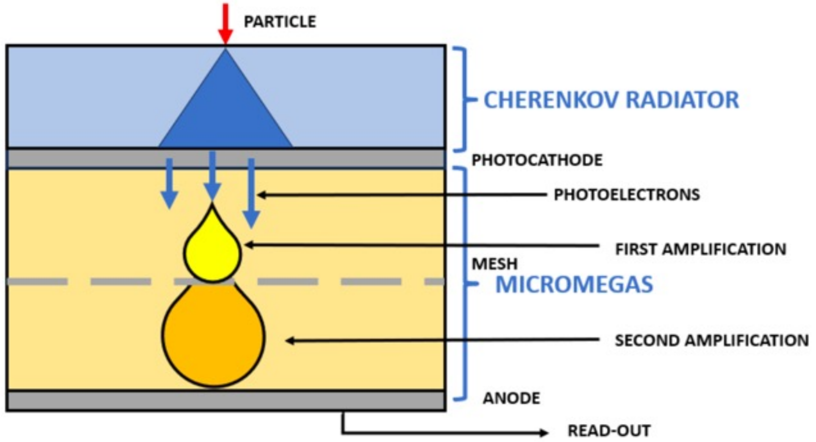
- **CALICE collaboration**: a sampling calorimeter using **gaseous detectors** (RPC) but also tested MicroMegas
- **SCREAM collaboration**: a sampling calorimeter combining RPWELL and resistive MicroMegas

R&D plan → systematically **compare** three MPGD technologies for hadronic calorimetry: resistive MicroMegas, µRWELL and RPWELL, while also investigating **timing**

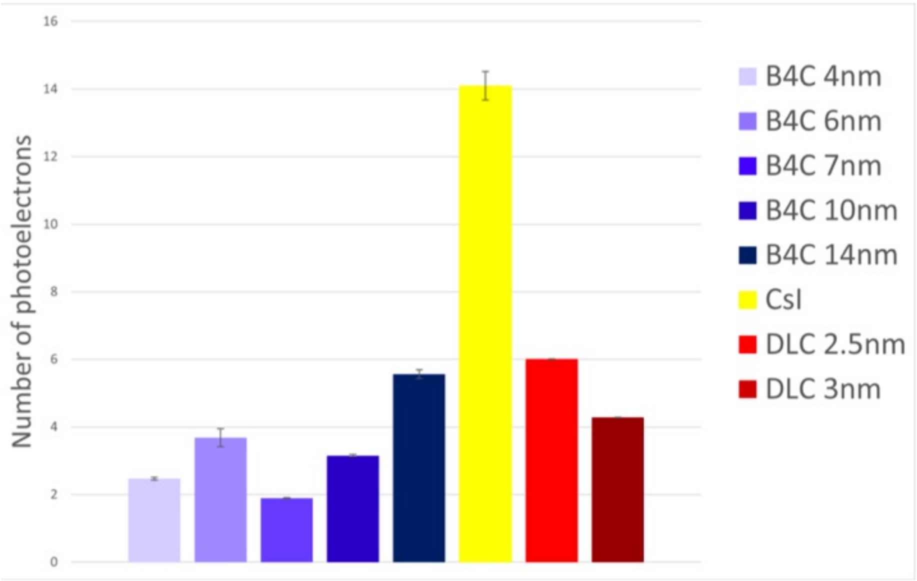
On-going R&D on muon detectors – DRD1 - PV

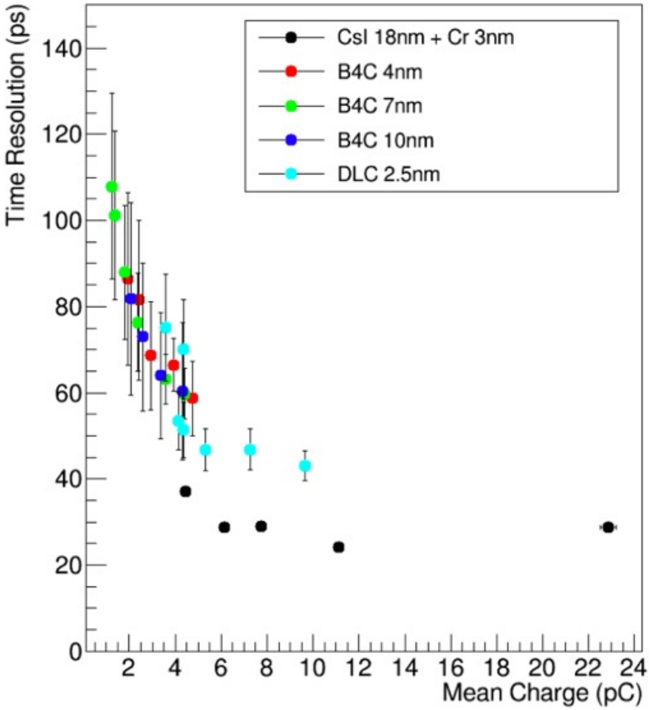
Muon detector based on PicoSec Micromegas: C. Aimè et al., 2024 JINST 19 C03052.

PicoSec MICROMEGAS detector is a valid option: time resolution better than 25 ps, very high rate capability



Test beams for the characterization are on-going





R&D TPC - HPTPC - BA

Gabriella Catanesi, Emilio Radicioni

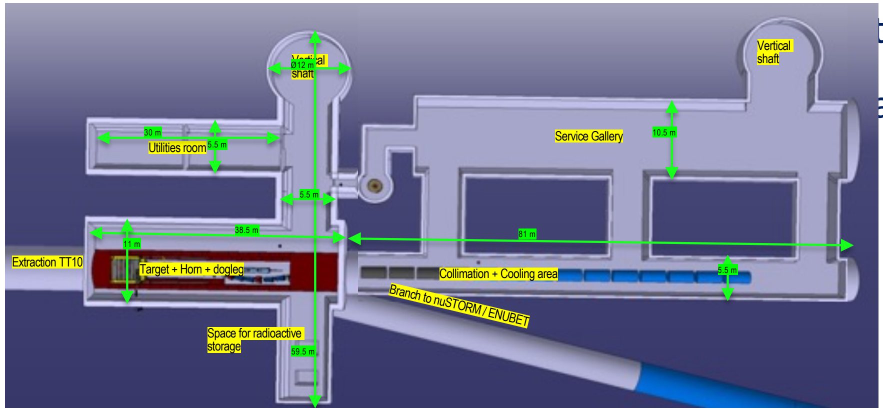
International MUON Collider Collaboration

The Demonstrator will produce a large number of muons/neutrinos of few hundred MeV or less

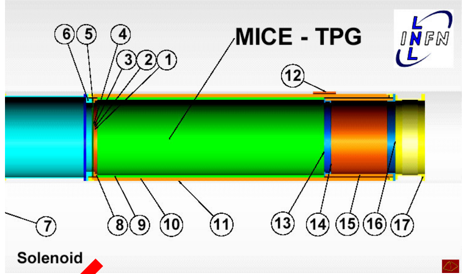
A TPC can be used as

tracker for the detection of muons in the cooling sector

and/or as active target to detect neutrinos



from MICE proposal



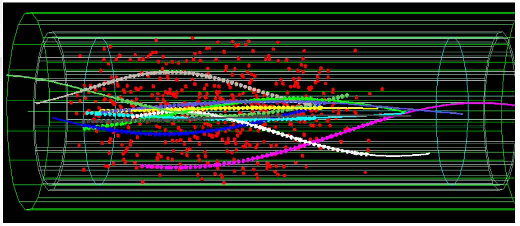
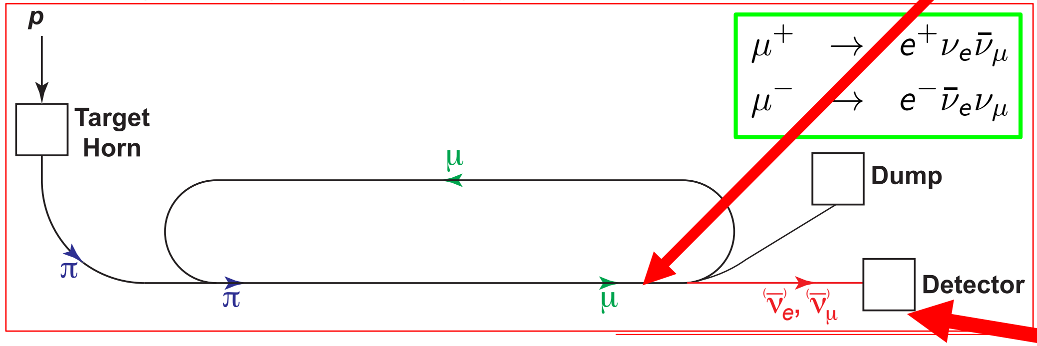
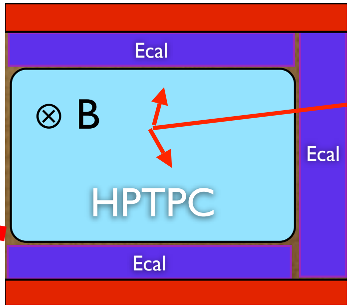


Figure 8.7: top: simulated track and noise hits in the TPG; middle: highlighted hits are those assigned by the pattern recognition to belong to the same track; bottom: track fitted on the selected hits.

a unique facility for neutrino physics and muon-collider test bed



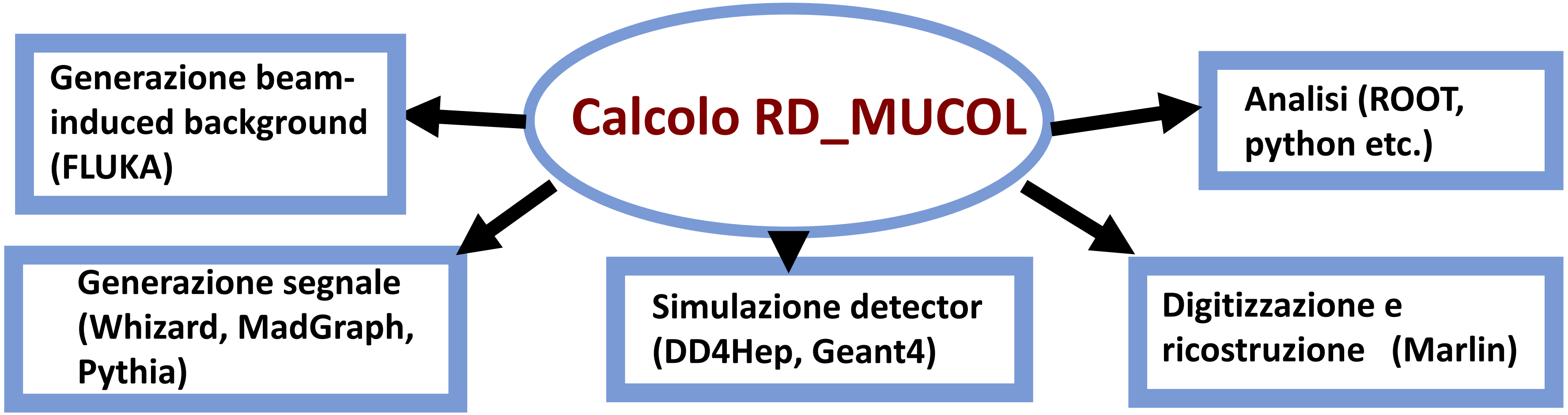
$$\mu^+ \rightarrow e^+\nu_e\bar{\nu}_\mu$$
$$\mu^- \rightarrow e^-\bar{\nu}_e\nu_\mu$$



Concept for a neutrino X-sec measurement

Risorse calcolo RD_MUCOL

PD: Lorenzo Sestini et al.
INFN-TO: Nazar Bartosik


Calcolo RD_MUCOL

Generazione beam-induced background (FLUKA)

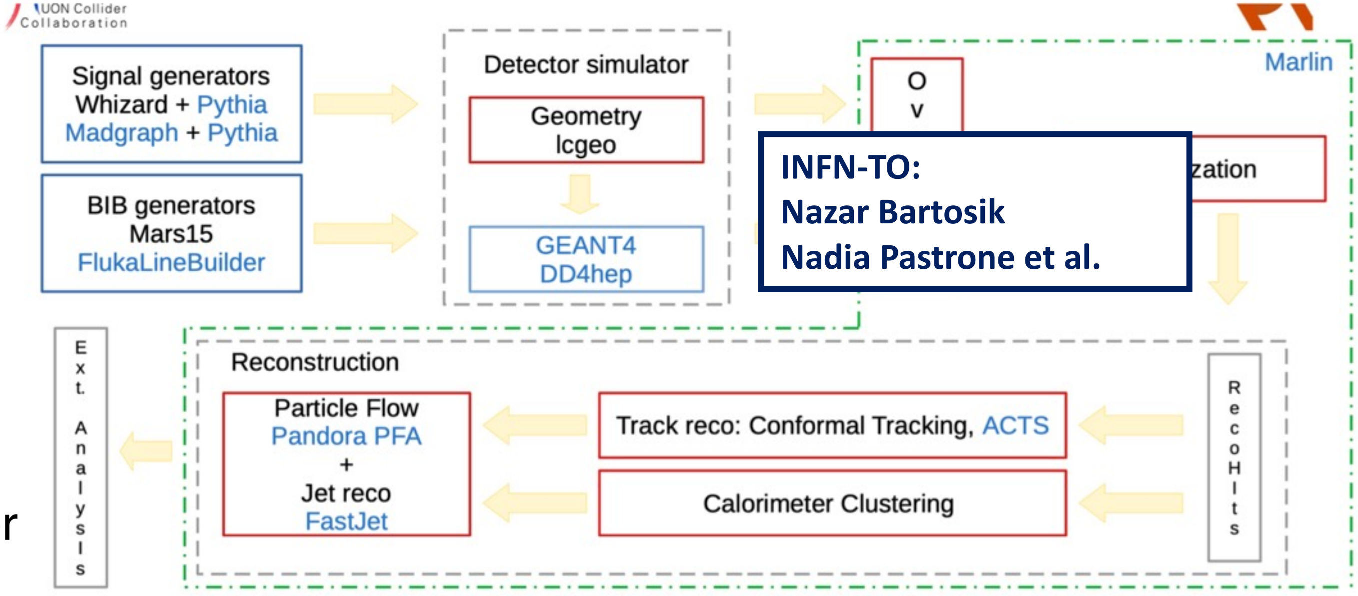
Generazione segnale (Whizard, MadGraph, Pythia)

Simulazione detector (DD4Hep, Geant4)

Digitizzazione e ricostruzione (Marlin)

Analisi (ROOT, python etc.)

- **Il modello di calcolo è piuttosto complesso**, ma è la conseguenza di lavorare su un ambiente nuovo (e.g. BIB, combinatorio elevato) e in costante sviluppo (algoritmi, detector etc.)
- Avere il calcolo distribuito su piattaforme eterogenee non è un vantaggio, **molte criticità (ad es. spostare i file da un sistema all'altro)**
- **Migrazione del framework su Key4hep in corso**



INFN-TO:
Nazar Bartosik
Nadia Pastrone et al.

https://github.com/MuonColliderSoft

Knowledge base
The new site for Muon Collider physics and detector https://mcd- wiki.web.cern.ch/
Back end on https://gitlab.cern.ch/ muon-collider/wiki

Unique physics case – more studies planned

Direct searches

Pair production, Resonances, VBF, Dark Matter, …

High-rate measurements

Single Higgs, self coupling, rare and exotic Higgs decays, top quarks, …

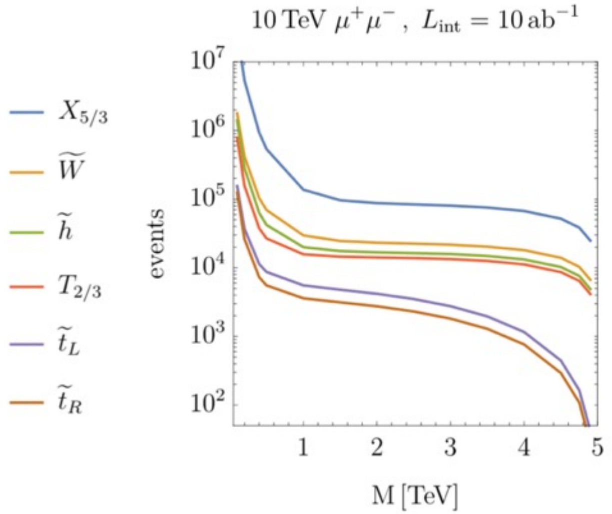
High-energy probes

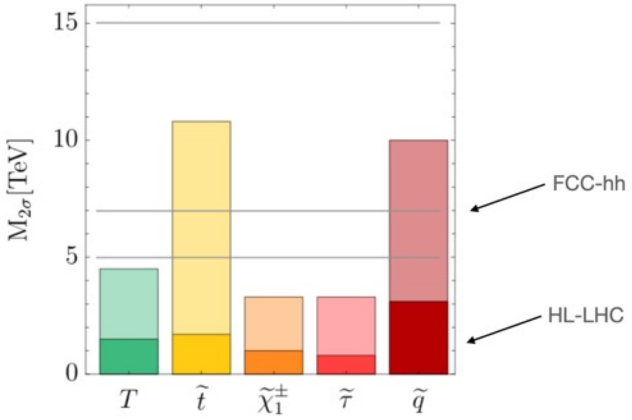
Di-boson, di-fermion, tri-boson, EFT, compositeness, …

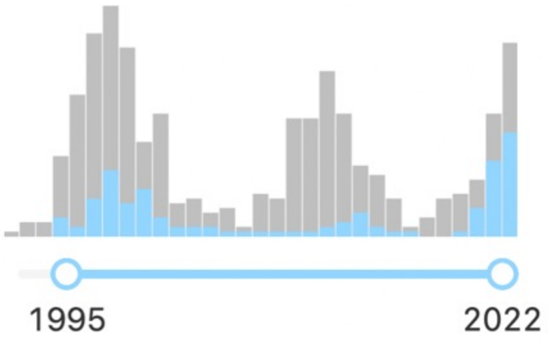
Muon physics

Lepton Flavor Universality, b → sμμ, muon g-2, …

Discovery potential



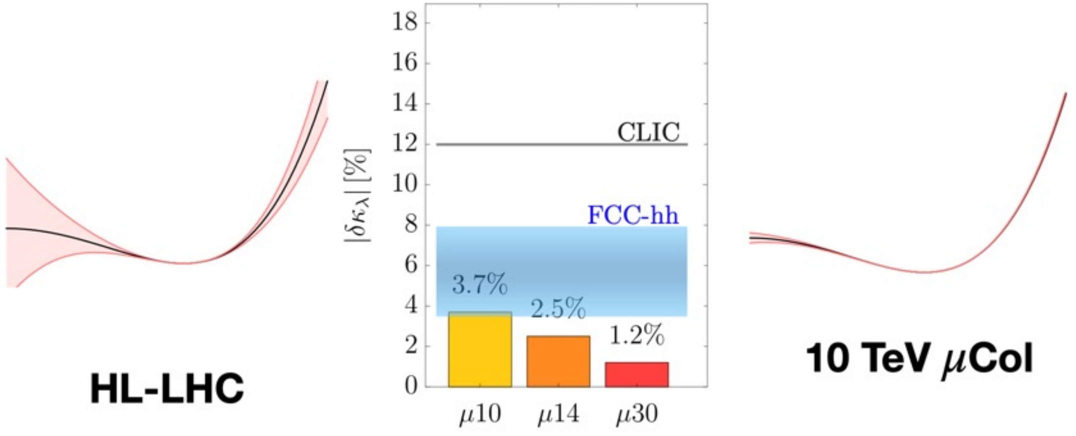




Muon Collider Pheno Papers

Precision measurements

High energy lets us finally improve on Higgs Potential



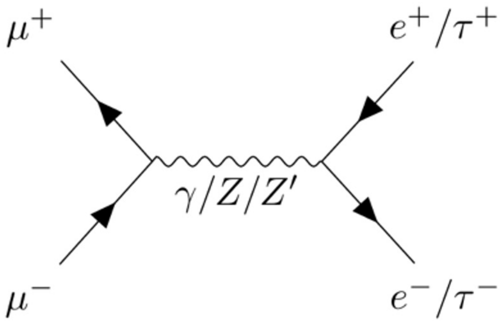
Note that we can get to threshold for EW phase transition at EW scale with FCC-hh and μCol

Z' searches

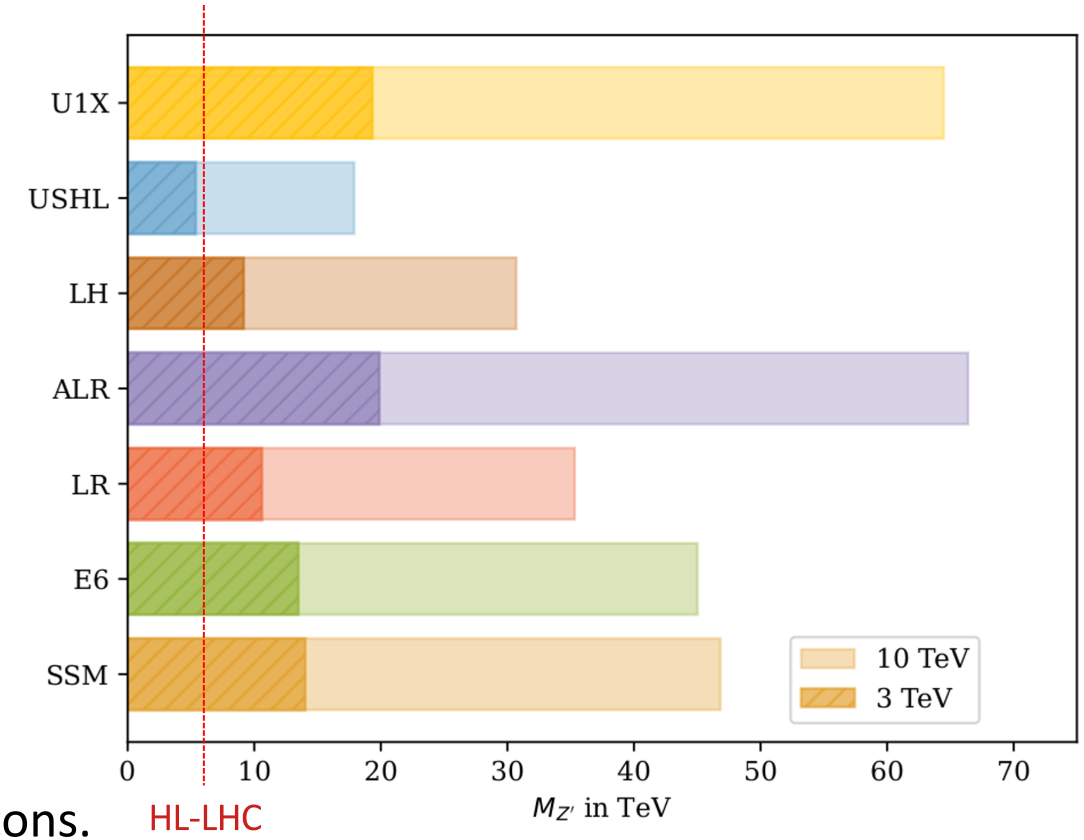
Z' bosons can be probed directly up to $M_{Z'} \sim \sqrt{s}$, but indirect searches extend much beyond:

example of a phenomenological study exploring the reach of a muon collide for additional neutral gauge bosons that couple to the standard model: K. Korshynska et al., arXiv:2402.18460.

Indirect discovery potential for a new Z' boson coupled to the standard model in the final states ee and ττ:



Z' exclusion limits at 95% C.L.



assumed 1 ab^{-1} at $\sqrt{s}$ = 3 TeV and 10 ab^{-1} at $\sqrt{s}$ = 10 TeV;

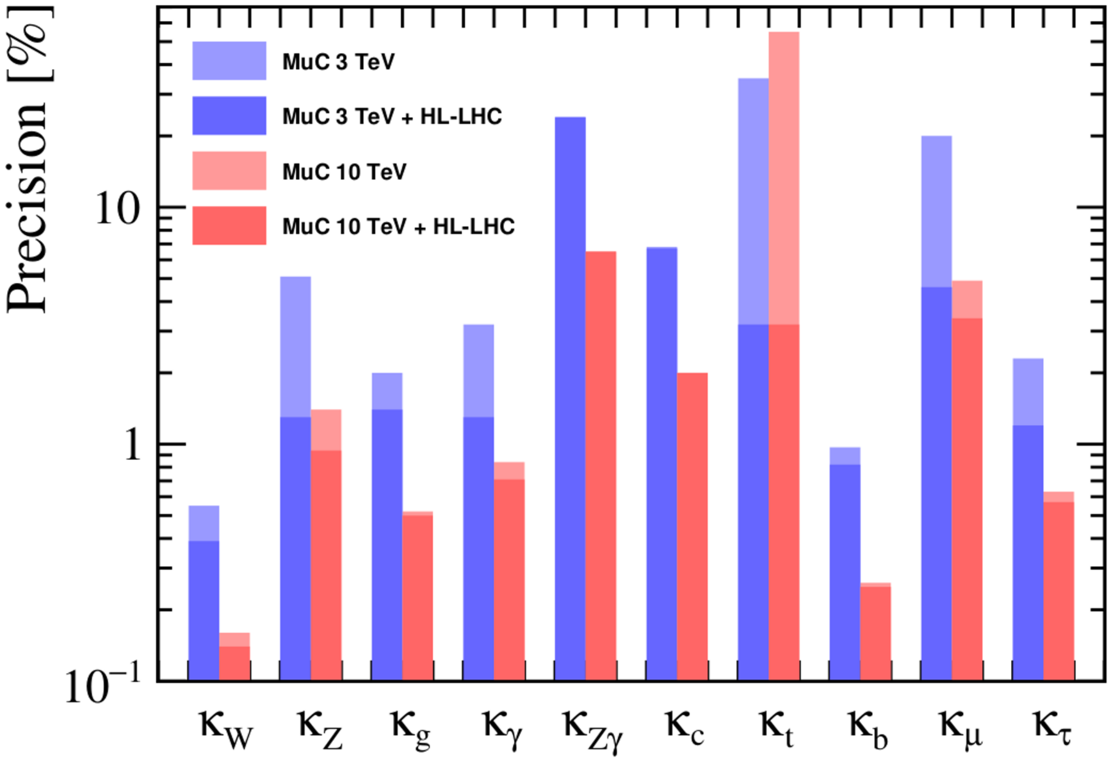
off-peak analysis based on observables of the final state leptons.

Expected performance on Higgs couplings

International
MUON Collider
Collaboration

Higgs boson couplings to fermions and bosons are extracted from a global fit to the Higgs boson production cross sections:

- ✓ the set of channels of full-simulation studies at 3 TeV is not yet complete for a global fit
- ✓ the muon collider potential at 3 TeV (1 ab^{-1})
  and 10 TeV (10 ab^{-1}) is evaluated with a parametric detector simulation
  (partially tuned on the detailed detector simulation at 3 TeV) by



M. Forslund and P. Meade and JHEP 08 (2022) 185

Davide Zuliani et al.
ICHEP 2024

M.Casarsa, D. Lucchesi, L. Sestini arXiv:2311.03280

Higgs Physics at a *s*√=3 TeV Muon Collider with detailed detector simulation

@ Torino: 16 persone - 3.21 FTE

RL: Nicola Amapane
RN: Nadia Pastrone

	RD_MUCOL	UE-MuCol	UE-IFAST
Anna Rita Altamura	50		
Nicola Amapane	20		
Nazar Bartosik	30		
Marco Ferrero	20		
Linda Finco	10		
Bilal Kiani	30		
Silvia Maselli	10		
Paolo Mereu		10	
Carlo Mingioni	10		
Marco Nenni	10		
Giacomo Ortona	20		
Luca Pacher	10		
Nadia Pastrone	15	10	5 + 1 **aMUSE**
Lorenzo Peroni	20		
Martina Scapin	20		
Valentina Sola	20		

ATTIVITÀ

- *Fisica: teoria ….*

- **Fisica: simulazioni**
- **Sviluppo software**
- **Studi di rivelatore**
- **R&D rivelatore**
- **Interfaccia acceleratore: MDI**
- **Studi cella di raffreddamento**
- **Altri R&D acceleratori**

Towards a multi-TeV Muon Collider

IMCC and MuCol Annual Meeting 2024

12-15 March 2024, CERN

Info & Registration

Scientific Program Committee - Chairs: L. Bottura & C. Carli (CERN) Members: M. Casarsa (INFN), A. Chance (CEA), R. Franqueira Ximenes (CERN), S.Gilardoni (CERN), D. Giove (INFN), A. Grudiev (CERN), S. Jindariani (FNAL), A.Lechner (CERN), R. Losito (CERN), D. Lucchesi (INFN), E. Metral (CERN), N.Milas (ESS), M. Palmer (BNL), N. Pastrone (INFN), L. Quettier (CEA), C. Rogers (STFC), D. Schulte (CERN), A. Wulzer (IFAE/ICREA), A. Yamamoto (CERN).

CERN Organising Committee : D. Schulte (Project Leader), A. Augier, M. Lancellotti.

Funded by the European Union (EU). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the EU or European Research Executive Agency (REA). Neither the EU nor the REA can be held responsible for them.

Poster design by R. Taylor

***FINAL GOAL**:*

to exploit the physics potential of such a unique facility aiming at the highest energy and highest luminosity

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

➔ Time scale is becoming feasible for a multi-TeV collider facility to be ready by 2050

- Muon Collider – a long story
- New Physics opportunities: Direct searches+Precision ➔ rich physics program

- To get people engaged, in particular the Early career scientists, it is important also to get **intermediate experimental setups/goals and synergies** where the new technologies in their infant status may be tested

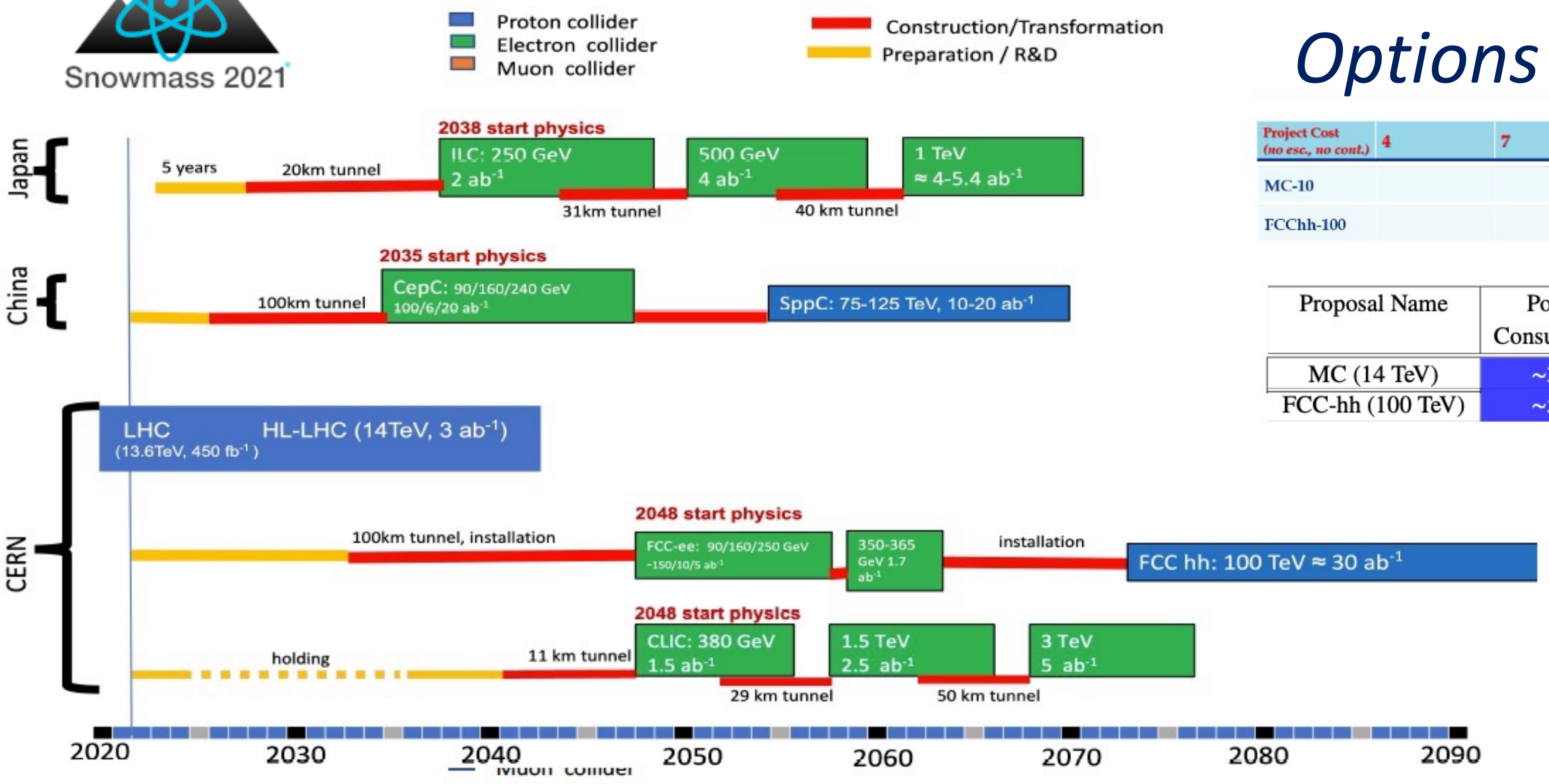
➔ **Muon Collider Demonstrator with physics cases**

- **Synergies for enabling technologies opens new opportunities now and in the next 5-10 years**
- **The level of complexity requires to plan ahead evaluating the needs but with an open mind for ingenuity**
- **Detector and accelerator fields are a great playground to deeply understand Nature and benefit Society**

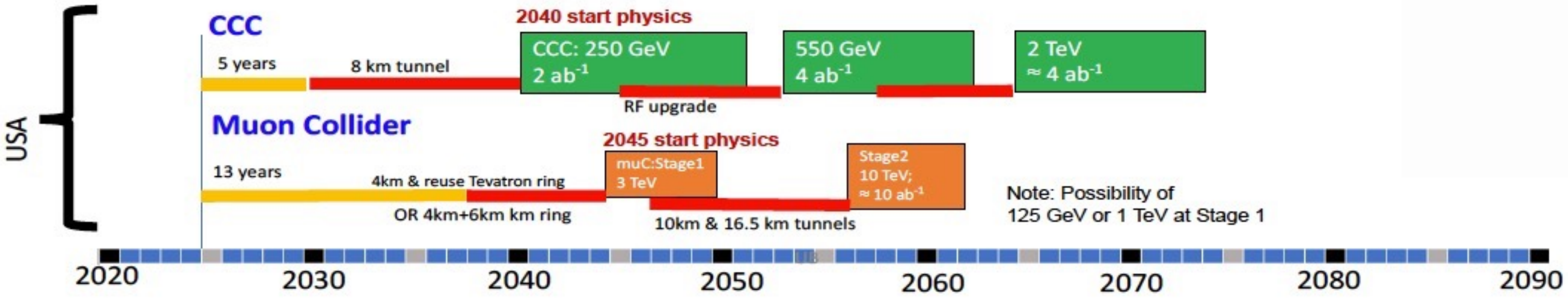
International
MUON Collider
Collaboration

extras

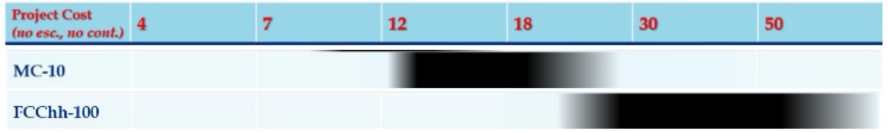
Colliders timescale: Snowmass2021



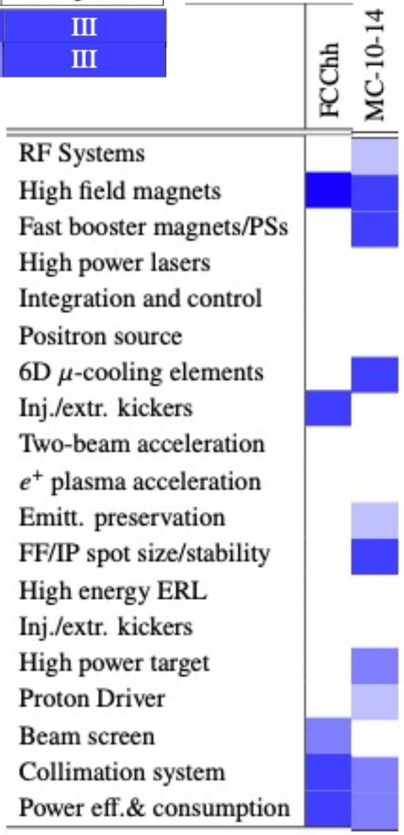
Proposals emerging from Snowmass 2021 for a US based collider



Options @ 10 TeV Scale



Proposal Name	Power Consumption	Size	Complexity	Radiation Mitigation
MC (14 TeV)	~300	27 km	III	III
FCC-hh (100 TeV)	~560	91 km	II	III

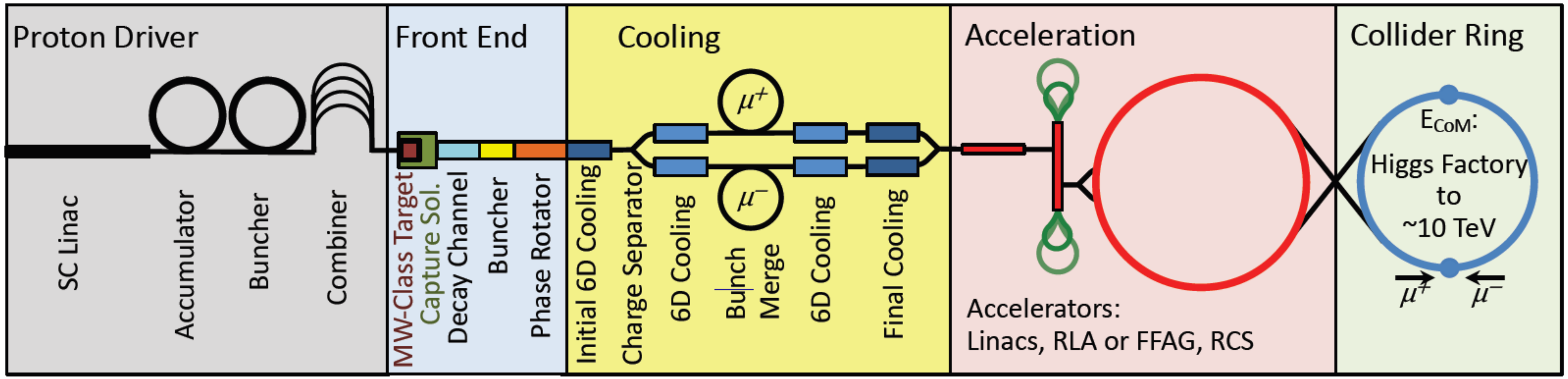


International
MUON Collider
Collaboration

Proton-driven Muon Collider Concept

International
MUON Collider
Collaboration

Fully driven by muon lifetime – lifetime is $\tau = \gamma$ x 2.2 μs



Short, intense proton bunches to produce hadronic showers

Pions decay into muons that can be captured

Muon are captured, bunched and then cooled

Acceleration to collision energy

Collision

MICE ionization cooling experiment

U.S. Muon Accelerator Program (MAP)

http://map.fnal.gov/

- Recommendation from 2008 Particle Physics Project Prioritization Panel (P5)
- Approved by DOE-HEP in 2011 ➔ Ramp down recommended by P5 in 2014

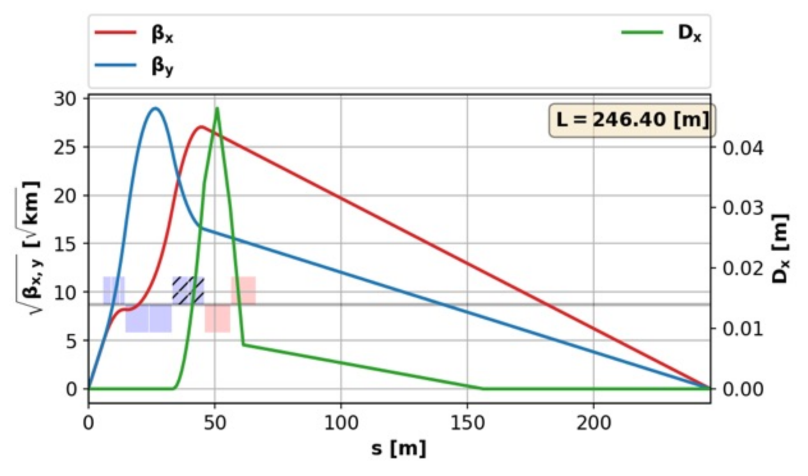
AIM: to assess feasibility of technologies to develop muon accelerators for the Intensity and Energy Frontiers

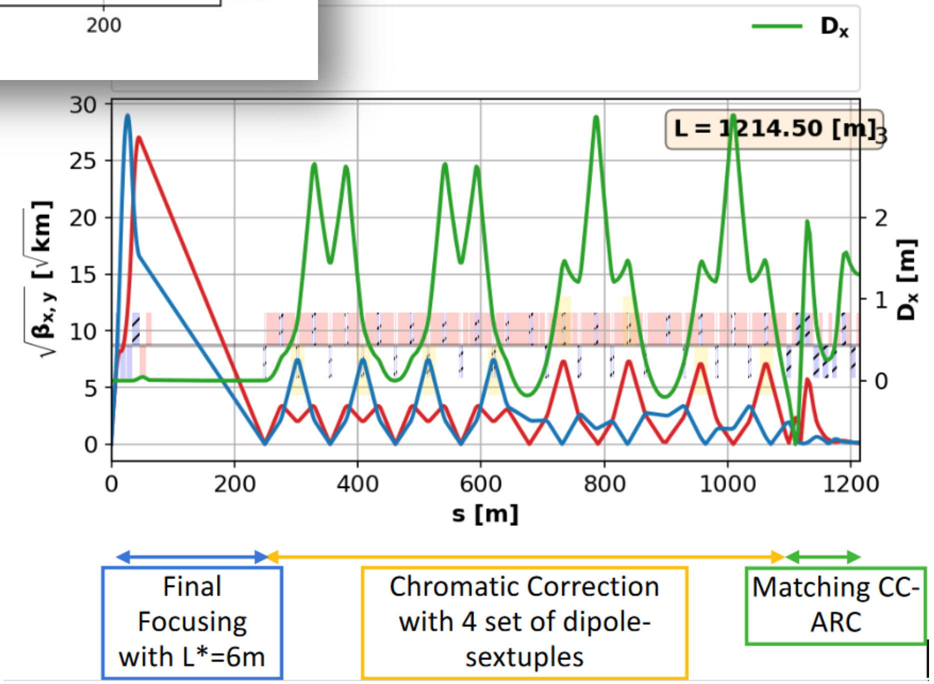
Status of IR lattice design @ 10 TeV

Challenges: small ß*, large ß functions in FF, strong chromatic effects

	$\sqrt{s}$=3 TeV	$\sqrt{s}$=10 TeV
Version	**US MAP**	**IMCC (v0.7)**
FF scheme	Quadruplet (with dipolar component)	Triplet (with dipolar component)
ß*	5 mm	1.5 mm
L*	6 m	6 m
Max. field at inner bore	12 T	20 T

10 TeV IR lattice (IMCC):



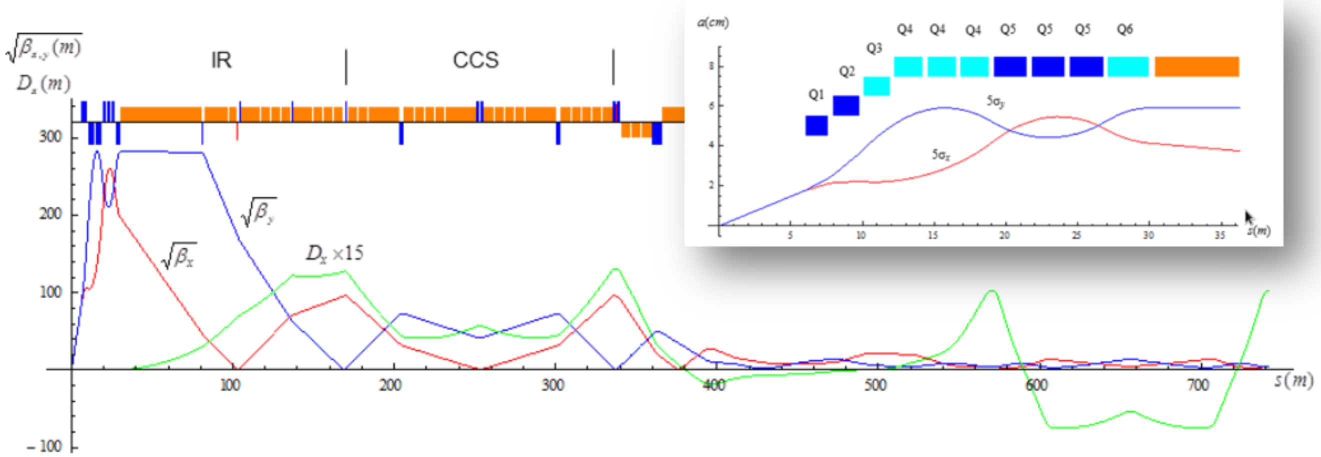


Final Focusing with L*=6m

Chromatic Correction with 4 set of dipole-sextuples

Matching CC-ARC

3 TeV IR lattice (MAP):



Tentative Staged Target Parameters

Target integrated luminosities

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

Need to spell out scenarios

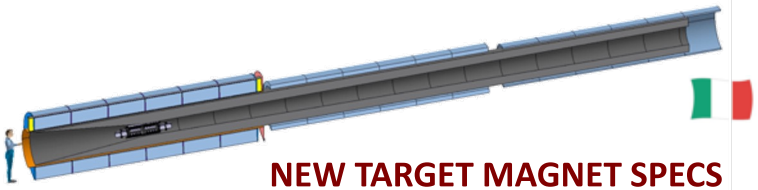
Need to integrate potential performance limitations for technical risk, cost, power, …

Parameter	Unit	3 TeV	10 TeV	10 TeV	10 TeV
L	**10^{34} cm^{-2}s^{-1}**	**1.8**	**20**	**tbd**	**13**
N	10^{12}	2.2	1.8	1.8	1.8
f_r	Hz	5	5	5	5
P_{beam}	**MW**	**5.3**	**14.4**	**14.4**	**14.4**
C	km	4.5	10	15	15
<B>	T	7	10.5	7	7
ε_L	MeV m	7.5	7.5	7.5	7.5
σ_E / E	%	0.1	0.1	tbd	0.1
σ_z	mm	5	1.5	tbd	1.5
β	mm	5	1.5	tbd	1.5
ε	µm	25	25	25	25
$\sigma_{x,y}$	µm	3.0	0.9	1.3	0.9

Examples as discussion basis

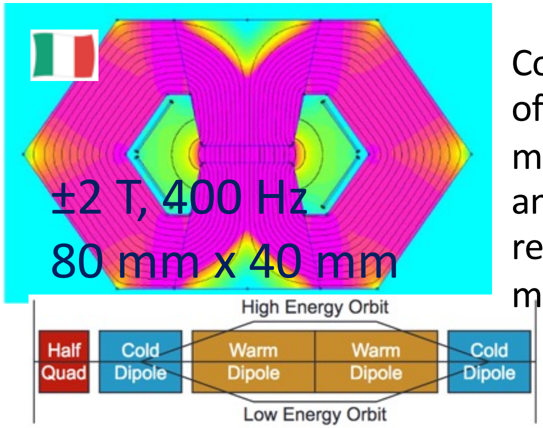
numbers will change

Magnet Demands @ Muon Collider



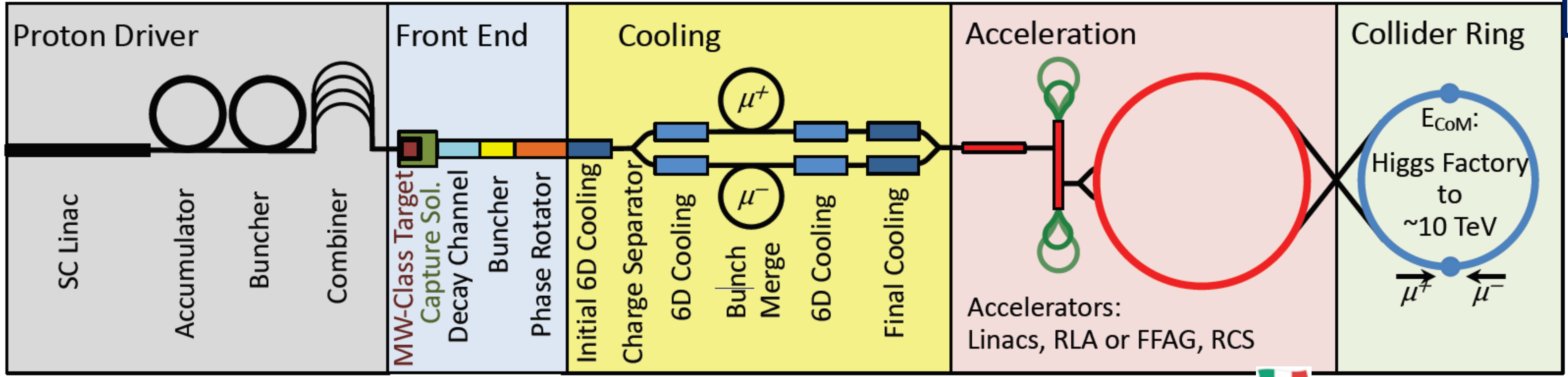
NEW TARGET MAGNET SPECS
Field: 20 T… 2T
Bore: 1200 mm
Length: 18 m
Radiation heat: ≈ 4.1 kW
Radiation dose: 80 MGy

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

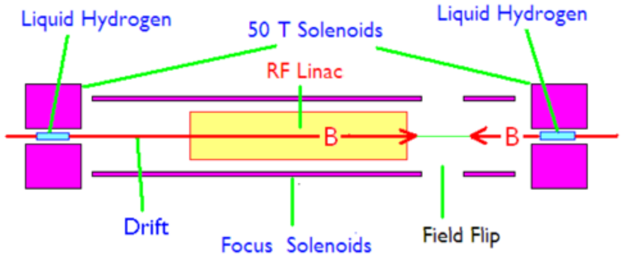


Combination of DC SC magnets (10 T) and AC resistive magnets (± 2T)

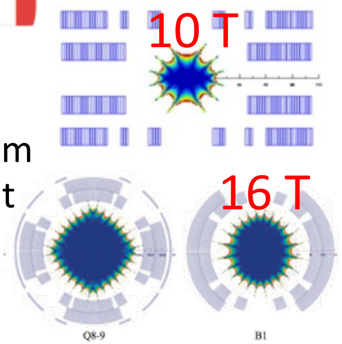
L. Rossi, M. Statera et al.
MI-LASA
B. Caiffi, A. Bersani et al.
Genova
M. Breschi et al.
Bologna



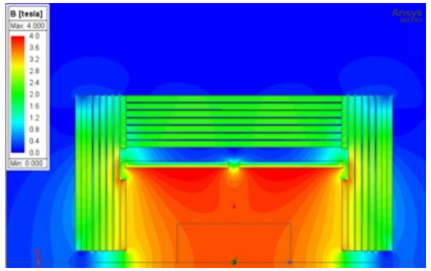
Ultra-high-field solenoids (40…60 T) to achieve desired muon beam cooling



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



Detector Magnet
to be designed for 10TeV

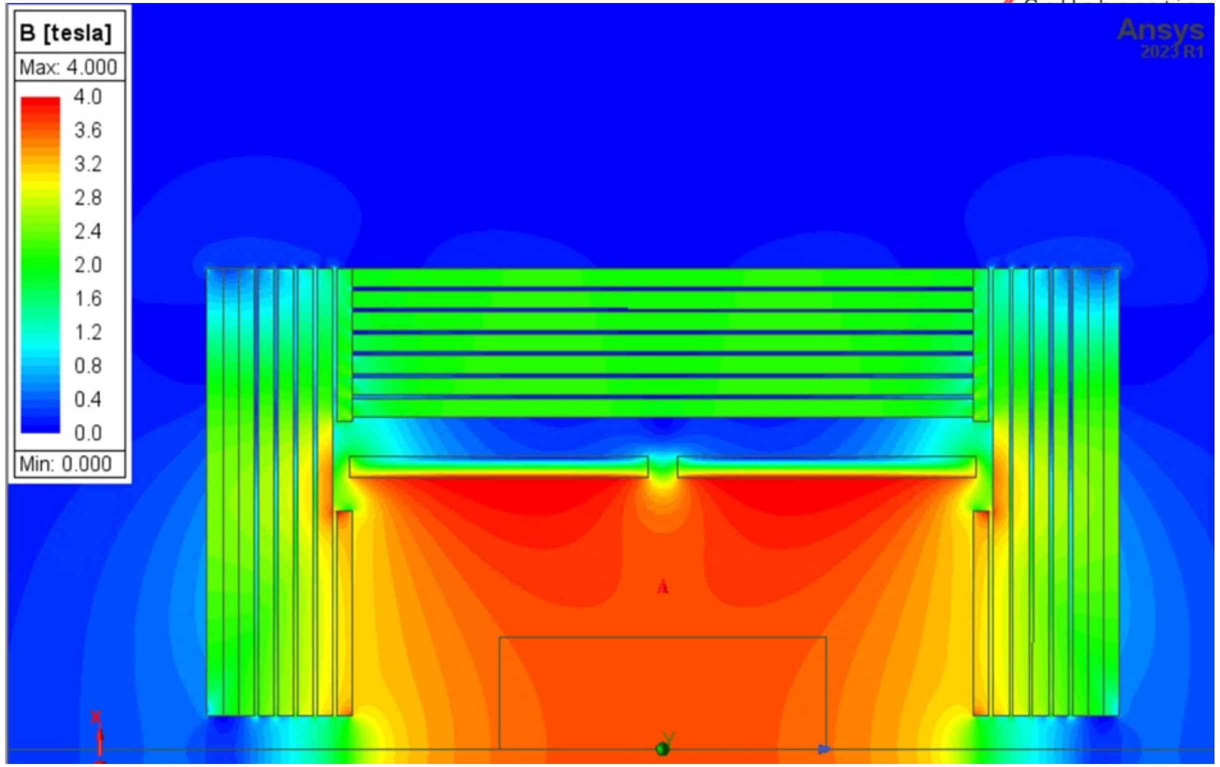


Preliminary study in detector magnet

Detector magnet workshop – 5 October 2023

Andrea Bersani et al.

Upon request from Detector group, some preliminary calculations on a possible solution for a detector solenoid has been performed, based on CMS cable



Main features:

- Tracker region: -2200 < z < 2200, 0 < r < 1500
- B at IP: 3.66 T
- B = 3.60 ± 0.08 T
- Field uniformity: ±2.3%
- (Almost no optimisation)
- Max Br = 0.12 T
- Stored energy: 2.25 GJ
- Current density: 12.3 MA/m^2
- Total coil thickness: 288 mm
- Current: 19.5 kA
- Cable size: 72 x 22 mm^2
- Inductance: 11.85 H

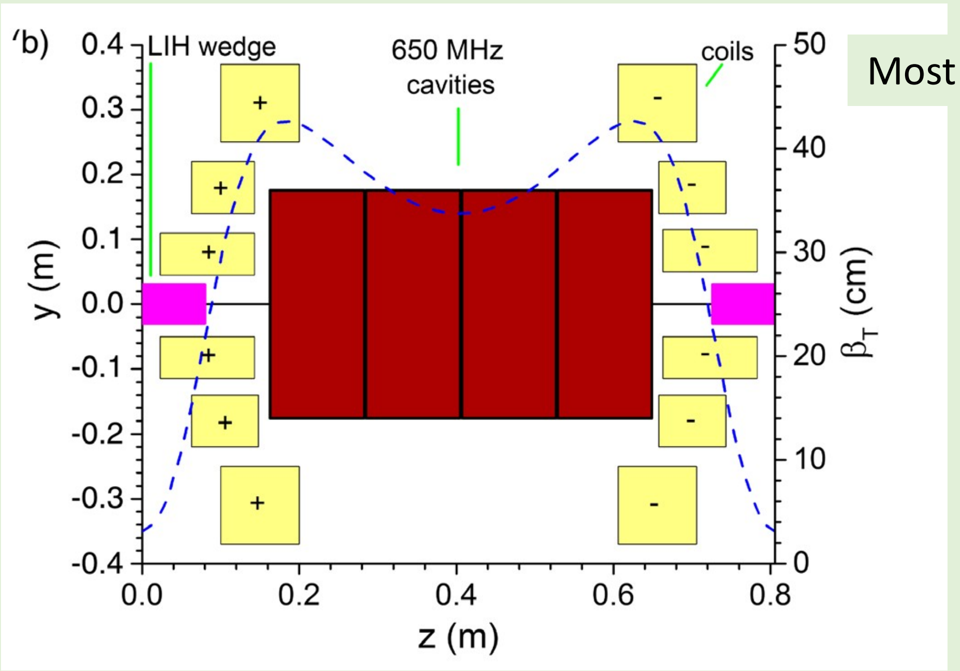
Realistic magnetic field map will be used in BIB generation and detector studies as soon as a decision is taken.

Main show stopper: no one produces aluminium stabilised cables
Main advantage: similar to something existing & working

Cooling Cell Technologies

Are developing example **cooling cell with integration**

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

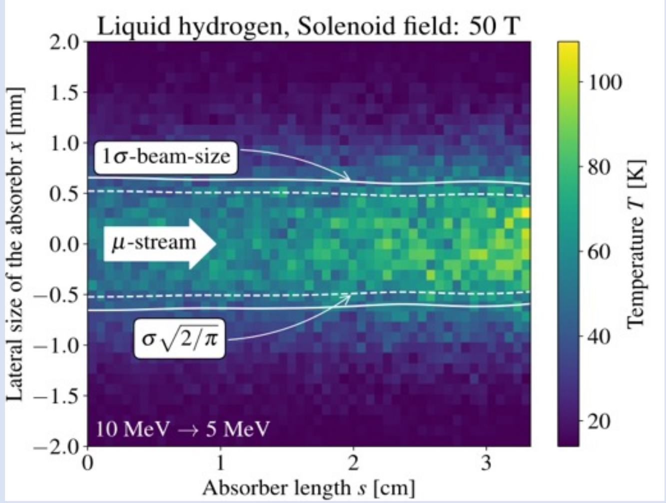


Most complex example 12 T

HTS solenoids
Ultimate field for final cooling
Also consider cost

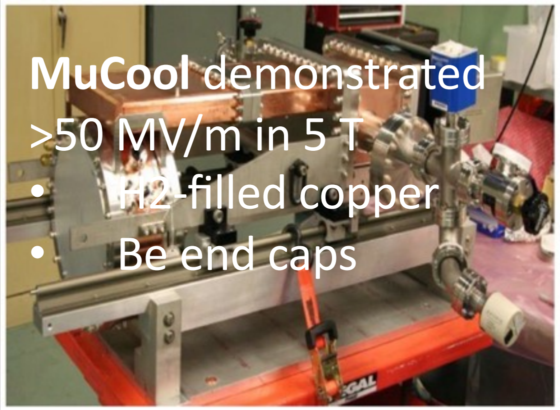
Windows and absorbers

- High-density muon beam
- Pressure rise mitigated by vacuum density
- First tests in HiRadMat



RF cavities in magnetic field
Gradients above goal demonstrated by MAP
New test stand is important

- Optimise and develop the RF
- Different options are being explored
- Need funding



MuCool demonstrated >50 MV/m in 5 T

- H2-filled copper
- Be end caps

Attività R&D Acceleratori

simulazioni – prototipi – misure di laboratorio

International MUON Collider Collaboration

MI, GE, LNL, LNS, NA, PD, TO, TS (FE, RM1, RM3)

- Magneti (MI-LASA, GE) ➔ progetto ESPP, EU-MuCol (WP7)
- Radiofrequenze SC (SC-RF) (MI-LASA) ➔ progetto ESPP , EU-MuCol (WP6)
- Radiofrequenze NC-RF (MI-LASA,LNL,LNS,NA) ➔ progetto ESPP , EU-MuCol (WP6)
- Integrazione cooling cell (MI-LASA,LNL,LNS,NA,TO) ➔ EU-MuCol (WP8)
- Machine Detector Interface ➔ progetto ESPP (personale), EU-MuCol (WP2-WP5)

⬇

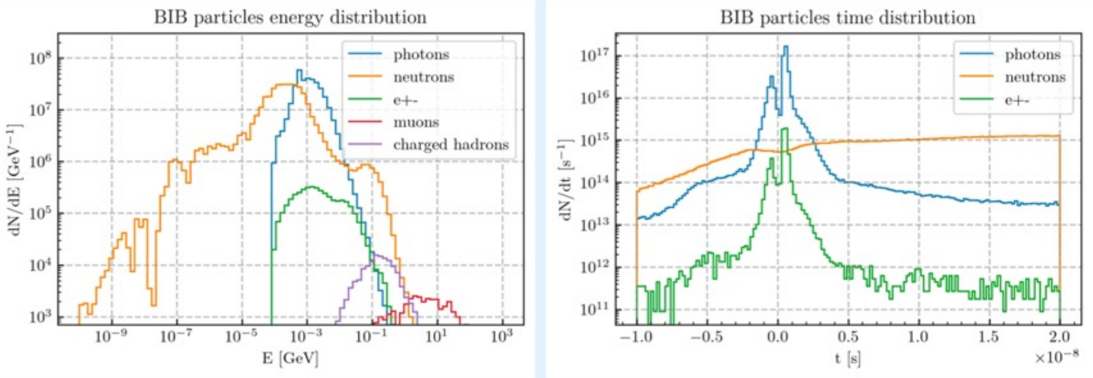
CRUCIALE PER STUDI DI FISICA E DETECTOR – PERFORMANCE MACCHINA

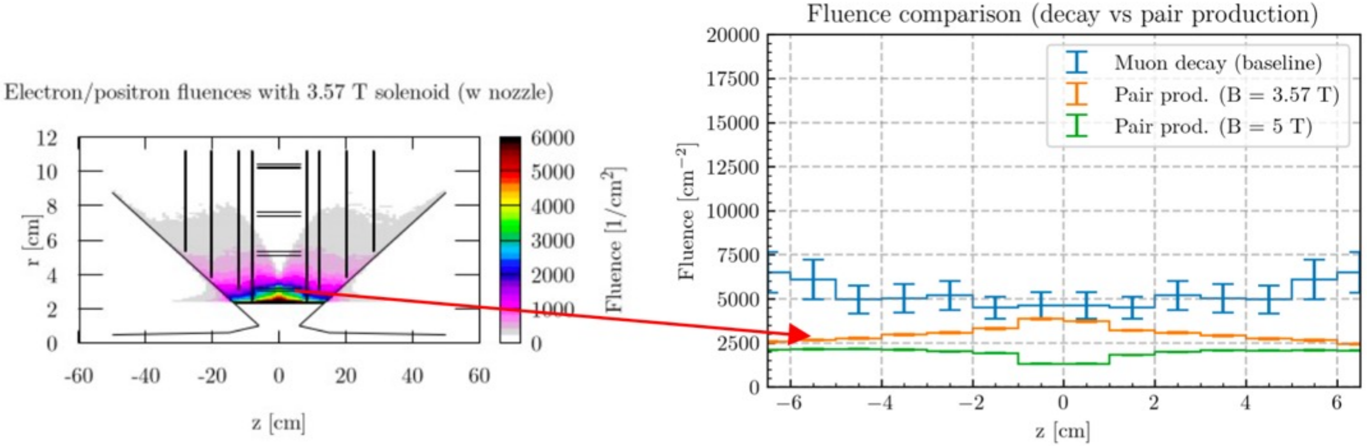
- *Cristalli per i fasci, misure di laboratorio per finestre sottili in fase di definizione*

ESPP_A_MUCOL ➔ approvato dal MAC INFN
WP1 - Machine Detector Interface
WP2 - Ionizing Cooling Cell design and integration:
  - normal-conducting RF cavities
  - high field solenoidal magnets
WP3 - Superconducting RF cavities: fast frequency tuner system
WP4 - High Field dipole Magnets technologies

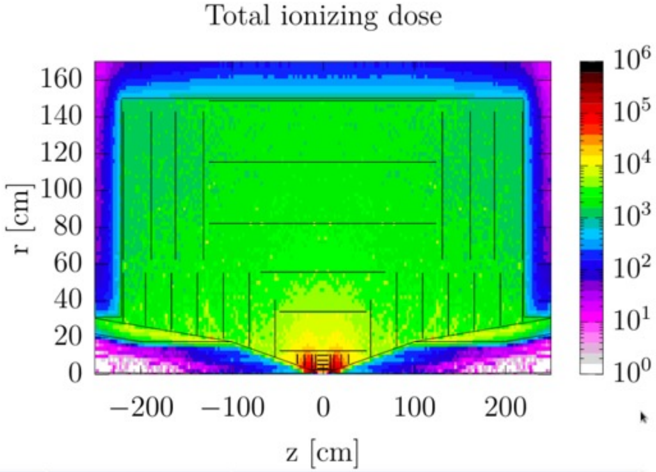
Experimental environment due to beam background

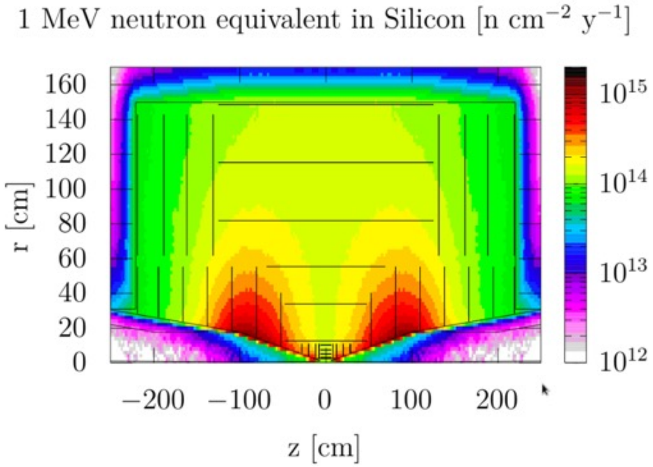
Time and energy spectra





*Radiation damage estimates for 10 TeV (**MAP nozzle, CLIC-like detector**)*
Includes only contribution of decay-induced background!





Donatella Lucchesi et al.

Per year of operation (140d)	Ionizing dose	Si 1 MeV neutron-equiv. fluence
Vertex detector	200 kGy	3×10^{14} n/cm²
Inner tracker	10 kGy	1×10^{15} n/cm²
ECAL	2 kGy	1×10^{14} n/cm²

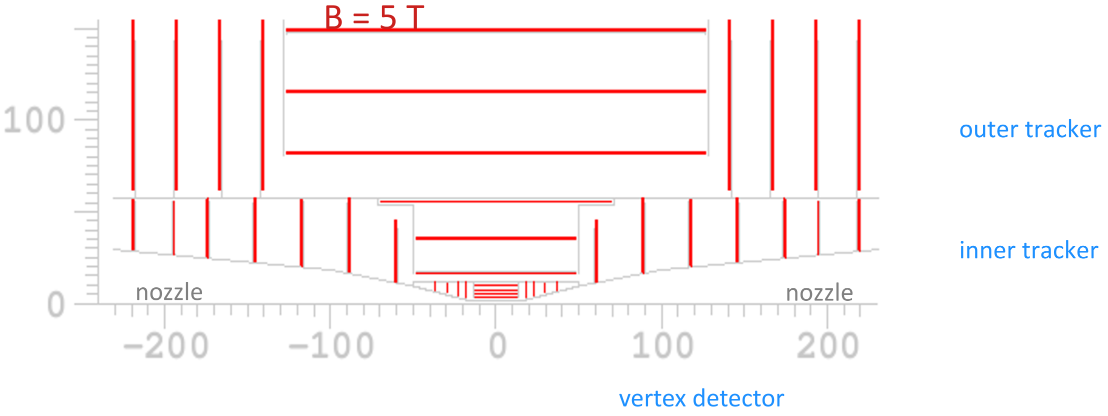
- **IMCC plans for final ESPPU report:**
  - Redo radiation damage calculations with optimized 10 TeV nozzle and lattice (and new detector design)
  - Calculate contribution of other source terms (e.g. incoherent pairs, halo losses)

Towards a detector @ 10 TeV: tracker studies

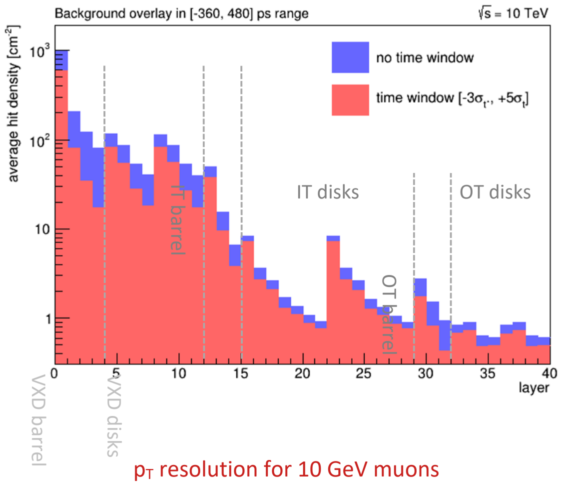
Comprehensive experiment designs are being developed for $\sqrt{s}$ = 3TeV and 10 TeV with optimisation studies of the MDI + detector happenning together

Example: cluster-shape filtering less effective at $\sqrt{s}$ = 10 TeV (BIB is more central)

BUT time filtering is more effective (different time structure of BIB hits)

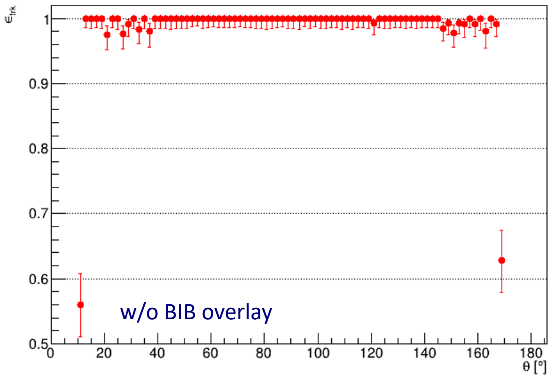


average hit density of BIB hits

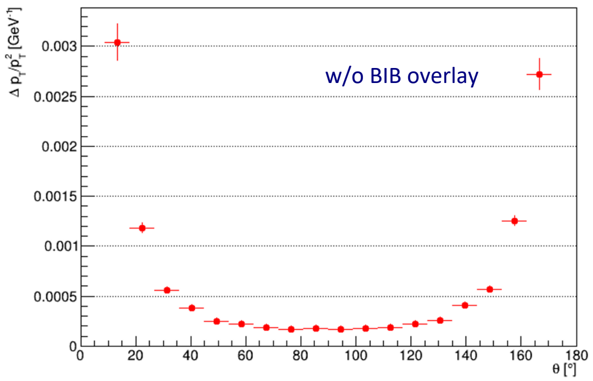


- **Vertex detector** (VXD):
  - 25x25 µm² Si pixels: 5 µm x 5 µm
  - spatial resolution and 30 ps time resolution.
- **Inner Tracker** (IT) and **Outer Tracker** (OT):
  - 50 µm x 1 mm Si macropixels:
  - 7 µm x 90 µm patial resolution and
  - 60 ps time resolution.

tracking efficiency for 10 GeV muons



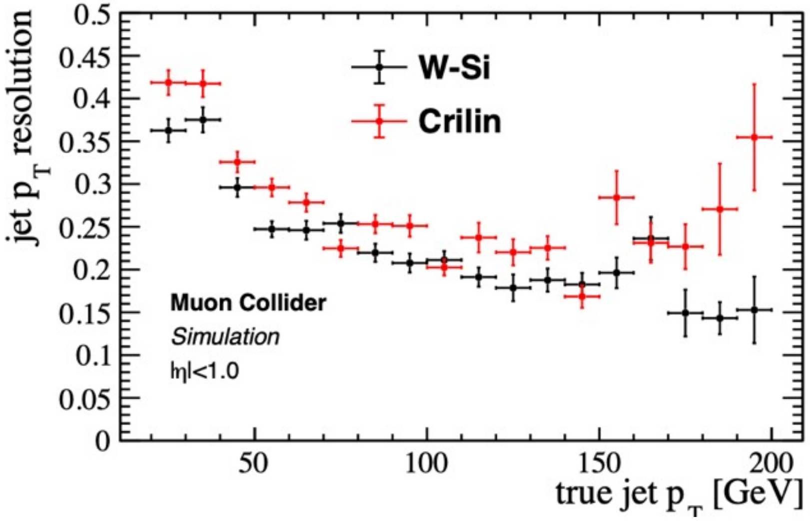
p_T resolution for 10 GeV muons

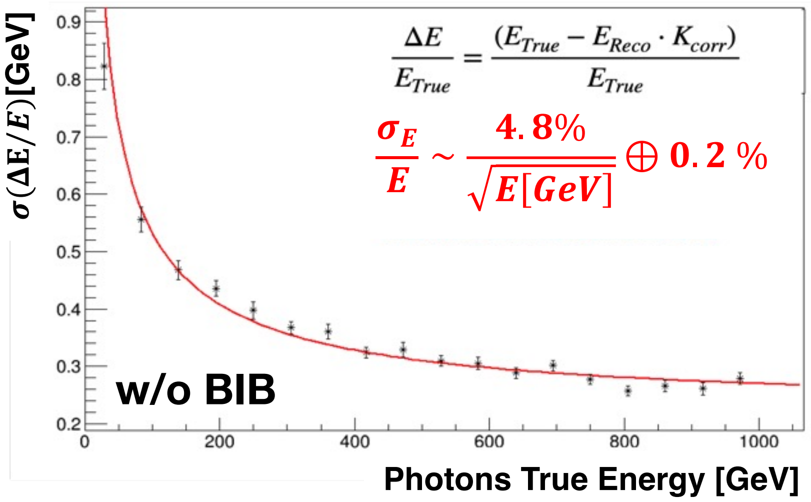


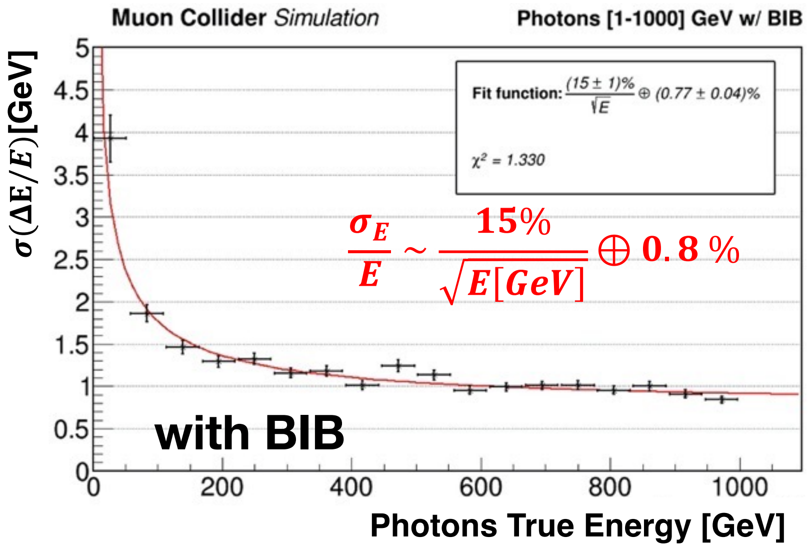
Simulated performances

- ECAL barrel with Crilin technology implemented in the simulation framework
  - 5 layers of 45 mm length, 10 X 10 mm^2 cell area → **21.5 X_0**
  - **In each cell:** 40 mm PbF_2 + 3 mm SiPM + 1 mm electronics + 1 mm air
- Design optimized for BIB mitigation: thicker layers, BIB energy integrated in large volumes → reduced statistical fluctuations of the average energy

5 layers wrt to 40 layers of the W-Si calorimeter → factor 10 less in cost (6 vs 64 MCHF)





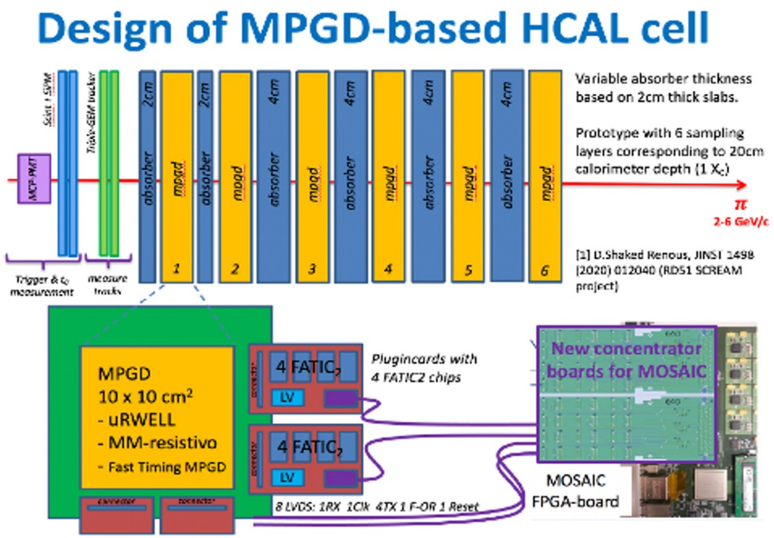


Prototypes and performances

Luigi Longo et al.
ICHEP 2024

RD51 common project:

Development of Resistive MPGD Calorimeter with timing measurement (2021-2023)



Design of MPGD-based HCAL cell

Variable absorber thickness based on 2cm thick slabs.

Prototype with 6 sampling layers corresponding to 20cm calorimeter depth (1 X_c)

[1] D.Shaked Renous, JINST 1498 (2020) 012040 (RD51 SCREAM project)

MPGD
10 x 10 cm²
- uRWELL
- MM-resistivo
- Fast Timing MPGD

Plugincards with 4 FATIC2 chips

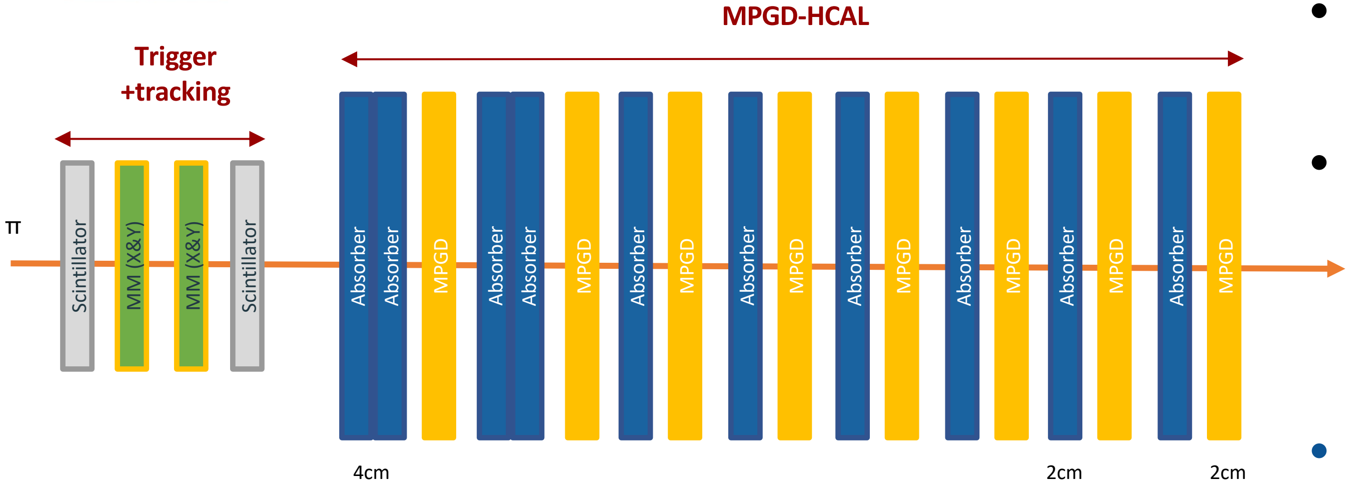
Detector design: Active area 20×20 cm², pad size 1×1 cm²
- 7 μ-RWELL - 4 MicroMegas - 1 RPWELL

Prototype characterization performed in BA, LNF, NA, RM3 INFN and Weizmann Institute of Science laboratories

Detector	Uniformity (%)
MM-RM3	$(12.3 \pm 0.8)\%$
MM-Na	$(11.6 \pm 0.8)\%$
MM-Ba	$(8.0 \pm 0.5)\%$
RPWELL	$(22.6 \pm 4.7)\%$
μrw-Na	(11.3 ± 1.0) %
μrw-Fr2	$(16.2 \pm 1.7)\%$
μrw-Fr1	$(16.3 \pm 1.1)\%$

SPS test beam:

Goal:
validating the readout detectors **with MIPs** and **compare MPGDs**

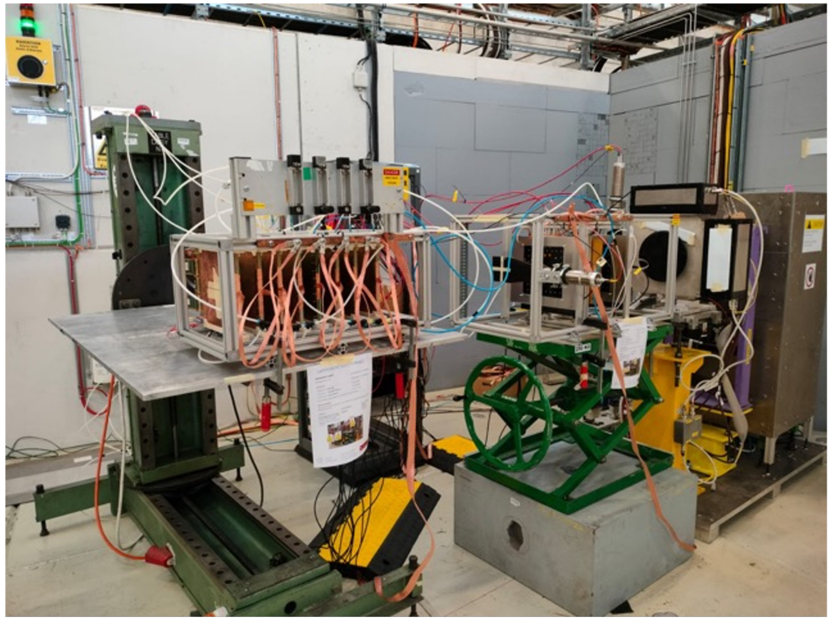


- Goal: **measuring** the energy resolution of a 1 λ calorimeter prototype with 1-10 GeV pions beam
- Developed **G4 simulation** for the **small prototype**, including a **digitization algorithm** to account for charge-sharing among adjacent pads and detector efficiency
- **Good data/MC comparison**

Next steps

2024-2025

- Consolidating results with present prototypes in two test beams in 2024
- **4 large detectors** (50×50 cm^2) to be built in 2025:
  - Design **optimization** to exclude cross-talk and simplify manufacturin



Long term plans:

- construction of 4 1x1m2 layers, 2 of them with embedded electronics

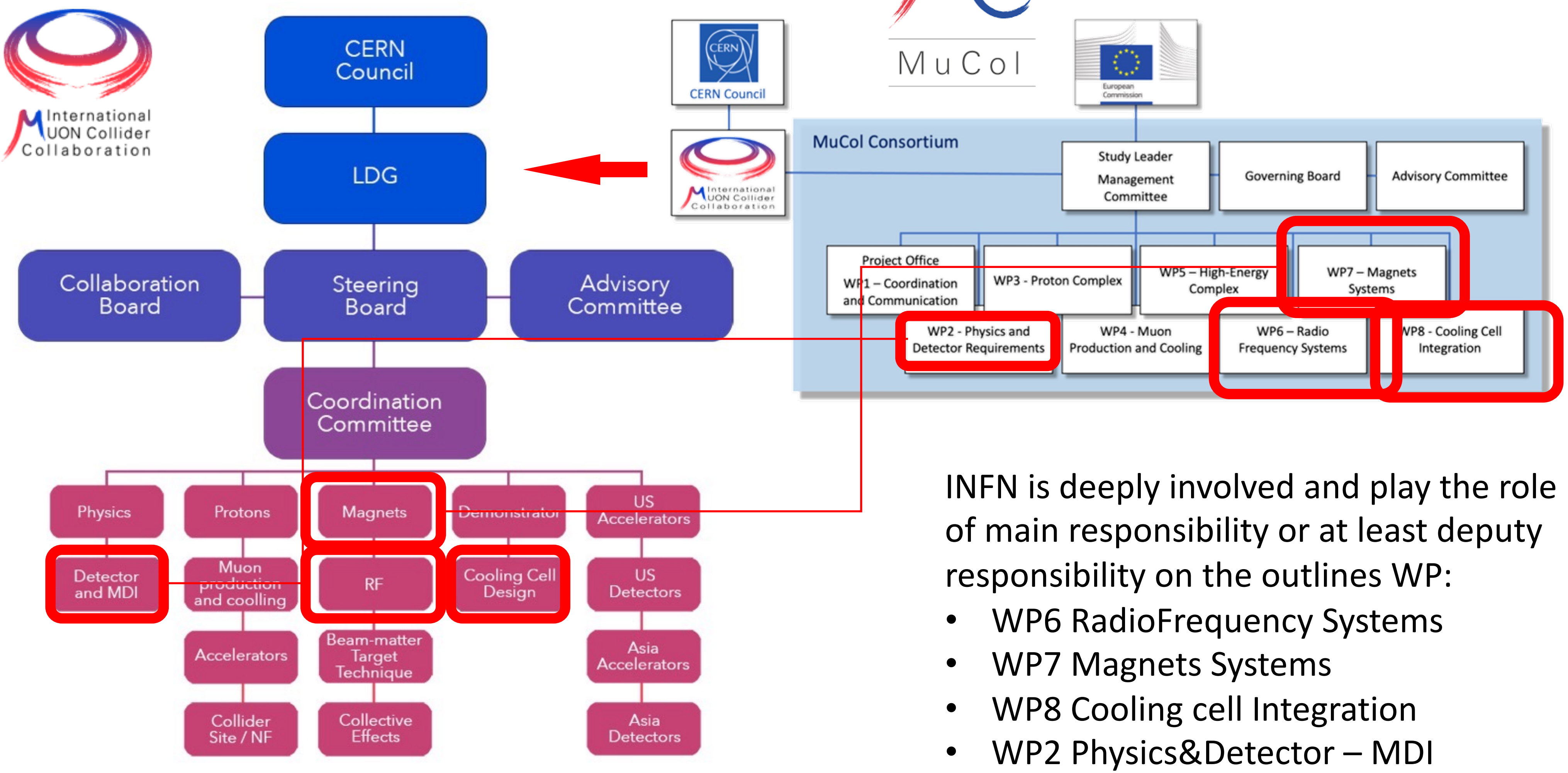
Bottlenecks:

- new electronics is needed:
  VMM3a or FATIC3 analog electronics considered requiring a step forward to digital embedded electronics
- Electronics R&D is expensive and need a lot of support not only on the chip but also on backend, firmware,...

Project Organization

International Muon Collider Collaboration

MuCol EU Design Study



CERN Council

LDG

Collaboration Board

Steering Board

Advisory Committee

Coordination Committee

Physics

Protons

Magnets

Demonstrator

US Accelerators

Detector and MDI

Muon production and coolling

RF

Cooling Cell Design

US Detectors

Accelerators

Beam-matter Target Technique

Asia Accelerators

Collider Site / NF

Collective Effects

Asia Detectors

CERN Council

MuCol

European Commission

MuCol Consortium

Study Leader Management Committee

Governing Board

Advisory Committee

Project Office WP1 – Coordination and Communication

WP3 - Proton Complex

WP5 – High-Energy Complex

WP7 – Magnets Systems

WP2 - Physics and Detector Requirements

WP4 - Muon Production and Cooling

WP6 – Radio Frequency Systems

WP8 - Cooling Cell Integration

INFN is deeply involved and play the role of main responsibility or at least deputy responsibility on the outlines WP:

- WP6 RadioFrequency Systems
- WP7 Magnets Systems
- WP8 Cooling cell Integration
- WP2 Physics&Detector – MDI

IMCC included as: “**Experiments and Projects under Study**”
https://greybook.cern.ch/experiment/detail?id=IMCC

Design Study activities: EU project

Total EU budget: 3 Meu start March 1 2023 – 4 years
18(+14) beneficiaries (associated) **END 28 FEB 2027**

HORIZON-INFRA-2022-DEV-01-01:
Research infrastructure concept development

MuCol

International
MUON Collider
Collaboration

INFN 510 keu **UniMI** 300 keu **UniPD** 100 keu + associate partners: UniBO, UniPV INCLUSO OVERHEAD

MuCol study will produce a coherent description of a novel particle accelerator complex that will collide muons of opposite charge at the energy frontier. The study will target a centre-of-mass energy (ECM) of 10 TeV with 3 TeV envisaged as a first stage.

The main outcome of MuCol will be a **report** documenting the facility design that should demonstrate that:

- the **physics case** of the muon collider is sound and **detector systems** can yield sufficient resolution and rejection of backgrounds;
- there are **no principle technology showstoppers** that will prevent the achievement of a satisfactory performance from the accelerator or from the detectors side;
- the muon collider provides **a highly sustainable energy frontier facility** as compared to other equivalent colliders;
- **exploiting synergies with other scientific and industrial R&D projects**, a valuable platform to provide Europe a leading edge not only in terms of discovery potential, but also for the development of associated technologies.

The final report will include a thorough assessment of benefits and risks of the accelerator and detector complex, including an evaluation of the scientific, industrial and societal return beyond high-energy physics, the cost scale and sustainability of the complex and the impact arising from an implementation on the CERN site.

INFN – BUDGET
Total: 408 keu

AdR: 362 keu
Altro: 46 keu

GE: 10 keu missioni
MI: 8 keu missioni
MI: 16 keu consumo
MI: 8 keu licenze
TO: 4 keu progetto

RF @ cooling cells: E-field in High Magnetic Gradients

- For the cooling cell integration: **preliminary scenario designed** with a target electric RF field of more than **30 MV/m for a 3 GHz cavity**

- The value of the **magnetic field in the cooling cell considered for the demonstrator is 7.2 T** (at the coils center), and a maximum gradient in longitudinal direction in excess of 24 T/m (at the cavity center).

- It is agreed to consider a magnetic system that will produce the field and field gradient, with flexibility on their combination, from a uniform field of **7 T (on axis), to a gradient field of 30 T/m (on axis) over the cavity volume**.

Preliminary design for a single RF cavity suitable to be installed in **a 500 mm diameter bore solenoid**

RF PARAMETERS TO BE STUDIED

- **the RF frequency**
- **the required gradient of the electric field in a cell vs. the peak gradient achievable in the RF structure**
- **expected breakdown rate and eventual mitigation strategy, especially in the high magnetic field and high magnetic gradient they experience**
- **specific materials and surface treatments for the cavity bodies.**
- **the type of RF coupling from cell to cell in a RF structure**
- **the space available to fit ancillaries (e.g. tuners, power couplers, cooling pipes etc...), considering the tight interference with the cryomagnetic system**
- **the available or realistically feasible power sources**

Implementation plan options: staging

Important timeline drivers:

Magnets

- HTS technology available for solenoids (expected in 15 years)
- Nb_3Sn available for collider ring, maybe lower performance HTS (expected in 15 years)
- High performance HTS available for collider ring (may take more than 15 years)

Muon cooling technology (expected in 15 years, with enough resources)

Detector technologies and design (R&D plan starting, finalized design expected in 15 years)

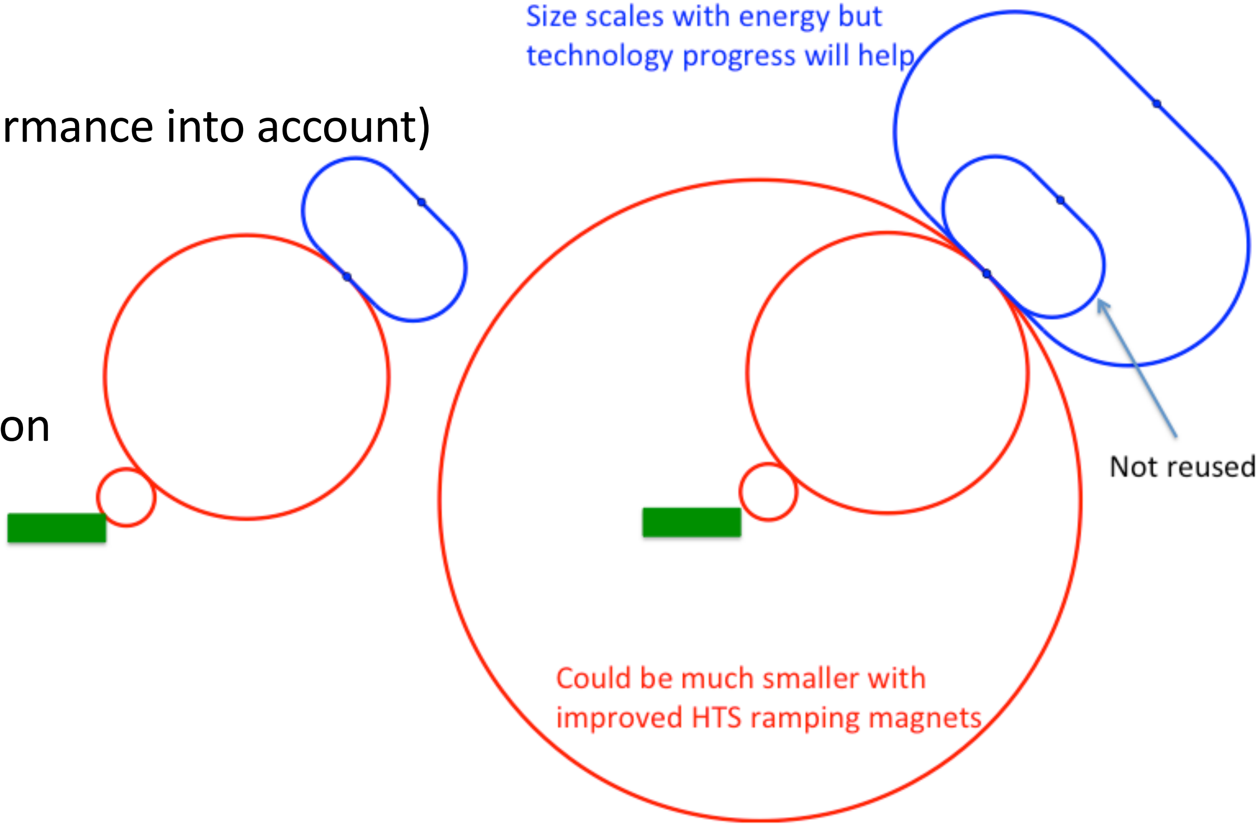
Energy staging

- Start at lower energy (e.g. 3 TeV, design takes lower performance into account)

Luminosity staging

- Start at 10 TeV with the highest reachable energy, but lower luminosity
- Main luminosity loss sources are arcs and interaction region
    - Can later upgrade interaction region (as in HL-LHC)

Consider reusing **LHC tunnel** and other infrastructures


Size scales with energy but technology progress will help

Not reused

Could be much smaller with improved HTS ramping magnets

Site Studies

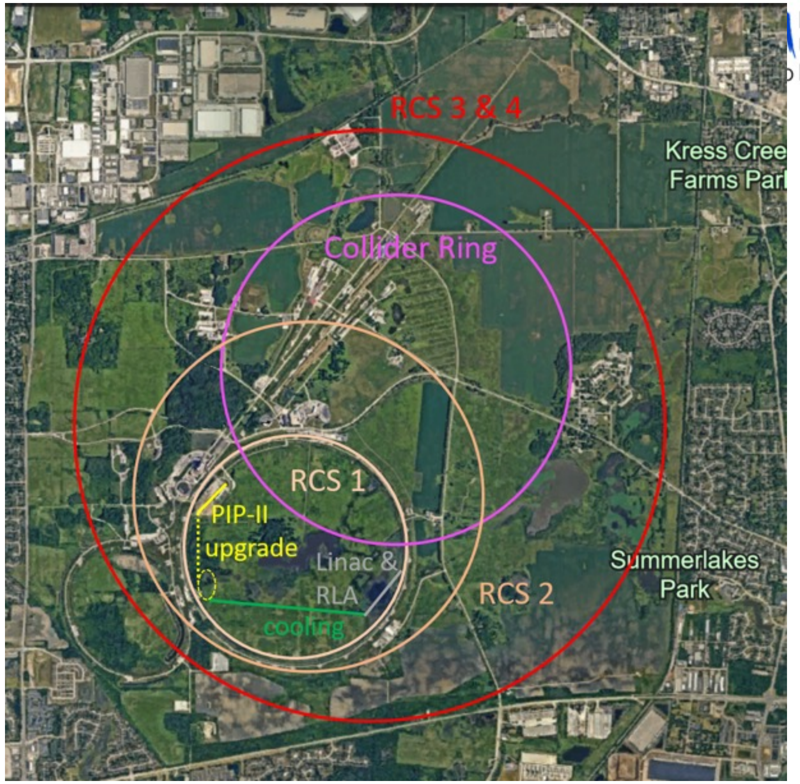
Candidate sites **CERN, FNAL,** potentially others **(**ESS, JPARC, …)

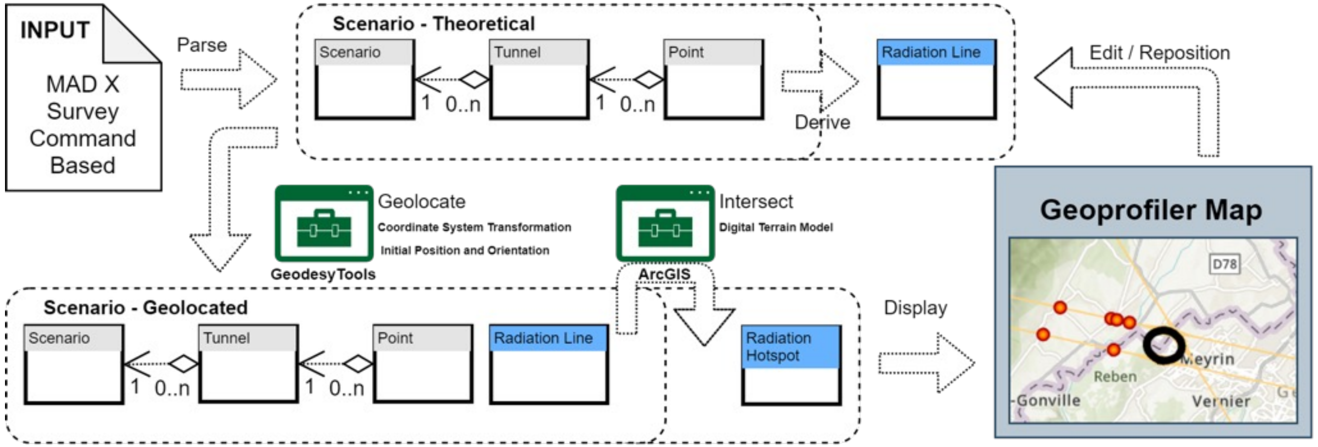
Study is mostly site independent

- Main benefit is existing infrastructure
- Want to avoid time consuming detailed studies and keep collaborative spirit
- Will do more later

Some considerations are important

- Neutrino flux mitigation at CERN
- Accelerator ring fitting on FNAL site





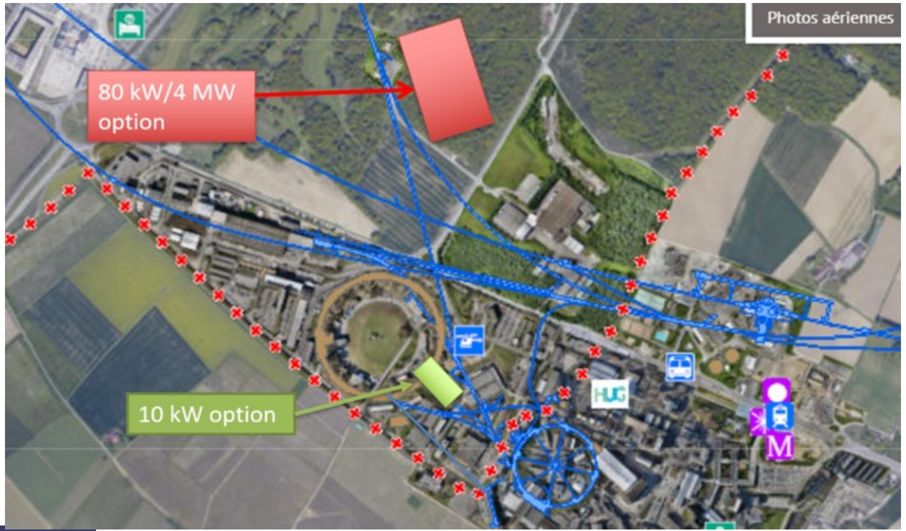
Potential site next to CERN identified

- Mitigates neutrino flux
  - Points toward mediterranean and uninhabited area in Jura
- Detailed studies required (280 m deep)

CDR Phase, R&D and Demonstrator Facility

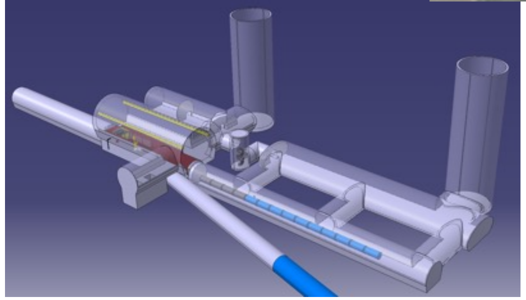
Broad R&D programme can be distributed world-wide

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



Cooling demonstrator is a key facility

- look for an existing proton beam with significant power

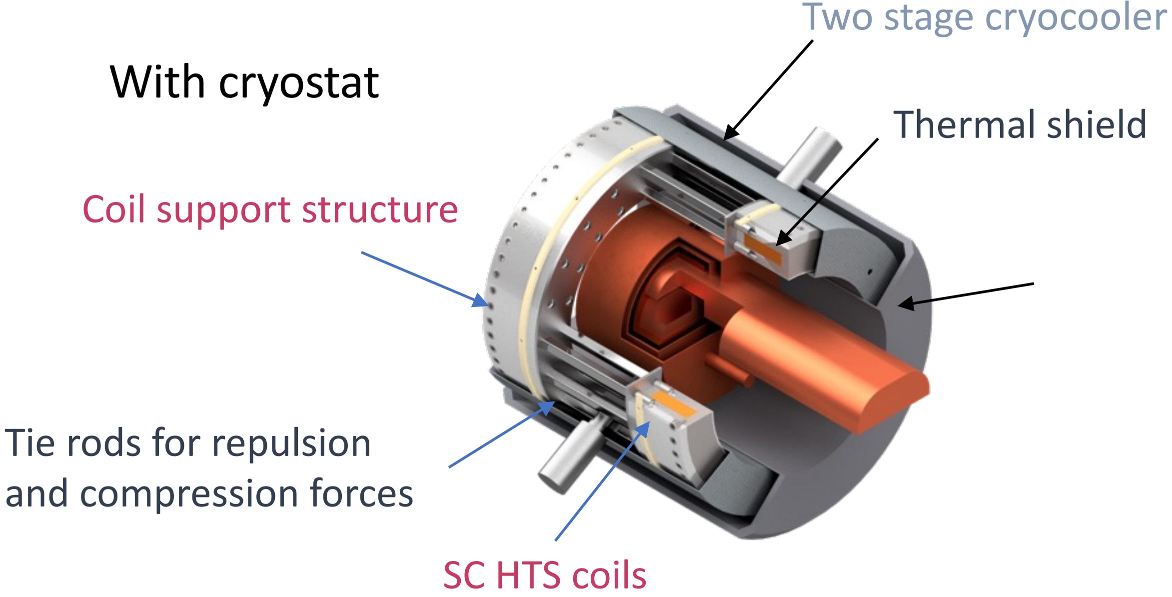


Different sites are being considered

- CERN, FNAL, ESS …
- Two site options at CERN

Muon cooling module test is important

- INFN is driving the work
- Could test it at CERN with proton beam



With cryostat

Two stage cryocooler

Thermal shield

Coil support structure

Tie rods for repulsion and compression forces

SC HTS coils

Summary of activities towards R&D plans

Each WP is working to identify challenges and R&D plans towards a baseline design:

- Physics and MDI
- Proton complex
- Target design
- Muon Cooling
- Accelerator Complex
- Collider Ring
- RF Technology
- Magnet Technology
- Cooling cell integration
- Demonstrator