62nd International Winter Meeting on Nuclear Physics

19 - 23 January 2026

Bormio, Italy

A multi-TeV muon collider: a challenging opportunity

Nadia Pastrone

INFN TORINO

International MUON Collider Collaboration

MuCol

The European Strategy for Particle Physics Update 2026 - ESPPU is on-going

HORIZON-INFRA-2022-DEV-01-01
Co-funded by the European Union (EU)

iFAST AIDA innova EURO-LABS aMUSE IRIS

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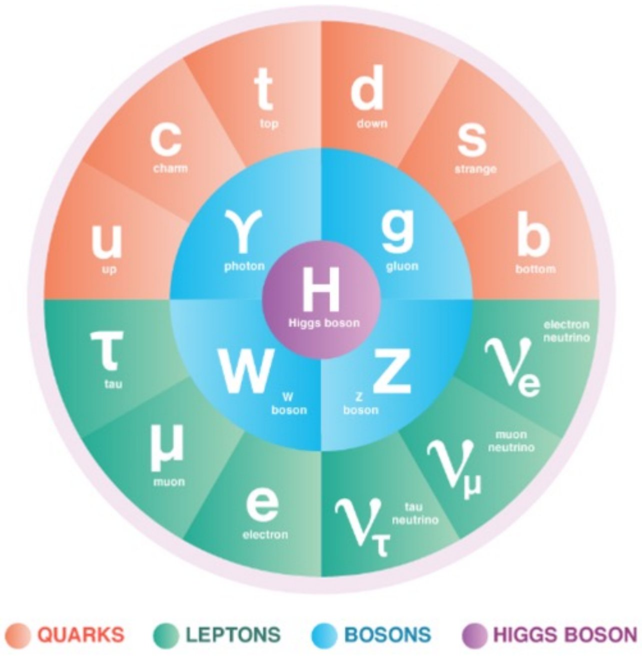
The present HEP landscape



The **Standard Model (SM) of Particle Physics is our best theory** to describe the most basic building blocks of the universe

It provides a good and unified description of Nature up to the O(1) TeV scale

With the Higgs boson discovery all SM particles were found

Not all interactions and parameters have been measured

The **SM has limits and leaves several open questions**:

- ✓ gravity is not adequately explained
- ✓ Higgs boson gives mass to quarks, charged leptons and W, Z bosons but what about the neutrinos' mass
- ✓ 95% of our universe is not made of ordinary matter: dark matter and dark energy do not fit into SM

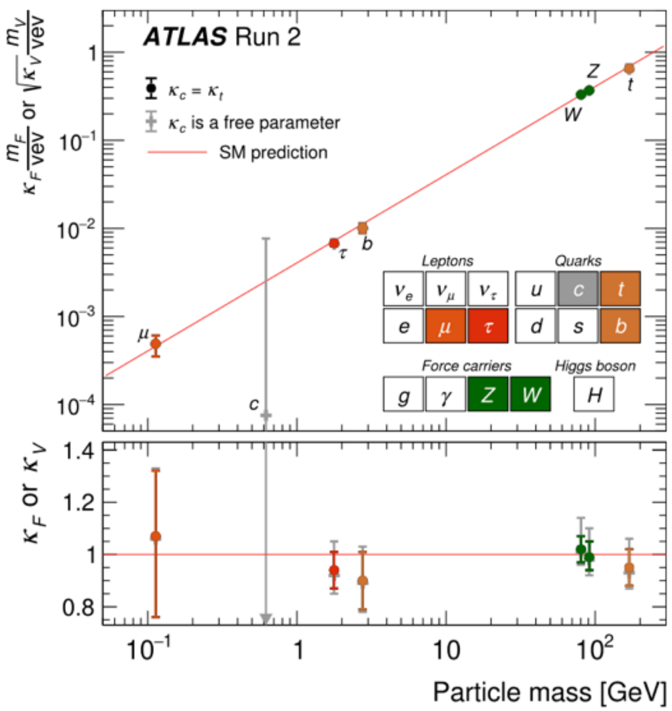
CERN is upgrading the LHC collider and experiments to reach the highest luminosity ➔ **HL-LHC**
to be fully exploited to complete SM measurements and **explore Beyond SM (BSM)**

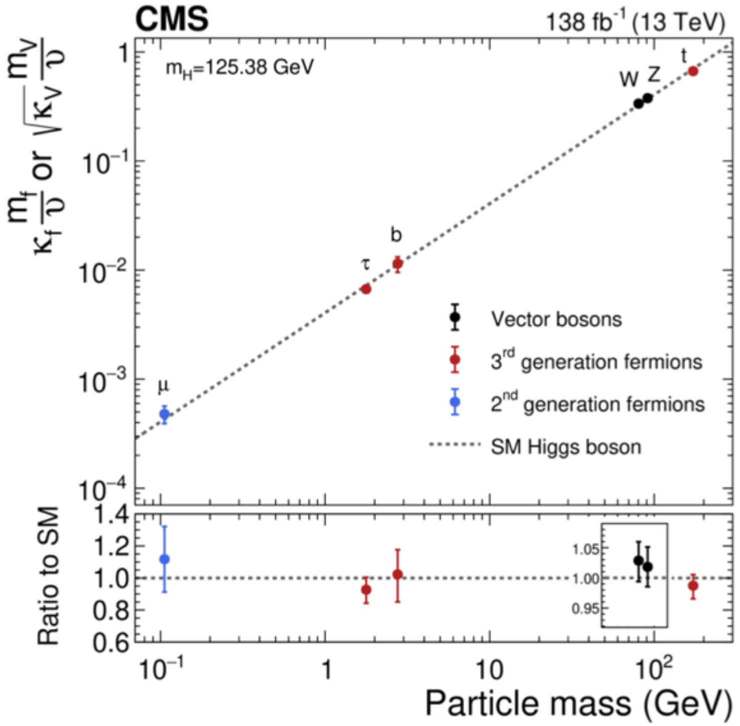
ESPPU-2026 ➔ future collider project @ CERN ~ 2045 – physics beyond collider – neutrino physics computing and detector instrumentation……

The Higgs boson @ LHC: present and future

The Higgs mechanism in the Standard Model predicts $m_i = g_i v$

- In impressive agreement with experiment

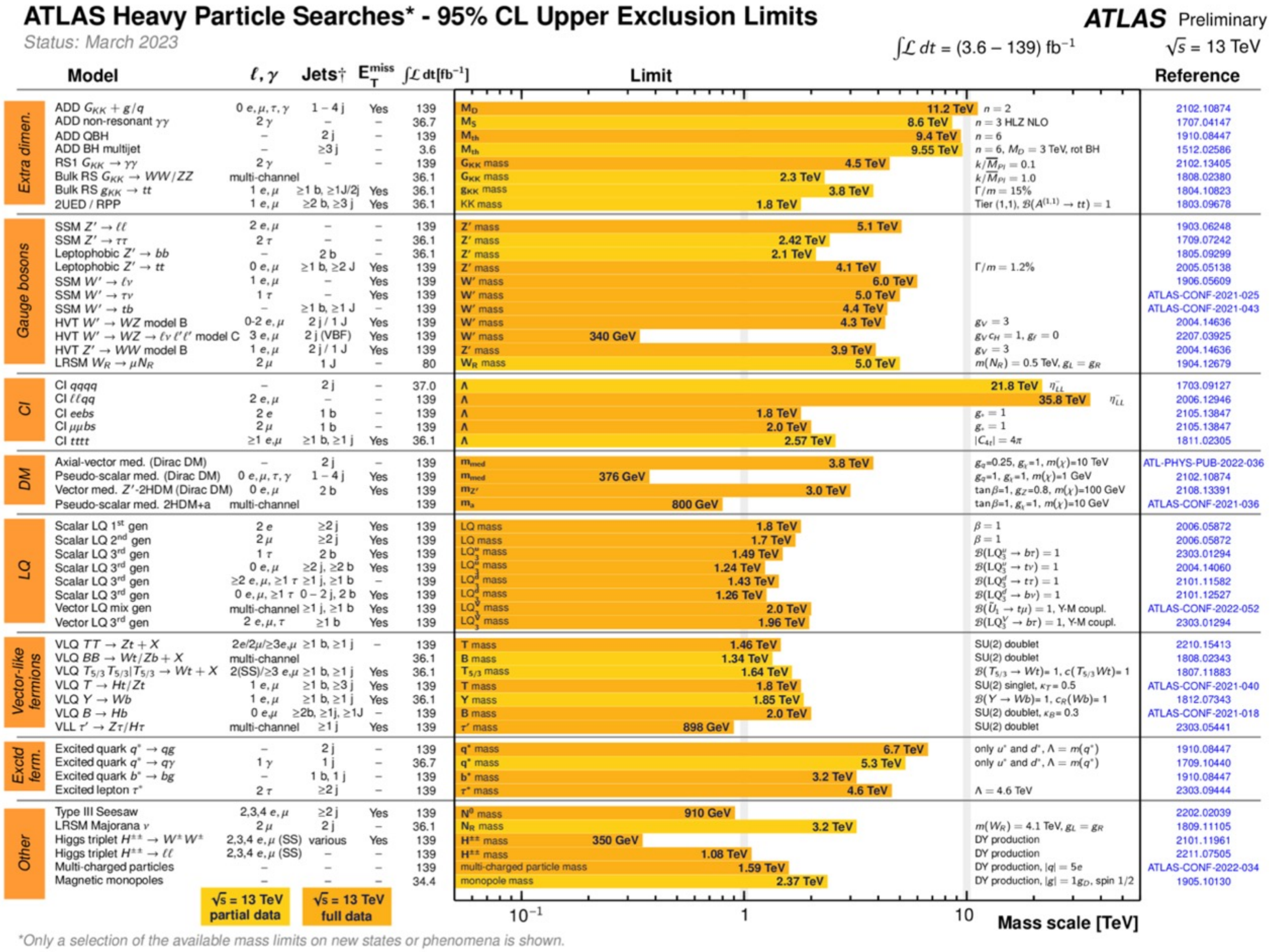




Higgs needs to be understood better!
Studying its properties remains the priority

GOAL:
- make huge numbers of Higgs bosons, to scrutinize its properties and interactions
- stress test the Standard Model in many ways

Energy frontier - searches @ LHC



Reaching a scale ~ TeV – 10 TeV

The EU HEP Strategy for the next 5-10-20 years

[Open Symposium on the European Strategy for Particle Physics]

[Plenary ECFA Meeting] @ CERN Nov. 2025

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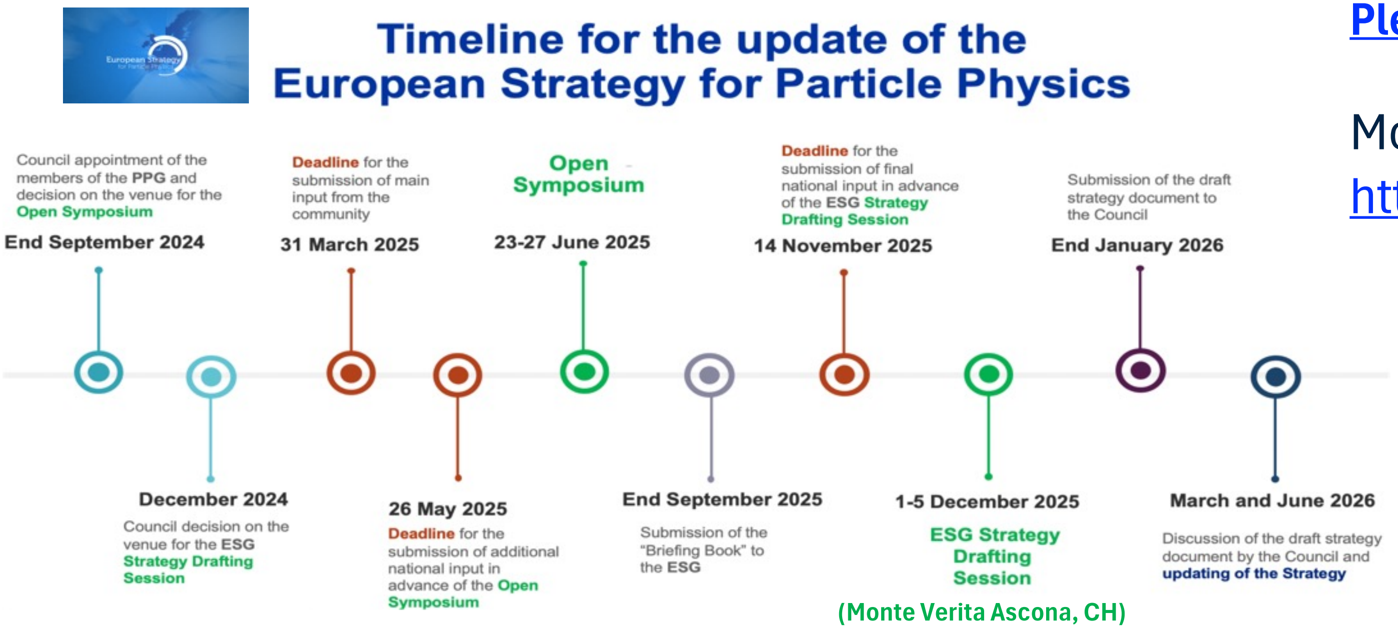
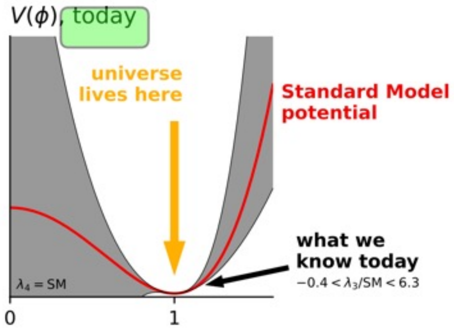
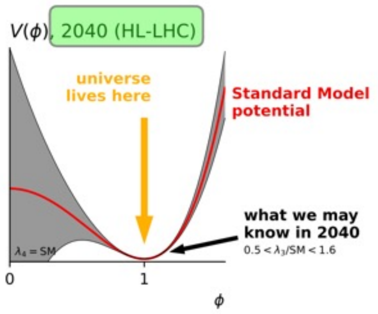


(Monte Verita Ascona, CH)

More details on the ESPPU web page:
https://europeanstrategyupdate.web.cern.ch/

A Higgs factory will improve our knowledge about the Higgs boson and its couplings tremendously by order of magnitude w.r.t HL-LHC



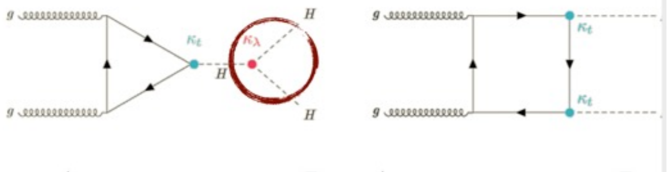


Higgs potential in unitary gauge after expanding around minimum

$$V(h) = \frac{1}{2} m_H^2 h^2 + \boxed{\lambda_3 v\, h^3} + \frac{1}{4} h^4$$

The HL-LHC can do better here than previously thought, through di-Higgs production

Expect 7σ observation of process by ATLAS+CMS



- Determination of tri-Higgs coupling to 30%

The proposed future collider projects: Higgs factory

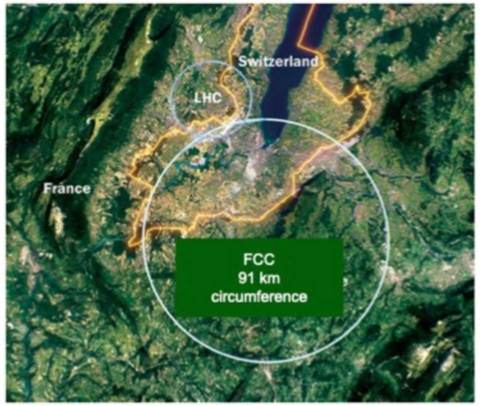
International MUON Collider Collaboration

Proposed large-scale projects at CERN, ~ 2045

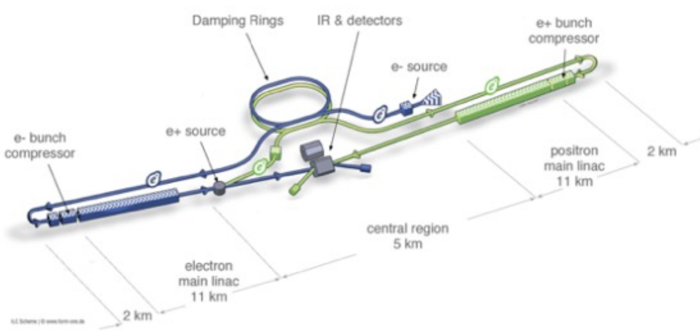
Karl Jakobs

e^+e^- colliders
("Higgs factories")

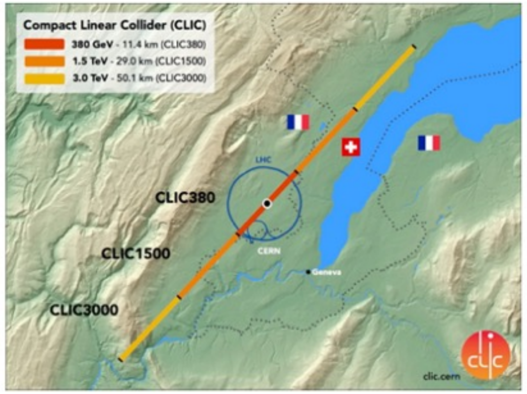
FCC-ee (e^+e^-, circular, 91 – 365 GeV)



LCF (e^+e^-, linear, 91 – 240, 550 GeV)



CLIC (e^+e^-, linear, 380 GeV, 1.5 TeV)

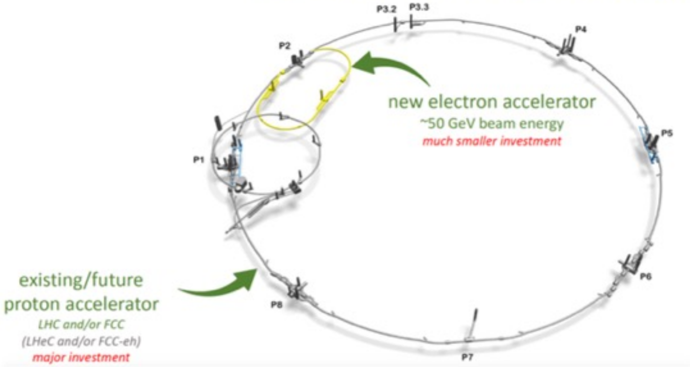


Intermediate projects

(Leave room (time, budget, resources) for further development of THE machine that can probe directly the energy frontier at the 10 TeV parton scale)

LEP3 (e^+e^-, circular, 91 – 230 GeV)

LHeC (ep, circular, electron ERL, 50 GeV e^-, > 1 TeV ep collisions)



The proposed future collider projects: energy frontier

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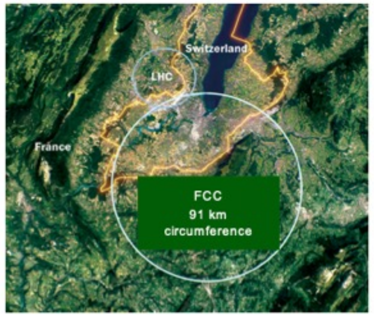
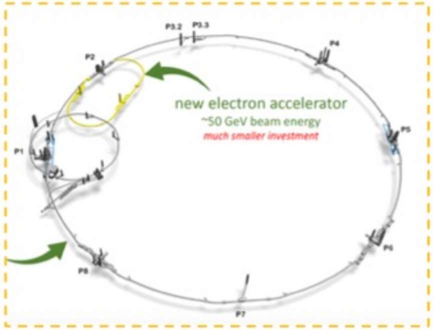
Potential for development: future 10 TeV parton-scale collider options

FCC-ee



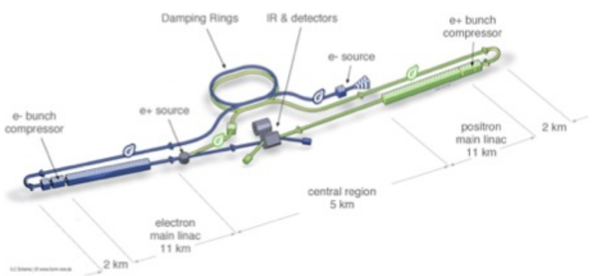
LEP3

LHeC

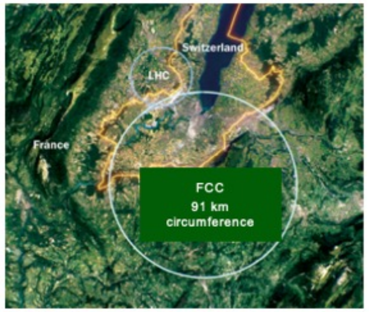


PERLE

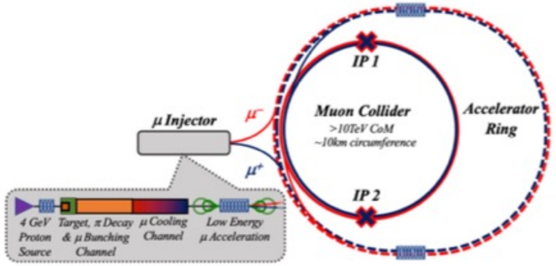
LCF, CLIC



Karl Jakobs



FCC-hh,
baseline 85 TeV (→ 120 TeV)
+ possibility for HI collisions



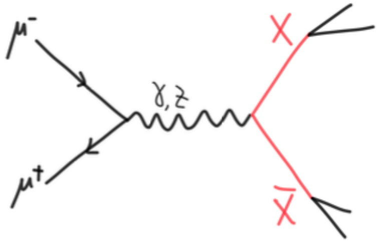
Muon Collider (3, 10 TeV)

R&D

e^+e^- with improved acceleration technologies
LCF, C^3 (→ 1 TeV), CLIC (1.5 TeV), HALHF, …
→ plasma acceleration for higher energies
(can $\mathcal{O}(10)$ TeV be reached? on what timescale?)

Direct probes of New Physics

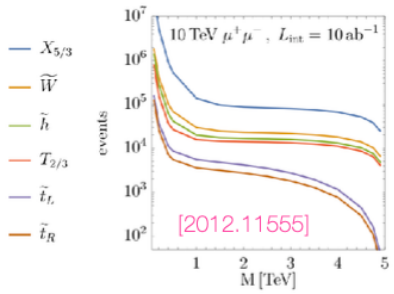
pair production



At the kinematical threshold, all the c.o.m. energy of a **muon collider** is available.

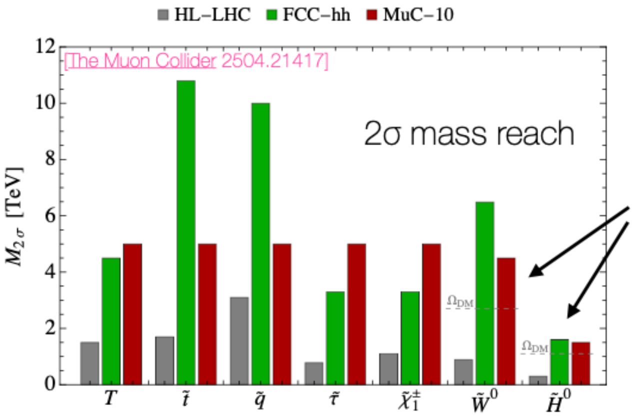
For any state that couples to photon or Z, the mass reach will be given by:

$$M_X = \frac{\sqrt{s_{\mu\mu}}}{2} \simeq \mathbf{5\ TeV}$$



The huge number of events would allow for a precise **characterization** of the new state.

A **hadron collider** has to pay the **PDF suppression** of partonic collisions.



The **WIMP dark matter paradigm can be fully tested**, for all DM representations in the "minimal DM" scenarios.

[Bottaro et al 2107.09688, 2205.04486] (more in backup slides)

International MUON Collider Collaboration

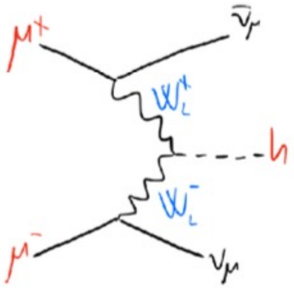
David Marzocca

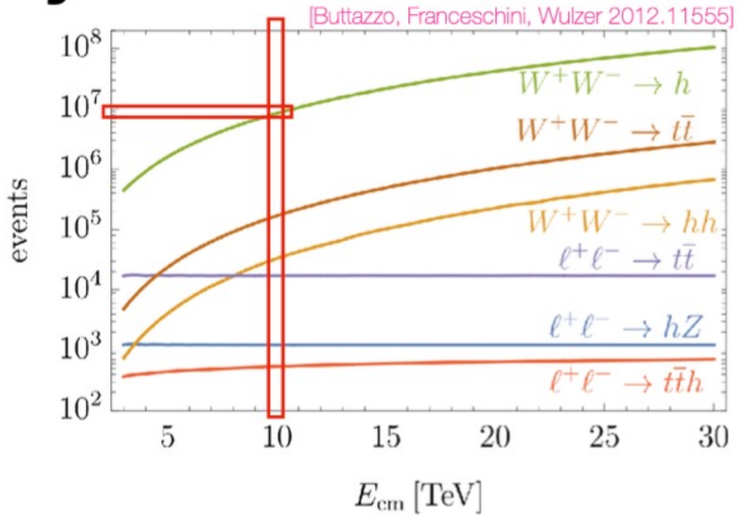
Higgs physics

From the cross sections we saw + assuming the luminosity scaling

$$\mathcal{L}_{TOT} \sim 10\,ab^{-1}\left(\frac{\sqrt{s}}{10\,TeV}\right)^2$$

A **10 TeV MuC** has **10^7 Higgs boson** events (~ # Z's at LEP)





Motivation for a multi-TeV Muon Collider

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**

International Muon Collider Collaboration - hosted at CERN, launched July 2020 by LDG - **PI: Daniel Schulte**

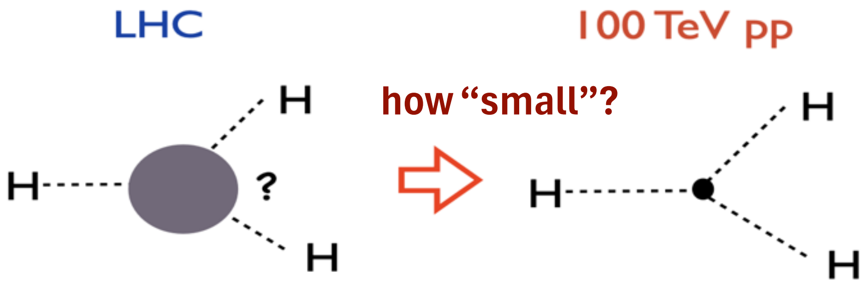
Technology and **design advances since the past ESPPU-2020**

- reviews of the muon collider concept in Europe and US found **no insurmountable obstacle**
- **identified required R&D**, documented and reviewed within the **LDG Accelerator R&D Roadmap**
- co-funded mainly by CERN (MTP dedicated line since 2021) - EU-MUCOL project (2023-2027)

Aim at **10+ TeV** and potential initial stage at **3 TeV -** Possible initial 10 TeV stage at reduced luminosity
New design to reuse existing CERN tunnels: SPS & LHC ➔ whole facility on CERN site
Interim report https://arxiv.org/abs/2407.12450

Strong support by US [P5 Report](#) @ December 2023

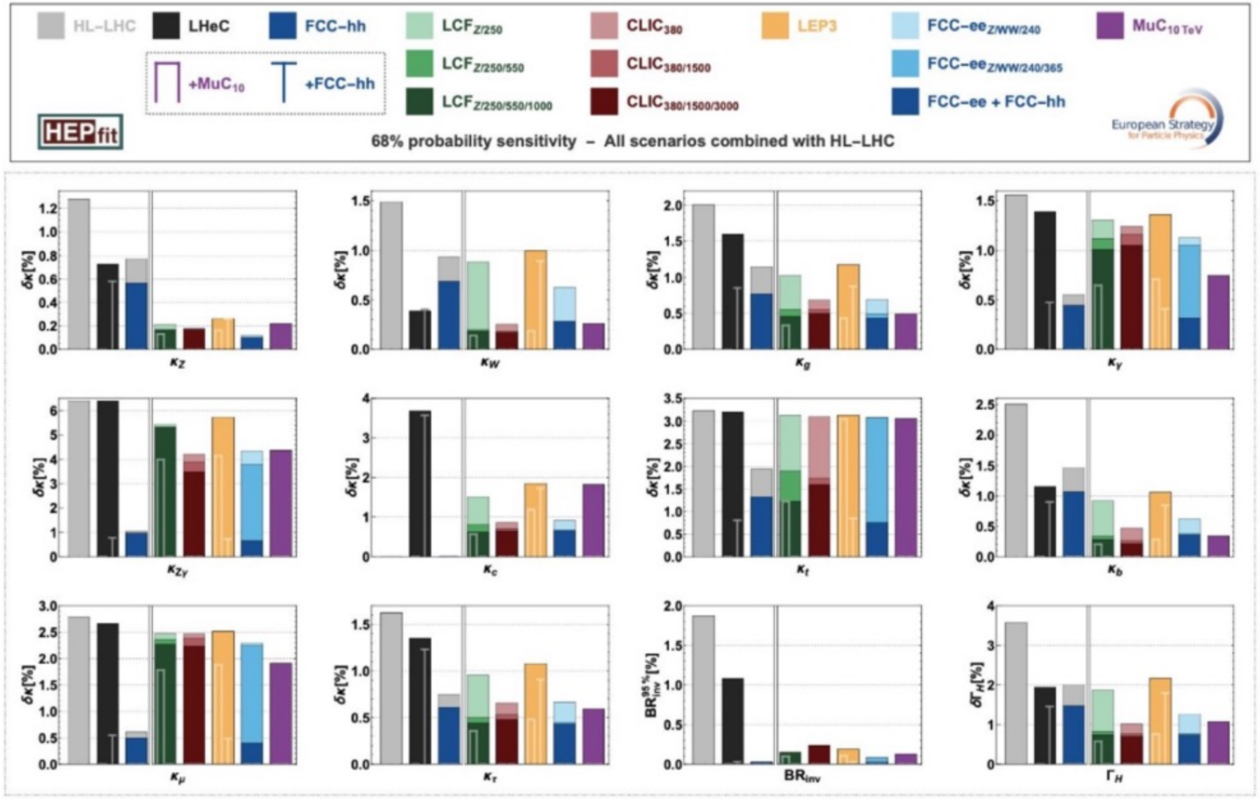
Higgs physics at 10 TeV pCM energy

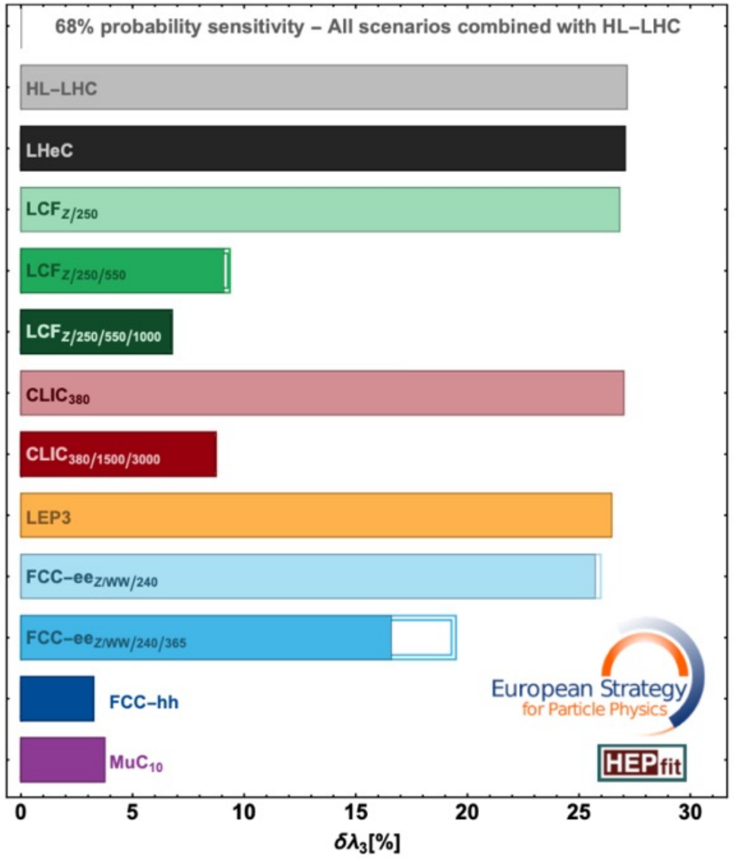


From European Strategy Briefing Book: https://cds.cern.ch/record/2944678?ln=en

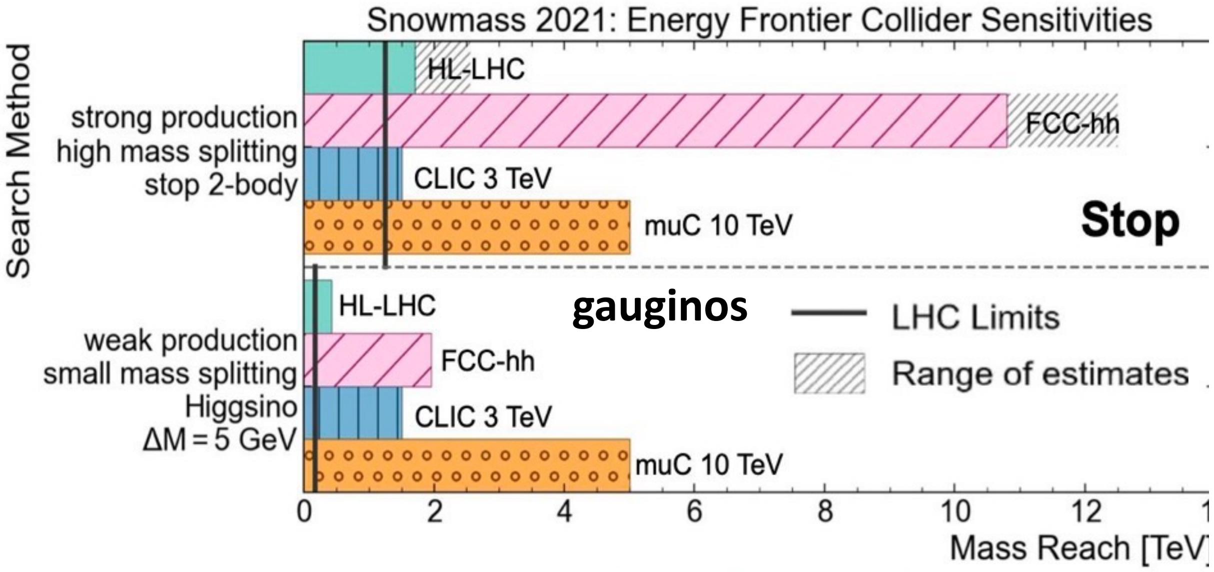
$$\mathcal{L}_h = \frac{1}{2} m_H^2 H^2 + \lambda_3 H^3 + \lambda_4 H^4$$

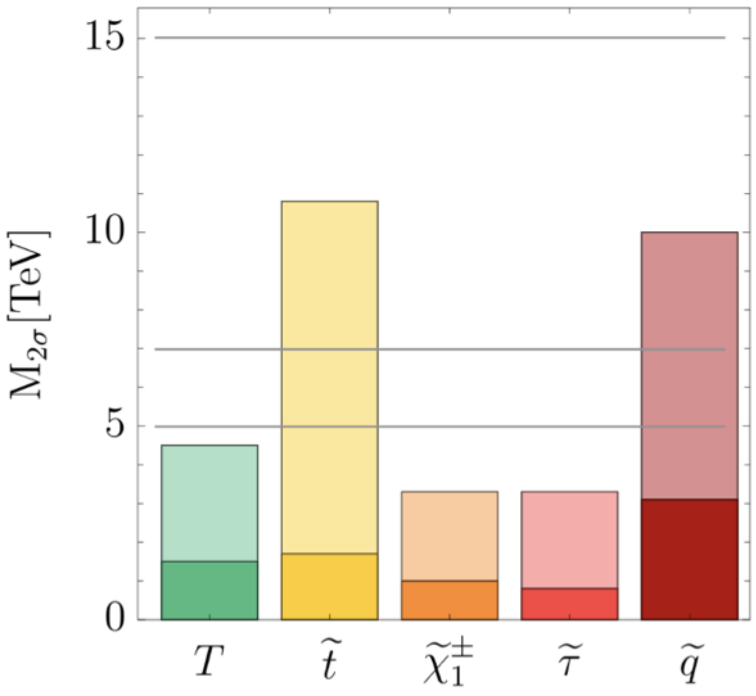
Kappa framework





Energy frontier: searches





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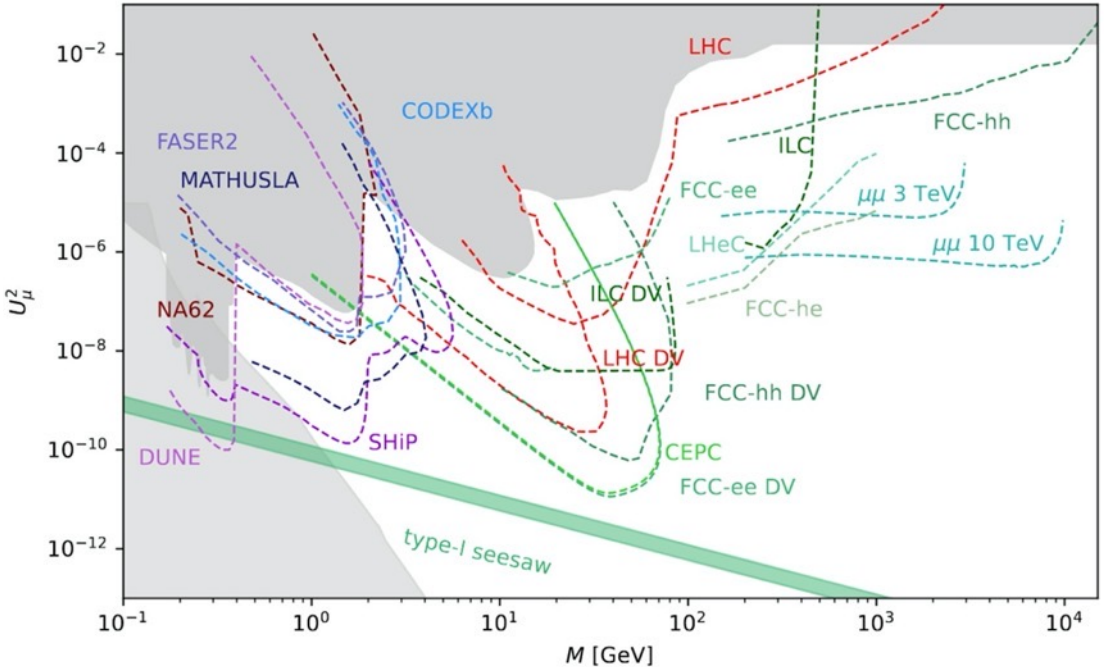
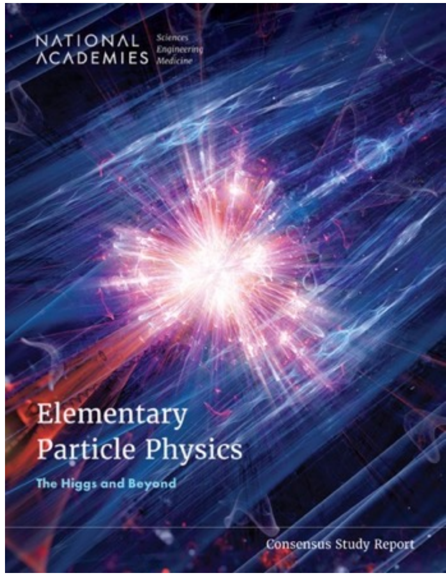


High-priority future initiatives [..] **ESPPU 2020**

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

National Academy of Science report - June 2025



Elementary Particle Physics: Progress and Promise

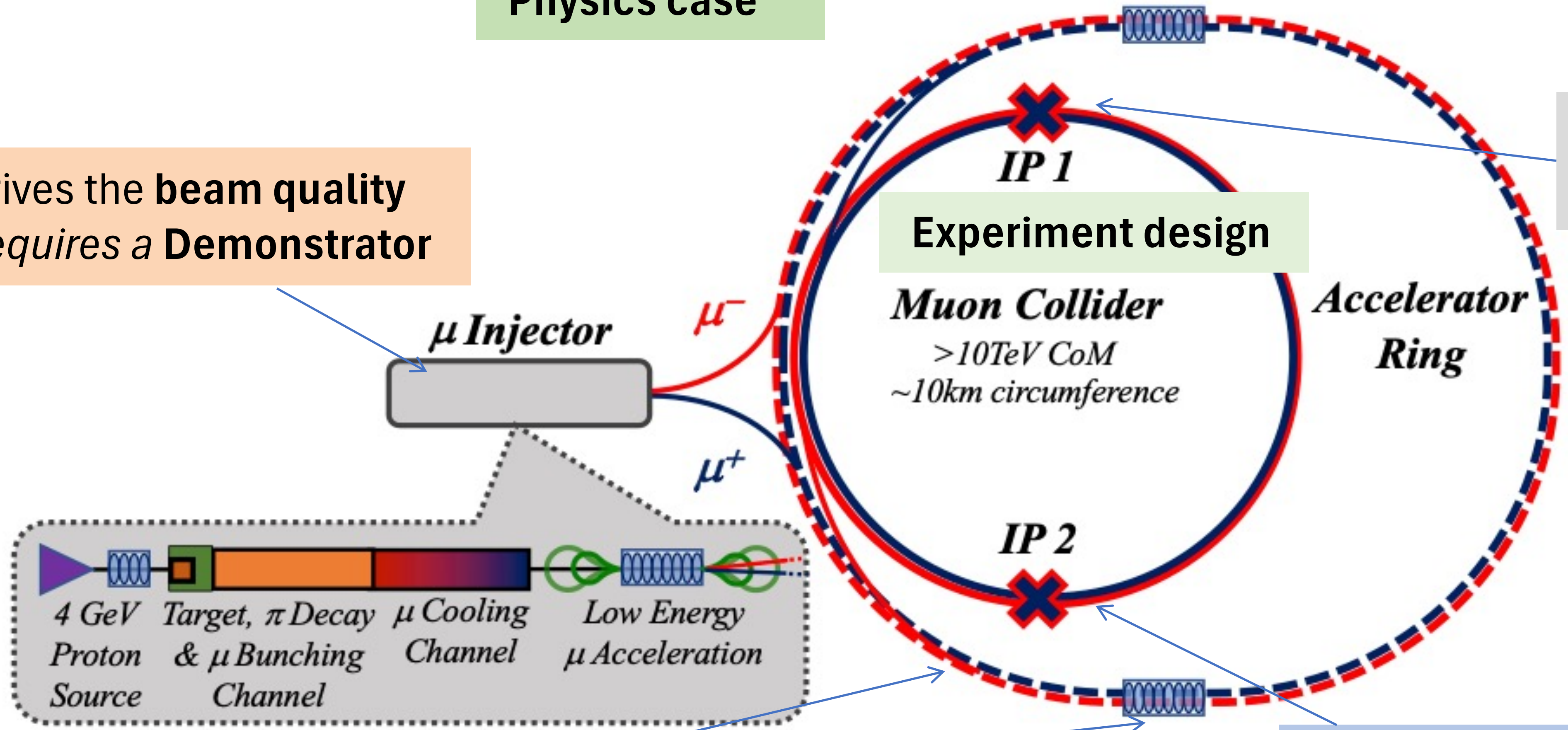
M. Spiropulu (*Co-Chair),* M. S. Turner (*Co-Chair),* N. Arkani-Hamed, B. C. Barish, J. F. Beacom, PH. H. Bucksbaum, M. Carena, B. Fleming, F. Gianotti, D. J. Gross, S. Habib, Y.-K. Kim, P. J. Oddone, J. R. Patterson, F. Pilat, C. Prescod-Weinstein, N. Roe, T. M.P. Tait
Staff: T. Konchady, D. Nagasawa, L. Walker, D. Wise, C. N. Hartman, A. Mozhi

A collider with approximately **10 times the energy of the Large Hadron Collider (LHC) is crucial** for addressing the big questions of particle physics and making discoveries.
A **10-TeV muon collider** on the Fermi National Accelerator Laboratory (Fermilab) site would have similar discovery reach as a 100-TeV proton collider.
A muon collider combines the physics advantages of an electron-positron and a proton-proton collider, with a much smaller size.

Muon Collider layout @ 10 TeV

Physics case

Drives the **beam quality**
Requires a **Demonstrator**



Experiment design

Beam-induced background

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

Target integrated luminosities based on physics
Increase as E_{cm}^2

Dense neutrino flux
mitigated by mover system and **site selection**

Cost and **power** consumption limit energy reach
e.g. 35 km accelerator for 10 TeV, 10 km collider ring
Also impacts **beam quality**

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

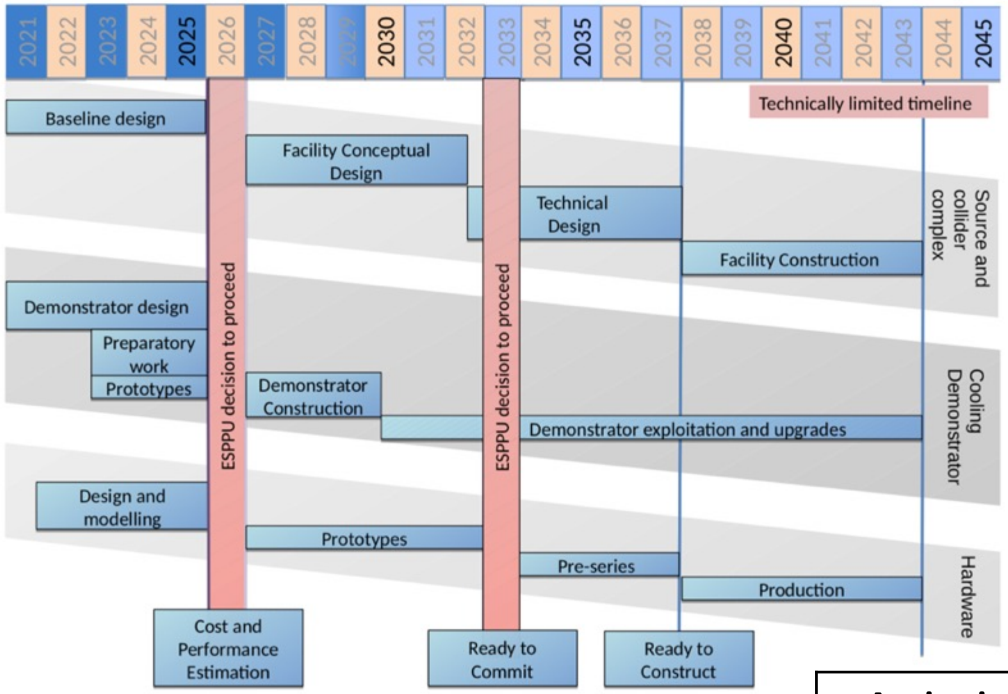
Associated members: A. Grudiev, R. Losito, D. Lucchesi

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

Roadmap Plan

MDI

Dipoles/solenoids
High field
(Nb3Sn, HTS?)

RF
cavities

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

Site Specific Designs

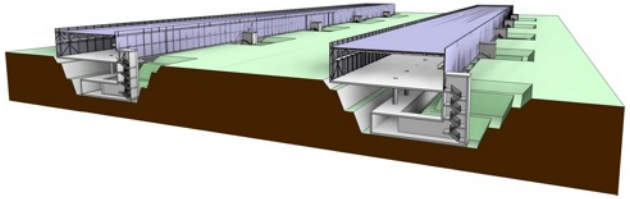
Started studies for concrete site at CERN and Fermilab, looks very promising

CERN:

One RCS in SPS and two in LHC

Construct facility on CERN land

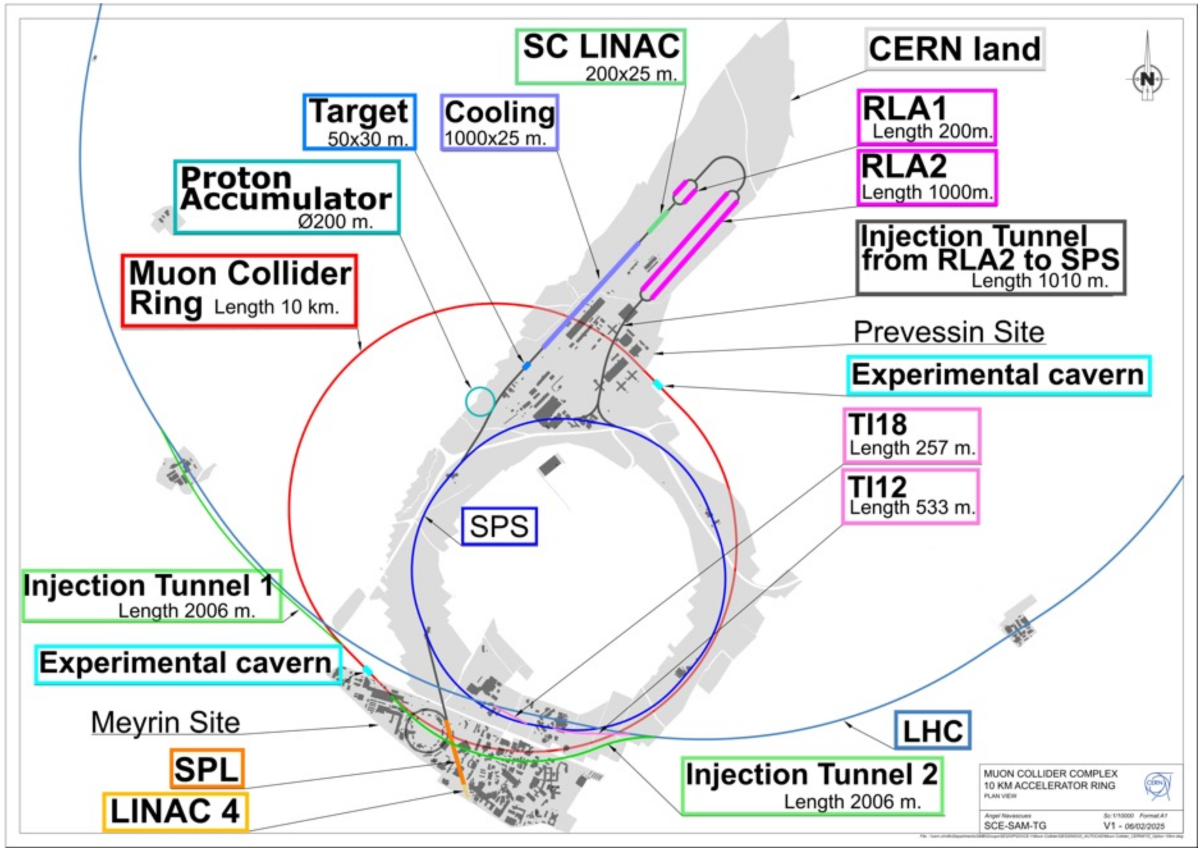
- Natural energy stages: 3.2 and 7.6 TeV
- 10 TeV maybe possible with better technology

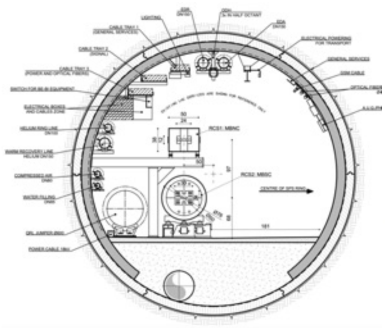


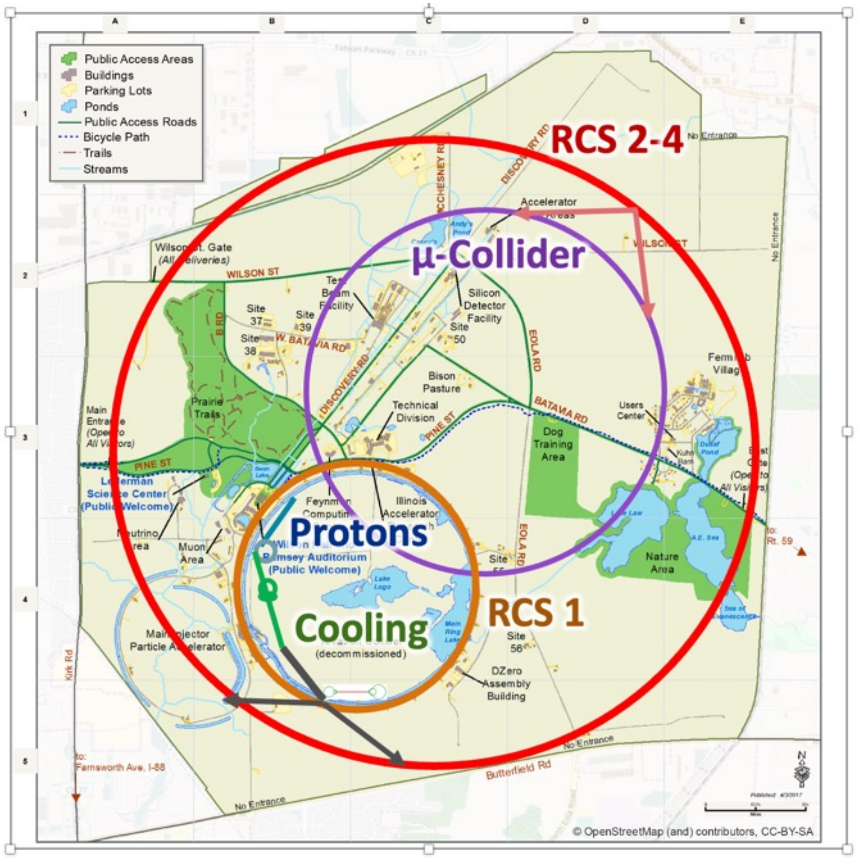
Fermilab:

One RCS in Tevatron tunnel,

Three RCSs in one site-filler tunnel







Key conclusions:

Looks promising

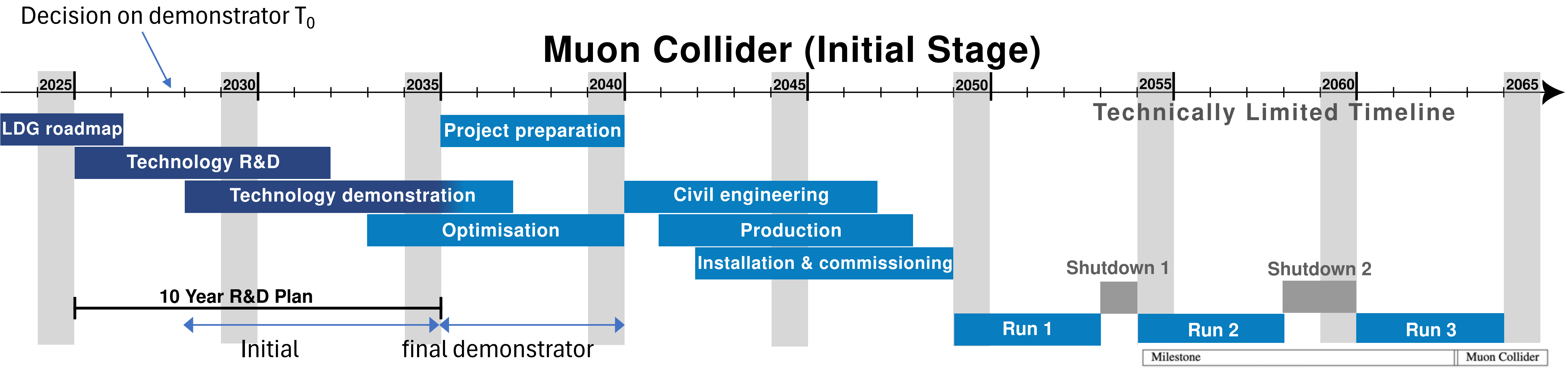
Detailed study needed

Key Target Parameters

Param.	Unit	Site independent		CERN 2 tunnels		CERN 1 tunnel	
Sqrt(s)	TeV	3	10	3.2	7.6	3.2	7.6
L/IP	10^{34} cm^{-2}s^{-1}	1.8	17.5	2	10	0.9	7.9
Int L	ab^{-1}	1	10	1	10	1	10
Accumulation time	years	2+2.8	2+2.9	2+2.5	2+5	2+5.6	2+6.3
C	km	4.5	11.4	4.8	8.7	11	11
B_{dipole}	T	11	14	11	14	4.8	11
Collider dipole technology		Nb3Sn	HTS	Nb3Sn	HTS	NbTi	Nb3Sn or HTS

Accumulation time: Time to obtain the integrated luminosity with two IPs.
Ramp-up over the first three years 5%, 25%, 70% of nominal.

Timeline and R&D Programme Proposal



Milestone	Muon Collider
Construction of RF test stands	2025 – 2028
Production of test cavities	2026 – 2039
Operation of test stands	2027 – 2040
Demonstration Phase	$T_0 - (T_0 + 7)$
Demonstrator technical design	
Construction of initial demonstrator	
Construction of muon cooling module (5 cells)	
Definition of the placement scenario for the collider	
Project Preparation Phase	$T_1 - (T_1 + 5)$
Final demonstrator	
Implementation studies with the Host states	
Environmental evaluation & project authorisation processes	
Main technologies R&D completion	
Industrialisation of key components	
Engineering Design completion	
Construction Phase (from ground breaking)	$T_2 - (T_2 + 9)$
Civil engineering	
TI installation	
Component construction	
Accelerator HW installation	
HW commissioning	
Beam commissioning	
Physics operation start	$T_2 + 10$

Timeline is **driven by R&D**

Most ambitious example to define R&D programme priorities

- Assumes firm commitment to enable the muon collider as next flagship after HL-LHC
- R&D is fully successful
- No delays due to decision making

Other options

- In Europe after a higgs factory
- In the US to become leader at the energy frontier

https://indico.cern.ch/event/1439855/contributions/6542430/

R&D Programme

Daniel Schulte et al.

Accelerator design

- Complete start-to-end design to validate and optimize performance, cost, power and risk

Muon cooling technology

- Implementation in steps important for timeline
- Need hardware, in particular RF test stands
- New detector technologies useful for instrumentation
- Cooling RF requires urgent test infrastructure

Detector

- Strong potential for further improve physics potential with technologies, AI and ML

Magnet programme

- Have conceptual designs, need hardware
- HTS solenoids have important synergy with society (also power converter)
  - Industry is ready to invest
  - Must not miss the opportunity

Detailed R&D programme proposal with deliverables defined

Year	I	II	III	IV	V	VI	VII	VIII	IX	X
Accelerator Design and Technologies										
Material (MCHF)	1.6	3.2	4.8	6.4	9.6	10.8	12.0	12.0	12.0	12.0
FTE	47.1	60.6	75.0	85.0	100.0	120.0	150.0	174.6	177.2	185.1
Demonstrator										
Material (MCHF)	0.6	2.2	3.9	5.4	7.8	15.1	25.9	32.4	31.8	12.6
FTE	9.5	11.0	12.5	29.2	29.7	30.5	25.5	27.7	26.7	25.5
Detector										
Material (MCHF)	0.5	1.1	1.6	2.1	2.1	2.1	2.1	2.6	3.1	3.1
FTE	23.4	46.5	70.0	93.0	93.0	93.0	93.0	116.4	139.5	139.5
Magnets										
Material (MCHF)	3.0	4.9	10.1	10.0	11.0	13.4	11.7	7.2	6.6	4.7
FTE	23.3	28.4	36.4	40.9	44.3	47.1	46.2	37.7	36.1	29.4
TOTALS										
Material (MCHF)	5.7	11.4	20.3	23.9	30.6	41.4	51.7	54.2	53.5	32.4
FTE	103.3	146.5	194.0	248.1	267.0	290.6	314.8	356.3	379.4	379.6

Key conclusions:

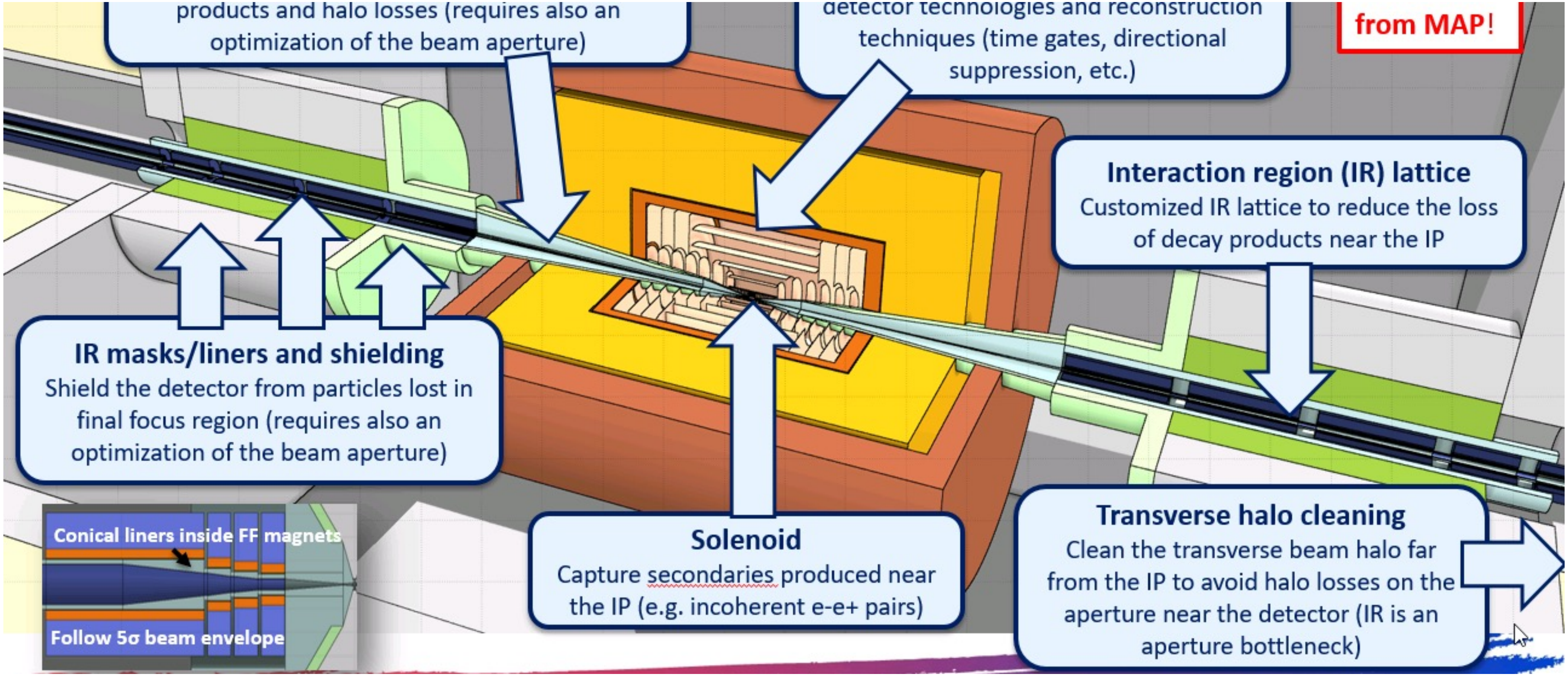
- Need the budget
- Start in Europe using exiting momentum
- Ramp up in the US and other regions

Machine Detector Interface - beam-induced background

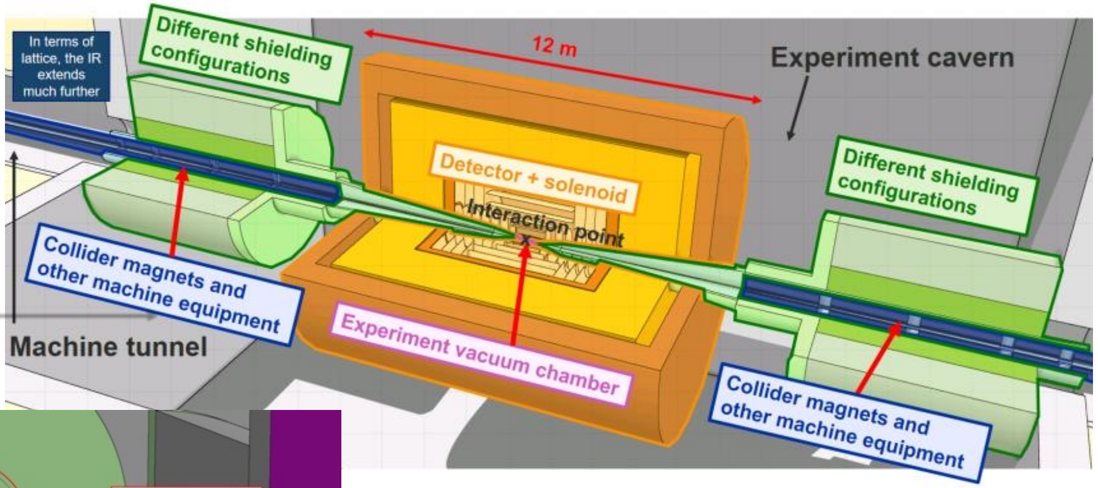
Background is a significant driver for MDI design - background sources:

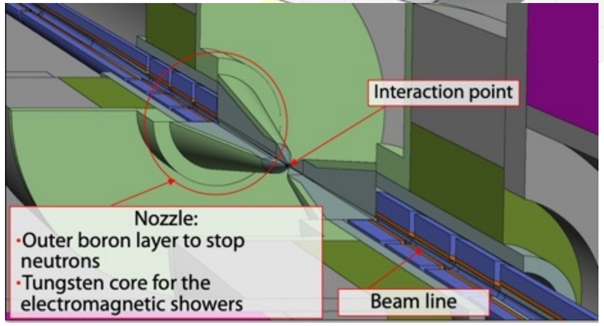
- **Muon decay**
- Beam halo losses and Beam-beam (mainly incoherent e-/e+ pair production)

Daniele Calzolari et al.



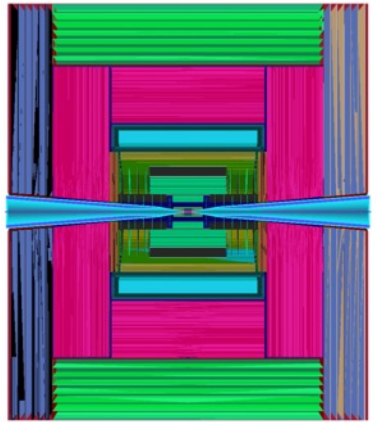
Experiment design @ 10 TeV Muon Collider





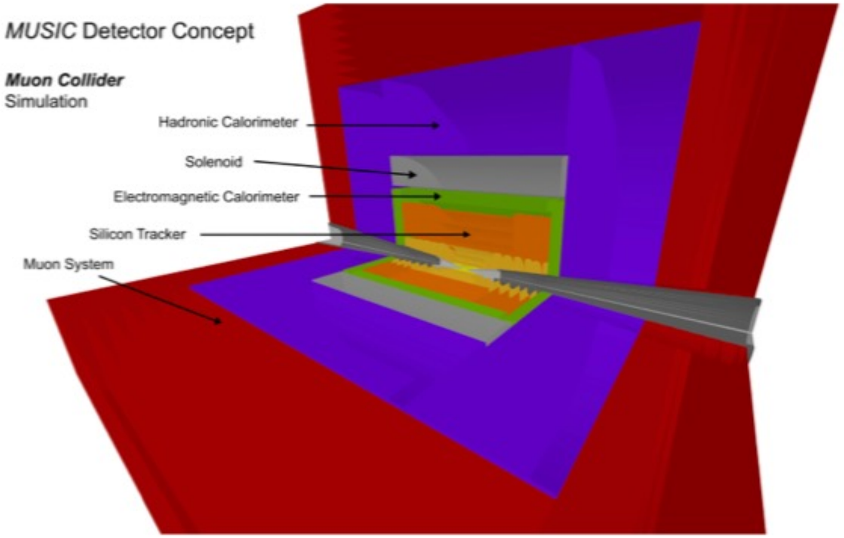
photons, electrons, positrons

(0.0003% of a BIB event)



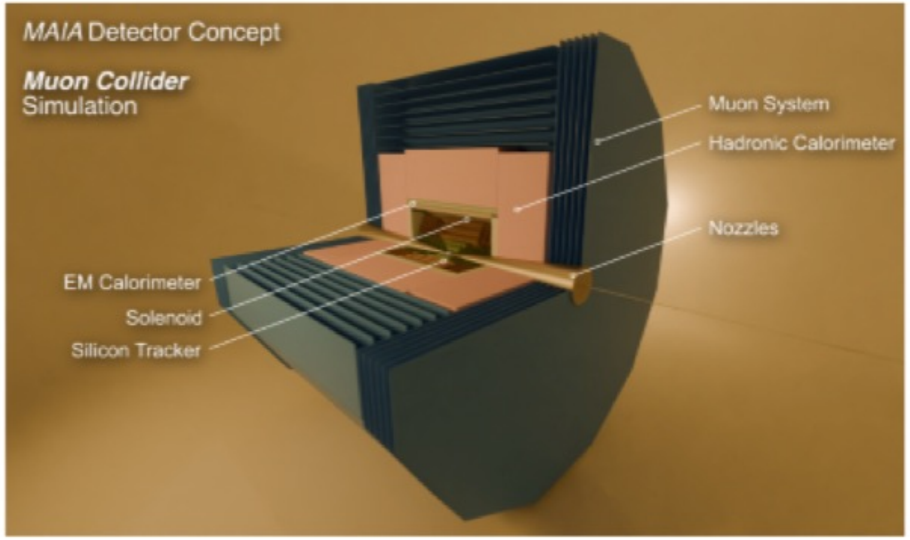
MUSIC

(MUon System for Interesting Collisions)



MAIA

(Muon Accelerator Instrumented Aperatus)



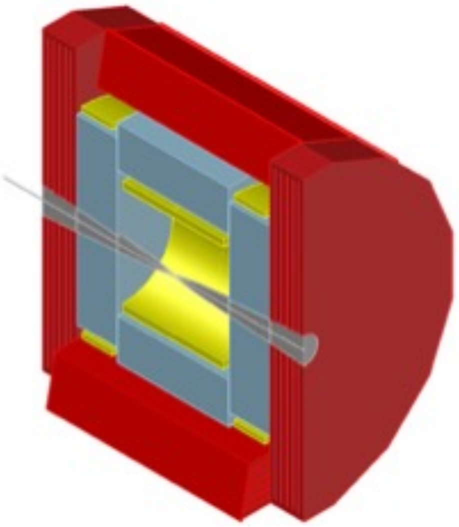
[MUSIC: A Multi-Purpose Detector Concept for Physics at the 10 TeV Muon Collider]

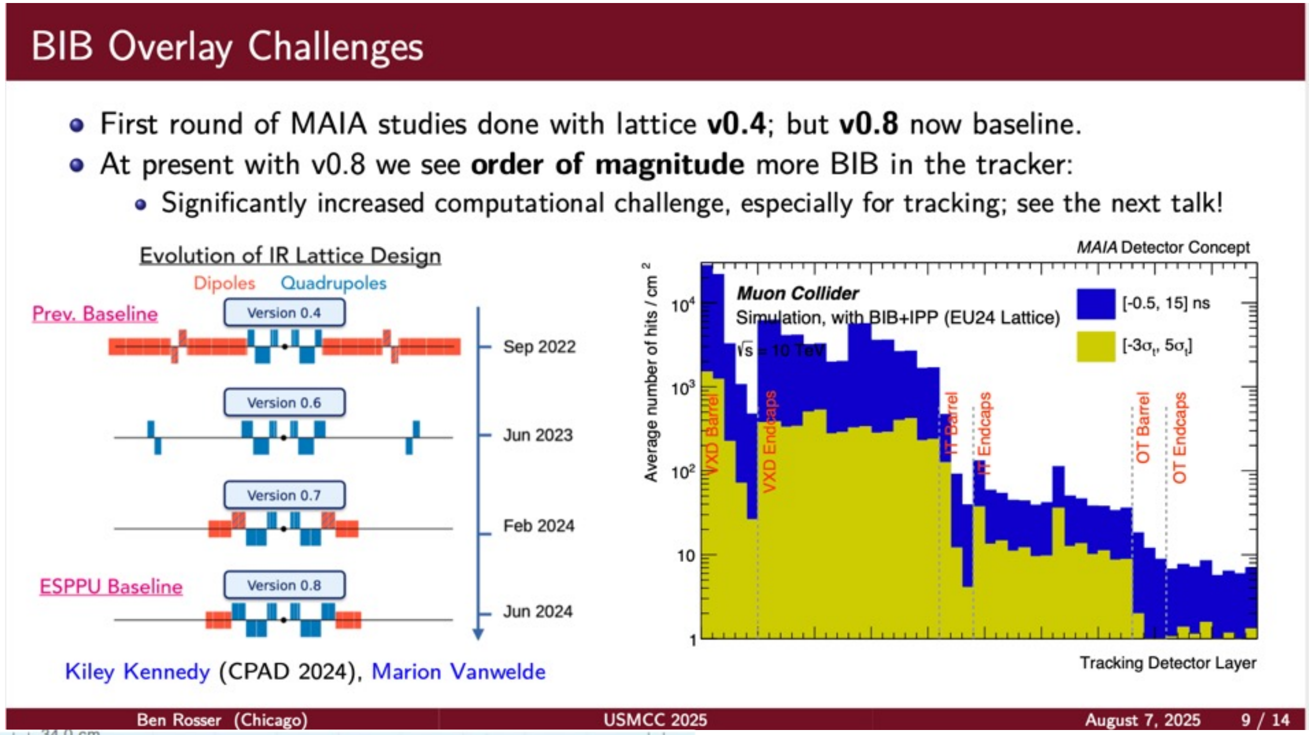
Backgrounds: beam induced (BIB)-incoherent e^+e^- pairs production

beam halo

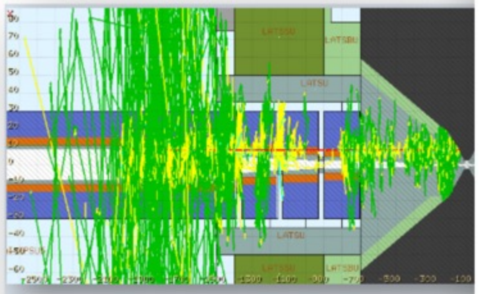
Crucial ingredients:

- Machine Lattice @ 10 TeV
- Machine detector interface (MDI)
- Nozzle structure
- Detector magnet

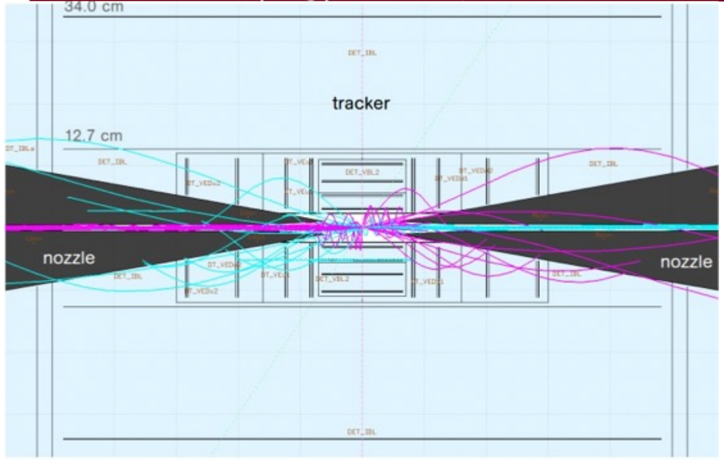




First IMCC halo-induced background studies for 10 TeV:



Secondary neutrons, photons and electrons (ma
surround the primary muon lost.



neutron BIB
on ECAL studies

Backgrounds distributions

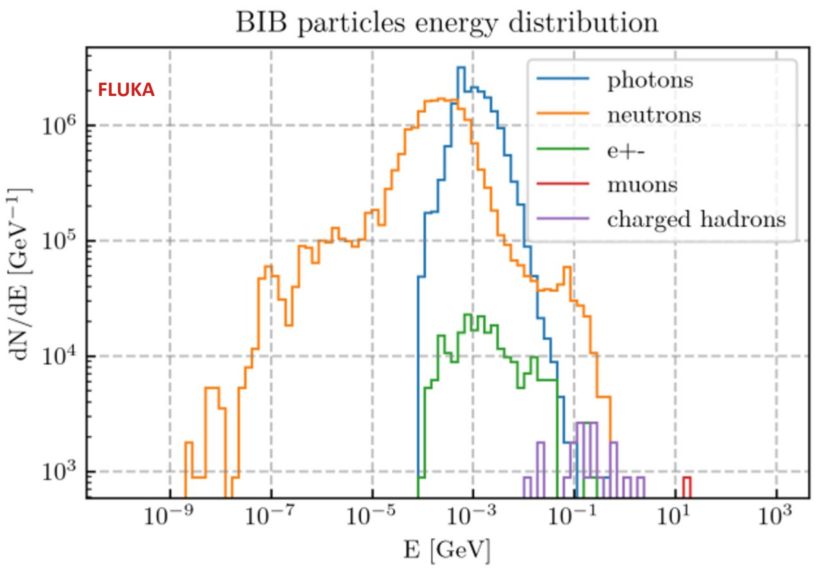
Beam-induced background (BIB) from muon decay products interacting with the machine components and the shields inside the detector (nozzles):

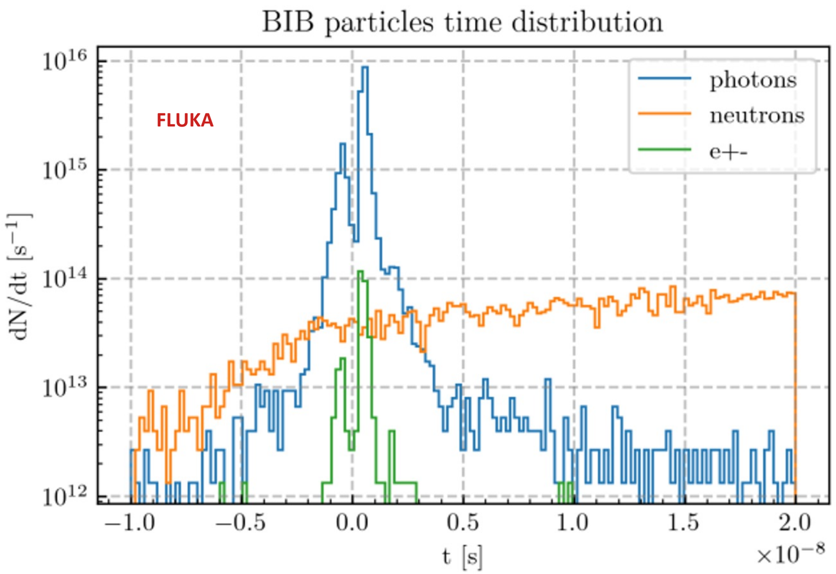
soft particles and mostly out of time w.r.t. the bunch crossing:

- $\sim 10^8$ photons,
- $\sim 10^7$ neutrons,
- $\sim 10^5$ electrons/positrons

enter the detector at every bunch crossing in the time window [1, 15] ns

Extensively studied with MARS15 and FLUKA since MAP studies





Detector requirements: @ 10 TeV

igular acceptance $\eta = -\log(\tan(\theta/2))$	$\lvert\eta\rvert < 2.5$	$\lvert\eta\rvert < 4$
inimum tracking distance [cm]	~ 3	< 3
rward muons ($\eta > 5$)	tag	$\sigma_p/p \sim 1$
ack σ_{p_T}/p_T^2 [GeV^{-1}]	4×10^{-5}	$1 \times 10^{-}$
oton energy resolution	$0.2/\sqrt{E}$	$0.1/\sqrt{E}$
eutral hadron energy resolution	$0.4/\sqrt{E}$	$0.2/\sqrt{E}$
ming resolution (tracker) [ps]	$\sim 30-60$	$\sim 10-$
ming resolution (calorimeters) [ps]	100	10
ming resolution (muon system) [ps]	~ 50 for $\lvert\eta\rvert > 2.5$	< 50 for $\lvert\eta\rvert$
avour tagging	b vs c	b vs c, s-ta
oosted hadronic resonance identification	h vs W/Z	W vs

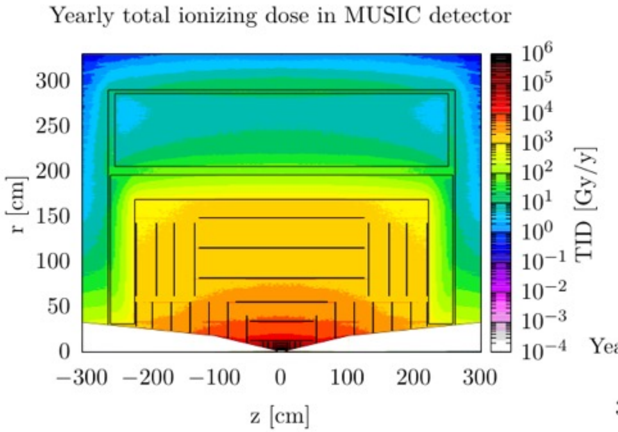
STRONG INTEREST IN DEVELOPING also @ DRD:

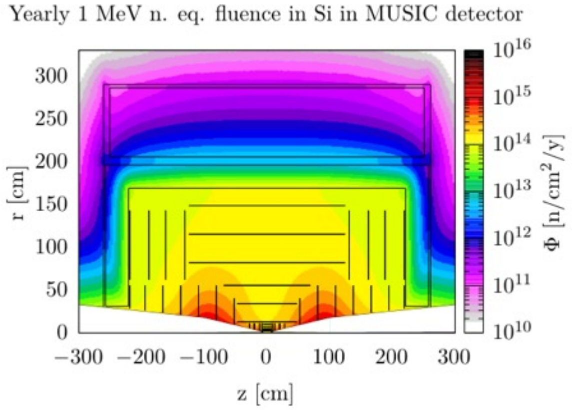
- 4D vertex and tracker sensors
- new calorimeters 4D or 5D ideas
- sustainable muon detector
- front-end electronics with on-board intelligence
- powerful reconstruction algorithm
- AI simulation and analysis tool

Maximum values

ionizing dose 1 MeV neutron-eq fluence

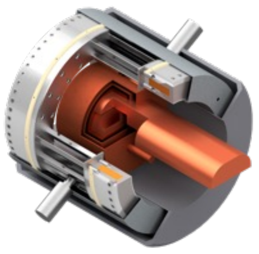
Component	Dose [kGy]		1 MeV neutron-equivalent fluence (Si) [10^{14} n/cm^2]	
	MAIA	MUSIC	MAIA	MUSIC
Vertex (barrel)	1000		2.3	
Vertex (endcaps)	2000		8	
Inner trackers (barrel)	70		4.5	4
Inner trackers (endcaps)	30		11.5	10
ECAL	0.58	1.4	0.15	1

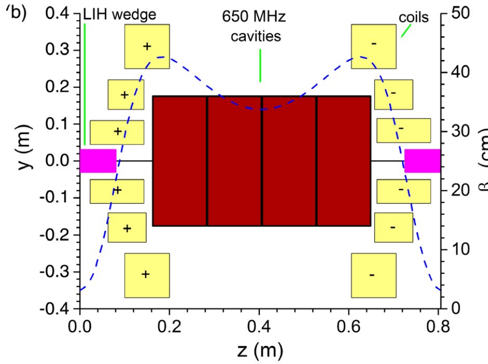




Time-critical Developments

Identified three main technologies that can limit the timeline

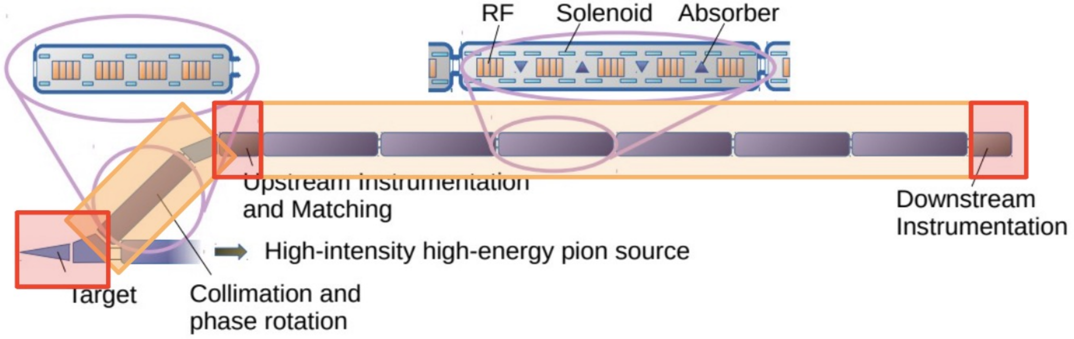




B8

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

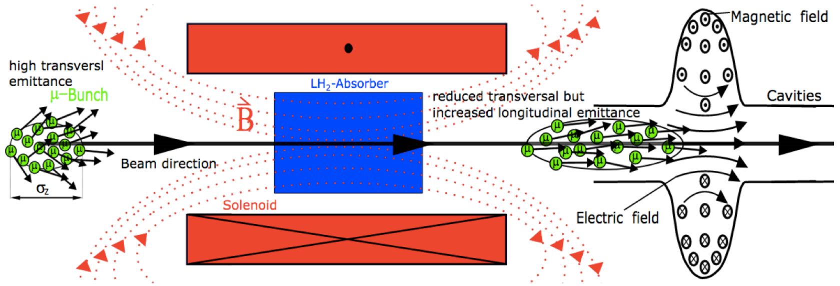
Important Developments

Detector technology and design

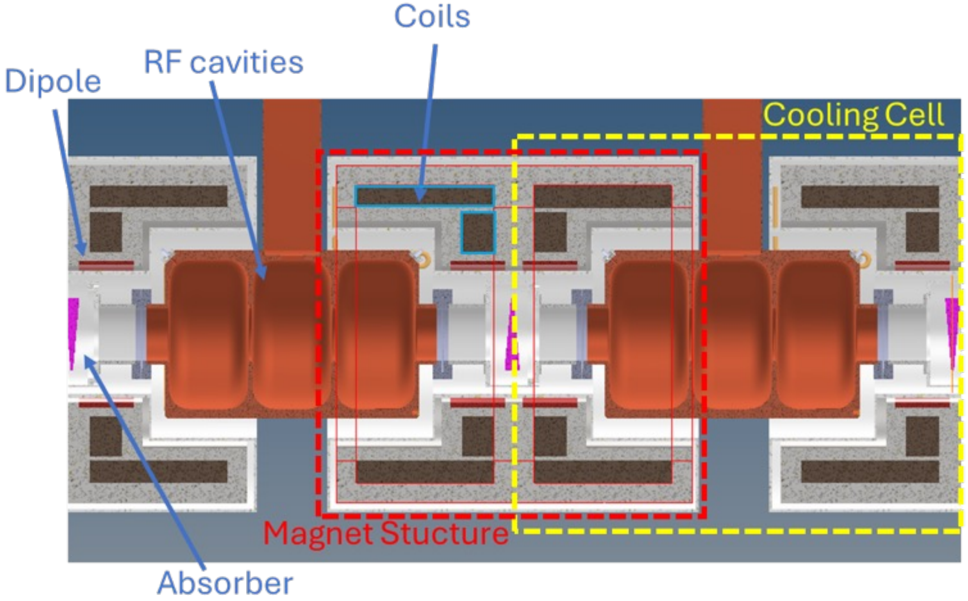
- Can do the important physics with near-term technology
- But available time will allow to improve further and exploit AI, MI and new technologies

Muon ionizing cooling cell studies and R&D

- Cooling is necessary after production to reduce the 6D emittance of the captured beam



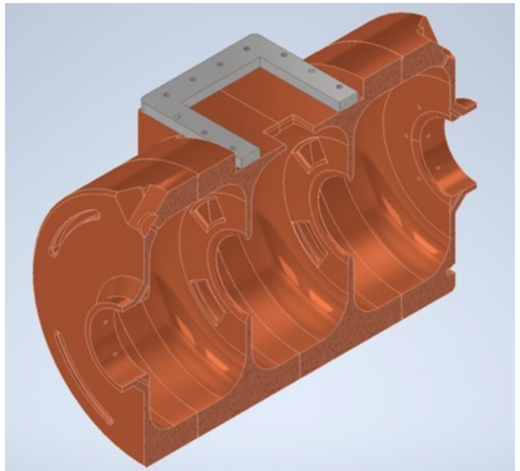
Novel, complex lattice with cavities and absorbers in solenoids - High magnetic field

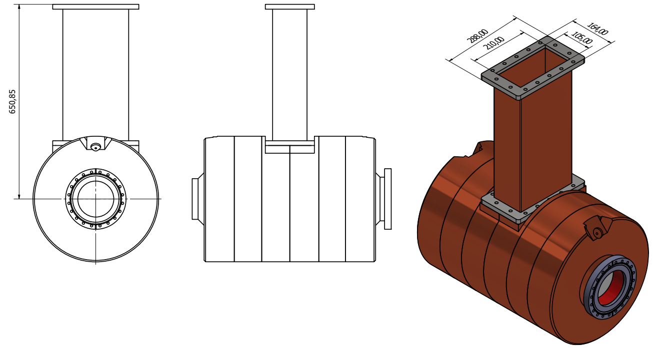


Cooling Cell Integration study: agreed concept

High magnetic field (up to 40 T) superconducting solenoids

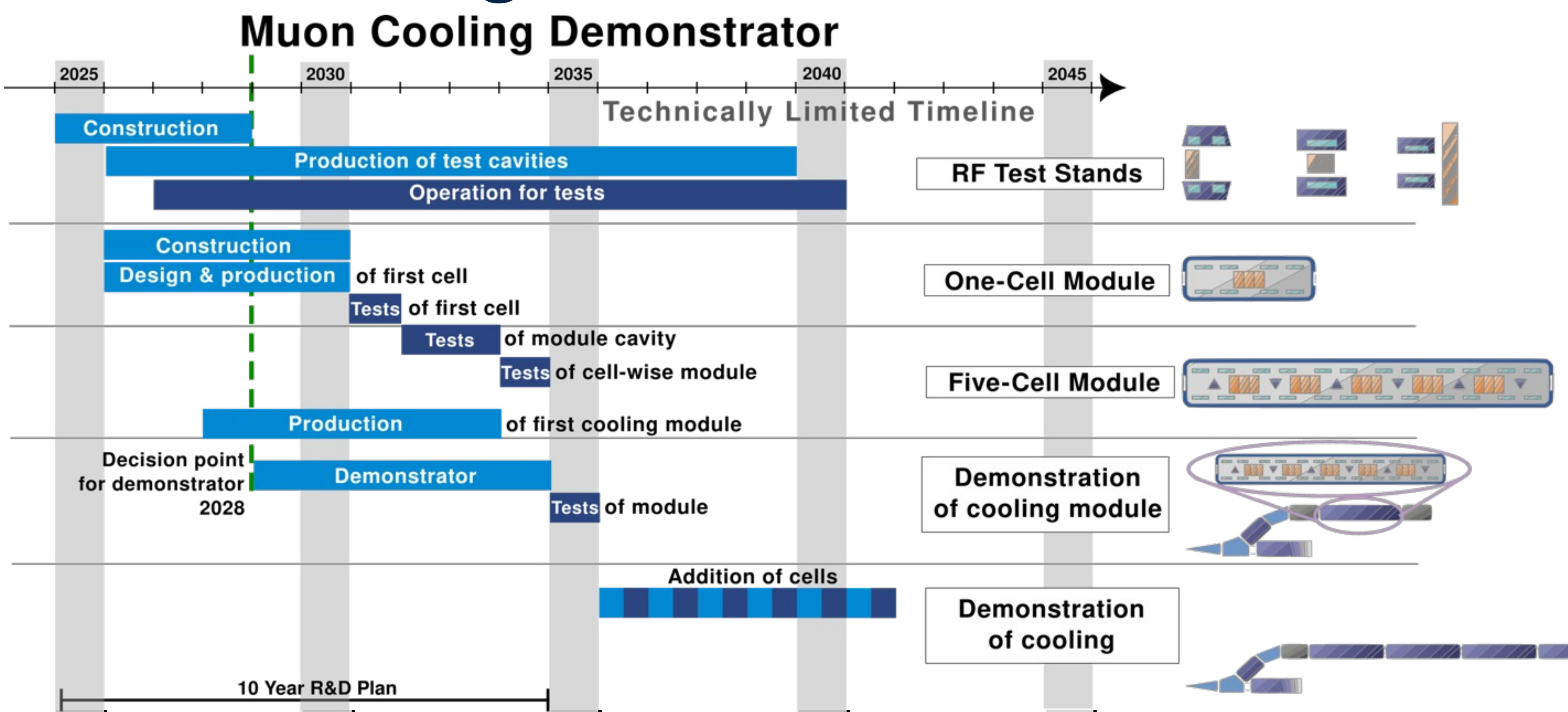
High electric field normal conducting RF cavities (30 MV/m)

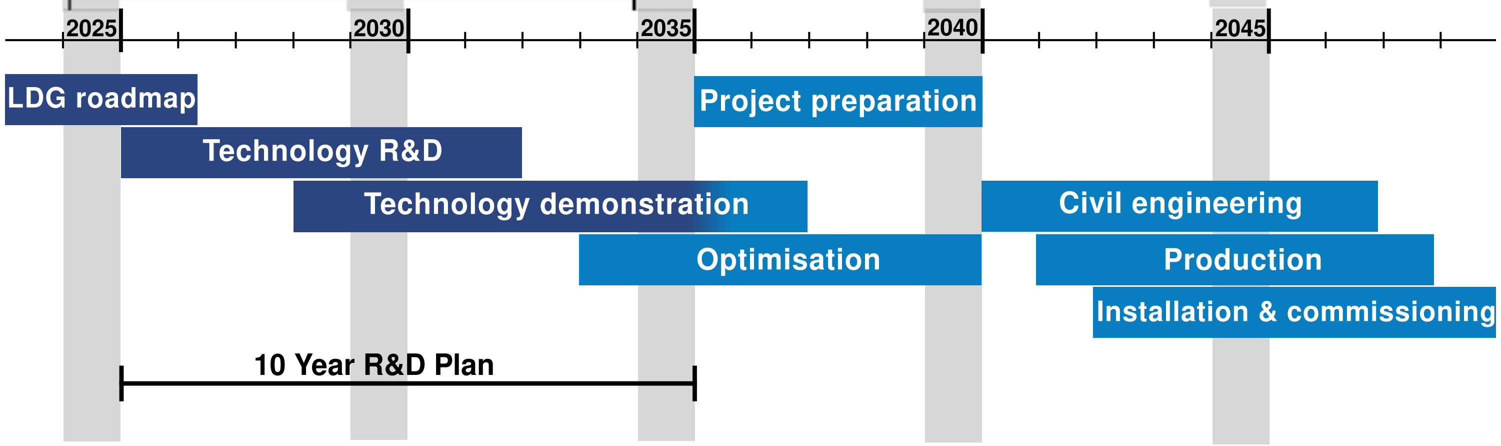




High gradient RF cavities required in muon cooling channels

Muon Cooling Demonstrator





Launch RF test stands and first module (700 MHz test stand) right away

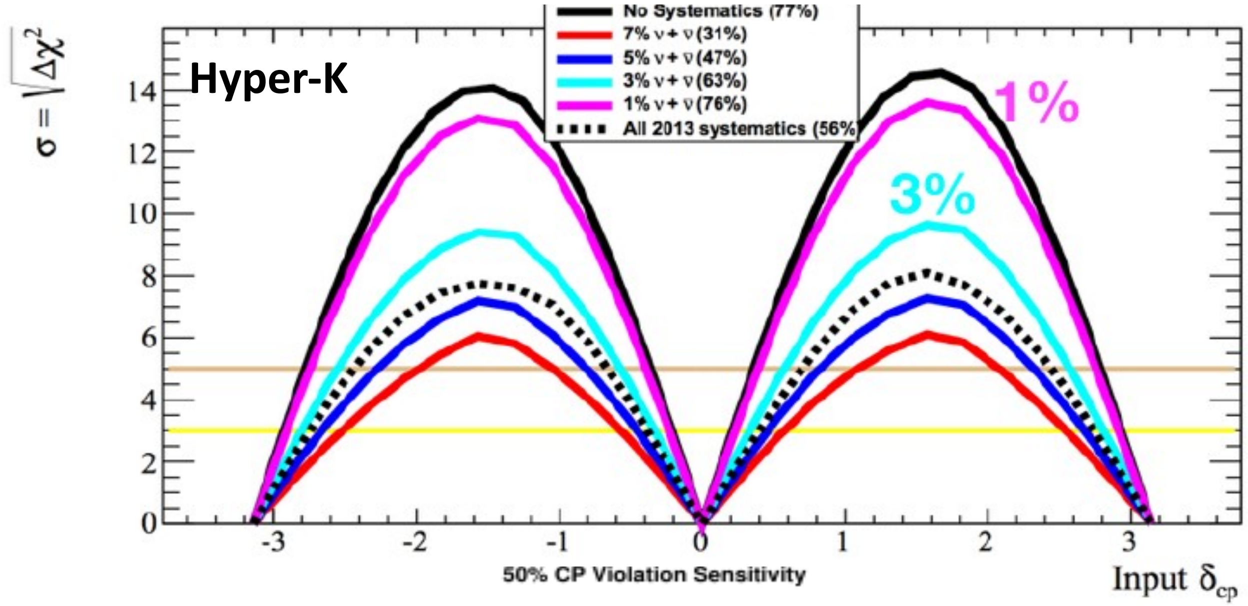
Important decision in 2028 on sharing of effort and demonstrator location

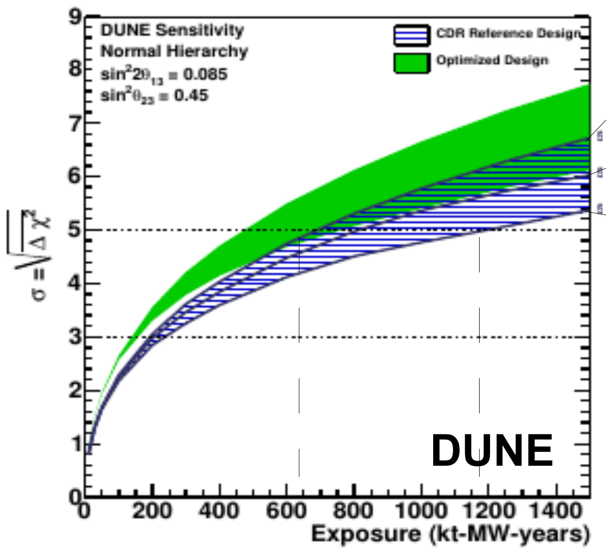
Two promising demonstrator site studies @ CERN

Fermilab site study started

Muon Cooling Demonstrator for neutrino low E xsec

Sensitivity of future Neutrino Oscillation Experiments





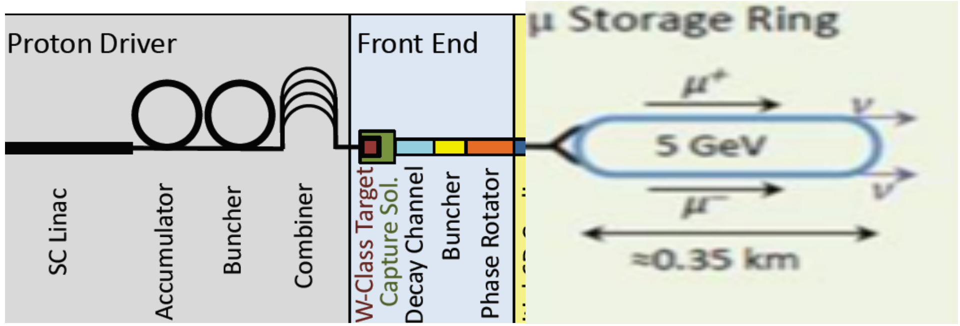
→ 5% ± 1%

→ 5% ± 2%

→ 5% ± 3%

→ equivalen to factor 2 in exposure!

First intense ν_e and $\overline{\nu}_e$ Beam in the word !!



$$+\quad \mu^+ \rightarrow e^+ \nu_e \overline{\nu}_\mu$$

$$\mu^- \rightarrow e^- \overline{\nu}_e \nu_\mu$$

- *neutrino beams via muon decay in the straight section of a storage ring.*
- Key advantages of generating neutrino beams from muon decays rather than meson decays are:
  - This enables precise measurements of ν_e, ν_μ, (anti)ν_e, and (anti) ν_μ.

Reflections on a multi-TeV Muon Collider

International
MUON Collider
Collaboration

- A unique innovative and never attempted project capable to reach the energy frontier in a sustainable design:
  - ➔ no showstoppers identified so far
  - ➔ many crucial challenging R&D required

- Despite the fact that available resources were not sufficient to cover all the proposed and approved plan prepared by the Accelerator R&D Roadmap
  - ➔ priorities were identified
  - ➔ great progresses pave the baseline design completion
  - ➔ 10 TeV lattice and MDI design allow to demonstrate with full simulation the huge physics potential
  - ➔ remarkable synergies on R&D technologies both for science and society
  - ➔ review are encouraging

- To accomplish the required R&D plan
  - ➔ the first set of prototyping and test must be accomplished
  - ➔ the collaboration has to be strengthed to provide more resources

Machine comparison flagship projects: Muon Collider

[Future Colliders Comparative Evaluation](#)

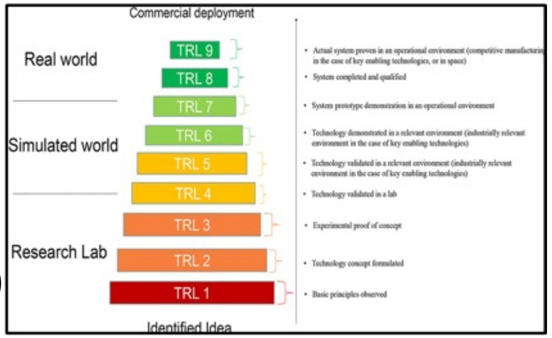
G. Arduini - Ph. Burrows

International MUON Collider Collaboration

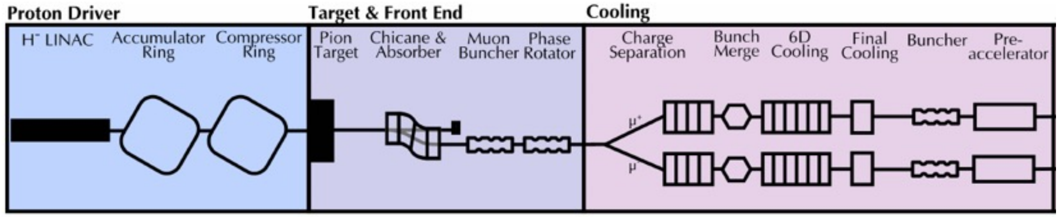
Technical Readiness Level: a standardized 9-level scale to measure how mature a technology is - from concept (TRL 1) to fully operational (TRL 9)

Cost-weighted average of TRL scores of the main subsystems to define the colour code (≥6, ≥4 and <6, <4) (FCC-ee costing assumptions as a reference)

Performance uncertainty: defined 3 ranges of luminosity uncertainty factors (<3, >3 and <10, >10)



- Together with FCC-hh, promises a potentially energy-efficient path toward high-luminosity collisions at 10 TeV pCM
- Not yet the level of maturity of the other ESPP2026 Large-Scale Project proposals assessed by WG2a



Project	Scope	TRL	R&D	Test facilities	Performance	Site preparation	Schedule	Cost	Risk
MC 3.2TeV,7.6TeV		3.2TeV: 3 - 5 7.6TeV: 2 - 5							

Table 15: Traffic light summary table for a MC.

CERN-specific muon collider parameters

Parameter	Symbol	unit	Scenario 1		Scenario 2	
			Stage 1	Stage 2	Stage 1	Stage 2
Centre-of-mass energy	E_{cm}	TeV	3.2	7.6	3.2	7.6
Target integrated luminosity	$\int \mathcal{L}_{target}$	ab^{-1}	1	10	1	10
Estimated luminosity	$\mathcal{L}_{estimated}$	$10^{34} cm^{-2}s^{-1}$	0.9	7.9	2.0	10.1
Collider circumference	C_{coll}	km	11	11	4.8	8.7
Collider arc peak field	B_{arc}	T	4.8	11	11	14
Collider dipole technology			NbTi	Nb_3Sn or HTS	Nb_3Sn	HTS

Scope level-of-definition: Preliminary WBS developed, project scope cannot support translation into an engineering design, at this stage

TRL, R&D, test-facilities: 6D Cooling demonstrator is a crucial milestone

- A **number of technological challenges** in the demonstrator and accelerator chain.

Final comments and step forward

International MUON Collider Collaboration

- A multi-TeV Muon Collider is an **extremely challenging but promising future project**:
  - ✓ outstanding physics potential
  - ✓ advanced concept design, still demanding for R&D on technology frontiers
  - ✓ demonstrate muon cooling technology in stages is critical for timeline
  - ✓ invaluable training on physics, accelerator and detector studies
  - ✓ ready to exploit synergies on physics and technologies with other projects

    but also enabling societal applications (i.e. HTS magnets for fusion reactors, wind power generators, motors, material science, health applications)

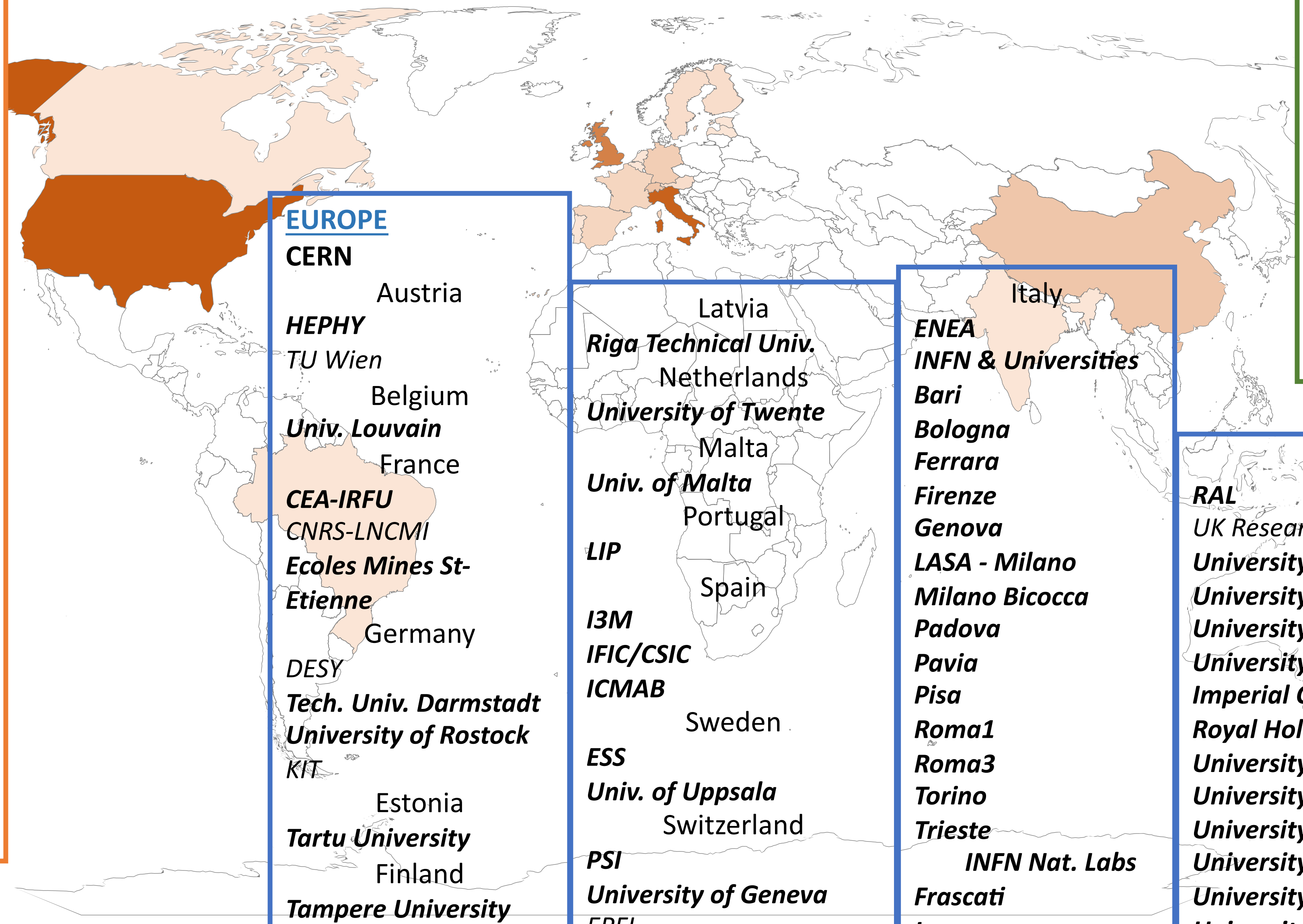
- **Update of the European Strategy for Particle Physics by the CERN Council** by May 2026
- Expected final deliberations on **future project approval** by the CERN Council by 2028

- Bright muon beams are an open new field to explore!

Thanks to many colleagues!

Thanks you all for the attention!

IMCC Countries and Institutes



AMERICA

Canada

Université Laval

U.S.A.

Iowa State University
University of Iowa
Wisconsin-Madison
University of Pittsburgh
Old Dominion
Chicago University
Florida State University
RICE University
Tennessee University
MIT Plasma science center
Pittsburgh PAC
Princeton
Stony Brook
Stanford/SLAC
Yale
FNAL
LBNL
JLAB
BNL

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University of CAS

Korea

Kyungpook National University
Yonsei University
Seoul National University

India

CHEP

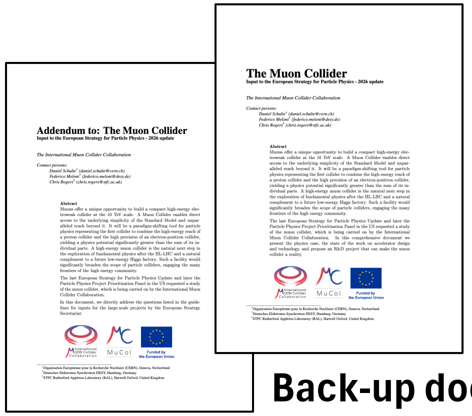
Signed MoC (61)
or *requested MoC* contributor

Muon Collider - Input Documents @ ESPPU

Submitted Input 5+1/266

207. The Muon Collider

207-Update-ESPPU_MuonCollider_v02.pdf
207-Update-ESPPU_MuonCollider_Addendum_v03.pdf
ESPPU_Muon_Collider_Backup.pdf



Back-up document
(406p, 450 signatories)

152. United States Muon Collider Community White Paper for the ESPPU

105. Magnet R&D for the Muon Collider

32. Performance study of the MUSIC detector in $\sqrt{s}$ = 10 TeV muon collisions

184. Sensitivity study on H→ $b\bar{b}$, H→ WW^* and H H → $b\bar{b}b\bar{b}$ cross sections and trilinear Higgs self-coupling with the MUSIC detector in $\sqrt{s}$ = 10 TeV muon collisions

251. Physics opportunities with high-brightness, high-intensity muon beams at CERN: a staged approach

Higgs physics - Lepton Photon - August 2025 -

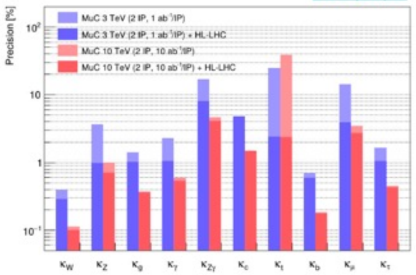
International MUON Collider Collaboration

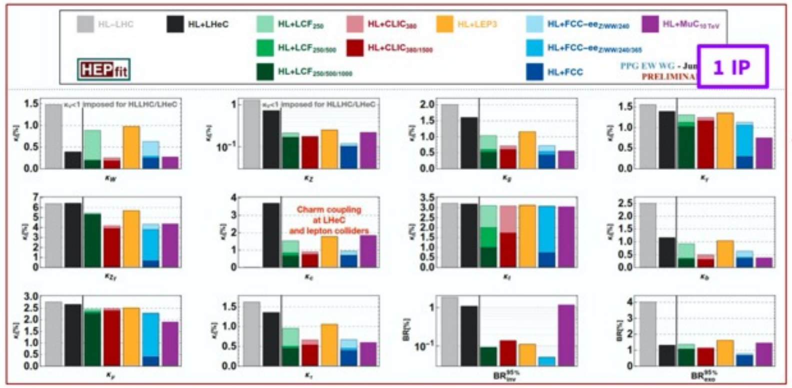
Higgs couplings overview

- Higgs couplings at 3 and 10 TeV are evaluated using parametric simulations, tuned on the detailed simulation results
- percent to permille precisions reached for 1 ab^{-1} at $\sqrt{s}$ = 3 TeV and 10 ab^{-1} at $\sqrt{s}$ = 10 TeV

How does it compare to other Future Colliders?

JHEP08(2022)185





All reported MuC results are evaluated as 1 IP, while FCC-hh as 2 IPs. For an equal comparison, MuC results are to be scaled for the doubled statistics.

from J. de Blas talk at the ESPPU Open Symposium

9

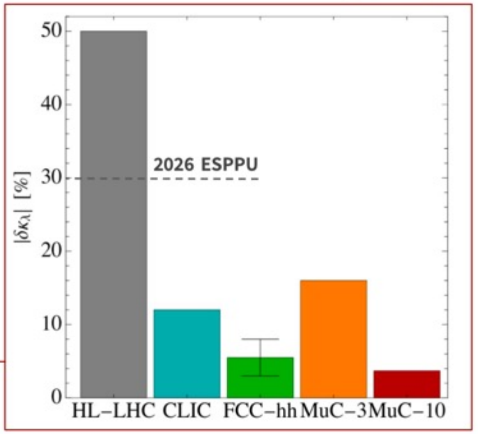
√s = 10 TeV Muon Collider would open the possibility of studying the Higgs sector with unprecedented accuracy, thanks to its large sample of single and double Higgs events, achievable in just 5 years of data taking

Detailed simulation studies to evaluate achievable results in presence of the main Beam Induced Background

Higgs trilinear self-coupling overview

arXiv:2504.21417

- The Higgs trilinear coupling at 3 and 10 TeV was evaluated using parametric simulations
  - ↳ tuned to previous detector performance, will be updated with improved results
- percent-level precision achievable in 5 years of operation
- compares well with the detailed simulation result
  - ↳ the detailed study of HH→bbWW* will be added soon



The reported MuC results is evaluated as 1 IP, while FCC-hh as 2 IPs. For an equal comparison, MuC result is to be scaled for the doubled statistics.

A 10 TeV Muon Collider is the only machine able to obtain a percent-level precision in the measurement of λ_3 in such a short time of operation

12

Cost and Power Scale

Design of collider and components advanced enough to estimate cost and power

Cost and power estimates based on conceptual designs
and scaling from know components

More work to be done

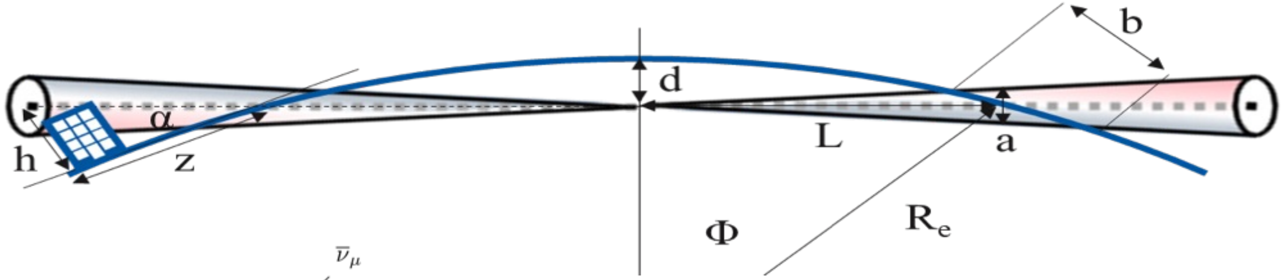
- Overall optimization
- Further R&D to reduce cost uncertainty (i. e. HTS solenoids)

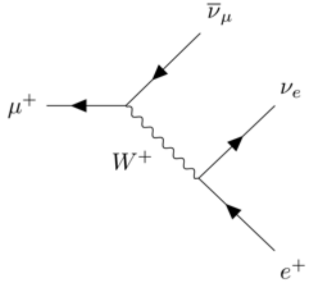
	Unit	3.2 TeV	7.6 TeV
Operation power	MW	117	182
Energy consumption	TWh	0.53	0.82
Stand-by power	MW	73	111
Energy consumption	TWh	0.09	0.14
Off state power	MW	58	69
Energy consumption	TWh	0.17	0.21
Yearly energy consumption	TWh	0.8	1.2

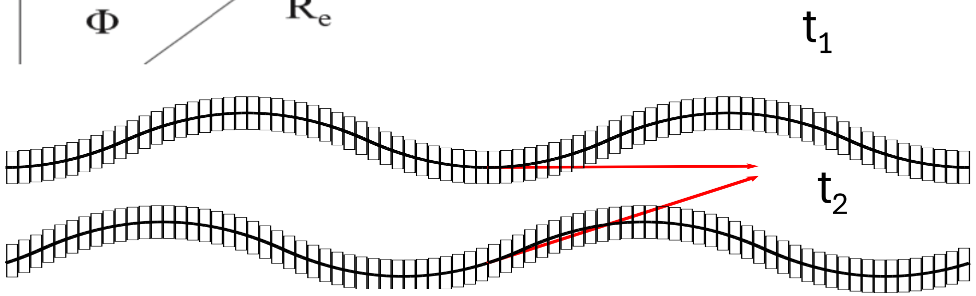
Placement Studies

Challenge:
Obtain negligible neutrino flux

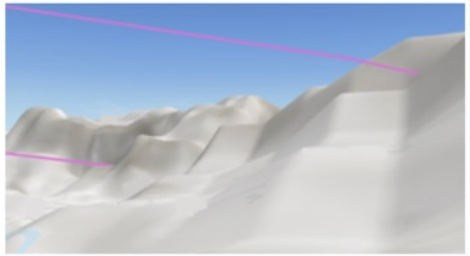
Achieved:
- Detailed modelling
- First good orientation found
- Mover system concept

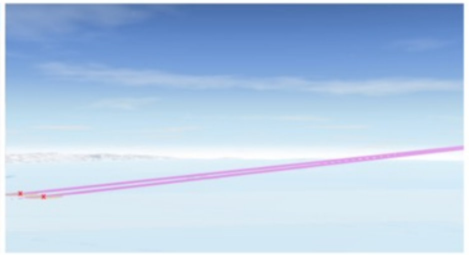




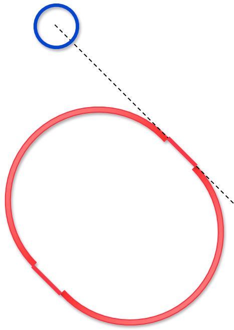


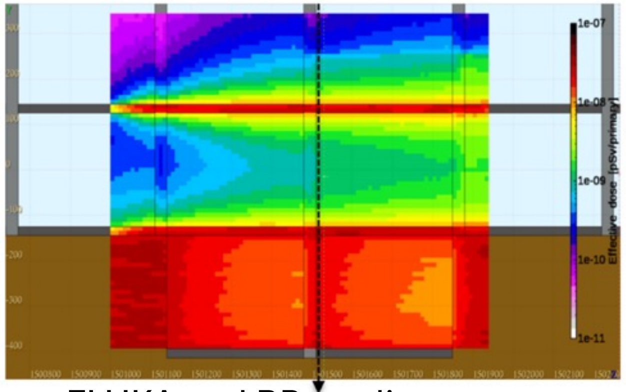
Arc mitigation concept

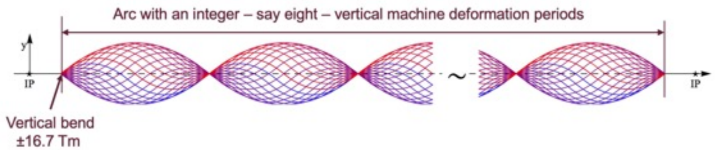




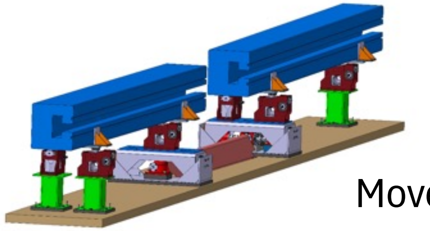

Site study at CERN for experimental insertion

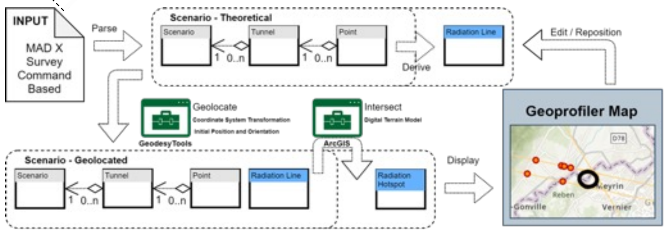



FLUKA and RP studies



Beam studies

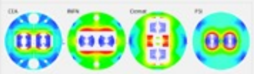
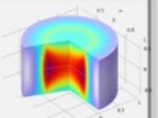
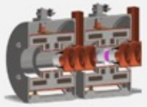
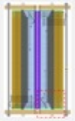
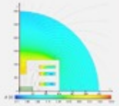
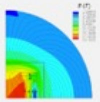

Mover system design



Key conclusions:
- Are close to a solution
- More work to be done
- Expand to all systems

Magnet R&D Impact

Luca Bottura

	HEP and NP 	High-field science 	NMR 	MRI	Fusion 	Motors/generators 
TM1 20@20 	→	**High field, low consumption**	→	→	**High-field, large bore and large stored energy**	
TM2 SOLID 	→	**High field, low consumption**	→	**High-field large bore, cryo-free technology**		
TM3 UHF-DEMO 	**FCC-ee, CLIC (e+ source)**	**Ultra-high-field**	**Ultra-high-field**	→	→	**High-field, compact windings**
TM4 RCS-String	→	**High pulsed power and energy recovery**	→	→	**High pulsed power and energy recovery**	
TM5 MBHY	**FCC-hh, SppC**					
TM6 MBHTS 	**FCC-hh, SppC**	→	→	→	→	**3D, compact pole winding**
TM7 MBHTSY 	**FCC-hh, SppC**	→	→	→	→	**3D, compact pole winding**
TM8 MQHTSY	**FCC-hh, SppC**	→	→	→	→	**3D, compact pole winding**

R&D Impact Examples

- **Fusion for Energy** (ITER EU Domestic Agency)
  - Framework agreement and first addendum in final negotiation
  - Contribution to the design of the HTS target solenoid, relevant to the central solenoid of DTT
- **EUROFusion** (next step European fusion reactor)
  - Framework agreement signed in 2023, first addendum signed in 2024
  - Contribution to the design of the HTS target solenoid, relevant to the magnets of a Volumetric Neutron Source proposed as next step in the European fusion strategy
- **Gauss Fusion** (one of the leading EU fusion start-ups)
  - Consultancy agreement signed in 2023
  - CERN contribution to the design of the LTS/HTS GIGA stellarator magnets, based on advances in the HTS target solenoid
- **ENI** (oil and gas energy giant)
  - Framework agreement and first addendum signed in 2024
  - Collaboration on the conceptual design and project proposal for the CERN construction of a large bore HTS solenoid (20@20 model coil) relevant to the muon collider and fusion
- **Infineon Technologies Bipolar** (world leader bipolar high-power semiconductors, focus on green grid)
  - IFAST-2 proposal to **INFRA-2025-TECH-01-02** (CERN, INFINEON, PSI)
  - Proposal of fast pulsed power cell + magnet system sent to IFAST-2 coordination for ranking at TIARA
  - Industrial interest in rapidly pulsed and large energy/power supplies