CSN1 – Venezia – 26 novembre 2024

Multi- TeV Muon Collider @ European Strategy

IMCC input documents in preparation

Nadia Pastrone

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

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

HORIZON-INFRA-2022-DEV-01-01

Input document requirements

International MUON Collider Collaboration

✓ **Comprehensive summary (maximum 10 pages)**

a comprehensive and self-contained summary should address:

- **scientific context**
- **objectives**
- **methodology**
- **readiness and expected challenges**
- **timeline**
- **construction and operational costs (if applicable)**

✓ **Back-up document**

Additional information and details can be submitted in a separate back-up document

National input questions

a) Which is the preferred next major/flagship collider project for CERN

b) What are the most important elements in the response to 3a)?

i. Physics potential
ii. Long-term perspective
iii. Financial and human resources: requirements and effect on other projects
iv. Timing
v. Careers and training
vi. Sustainability

c) Should CERN/Europe proceed with the preferred option set out in 3a) or should alternative options be considered:
  i. if Japan proceeds with the ILC in a timely way?
  ii. if China proceeds with the CEPC on the announced timescale?
  iii. if the US proceeds with a muon collider?
  iv. if there are major new (unexpected) results from the HL-LHC or other HEP experiments?

d) Beyond the preferred option in 3a), what other accelerator R&D topics (e.g. highfield magnets, RF technology, alternative accelerators/colliders) should be pursued in parallel?

e) What is the prioritised list of alternative options if the preferred option set out in 3a) is not feasible (due to cost, timing, international developments, or for other reasons)?

f) What are the most important elements in the response to 3e)? (The set of considerations in 3b should be used).

Scientific context

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 mainly in accelerator R&D Roadmap
- first parameters' report submitted October 2023

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

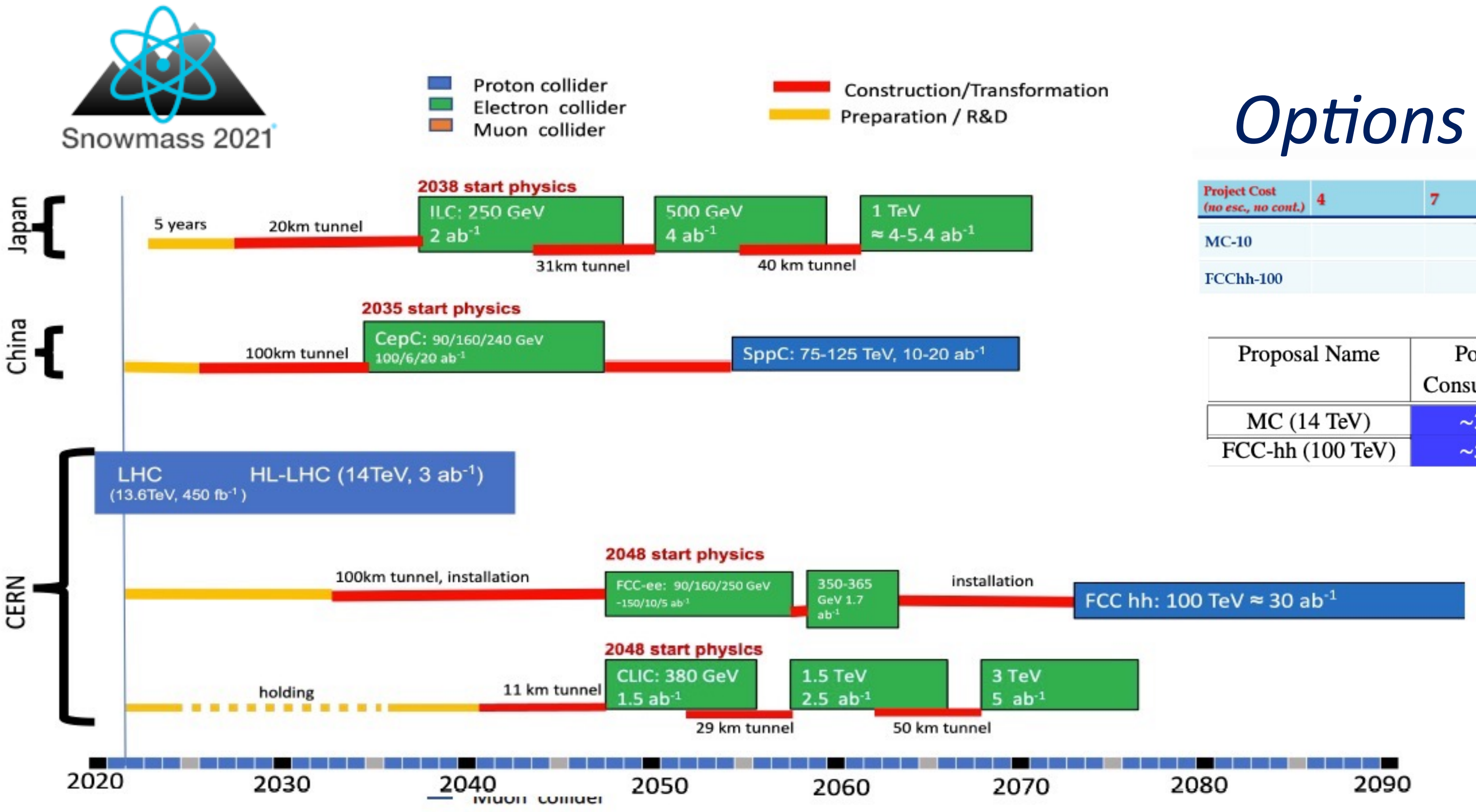
NEW OPTION: initial 10 TeV stage at reduced luminosity

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

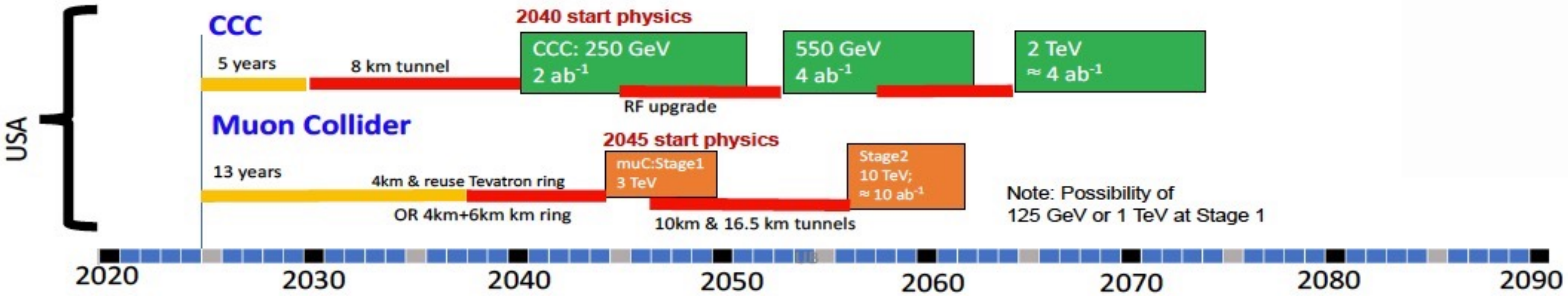
Towards a muon collider,
Eur. Phys. J. C 83 (2023) 864

Strong support by P5 Report @ December 2023

Colliders timescale: Snowmass2021

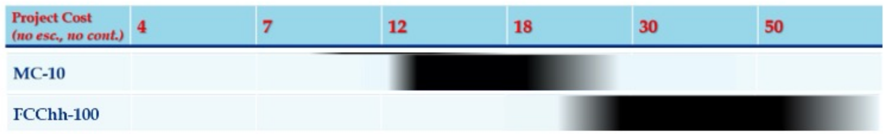


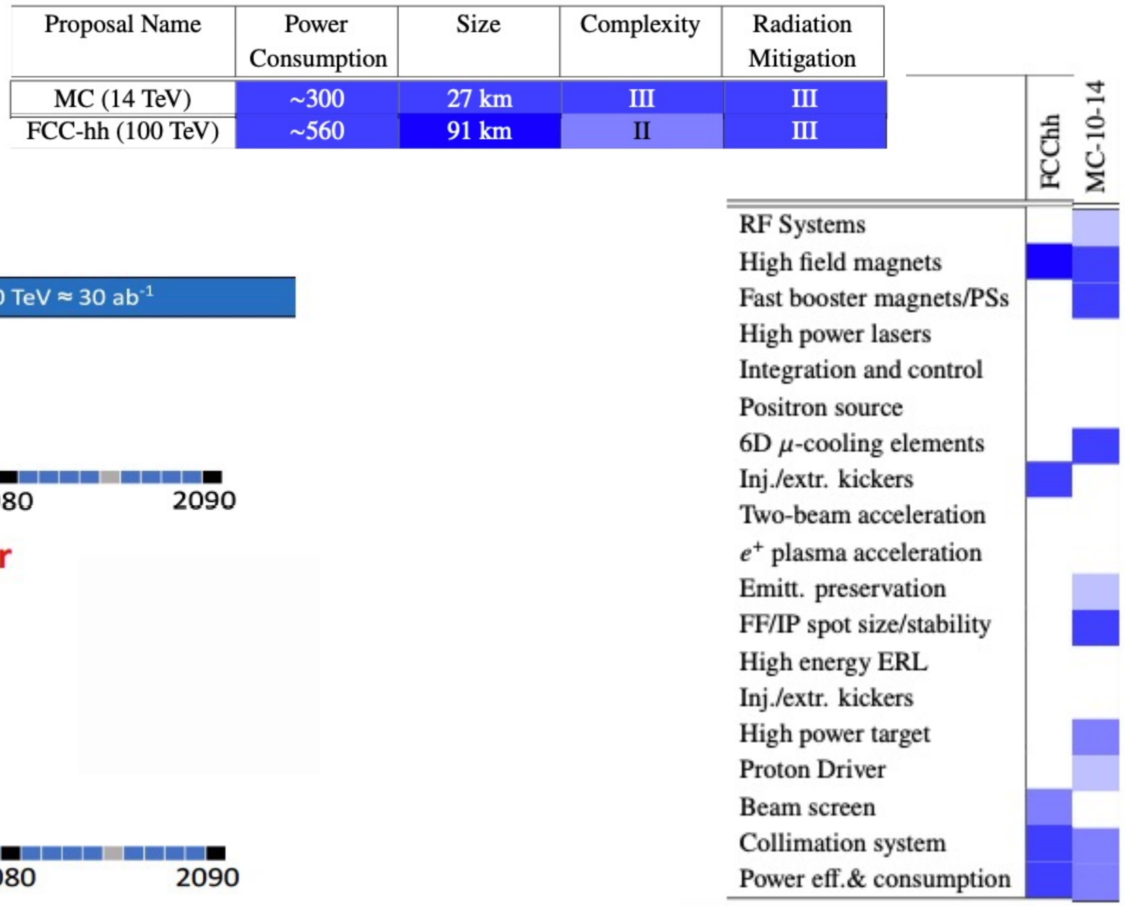
Proposals emerging from Snowmass 2021 for a US based collider



International
MUON Collider
Collaboration

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

	FCChh	MC-10-14
RF Systems		🟦
High field magnets	🟦	🟦
Fast booster magnets/PSs		🟦
High power lasers		
Integration and control		
Positron source		
6D μ-cooling elements		🟦
Inj./extr. kickers	🟦	
Two-beam acceleration		
e^+ plasma acceleration		
Emitt. preservation		🟦
FF/IP spot size/stability		🟦
High energy ERL		
Inj./extr. kickers		
High power target		🟦
Proton Driver		🟦
Beam screen	🟦	
Collimation system	🟦	🟦
Power eff.& consumption	🟦	🟦

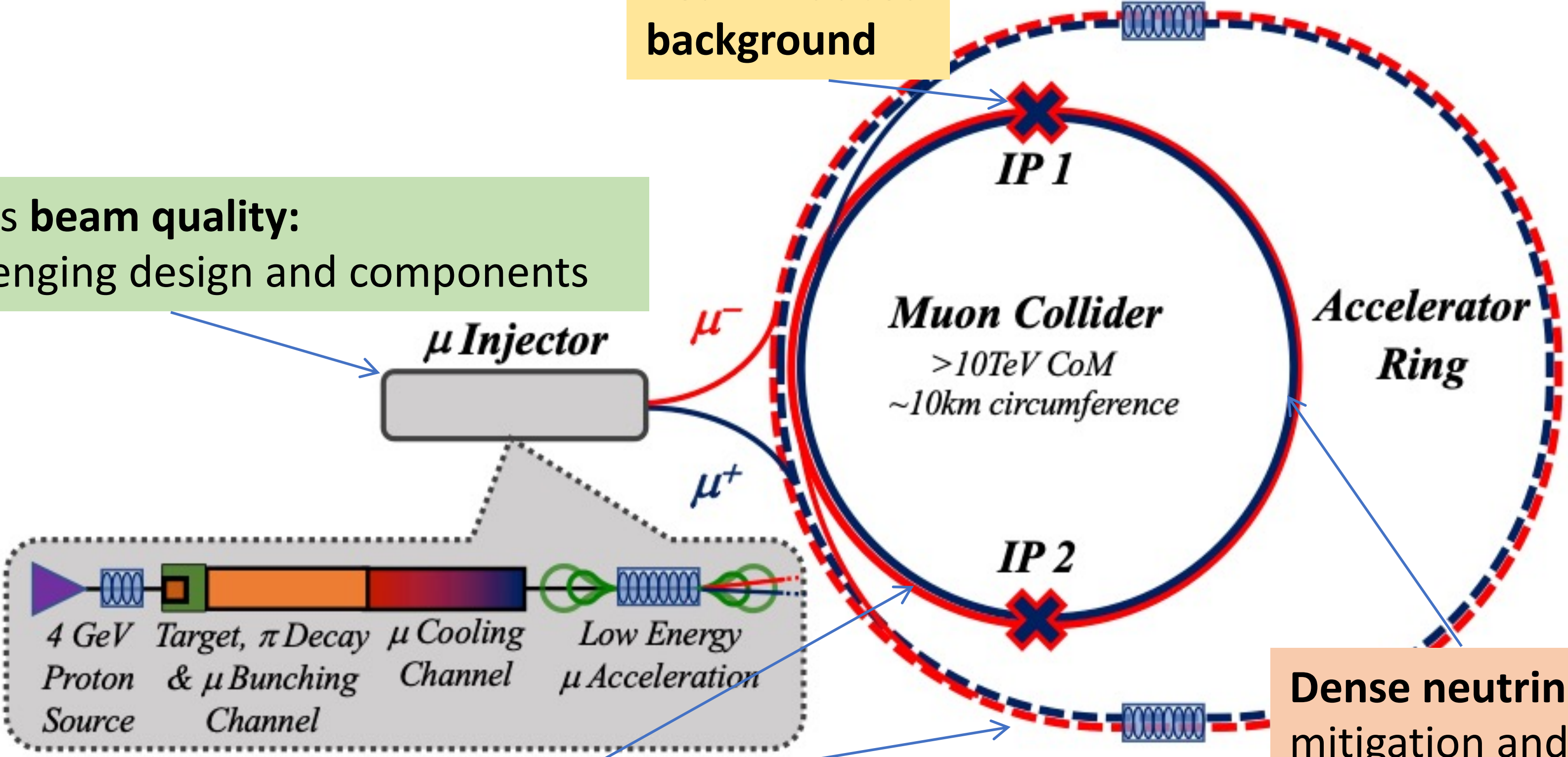
Objectives of the facility @ 10 or higher TeV

Proton driver production
Baseline @ International Design Study

10+ TeV completely new regime to explore!

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

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



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

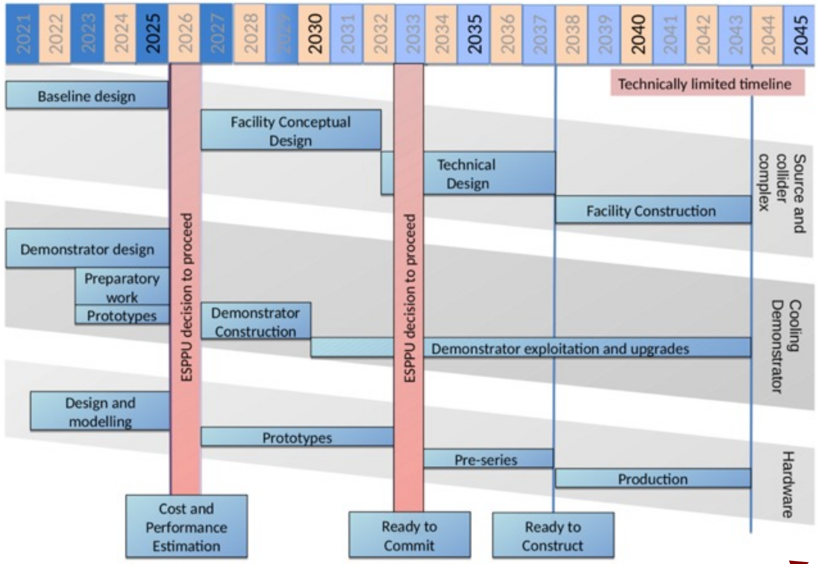
Accelerator R&D Roadmap

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

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

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

Accelerator R&D Roadmap implementation

LDG review - February 24-26, 2025 @ CERN

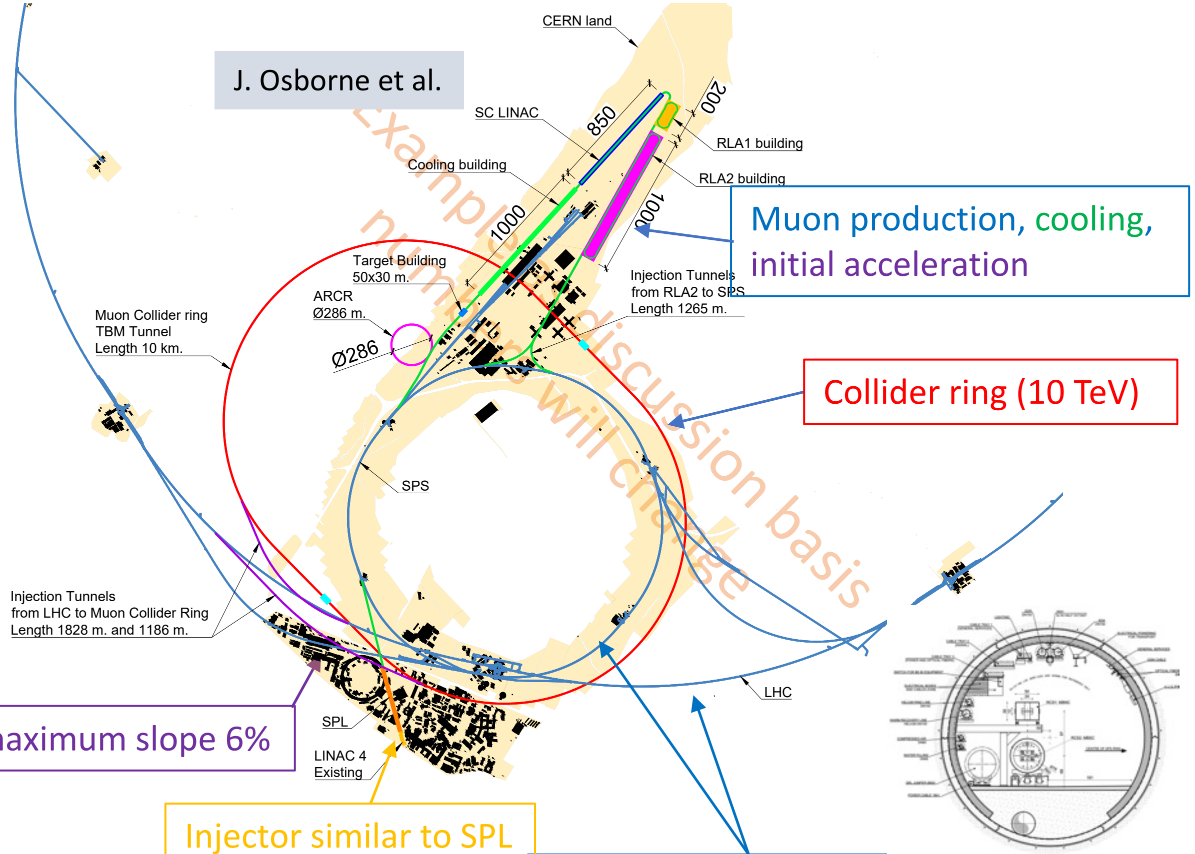
to review:

- R&D plan
- Demontrator design and proposal

- First collider ring site identified @ CERN
- SPS and LHC tunnels reused
- All construction on CERN
- Energy stages maybe 2.5 and 8 TeV

10 TeV Muon Collider Beam Requirements

Parameters	Symbol	$\sqrt{s}=10$ TeV
Particle energy [GeV]	E	5000
Luminosity [10^{34} cm^{-2} s^{-1}]	$\mathcal{L}$	20
Bunch population [10^{12}]	N_p	1.8
Transverse normalized rms emittance [μm]	ε_n	25
Longitudinal emittance ($4\pi\ \sigma_E\ \sigma_T$) [eVs]	ε_l	0.314
Rms bunch length [mm]	σ_z	1.5
Relative rms energy spread [%]	p_T	0.1
Beta function at IP [mm]	β^*	1.5
Beam power with 10 Hz repetition rate [MW]	P_{beam}	14.4



J. Osborne et al.

Muon production, cooling, initial acceleration

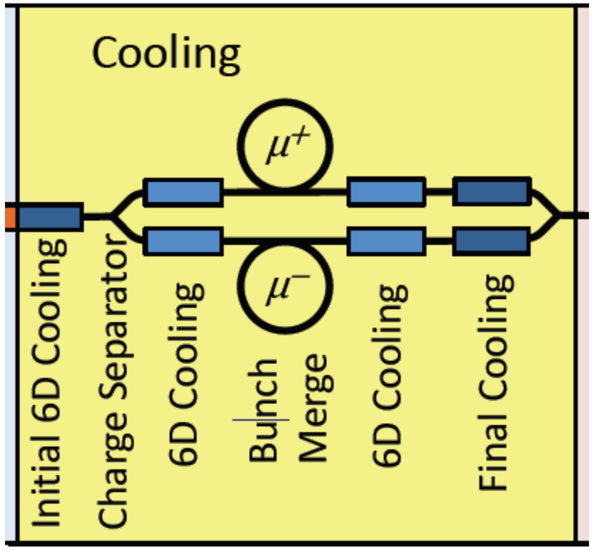
Collider ring (10 TeV)

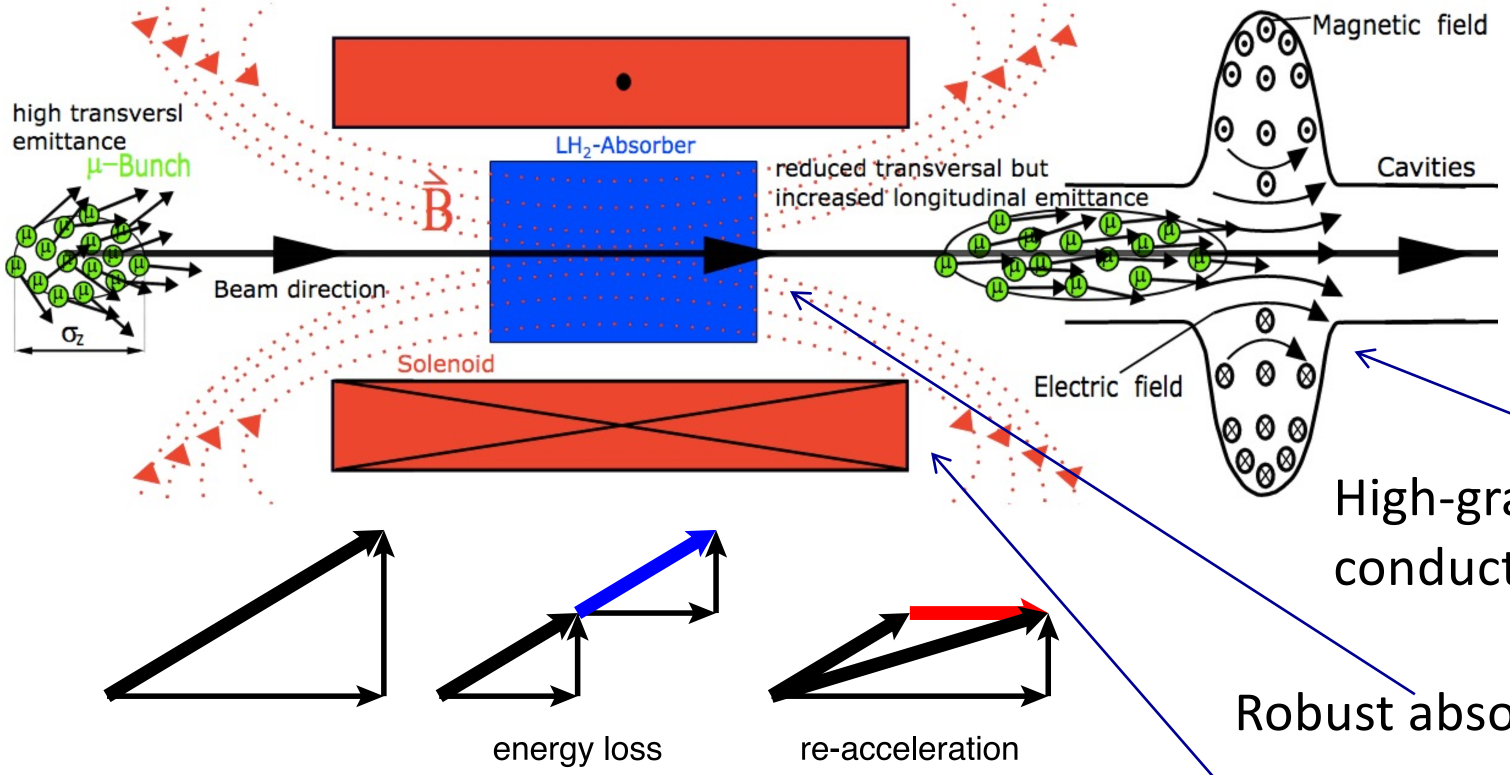
Transferline maximum slope 6%

Injector similar to SPL

SPS and LHC used for RCSs

Muon Cooling Principle

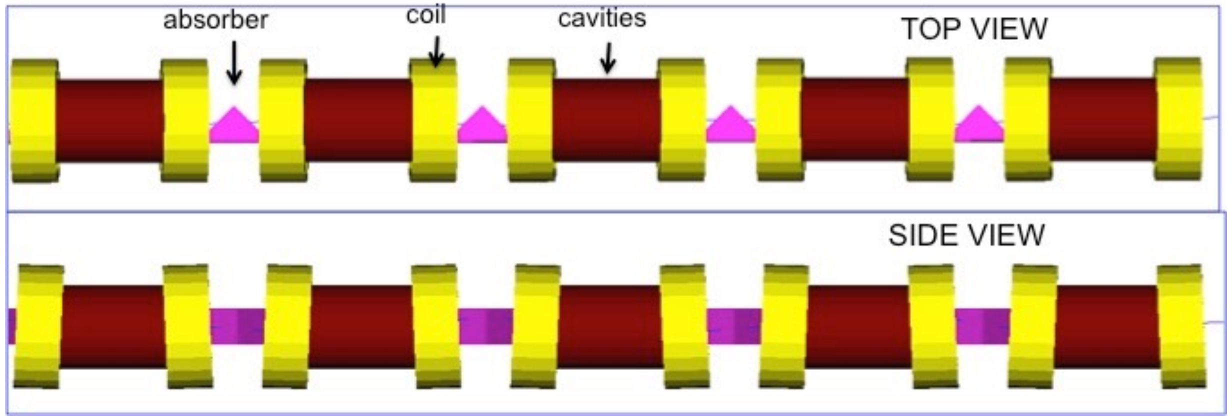




High-gradient normal-conducting cavities

Robust absorbers

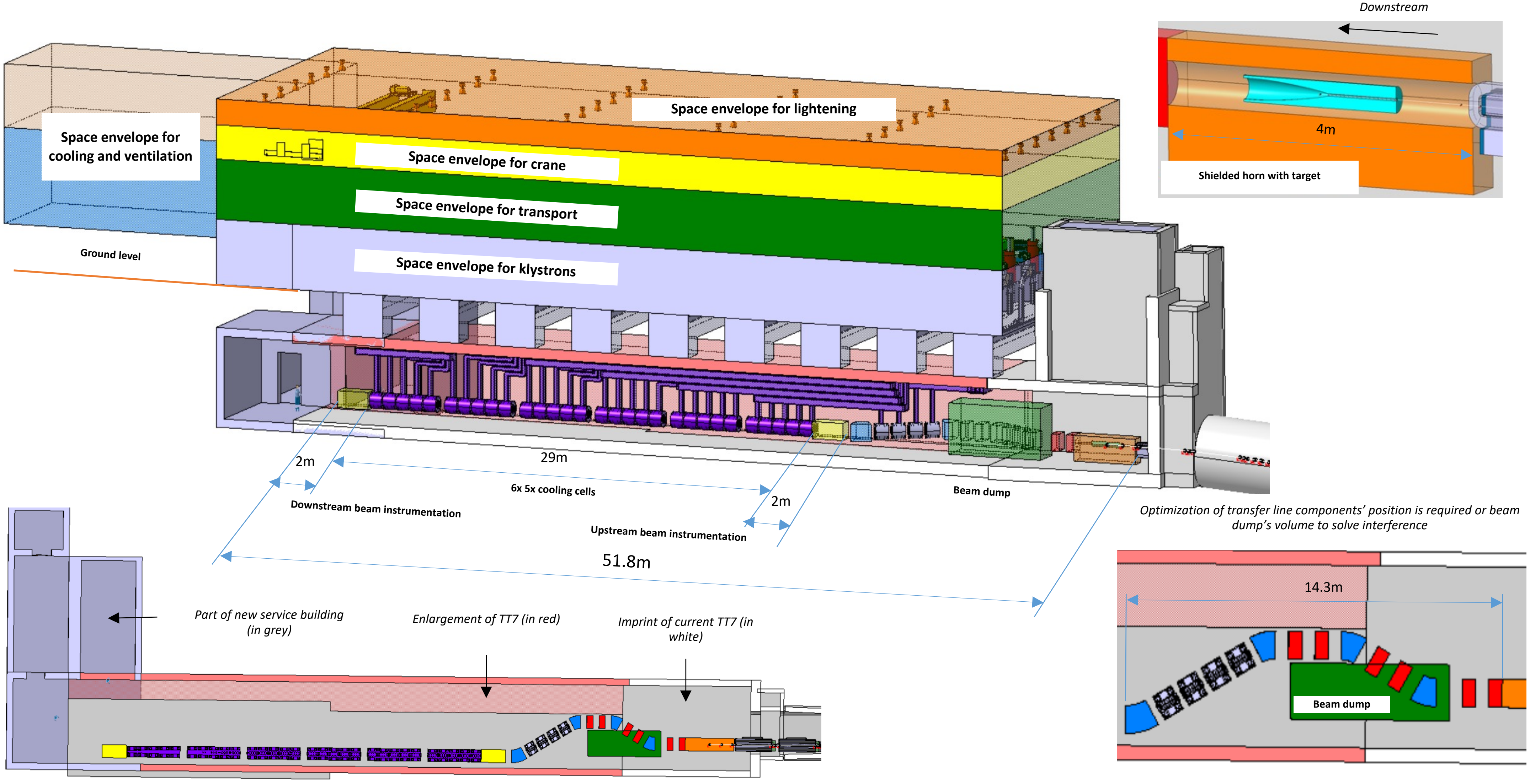
High-field, superconducting solenoid



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

CERN as a host site for Demonstrator

CERN: integration - Demonstrator in TT7



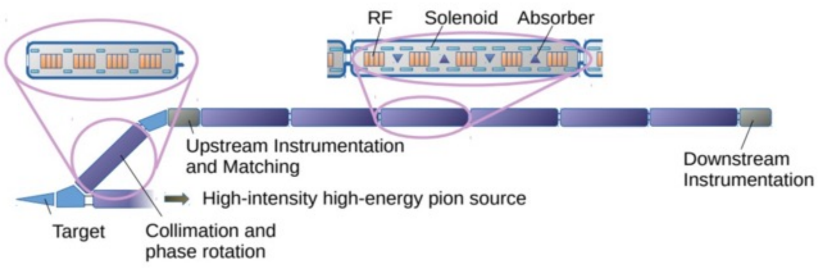
Optimization of transfer line components' position is required or beam dump's volume to solve interference

Part of new service building (in grey)

Enlargement of TT7 (in red)

Imprint of current TT7 (in white)

Demonstrator Facility: a crucial step forward!



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

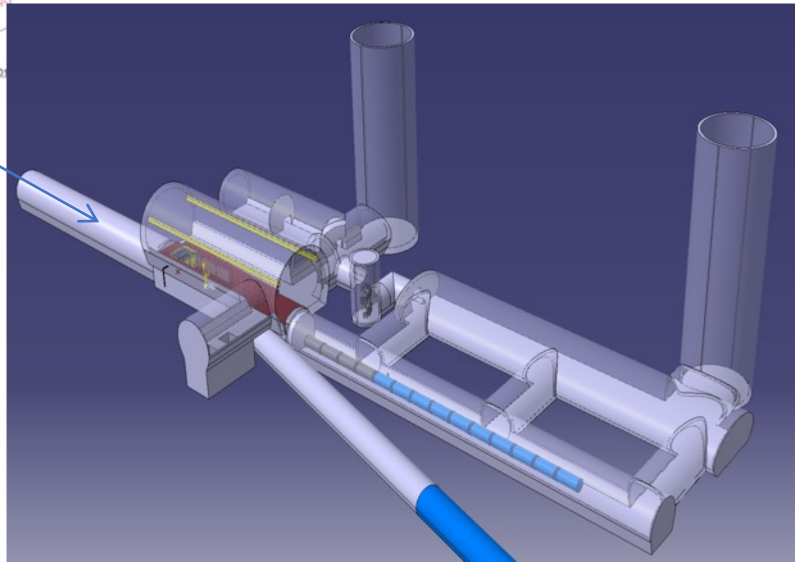
Suitable **site exists** on CERN land and can use **PS proton beam**

- could combine with other option - synergies on neutrino and other measurements

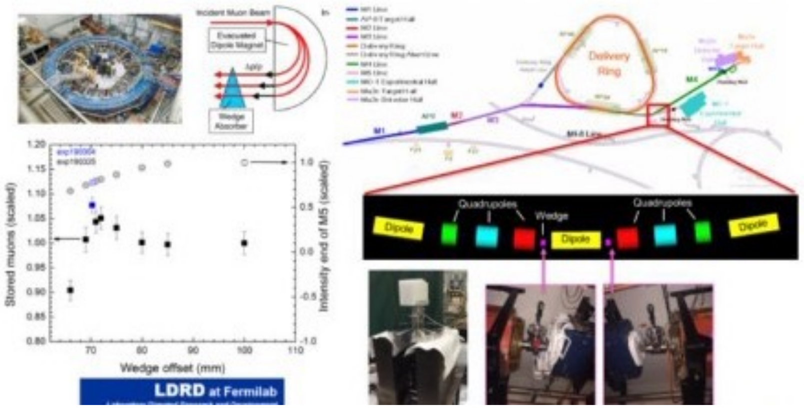
M. Benedikt, LHC Performance Workshop, Chamonix 2010

CERN-AB-2007-061

@ CERN



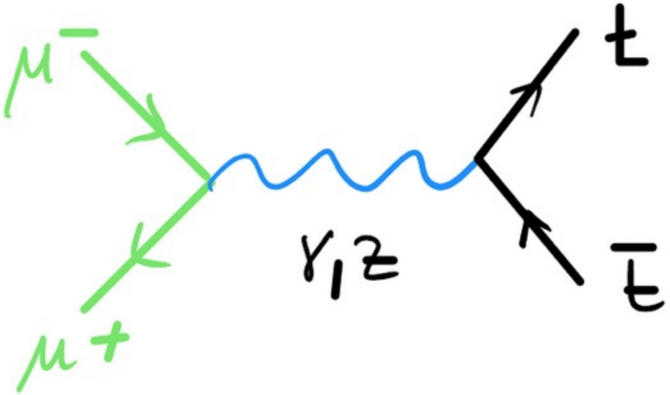
@ FNAL



[International Muon Collider Collaboration: Demonstrator Workshop]

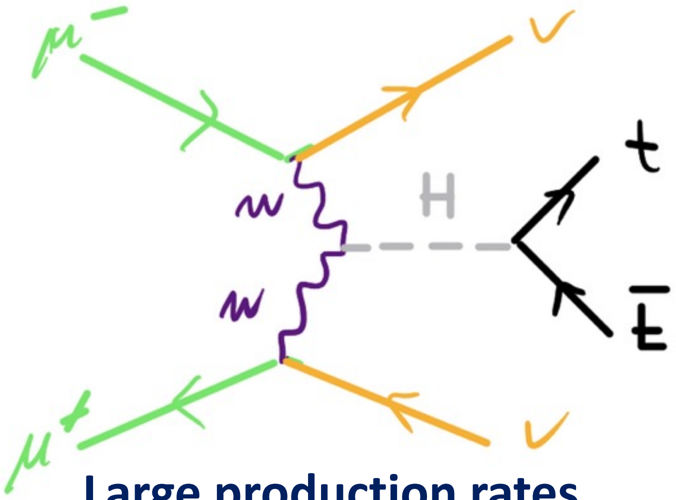
@ FNAL October 30 – November 1, 2024

multi-TeV Muon Collider: two colliders in one!



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

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]

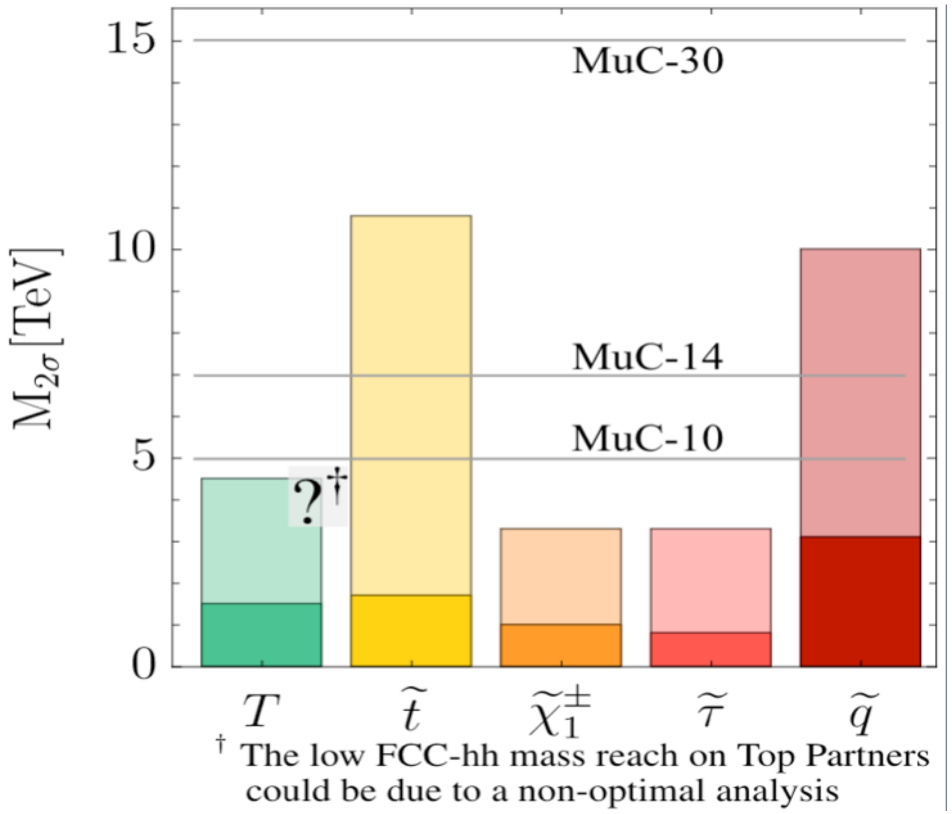
Strong and crucial synergies to design the machine and the experiment
to reach the physics goals with energy and luminosity allowing % precision measurements

➔ Physics benchmarks steer machine parameters and experiment design

Physics potential

International MUON Collider Collaboration

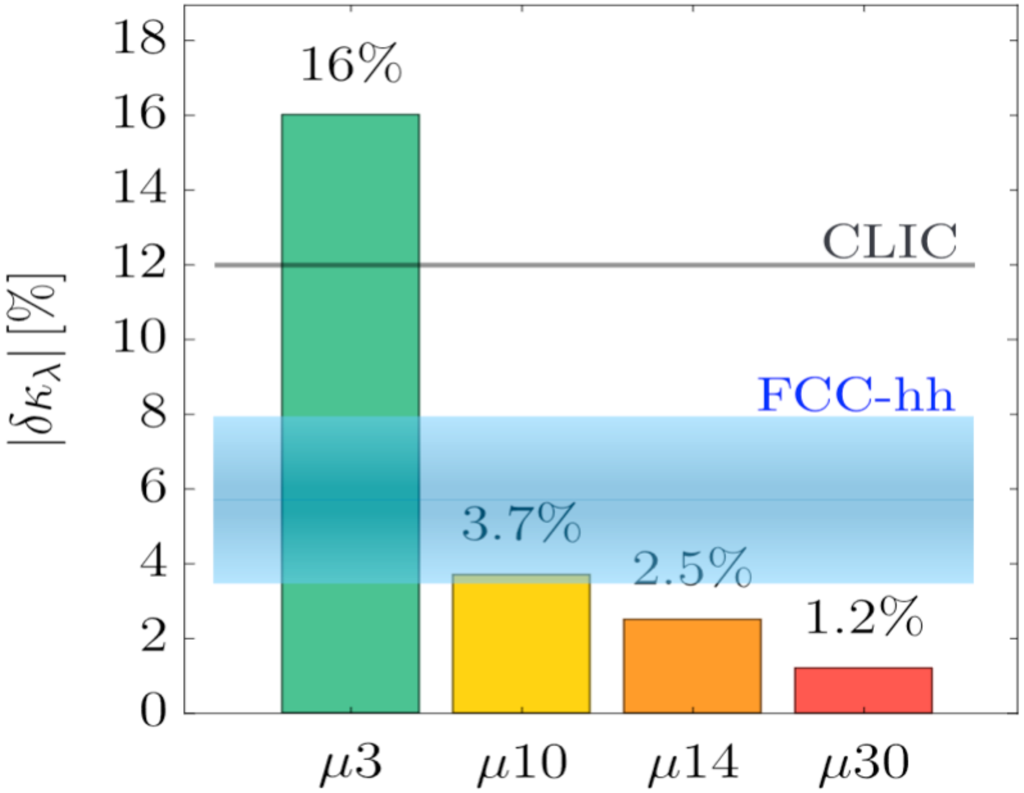
Discovery potential



† The low FCC-hh mass reach on Top Partners could be due to a non-optimal analysis

HL-LHC and FCC-hh exclusion mass reach for several beyond the Standard Model particles

Precision measurements



Sensitivity to the Higgs trilinear coupling modifier $\delta\kappa_\lambda$

Methodology

Long-term perspective

Plans towards the 10 or higher TeV center of mass facility:

- development of a muon cooling demonstrator within the next decade
  - ✓ planned stages: starting with a target and a few cooling cells towards constructing a full-power cooling system
  - ✓ Operate and verify feasibility
- decision for the full collider facility:
  - ✓ the accelerator and collider rings can be designed to operate at different initial center-of-mass energies or luminosities

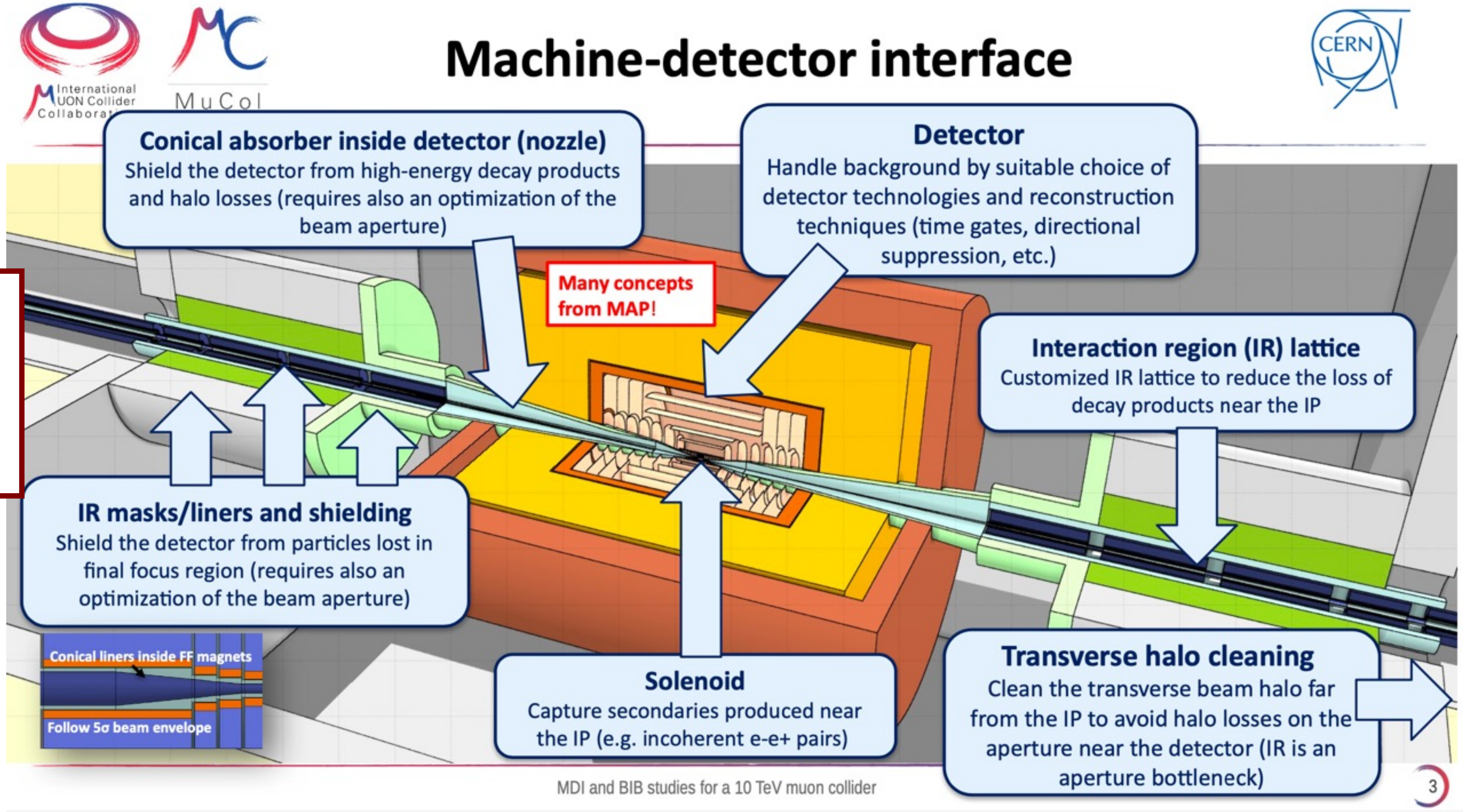
The constraint & the challenge to design and operate an experiment

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



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)

MDI and BIB studies for a 10 TeV muon collider

3

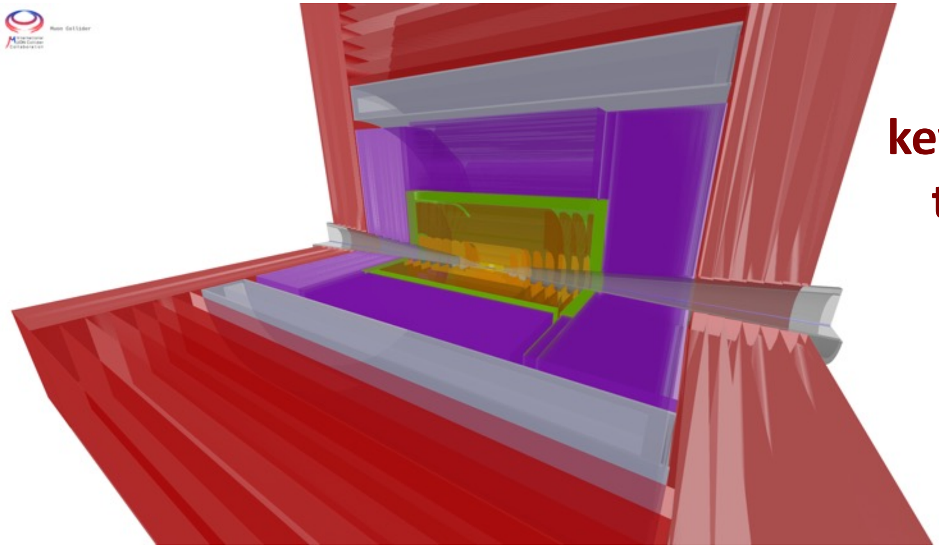
[Workshop](#) @ CERN 11 – 12 March 2024
[Workshop](#) @ CERN 25 – 26 June 2024

Detector concepts for 10 TeV collisions

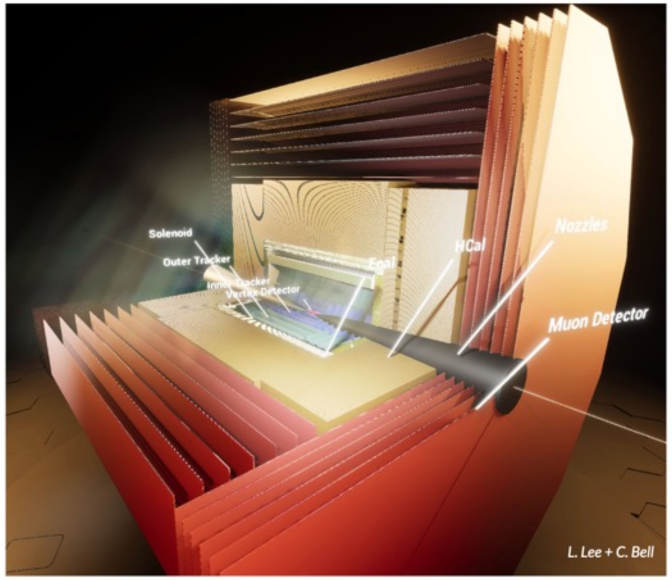
under development two different layouts

MUSIC
(MUon System for Interesting Collisions)

MAIA
(Muon Accelerator Instrumented Aperatus)



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



Ongoing work to update to latest collider lattice for ESPPU

- BIB expected to have a harder energy spectrum: final performance comparable (larger stress on computing)
- Over the next several years, migrate reconstruction algorithms to fully exploit LHC know-how.:
  - Local pile-up subtraction → BIB subtraction
  - Multivariate/AI approaches to flavour tagging (for which we demonstrated only basic inputs)

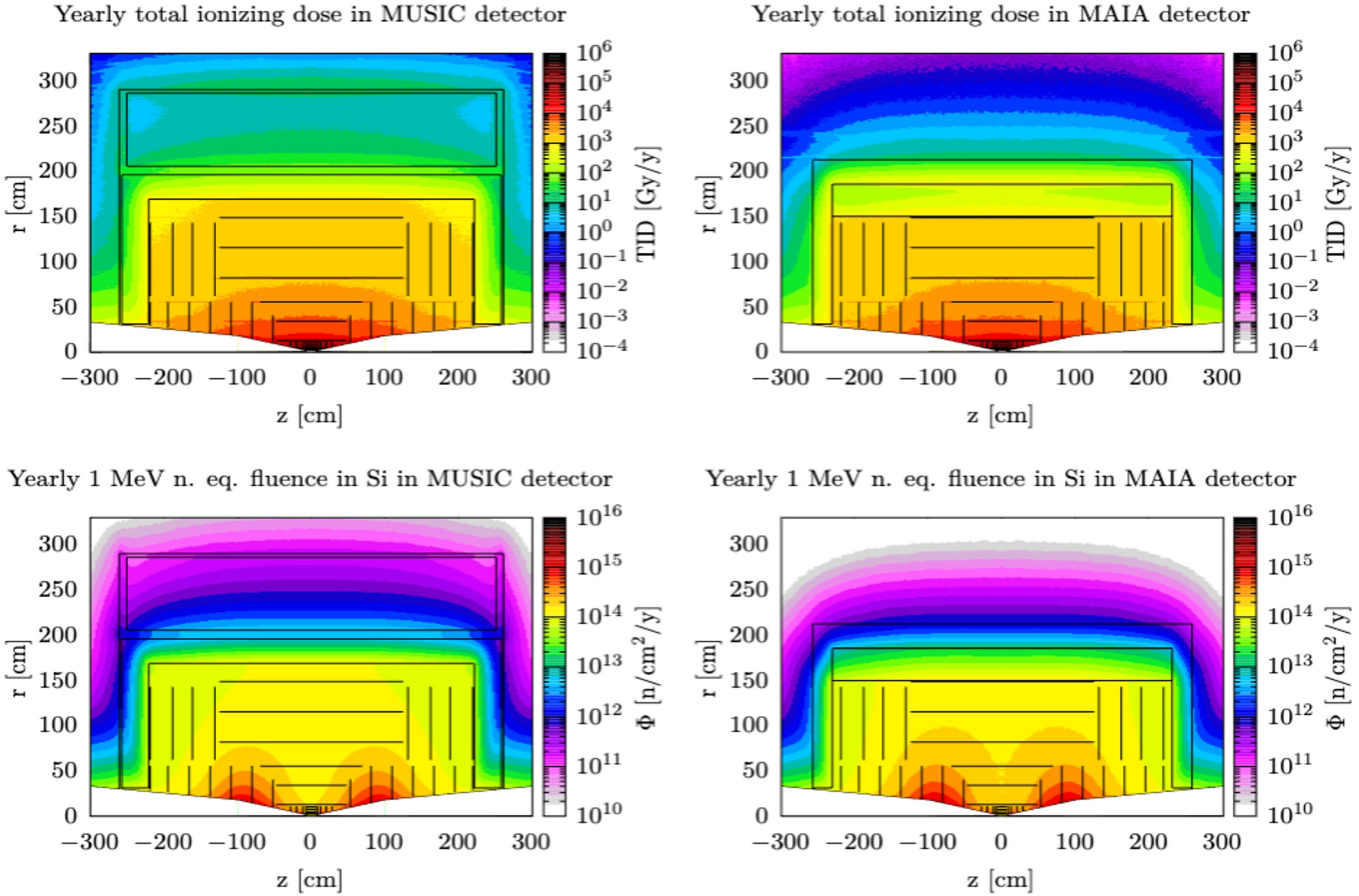
Unique background conditions

	Description	Relevance as background
Muon decay	**Decay of stored muons around the collider ring**	**Dominating source**
Synchrotron radiation by stored muons	Synchrotron radiation emission by the beams in magnets near the IP (including IR quads → large transverse beam tails)	**Small**
Muon beam losses on the aperture	Halo losses on the machine aperture, can have multiple sources, e.g.: • Beam instabilities • Machine imperfections (e.g. magnet misalignment) • Elastic (Bhabha) μμ scattering • Beam-gas scattering (Coulomb scattering or Bremsstrahlung emission) • Beamstrahlung (deflection of muon in field of opposite bunch)	**Can be significant** (although some of the listed source terms are expected to yield a small contribution like elastic μμ scattering, beam-gas, Beamstrahlung)
Coherent e^-e^+ pair production	Pair creation by real* or virtual photons of the field of the counter-rotating bunch	**Expected to be small** (but should nevertheless be quantified)
Incoherent e^-e^+ pair production	Pair creation through the collision of two real* or virtual photons emitted by muons of counter-rotating bunches	**Significant**

Status: radiation environment

BIB sets the requirements for radiation hardness of detector technologies.

Expected in line with HL-LHC



Yearly total ionizing dose in MUSIC detector

Yearly total ionizing dose in MAIA detector

Yearly 1 MeV n. eq. fluence in Si in MUSIC detector

Yearly 1 MeV n. eq. fluence in Si in MAIA detector

Experiment design requirements @ 10 TeV

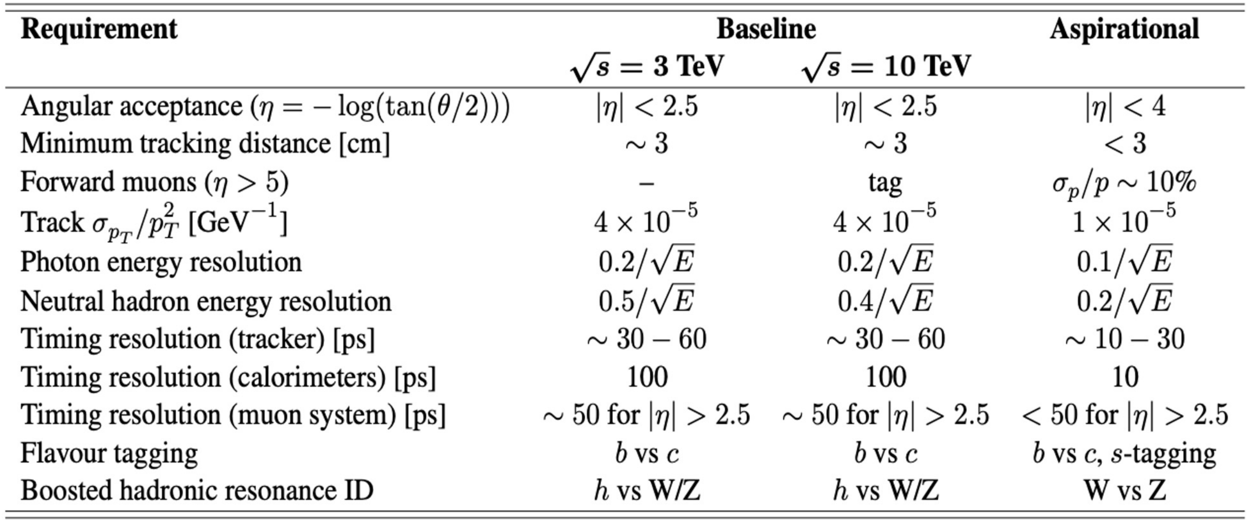
Aim at **10+ TeV** and potential initial stage at **3 TeV**

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



Requirement	**Baseline** $\sqrt{s} = 3$ **TeV**	**Baseline** $\sqrt{s} = 10$ **TeV**	**Aspirational**
Angular acceptance ($\eta = -\log(\tan(\theta/2))$)	$\|\eta\| < 2.5$	$\|\eta\| < 2.5$	$\|\eta\| < 4$
Minimum tracking distance [cm]	~ 3	~ 3	< 3
Forward muons ($\eta > 5$)	–	tag	$\sigma_p/p \sim 10\%$
Track σ_{p_T}/p_T^2 [GeV^{-1}]	4×10^{-5}	4×10^{-5}	1×10^{-5}
Photon energy resolution	$0.2/\sqrt{E}$	$0.2/\sqrt{E}$	$0.1/\sqrt{E}$
Neutral hadron energy resolution	$0.5/\sqrt{E}$	$0.4/\sqrt{E}$	$0.2/\sqrt{E}$
Timing resolution (tracker) [ps]	$\sim 30 - 60$	$\sim 30 - 60$	$\sim 10 - 30$
Timing resolution (calorimeters) [ps]	100	100	10
Timing resolution (muon system) [ps]	~ 50 for $\|\eta\| > 2.5$	~ 50 for $\|\eta\| > 2.5$	< 50 for $\|\eta\| > 2.5$
Flavour tagging	b vs c	b vs c	b vs c, s-tagging
Boosted hadronic resonance ID	h vs W/Z	h vs W/Z	W vs Z

Detector technology R&D and design

- 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

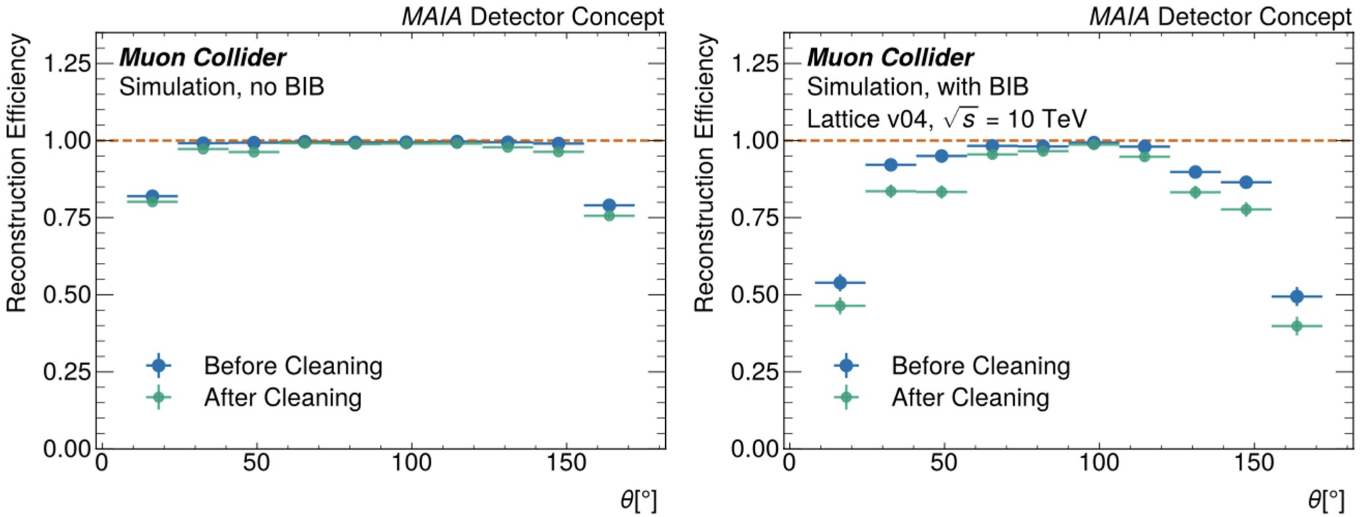
Tracking studies

BIB and incoherent pairs affect reconstruction performance via hit multiplicity.

Tracking performance well under control (using LHC CKF reconstruction)

The main bottleneck in algorithmic execution time

- The O(5%) inefficiencies present in the current reconstruction are caused by the need of keeping the CPU time within O(minutes) per event.
  Track parameter resolutions (pT, d0, z0) are unaffected by BIB.
- Expected to improve with future computing hardware and seeding strategies



(a) No BIB

(b) BIB

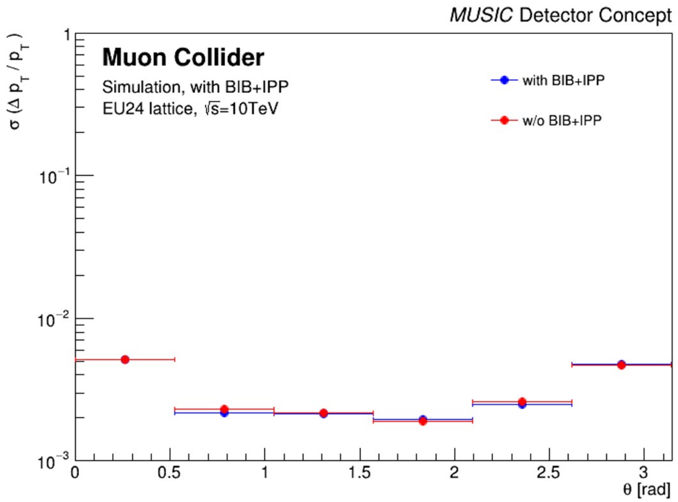
Tracking studies: MUSIC efficiency/performance

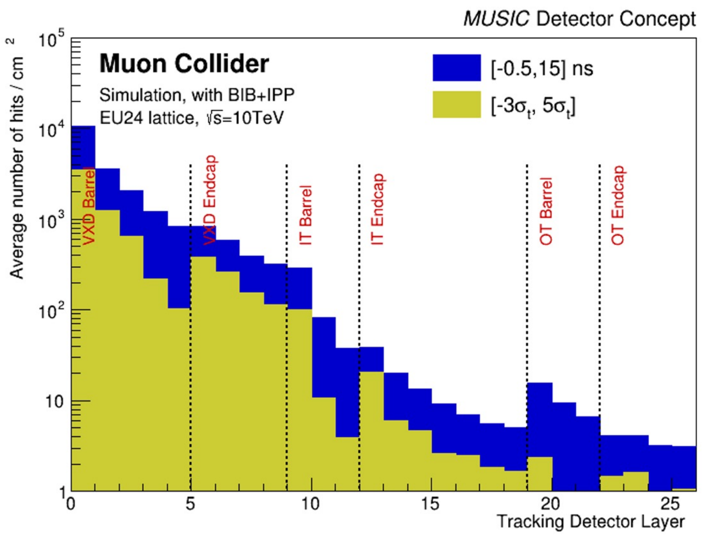
Tracking system optimized for a better coverage up to the nozzle angle.

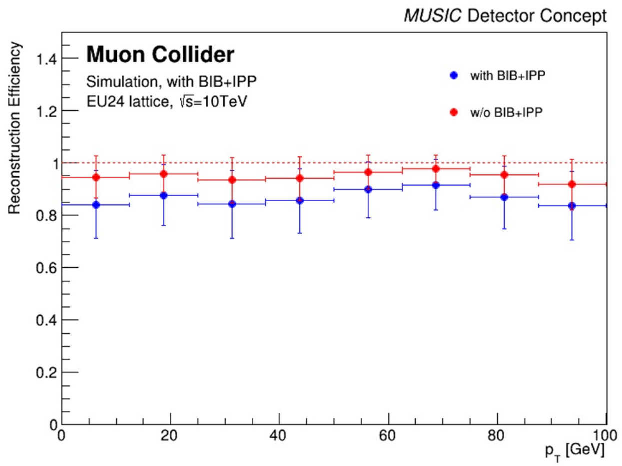
Performance evaluated with **BIB** and **incoherent pair production (IPP) events** produced with Interaction Region version EU24 frozen for ESPPU

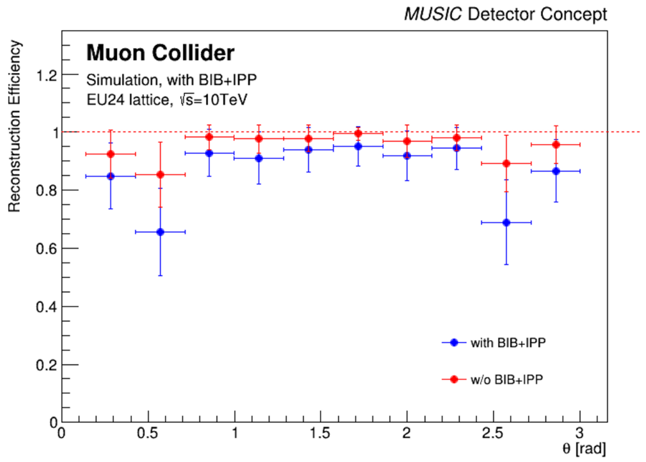
Despite the high occupancy, track reconstruction optimized (not fully) to reach high performance.

The resolution on track parameters are not impacted by the BIB presence







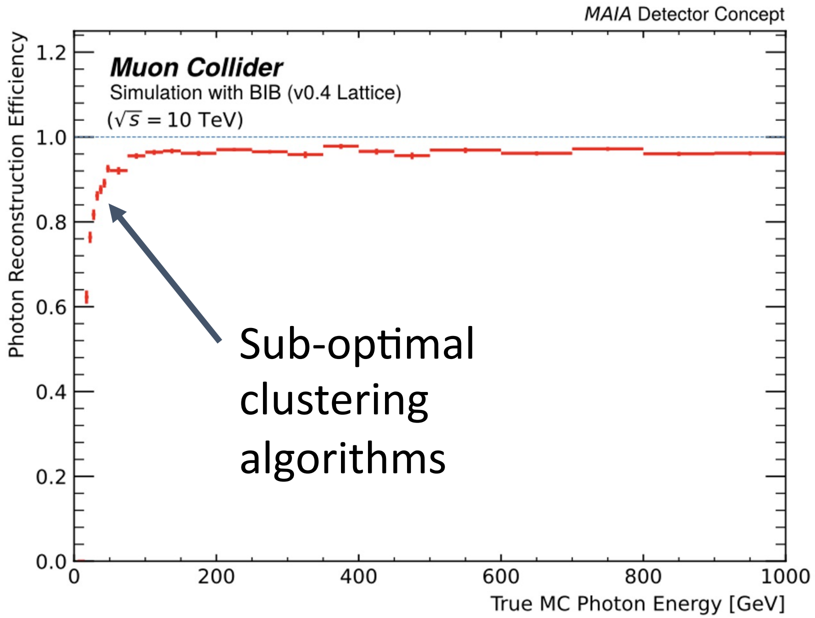


Calorimeter studies

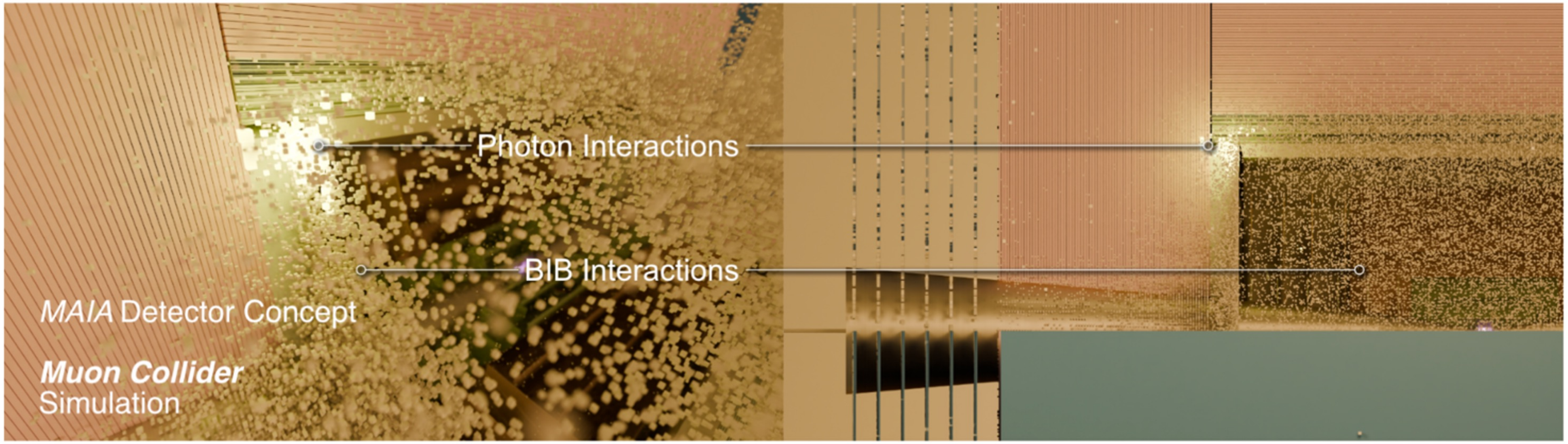
BIB impact on calorimetry more different across 10 TeV detector concepts

- Solenoid placement
- Technological choices - semi-homogeneous (MUSIC) vs sampling (MAIA)

Performance close to minimal targets, limited by reconstruction algorithms (most notably clustering and background subtraction)



Sub-optimal clustering algorithms

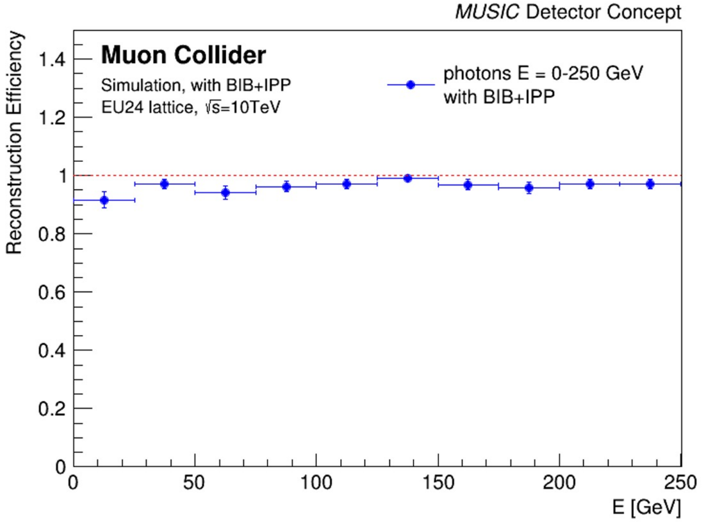


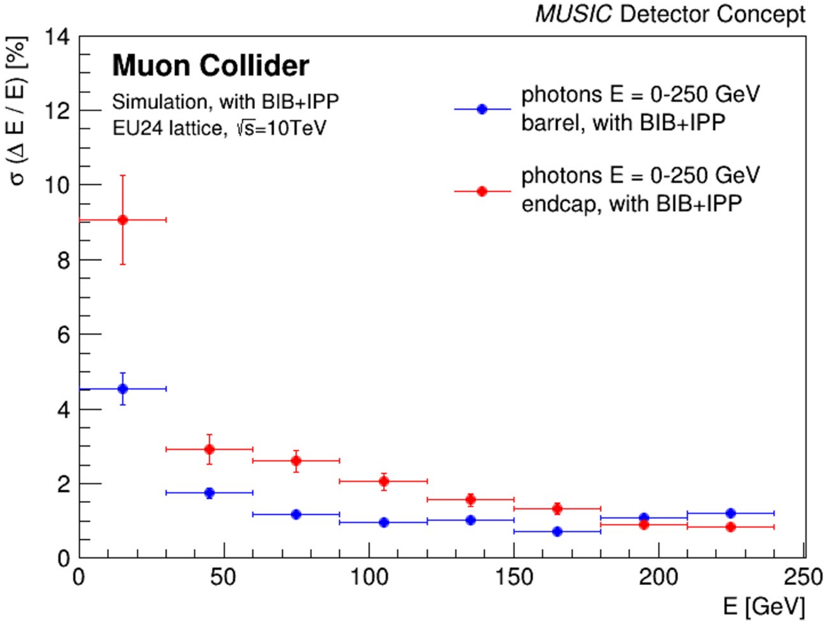
Calorimeter studies: MUSIC with CRILIN

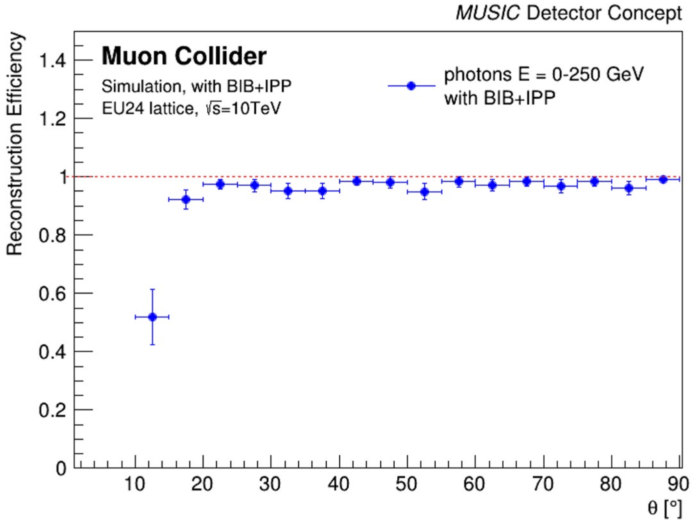
MUSIC calorimeter system:

- ECAL: CRILIN, *CRystal calorImeter with Longitudinal INformation* designed for MuC
- HCAL: Iron-scintillator sampling calorimeter common to other detectors

So far reconstructed: photons and electrons, jets in progress.



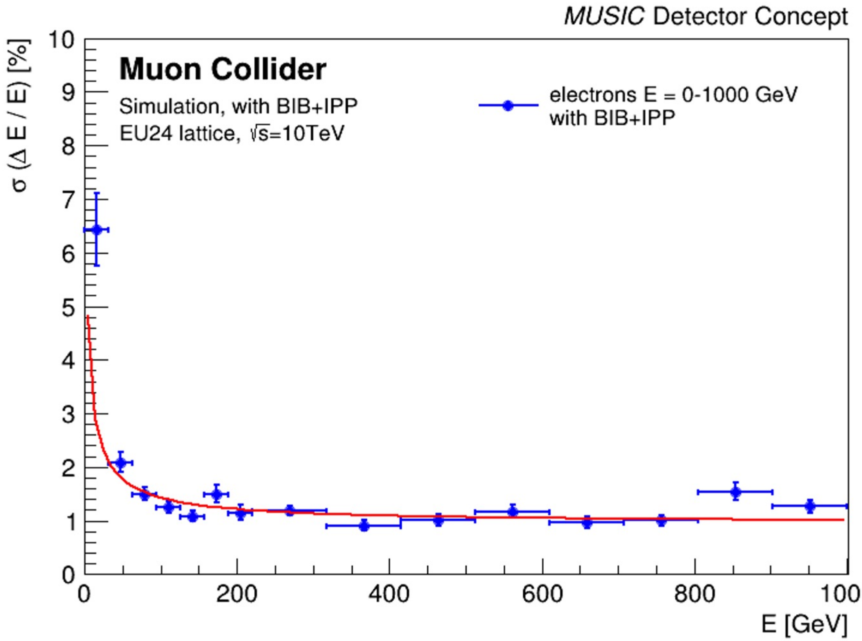


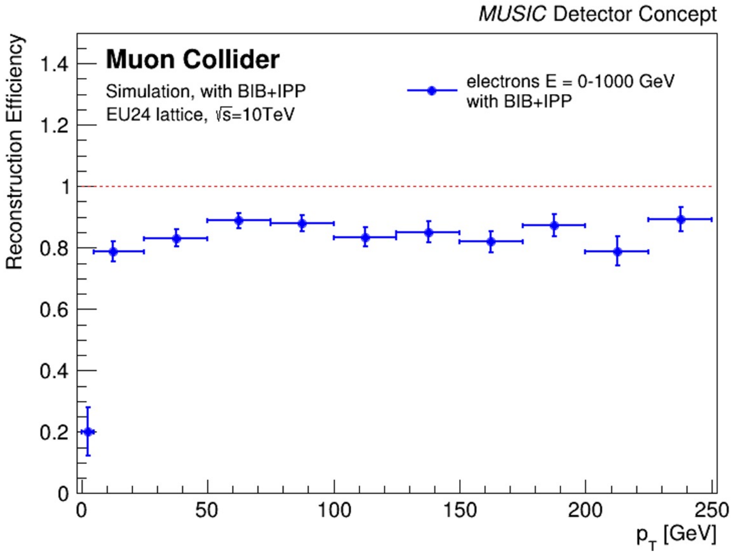


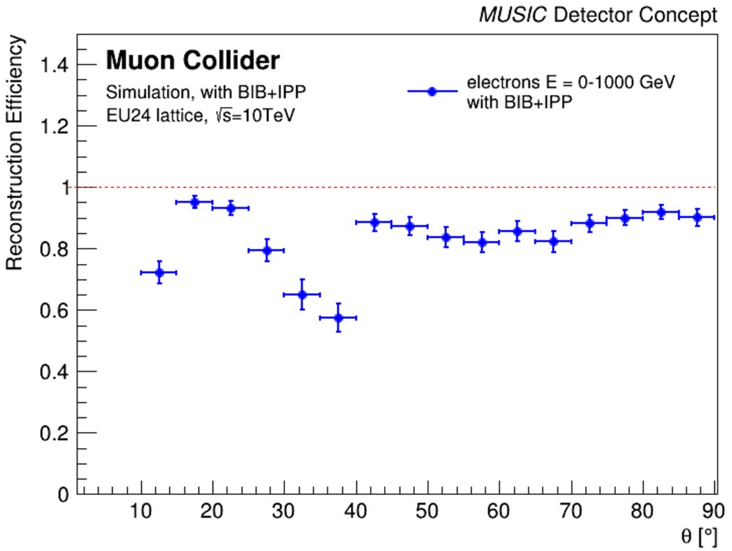
Calorimeter studies: MUSIC with CRILIN

The electron are reconstructed for the first time in muon collisions at 10 TeV CoM

Tracks reconstructed with ACTS are matched to a ECAL cluster by using PandoraPFA. The results show that even if not optimized (there is no Bremsstrahlung recovery yet) the MUSIC detector performs very well also for electrons







Forward muons

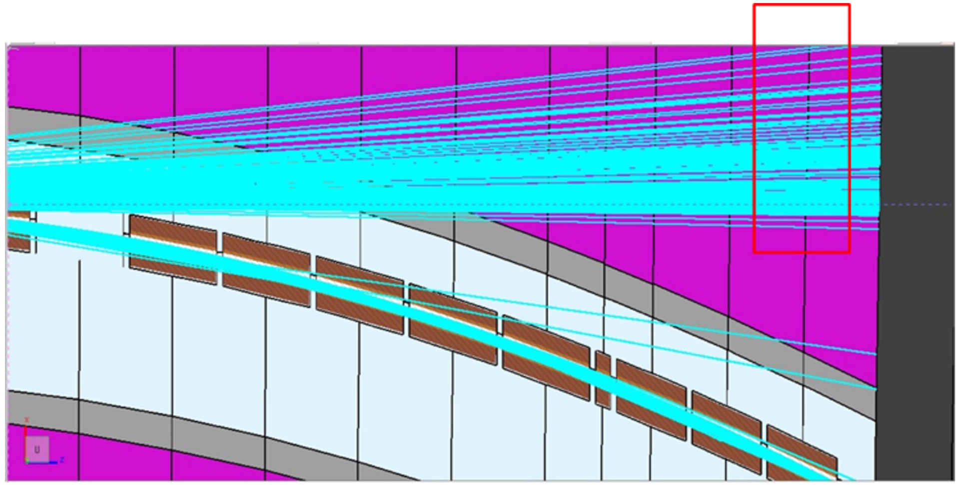
Muon systems are almost free from BIB contributions

- Performance at 10 TeV not yet studied in detail, as it is not expected to be a challenging task

Both concepts don't foresee a dedicated muon spectrometer but rather rely on inner detector tracks with a PID match from a barebones muon system placed beyond the HCAL

- Choice motivated by track resolution being dominated by inner tracker measurement across pT spectrum

Forward (~10 deg) and very forward (5 deg) regions require dedicated studies and development of detector concepts for which only initial studies have been performed.



Readiness and expected challenges

International
MUON Collider
Collaboration

Time-critical Developments

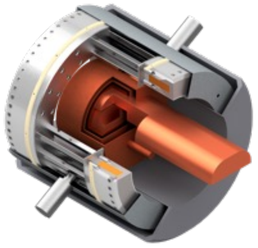
Identified three main technologies that can limit the timeline

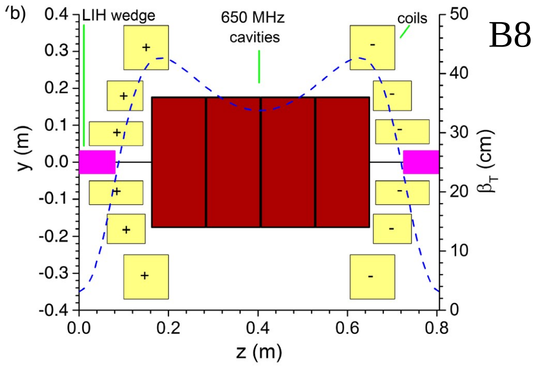
Muon cooling technology

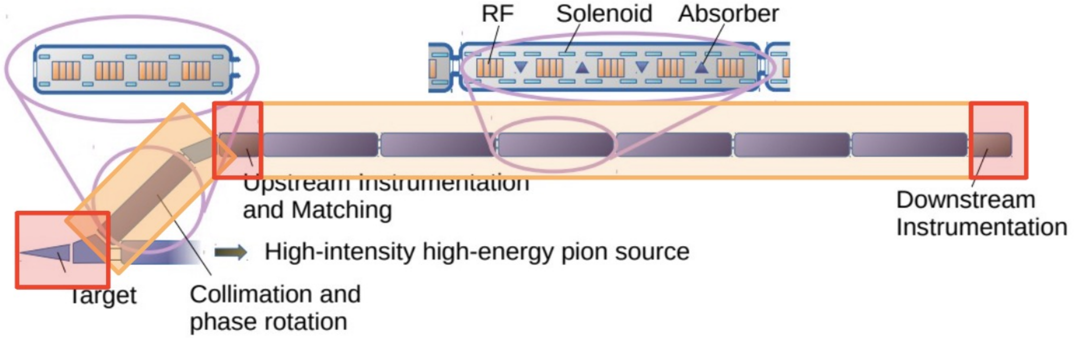
- **RF test stand** to test cavities in magnetic field
- **Muon cooling cell** test infrastructure
- **Demonstrator**
  - Muon beam production and cooling in several cells

Magnet technology

- HTS solenoids
- Collider ring magnets with Nb3Sn or HTS





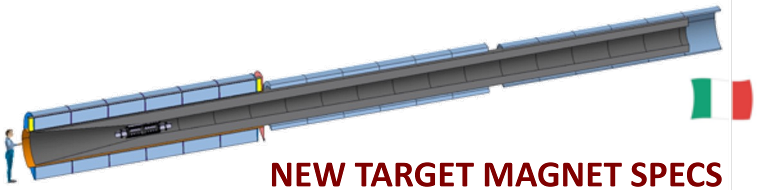


Important Developments

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

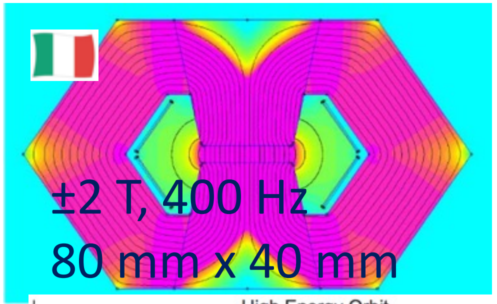
Magnet Demands @ Muon Collider



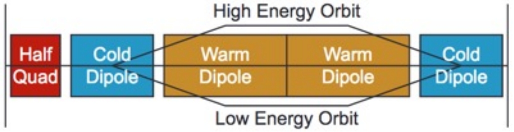
NEW TARGET MAGNET SPECS

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

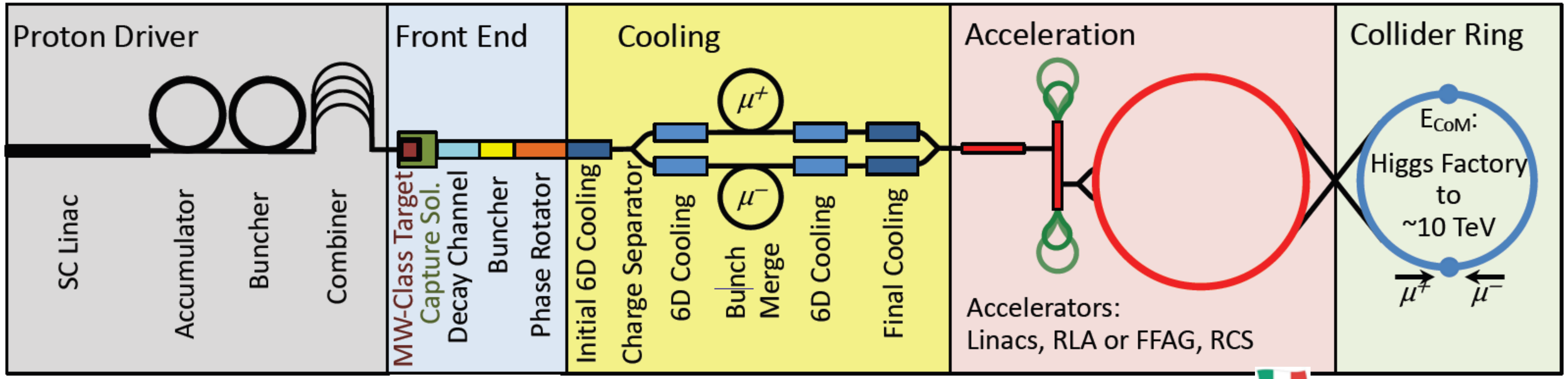
High-field and large aperture target solenoid with heavy shielding to withstand heat (100 kW/m) and radiation loads



±2 T, 400 Hz
80 mm x 40 mm



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



Proton Driver
SC Linac
Accumulator
Buncher
Combiner

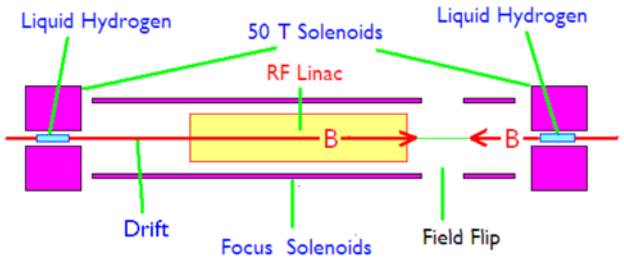
Front End
MW-Class Target
Capture Sol.
Decay Channel
Buncher
Phase Rotator

Cooling
Initial 6D Cooling
Charge Separator
6D Cooling
Bunch Merge
6D Cooling
Final Cooling
μ^+
μ^-

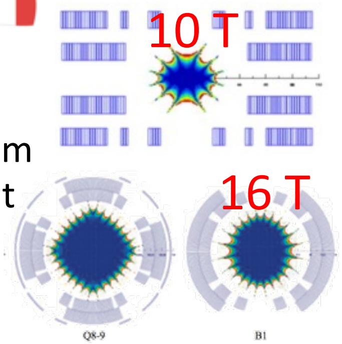
Acceleration
Accelerators:
Linacs, RLA or FFAG, RCS

Collider Ring
E_{CoM}:
Higgs Factory
to
~10 TeV
μ^+ μ^-

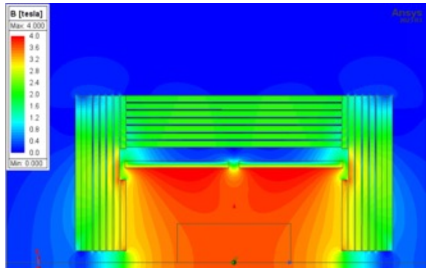
Ultra-high-field solenoids (40…60 T) to achieve desired muon beam cooling



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

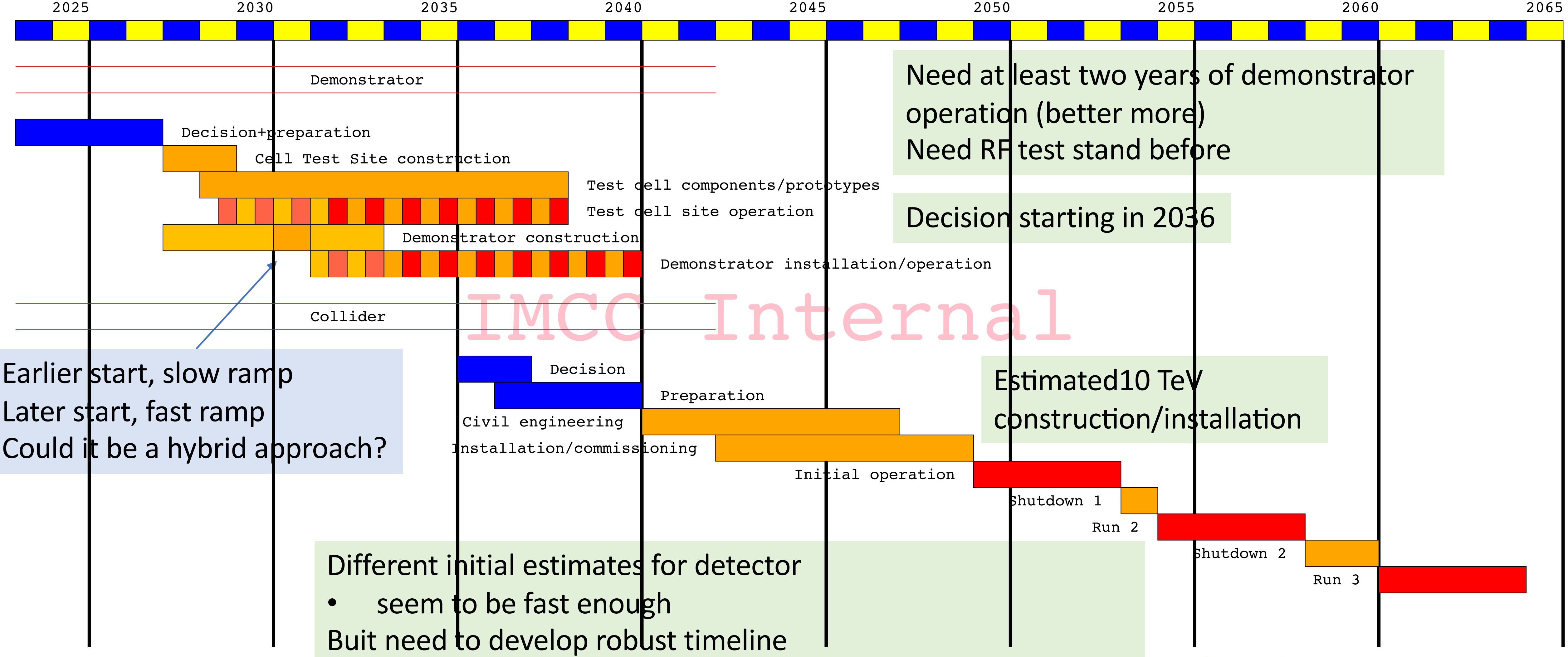


Detector Magnet
to be designed for 10TeV



Tentative Timeline (Fast-track 10 TeV)

Only a basis to start the discussion, will be reviewed by March 2025



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

Decision starting in 2036

Earlier start, slow ramp
Later start, fast ramp
Could it be a hybrid approach?

Estimated10 TeV construction/installation

Different initial estimates for detector
- seem to be fast enough

Buit need to develop robust timeline

Timing

Construction and operational costs (if applicable)

Financial and human resources: requirements and effect on other projects

In preparation for LDG and ESPPU

Careers and training

Muon Collider facility requires extensive studies and R&D across multiple key areas:

- target for muon production
- cooling of muon beams
- advanced magnets and radio-frequency systems for the accelerator and collider ring
- shielding structures for the detector.

A completely new and challenging field of research
renewing the interest of students and young researchers
in accelerator physics and experimental physics at particle accelerators

Opportunity to develop cutting-edge instruments while gaining hands-on training

Unique chance to contribute to the design, testing, and integration of a novel accelerator

Sustainability

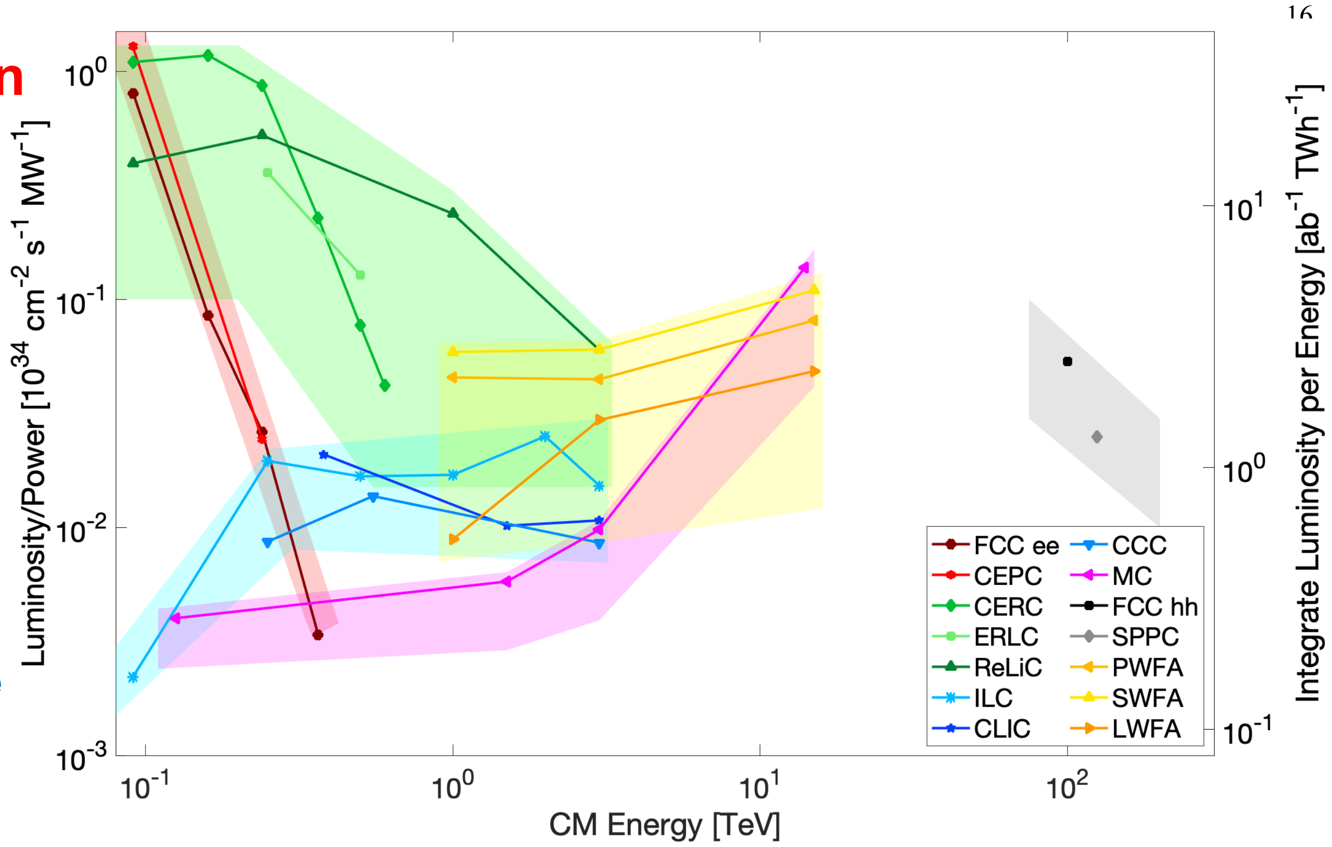
- a multi-TeV muon collider has the smallest footprint compared to other alternatives
- the luminosity-to-electricity consumption ratio improves as the center-of-mass energy increases, making the muon collider significantly more energy-efficient than alternatives.

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

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

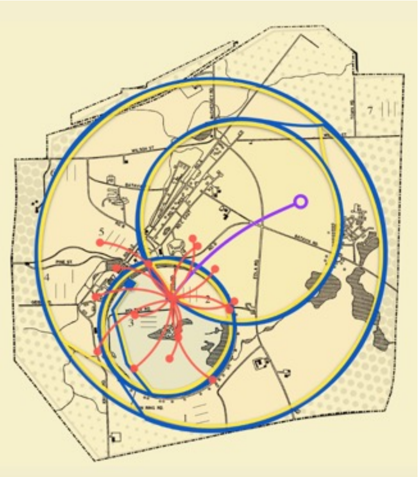
$15
29 MARCH 2024
science.org

AAAS

A radical new particle accelerator concept emerges. Call it physicists'

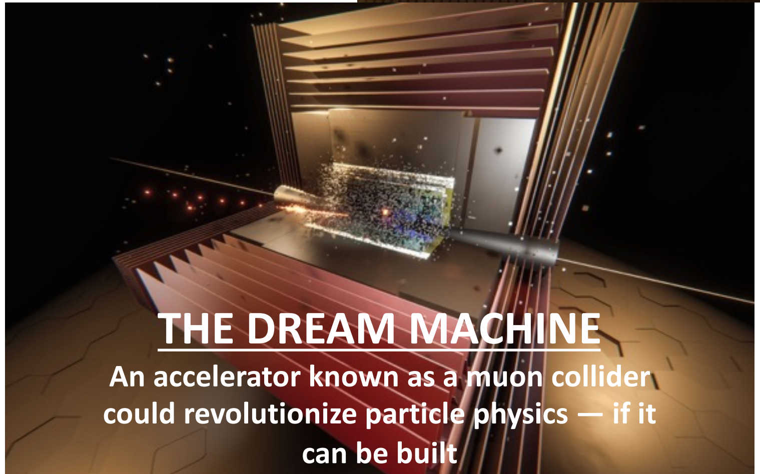
MUON SHOT

p. 1405



INAUGURAL US MUON COLLIDER COMMUNITY MEETING

FNAL – August 9, 2024



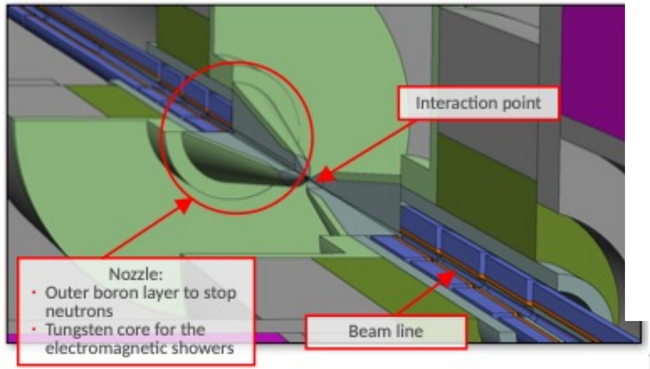
THE DREAM MACHINE

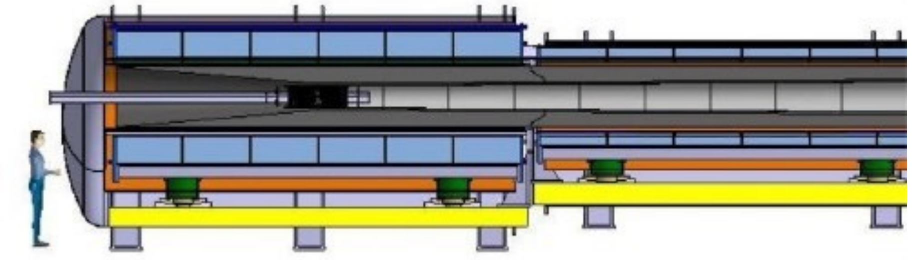
An accelerator known as a muon collider could revolutionize particle physics — if it can be built

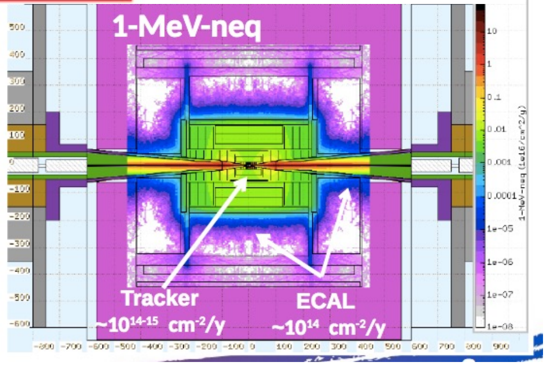
Summary of activities towards R&D plans

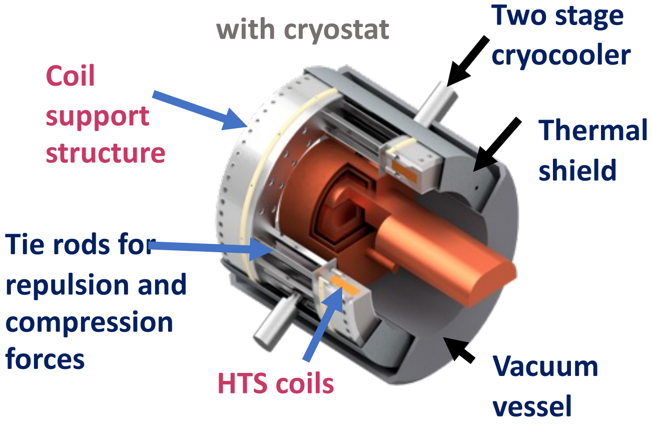
Each WP is working to identify challenges and R&D plans towards a baseline design:

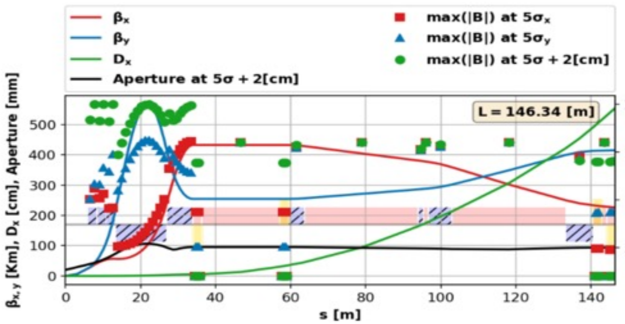
- Physics and MDI
- Proton complex
- Target design
- Muon Cooling
- Accelerator Complex
- Collider Ring
- RF Technology
- Magnet Technology
- Cooling cell integration
- Demonstrator

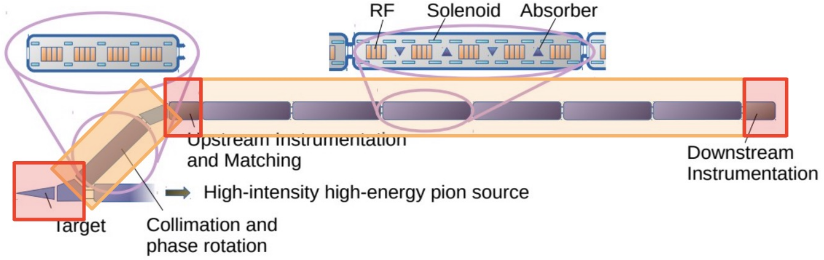


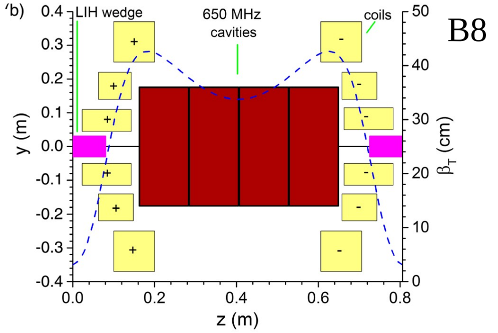












Towards a multi-TeV Muon Collider

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

Advances in accelerator and detector pair with the opportunities of the physics case
➔ Time scale is conceived for a multi-TeV collider facility to be ready by 2050

- 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**

- **Donatella Lucchesi** and Federico Meloni (DESY) are the IMCC contact for the Preparatory Group

Please partecipate to:

Workshop on FCC-ee and Lepton Colliders @ LNF - January 22-24, 2025

Muon4Future @ Venezia - May 26-30, 2025

International
MUON Collider
Collaboration

Thanks to all the young and senior collabotators

Thanks for the attention!

Unique physics case – more studies planned

International
MUON Collider
Collaboration

Direct searches

Pair production,
Resonances, VBF,
Dark Matter, …

High-rate measurements

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

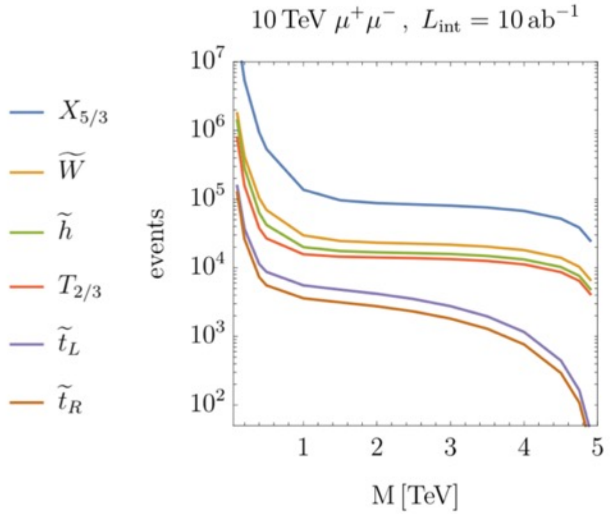
High-energy probes

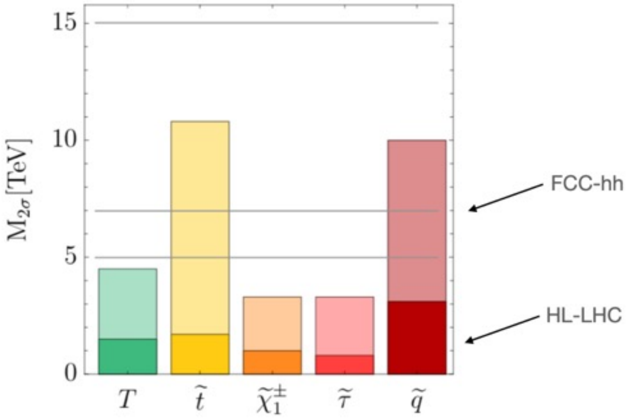
Di-boson, di-fermion,
tri-boson, EFT,
compositeness, …

Muon physics

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

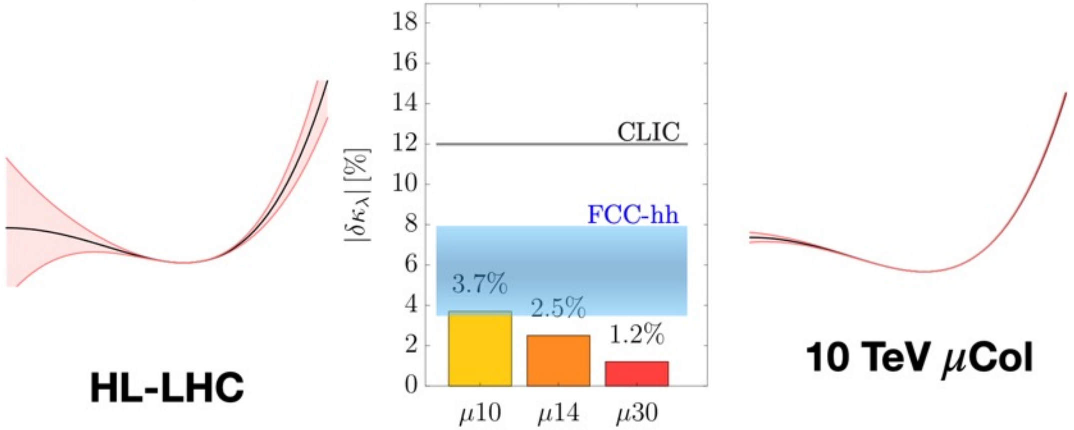
Discovery potential





Precision measurements

High energy lets us finally improve on Higgs Potential



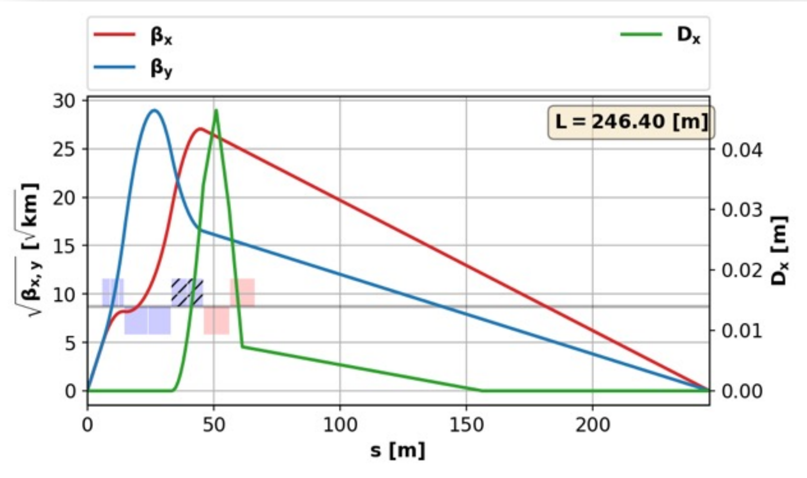
Note that we can get to threshold for EW phase transition at EW scale with FCC-hh and μCol

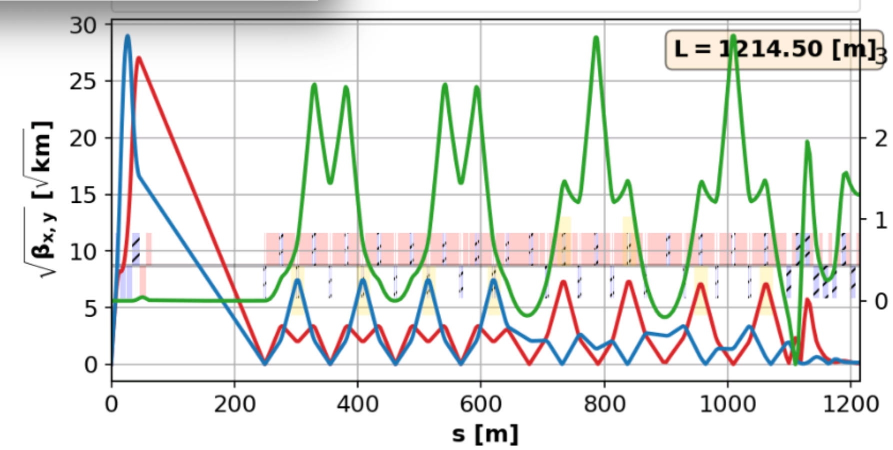
Status of IR lattice design @ 10 TeV

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):



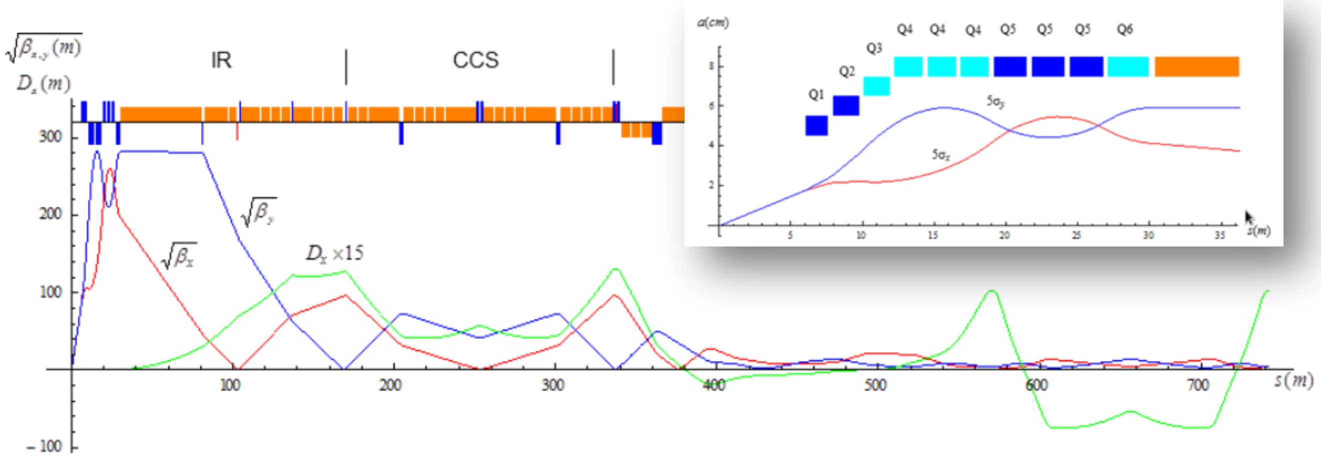


Final Focusing with L*=6m

Chromatic Correction with 4 set of dipole-sextuples

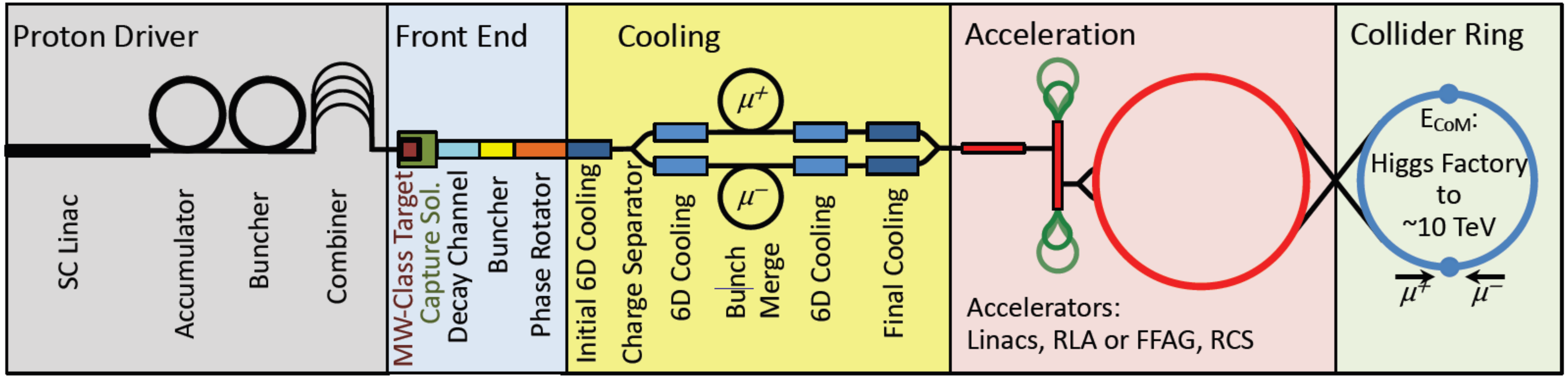
Matching CC-ARC

3 TeV IR lattice (MAP):



Proton-driven Muon Collider Concept

Fully driven by muon lifetime – lifetime is $\tau = \gamma \times 2.2\ \mu s$



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/

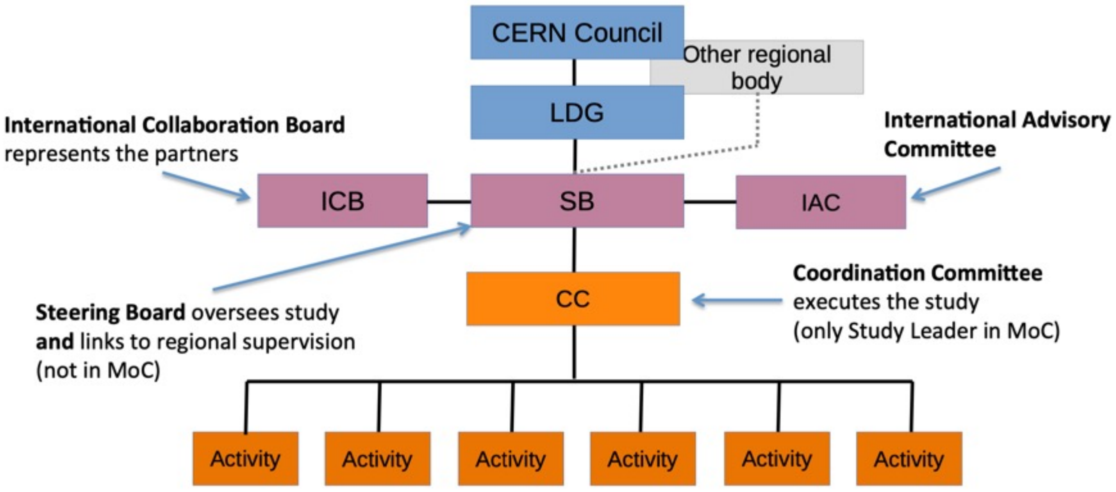
- Recommendation from 2008 Particle Physics Project Prioritization Panel (P5)
- Approved by DOE-HEP in 2011 ➔ Ramp down recommended by P5 in 2014

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

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



CERN Council

Other regional body

LDG

International Collaboration Board represents the partners

International Advisory Committee

ICB

SB

IAC

Steering Board oversees study **and** links to regional supervision (not in MoC)

CC

Coordination Committee executes the study (only Study Leader in MoC)

Activity

Activity

Activity

Activity

Activity

Activity

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

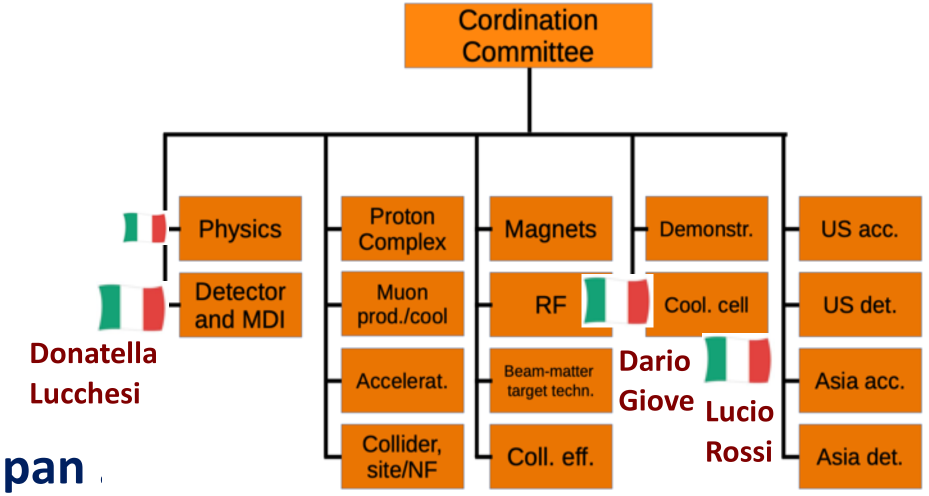
19 countries: CERN, IT, US, UK, FR, DE, CH, ES……
CHINA, KOREA, INDIA….. Interest from Japan

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



Cordination Committee

Physics

Detector and MDI

Donatella Lucchesi

Proton Complex

Muon prod./cool

Accelerat.

Collider, site/NF

Magnets

RF

Beam-matter target techn.

Coll. eff.

Dario Giove

Demonstr.

Cool. cell

Lucio Rossi

US acc.

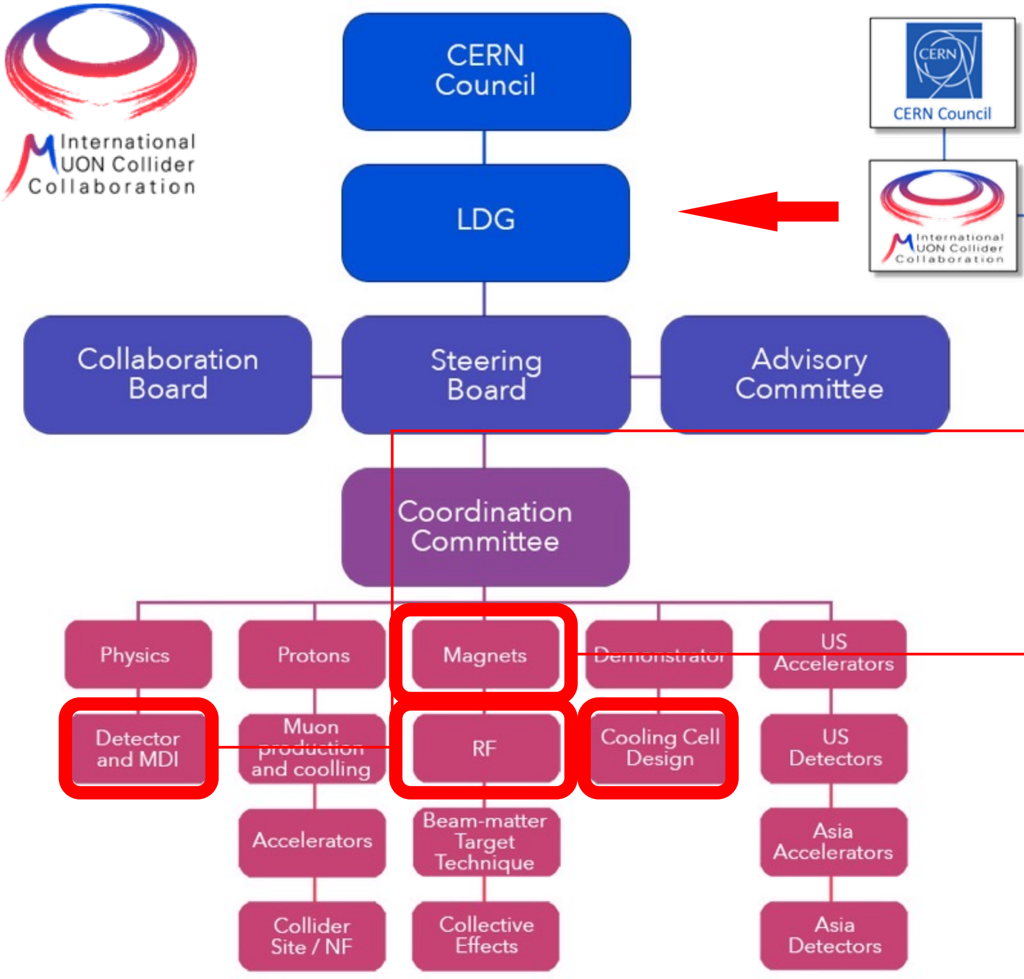
US det.

Asia acc.

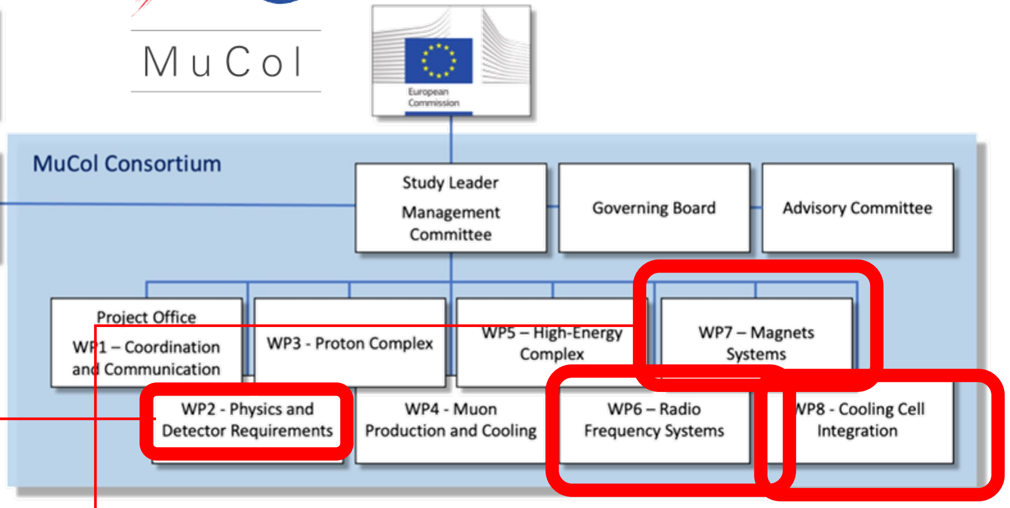
Asia det.

Project Organization

International Muon Collider Collaboration



MuCol EU Design Study



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

Preliminary study in detector magnet

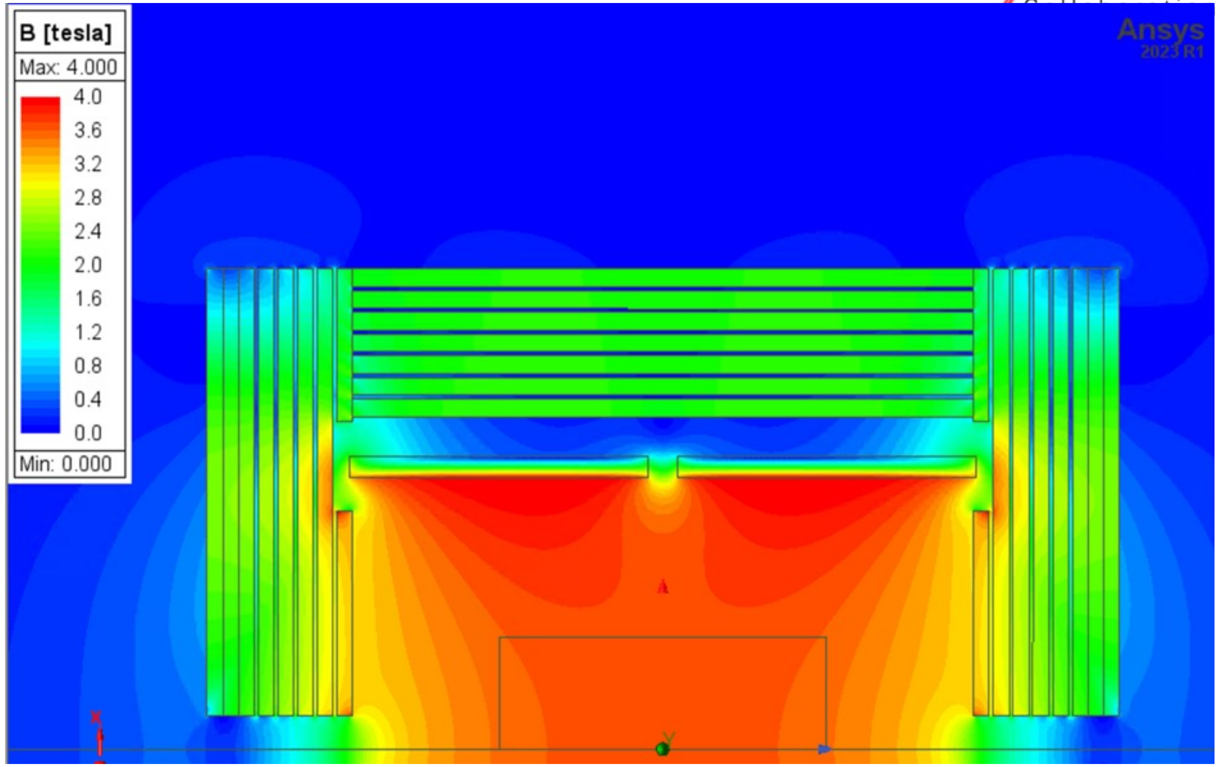
[Detector magnet workshop](#) – 5 October 2023

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

Site Studies

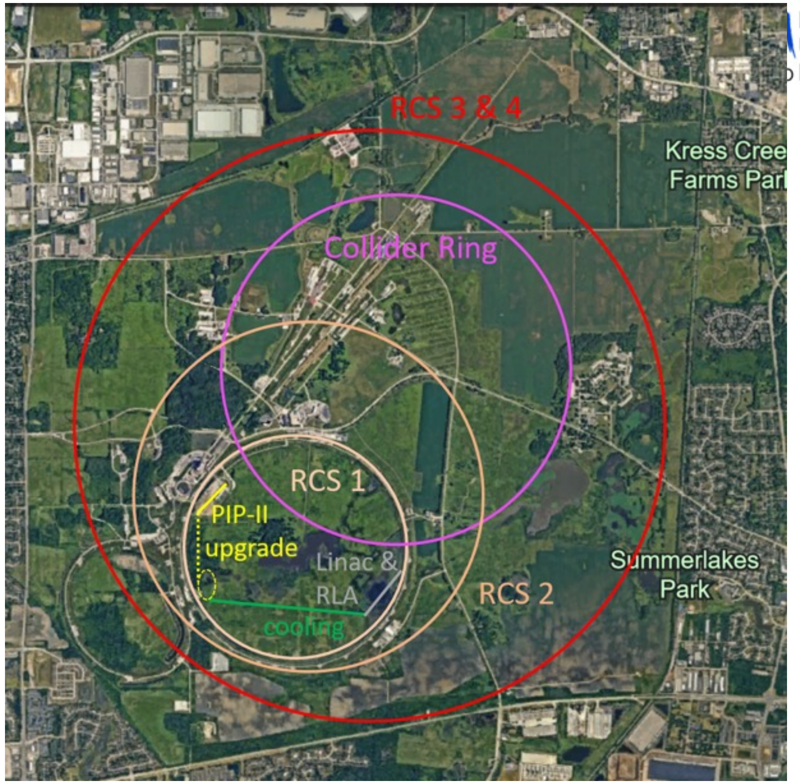
Candidate sites **CERN, FNAL,** potentially others **(**ESS, JPARC, …)

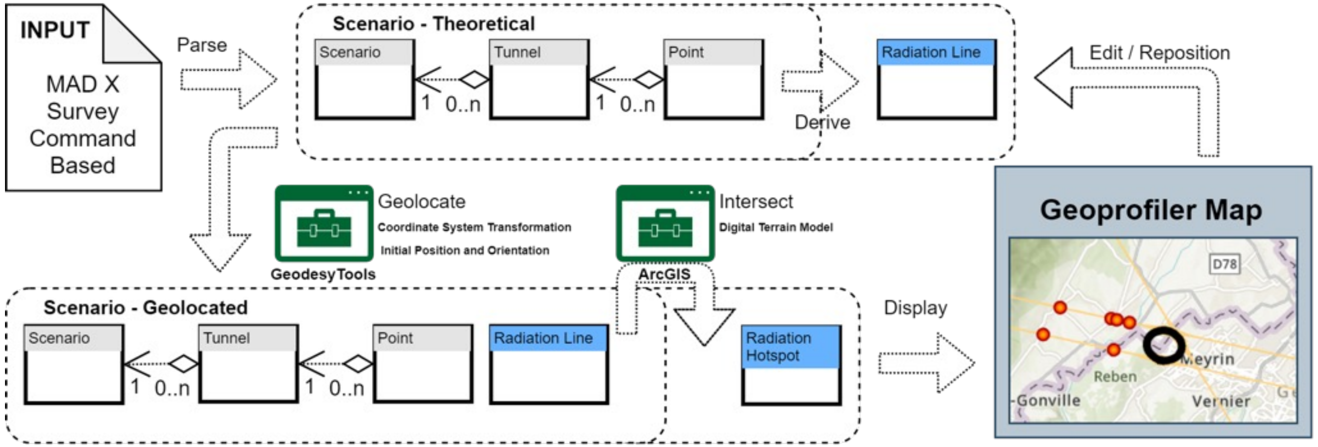
Study is mostly site independent

- 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)

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)

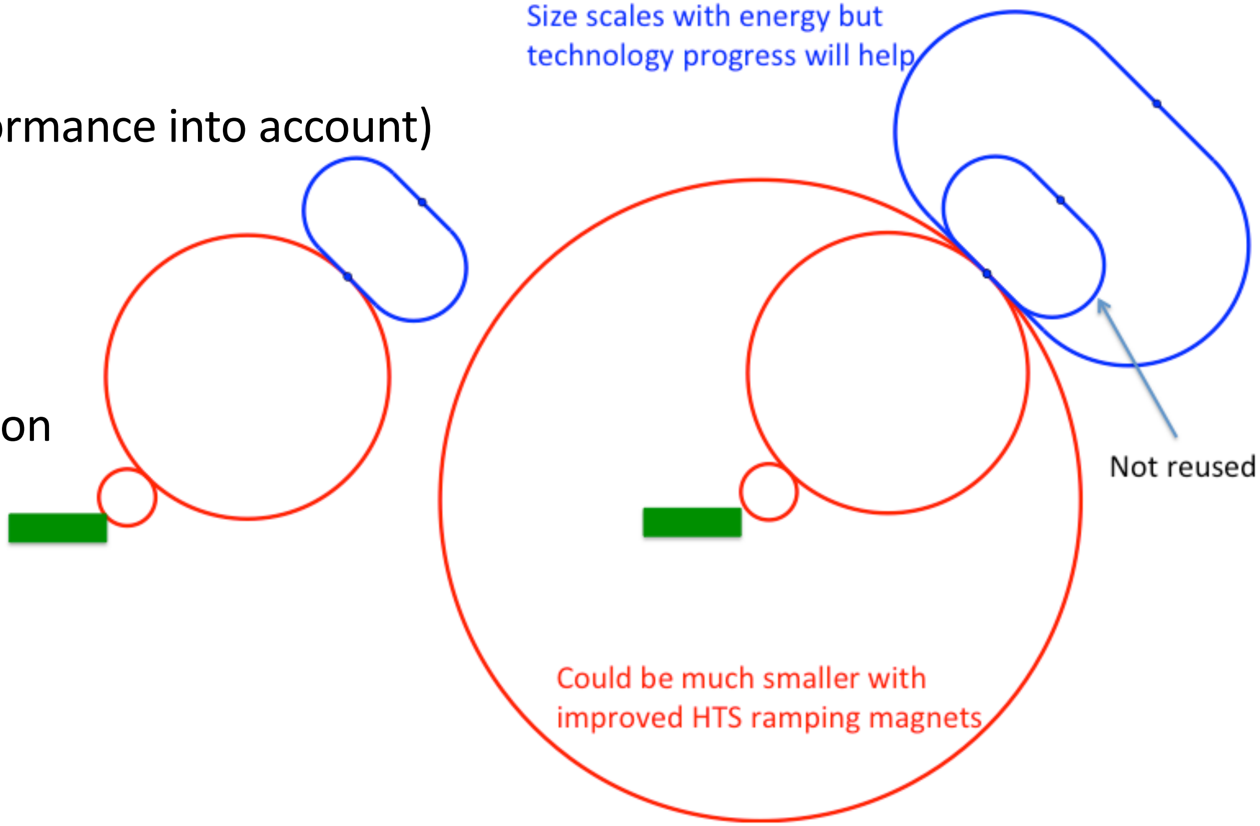
Energy staging

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

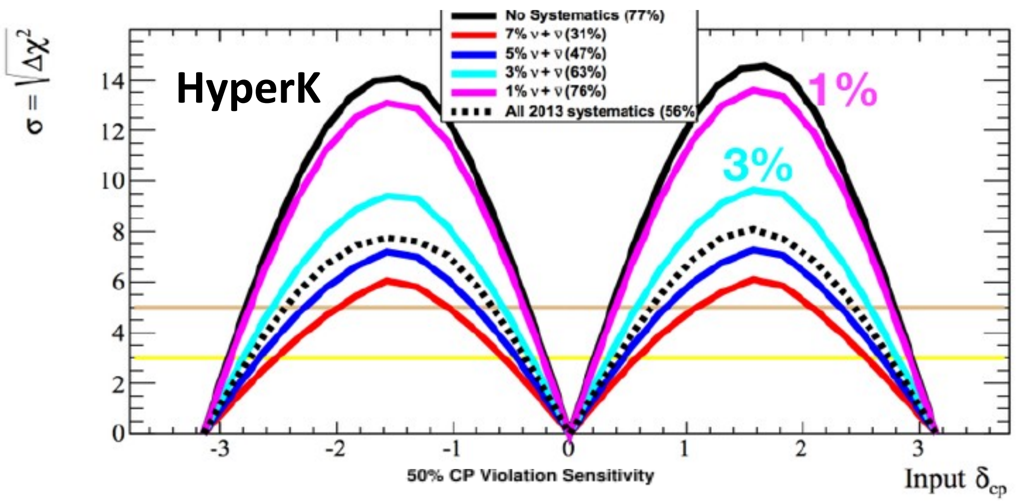
Luminosity staging

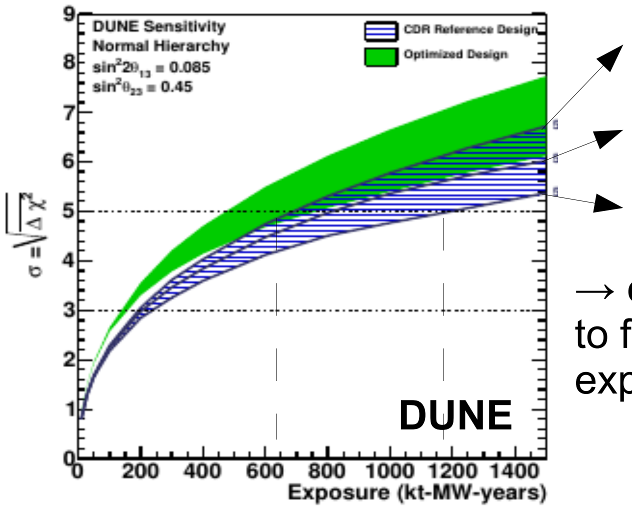
- Start at 10 TeV with the highest reachable energy, but lower luminosity
- Main luminosity loss sources are arcs and interaction region
  - Can later upgrade interaction region (as in HL-LHC)

Consider reusing **LHC tunnel** and other infrastructures



Future Neutrino Oscillation Experiments





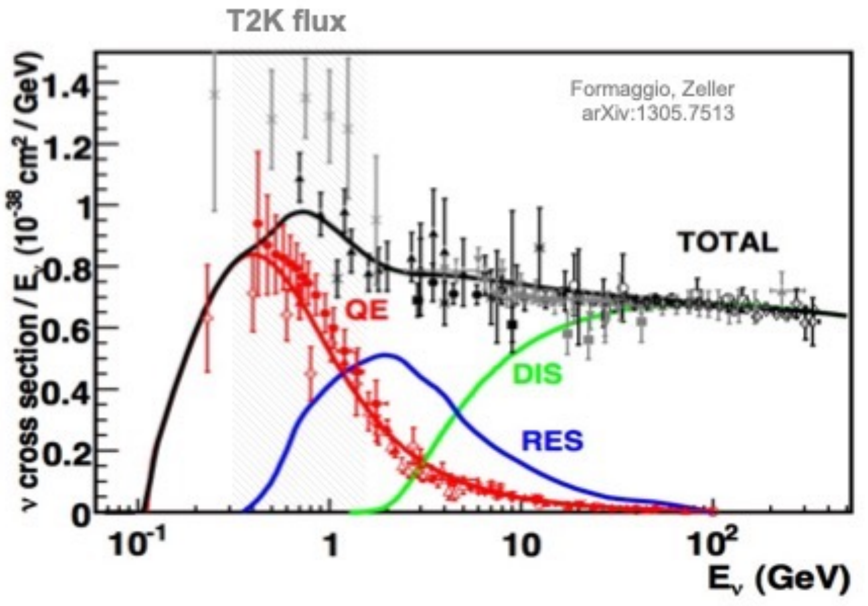
5% ± 1%

5% ± 2%

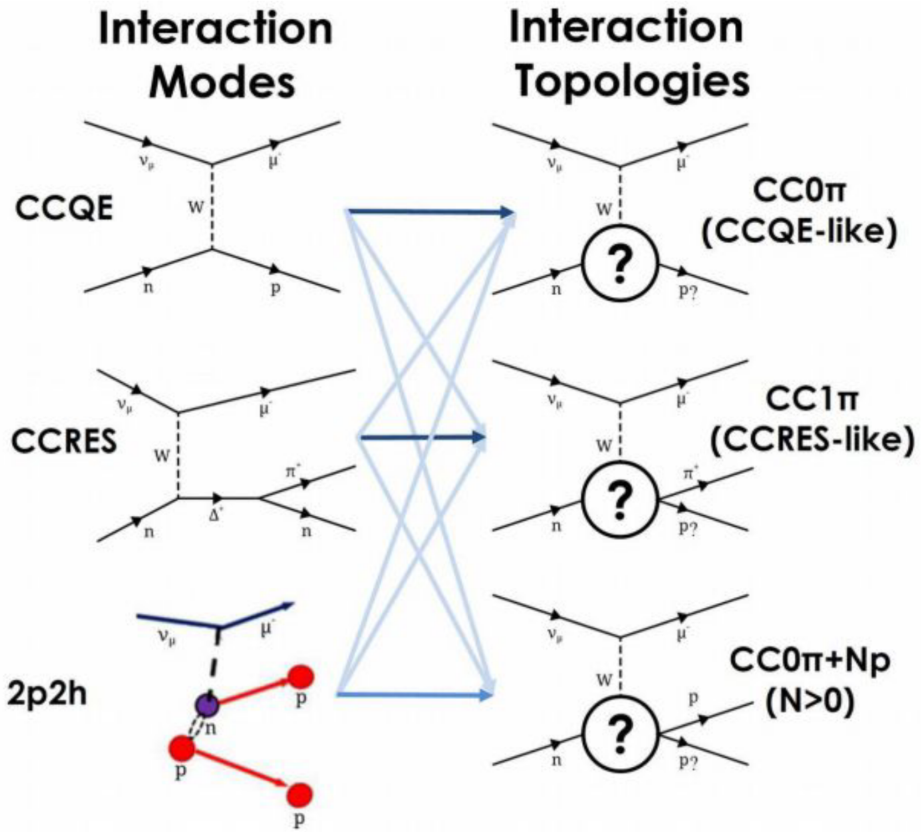
5% ± 3%

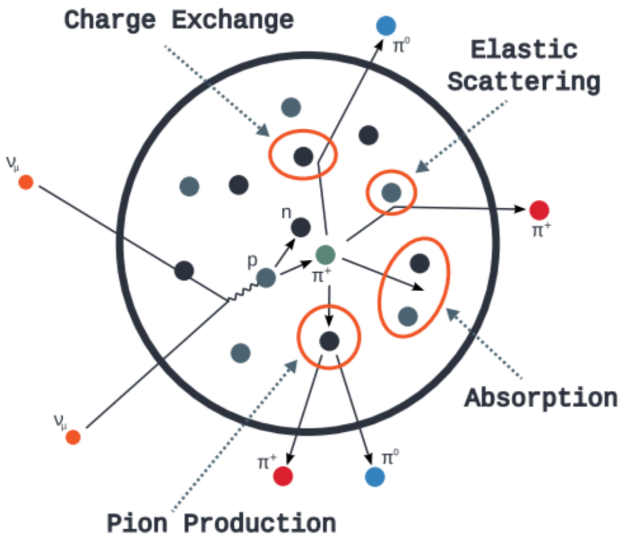
→ equivalen
to factor 2 in
exposure!

- La sensibilita' dei futuri esperimenti di oscillazione di neutrino dipende fortemente dalla capacita' di ridurre l'impatto degli errori sistematici nell'ordine del %.
- Le incertezze nelle misure delle sezioni d'urto a bassa energia (0.3-5 GeV/c) e nei modelli montecarlo incidono nell'estrapolazione dei flussi dai Near Detector (ND) ai Far Detector (FD) , limitandone la precisione dei risultati



Cosa bisogna misurare?



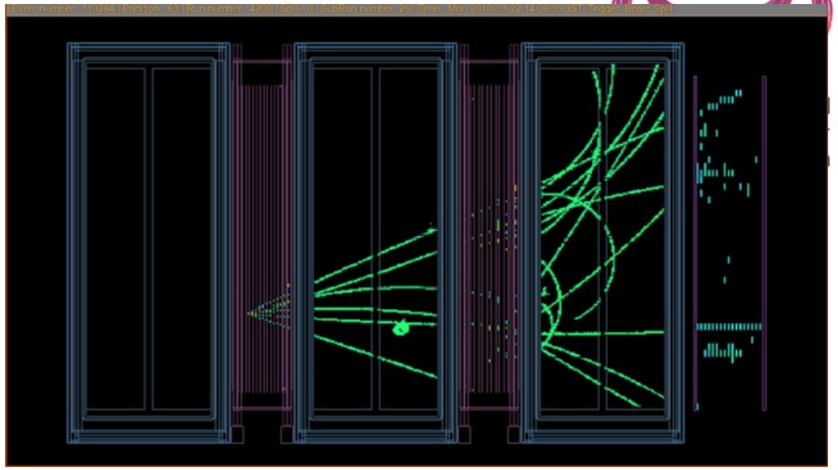


T. Golan, What is inside MC generators and why it is wrong. NuSTEC 2015

Uncertainties in ND→FD extrapolation :

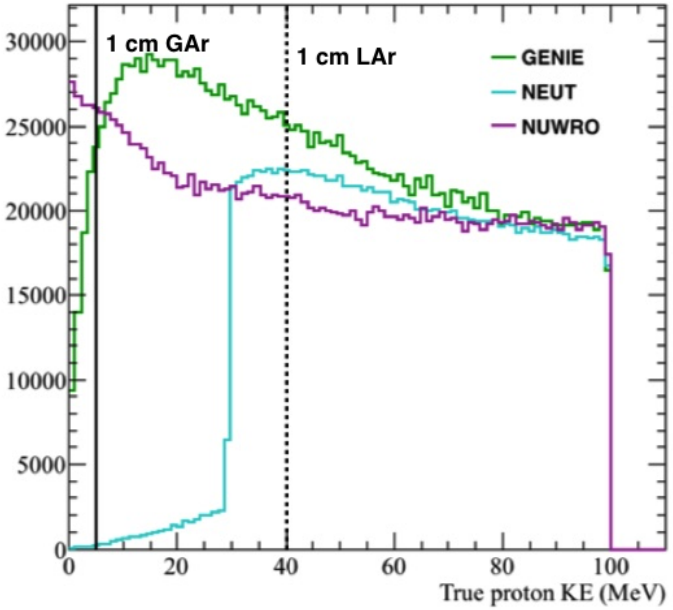
✔	different E_ν distribution (because of oscillation)	⇨	need to reconstruct the neutrino energy from the final state particles
✔	different target	⇨	A-scaling: measure cross-sections on different targets (and/or on the same target of FD)
➔	different acceptance	⇨	measurement of cross-section in the larger possible phase-space: increase angular acceptance of ND
➔	different neutrino flavor (because of oscillation) ν ($\bar{\nu}$) flux has typically a wrong sign component	⇨	measure cross-section asymmetries between different neutrino species (eg ν vs $\bar{\nu}$ important for for δ_{CP})

Why a HP-TPC with optical readout as neutrino detector at low energy (below 1GeV)



A neutrino interaction in the T2K near detector

- Target = detector
- 3D reconstruction capabilities.
- Possibility to exchange targets changing gas
- low density → low thresholds
- excellent PID capabilities.
- Almost uniform 4π acceptance.
- low number of interactions → requires high pressure and large volume.
- requires in addition a magnet to measure momentum and to distinguish between neutrinos and anti-neutrinos
- Very large volumes require low cost per readout channel (pixel)



Differences within models are at low KE and are below the threshold of a liquid argon device

The flow of neutrinos at low energy produced by a demonstrator at CERN can fit very well the requirements for a neutrino's X-sec experiments