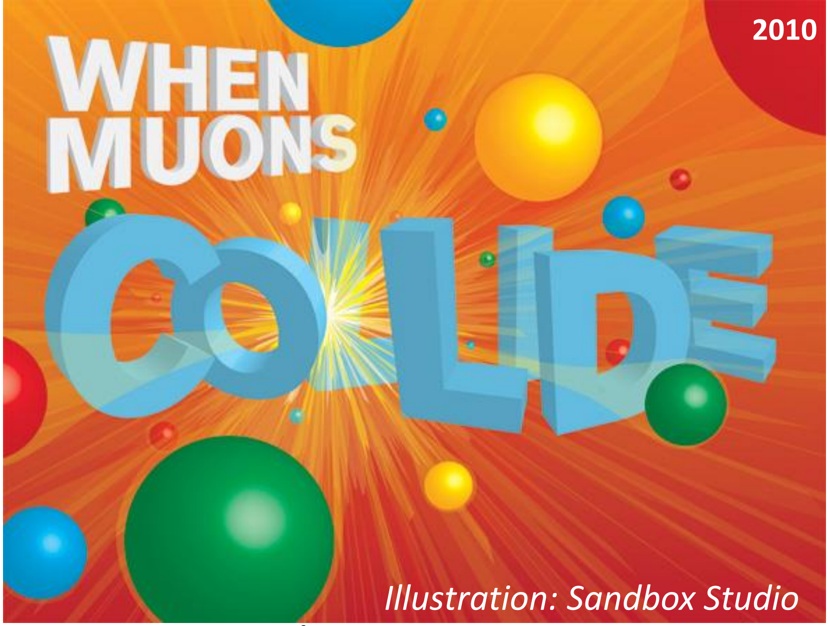


www.symmetrymagazine.org

Napoli Seminar
June 6, 2022

Muon Colliders
a challenging opportunity

Nadia Pastrone
INFN TORINO

International MUON Collider Collaboration

Thanks to many colleagues in Italy, EU, USA

Input to EU Strategy of Particle Physics

European Strategy Update

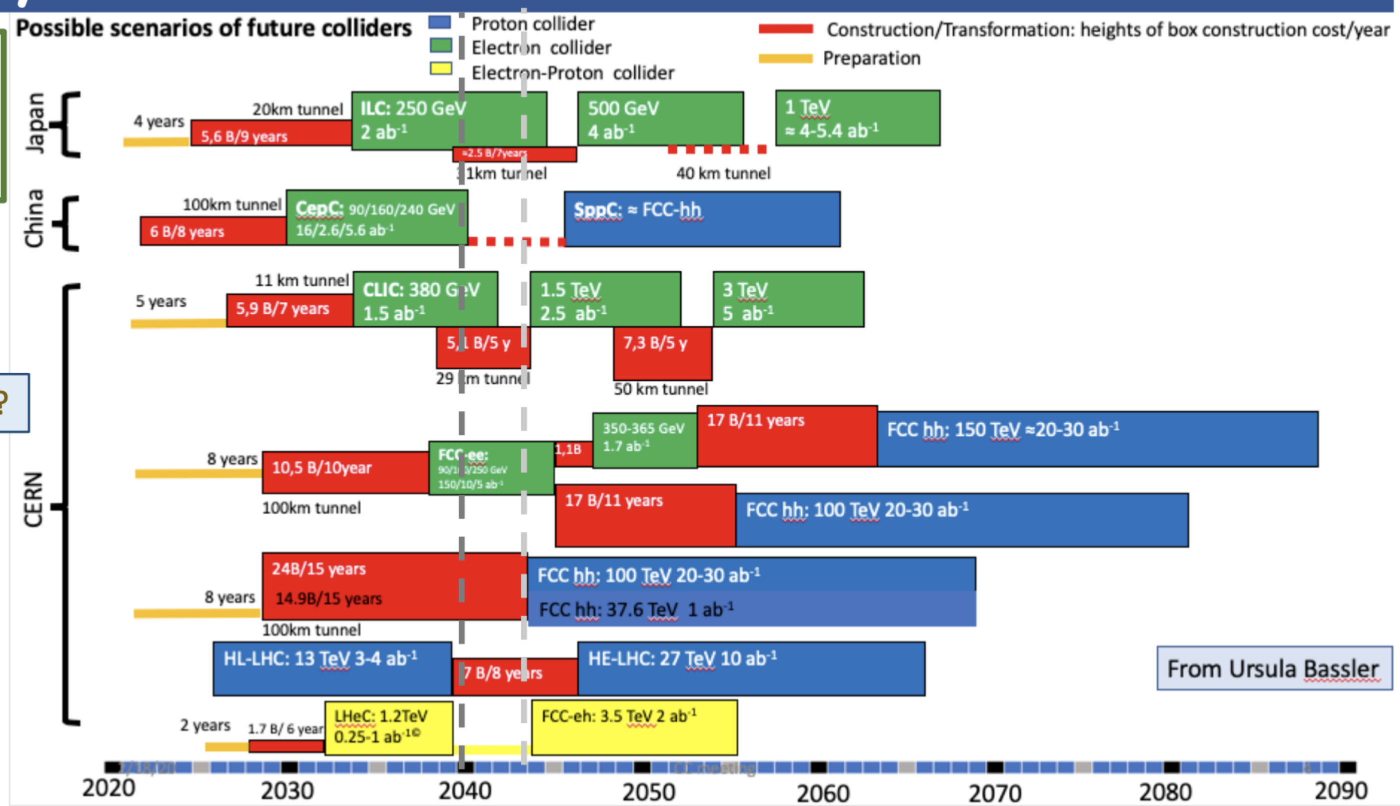
2020 Strategy Update

Halina Abramowicz

High-priority future initiatives

Map of possible future facilities submitted as input to the Strategy Update

Where is the muon collider?



Input Document to EU Strategy Update - Dec 2018:

"Muon Colliders," [arXiv:1901.06150](https://arxiv.org/abs/1901.06150)

by *CERN-WG on Muon Colliders*

J.P. Delahaye et al.

High-energy Frontier Proposals

European Strategy Proces: finished 2020

Four main high-energy facilities proposed:
- two at CERN
- two in Asia

FCC (Future Circular Collider):

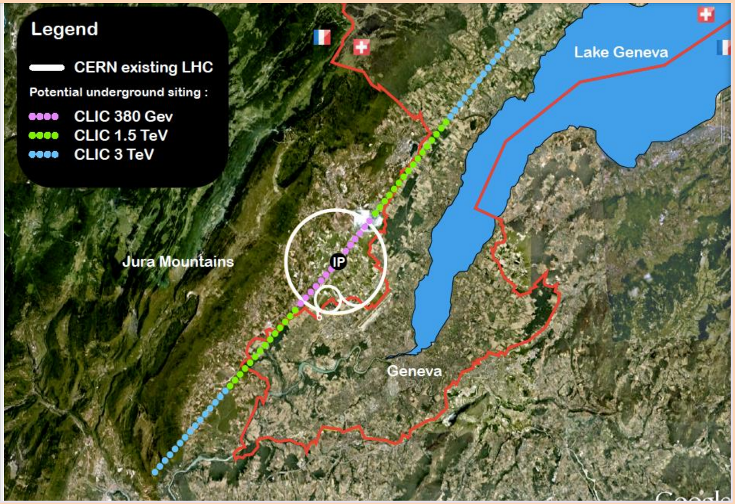
FCC-hh
- pp collider @ 100 TeV
- ion option

FCC-ee
- Potential e^+e^- first stage

FCC-eh
- additional option

ILC
- 250 GeV electron-positron linear collider
- Japan might host
- limited in energy reach

CLIC
- 380 GeV, 1.5 TeV and 3 TeV electron positron collider



CEPC / SppC

CEPC
- e^+e^- collider 90-240 GeV

SppC
- 75-150 TeV hadron collider later – same tunnel

2020 Update of the European Strategy for Particle Physics

19 June 2020 [10.17181/CERN.JSC6.W89E](https://doi.org/10.17181/CERN.JSC6.W89E)

- Ensure Europe's continued **scientific and technological leadership**
- **Strengthen the unique ecosystem of research centres in Europe**

3 High-priority future initiatives

- **An electron-positron Higgs factory is the highest-priority next collider**.
  For the longer term, the European particle physics community has the **ambition to operate a proton-proton collider** at the highest achievable energy.
  These compelling goals will require **innovation and cutting-edge technology:**
  - ✓ ramp up R&D on advanced accelerator technologies, in particular **high-field superconducting magnets**, **including high-temperature superconductors**
  - ✓ investigate the **technical and financial feasibility of a future hadron collider at CERN** with a centre-of-mass energy of at least **100 TeV** and **with an electron-positron Higgs and electroweak factory as a possible first stage**
  - ✓ the ILC in Japan would be compatible with this strategy
- The European particle physics community must **intensify accelerator R&D** and sustain it with adequate resources. **A roadmap should prioritise the technology**

Muon Collider Working Group

*Jean Pierre Delahaye, CERN, Marcella Diemoz, INFN, Italy, Ken Long, Imperial College, UK, Bruno Mansoulie, IRFU, France, **Nadia Pastrone, INFN, Italy (chair)**, Lenny Rivkin, EPFL and PSI, Switzerland, Daniel Schulte, CERN, Alexander Skrinsky, BINP, Russia, Andrea Wulzer, EPFL and CERN*

appointed by CERN Laboratory Directors Group in September 2017
to prepare the Input Document to the European Strategy Update
"Muon Colliders," **arXiv:1901.06150**

de facto was the seed for a renewed international effort till 2020
with the crucial contribution of many INFN colleagues

FINDINGS and RECCOMENDATIONS:
Set-up an international collaboration to promote muon colliders
and **organize the effort on the development of both accelerators and detectors**
and to define the road-map towards a CDR by the next Strategy update….
Carry out the R&D program toward the muon collider

Past experiences and new ideas discussed at the joint ARIES Workshop
July 2-3, 2018 - Università di Padova - Orto Botanico
https://indico.cern.ch/event/719240/overview

EU Strategy ➔ Accelerator R&D Roadmap

European **Strategy Update – June 19, 2020**:

3 High-priority future initiatives

High-priority future initiatives [..]

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

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

CERN Laboratory Directors Group (LDG) established an Accelerator R&D roadmap

to define a route towards implementation of the goals of the 2020 ESPPU bringing together the capabilities of CERN and the LNLs to carry out R&D and construction and operation of demonstrators

The compelling physics reach justifies establishment of an international collaboration to develop fully the muon collider design study and to pursue R&D priorities, according to an agreed upon work plan.

To facilitate implemention of the European Strategy LDG decided (July 2 2020) to:

Agree to start building the collaboration for international muon collider design study

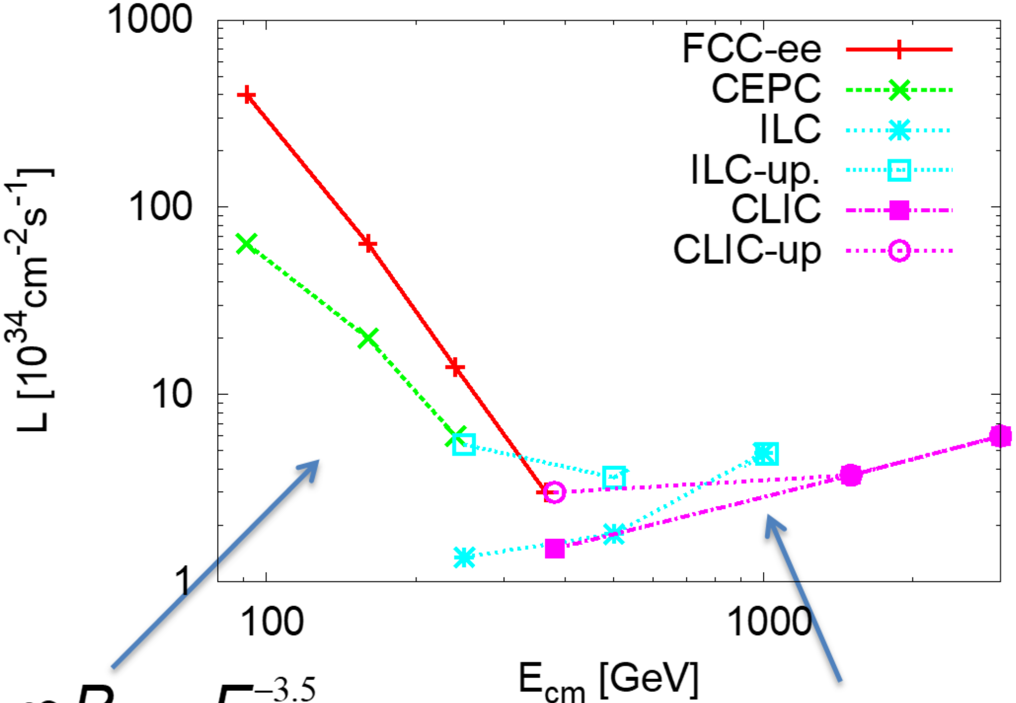
➔ **International Muon Collider Collaboration kick-off virtual meeting**

(>260 participants) https://indico.cern.ch/event/930508/

July 3rd, 2020

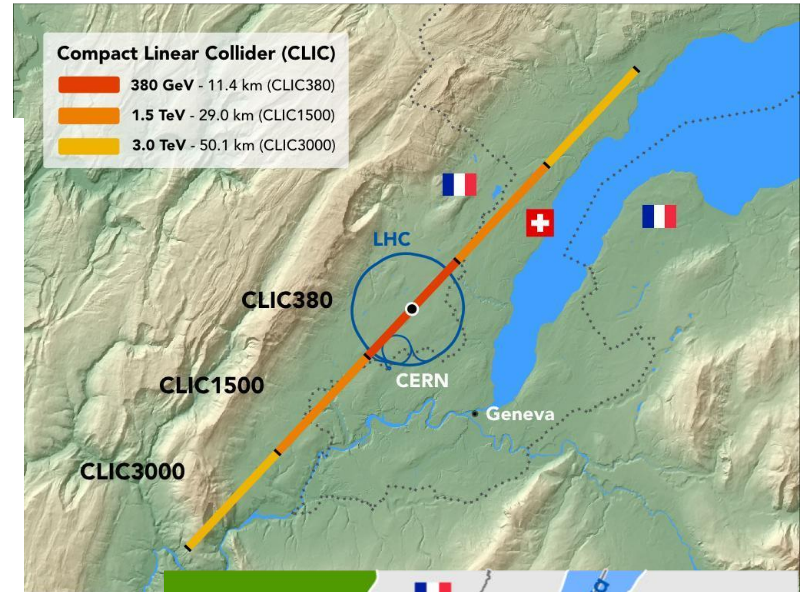
Linear vs Circular lepton e^+e^- collider

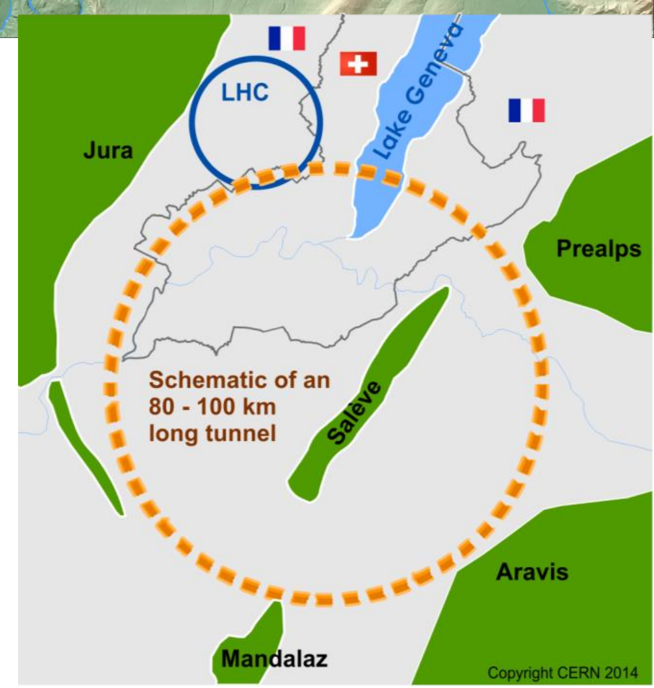
Luminosity per facility



$L \propto P_{synrad} E_{cm}^{-3.5}$

$L \propto P_{RF} E_{cm}$





CLIC at 3 TeV has been optimised over decades:
18 GCHF, 590 MW power consumption

Muon beams specific properties

Muons are leptons with mass (105.7 MeV/c^2) 207 times larger than $e^{\pm}$

➔ **Negligible synchrotron radiation emission ($\propto m^{-4}$)**

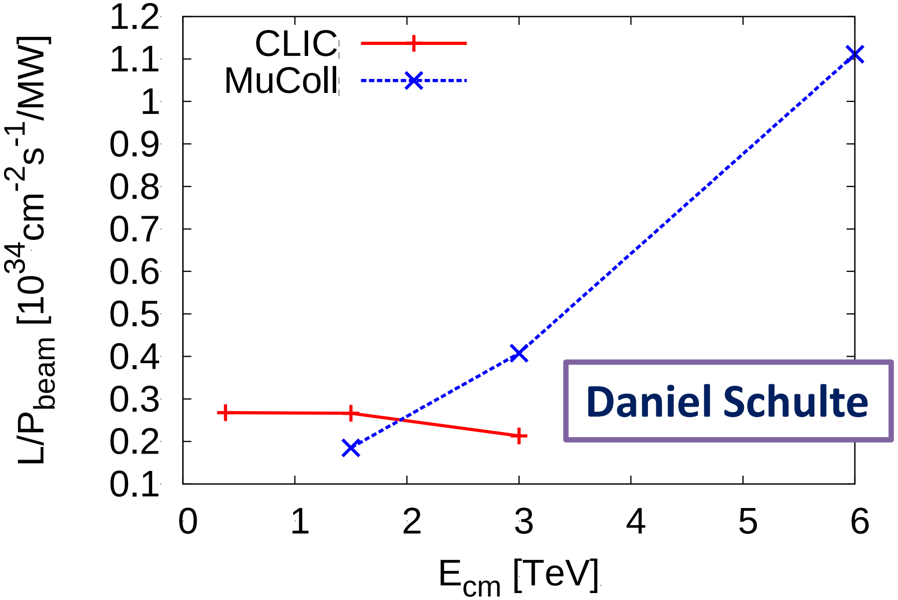
- **Multi-pass collisions (1000 turns) in collider ring:**
  - **High luminosity with reasonable beam power and wall plug power needs**
    - **relaxed beam emittances & sizes, alignment & stability**
  - **Multi-detectors supporting broad physics communities**
  - **Large time (15 ms) between bunch crossings**
- **No beam-strahlung at collision:**
  - **narrow luminosity spectrum**
- **Multi-pass acceleration in rings or RLA:**
  - **Compact acceleration system and collider**
  - **Cost effective construction & operation**
- **No cooling by synchrotron radiation in standard damping rings**
  - **Requires development of novel cooling method**

Why a multi-TeV Muon Collider?

cost-effective and unique opportunity

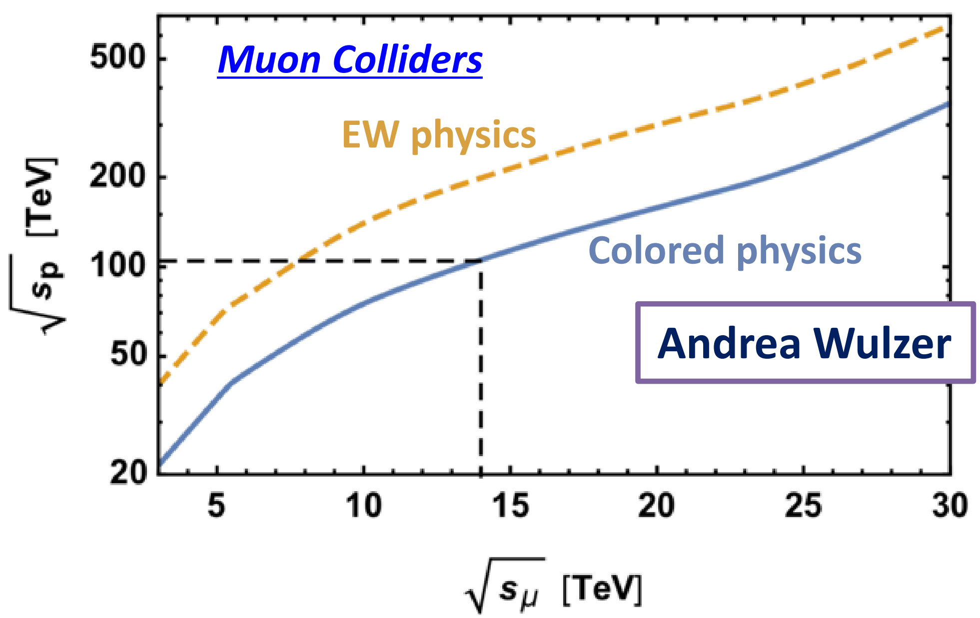
for lepton colliders @ Ecm > 3 TeV

Energy Efficiency



sufficient luminosity required

Energy at which $\sigma_{pp} = \sigma_{\mu\mu}$



Strong interest to reuse existing facilities and infrastructure (i.e. LHC tunnel) in Europe

Muons: Issues & Challenges

– Limited lifetime: 2.2 μs at rest

- **Race against death: fast generation, acceleration & collision before decay**
- ☹ **Muons decay in accelerator and detector**
  - – **Physics feasibility with large background?**
  - – **Shielding of detector and facility irradiation**
- **Decays in neutrinos:**
  - – **Ideal source of well defined electron and muons neutrinos in equal quantities :**

☺

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

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

The neutrino factory concept

☹ » **Limitation in energy reach by neutrino radiation**

– Generated as tertiary particles in large emittances

☹
- – **powerful MW(s) driver**
- – **novel cooling method (6D 10^6 emittance reduction)**

☺ **Development of novel ideas and technologies with key accelerator and detector challenges!**

A unique facility

Jan 2021 **nature physics**

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

K.Long, **D.Lucchesi**, M.Palmer, **N.Pastrone**, D.Schulte, V. Shiltsev

an idea over 50 years old has now the opportunity to become feasible

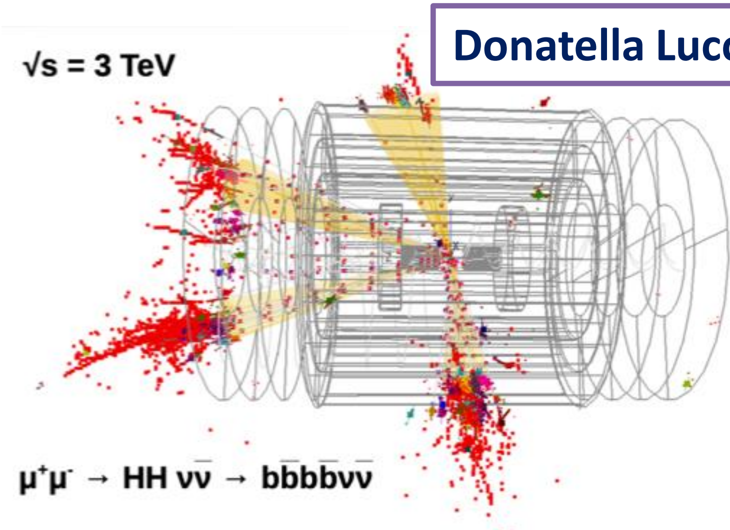
ESPP Input document: [Muon Colliders](#)

Muons – fundamental particles – leptons ~ 200 times heavier than electron decay with lifetime at rest of 2.2 μs

Overwhelming physics potential:

- **Precision measurements**
- **Discovery searches**

Donatella Lucchesi et al.



Challenging Facility Design:

- **Key issues/risks**
- **R&D plan - synergies**

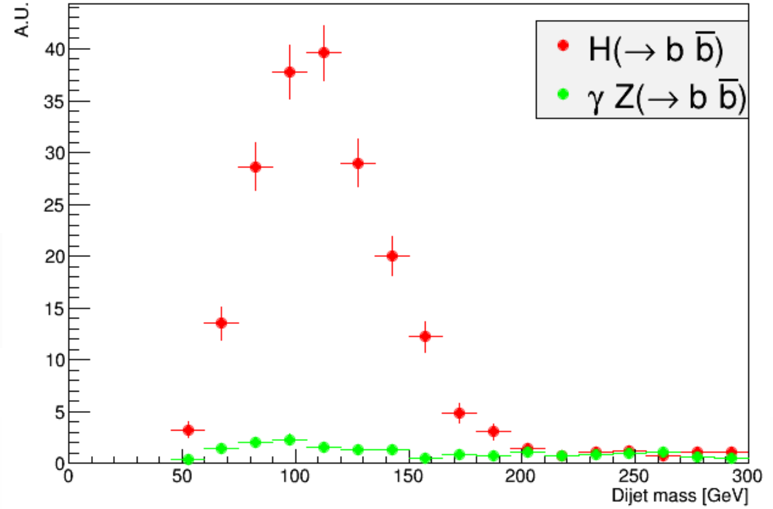
cost effective ➔ need real study to confirm cost
power efficient ➔ need a more detailed study
compact site ➔ more with better ramping magnets

Different phyiscs benchmark simulated with Beam-Induced Background at 3 TeV to demonstrate feasibility and physics potential reach

$H \to bb$ @ 1.5 TeV

JINST 15 (2020) 05, P05001

D. Lucchesi et al.



$\mu^+\mu^- \to H\nu\bar{\nu} \to b\bar{b}\nu\bar{\nu}$ + beam-induced background fully simulated

Higgs $b\bar{b}$ Couplings Results

- The instantaneous luminosity, $\mathcal{L}$, at different √s is taken from MAP.
- The acceptance, A, the number of signal events, N, and background, B, are determined with simulation.

$\sqrt{s}$ [TeV]	A [%]	ϵ [%]	$\mathcal{L}$ [cm^{-2}s^{-1}]	$\mathcal{L}_{int}$ [ab^{-1}]	σ [fb]	N	B	$\frac{\Delta\sigma}{\sigma}$ [%]	$\frac{\Delta g_{Hbb}}{g_{Hbb}}$ [%]
1.5	35	15	$1.25 \cdot 10^{34}$	0.5	203	5500	6700	2.0	1.9
3.0	37	15	$4.4 \cdot 10^{34}$	1.3	324	33000	7700	0.60	1.0
10	39	16	$2 \cdot 10^{35}$	8.0	549	270000	4400	0.20	0.91

	$\sqrt{s}$ [TeV]	$\mathcal{L}_{int}$ [ab^{-1}]	$\frac{\Delta g_{Hbb}}{g_{Hbb}}$ [%]
Muon Collider	1.5	0.5	1.9
	3.0	1.3	1.0
	10	8.0	0.91
CLIC	0.35	0.5	3.0
	1.4	+1.5	1.0
	3.0	+2.0	0.9

CLIC numbers are obtained with a model-independent multi-parameter fit performed in three stages, taking into account data obtained at the three different energies.

Results published on JINTST as Detector and Physics Performance at a Muon Collider

International Collaboration

Project Leader: *Daniel Schulte*

Objective:
In time for the next European Strategy for Particle Physics Update, the Design Study based at CERN since 2020 aims to **establish whether the investment into a full CDR and a demonstrator is scientifically justified**.
It will **provide a baseline concept**, well-supported performance expectations and assess the associated key risks as well as cost and power consumption drivers.
It will also **identify an R&D path to demonstrate the feasibility of the collider**.

Scope:

- Focus on the high-energy frontier and two energy ranges:
  - **3 TeV** if possible with technology ready for construction in 10-20 years
  - **10+ TeV** with more advanced technology, **the reason to choose muon colliders**
- Explore synergies with other options (neutrino/higgs factory)
- Define **R&D path**

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

Physics potential

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

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, …

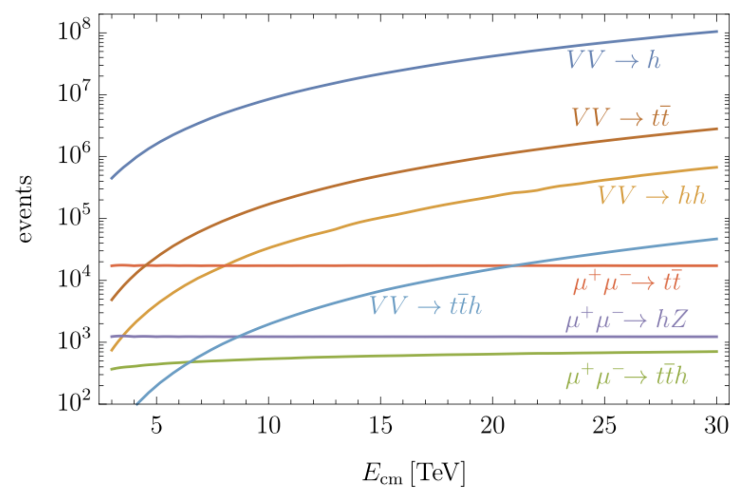
Muon physics
Lepton Flavor Universality, b → sμμ, muon g-2, …

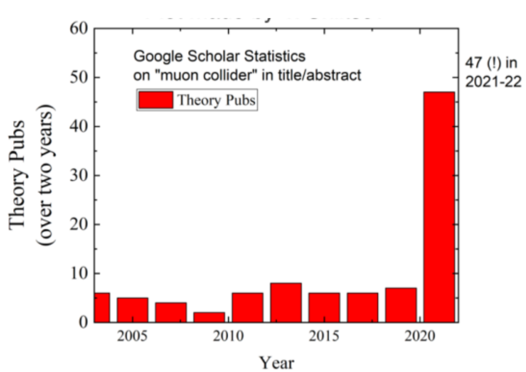
Muon Collider can be the game changer!

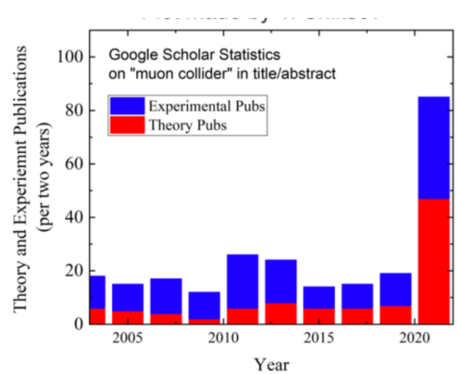
Great and growing interest in the theory community ➔ many papers recently published, as:

The Muon Smasher's Guide,
https://doi.org/10.48550/arXiv.2103.14043

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**



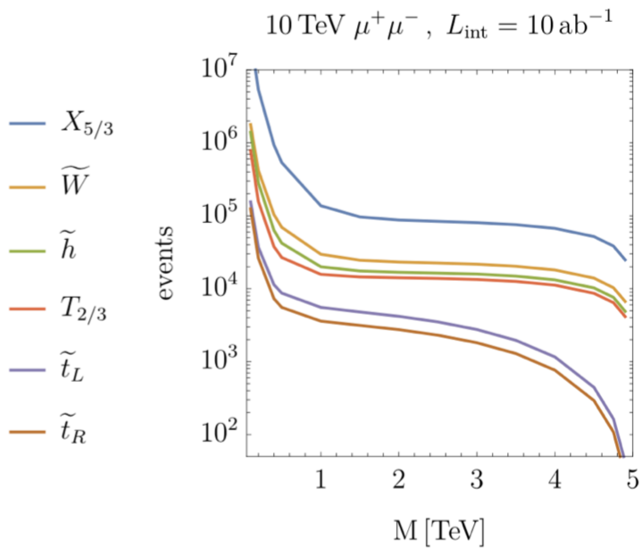


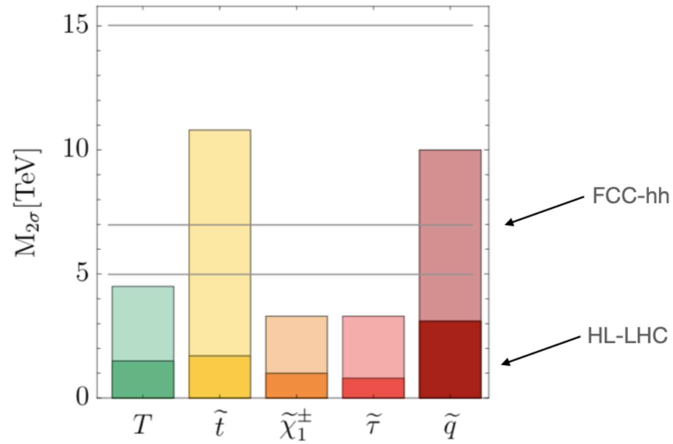


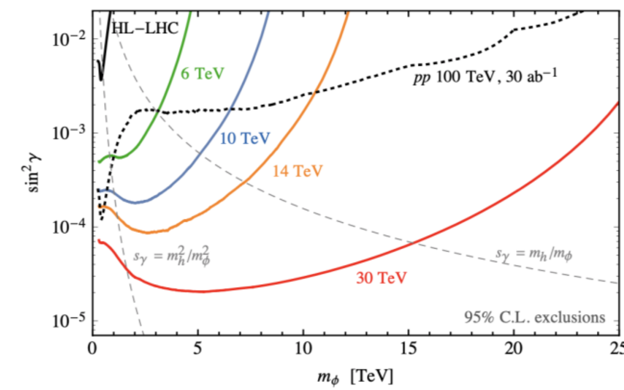
Physics reach in a nutshell

arXiv:2203.07256 **Muon Collider Physics Summary**

arXiv:2203.07261 **The physics case of a 3 TeV muon collider stage**







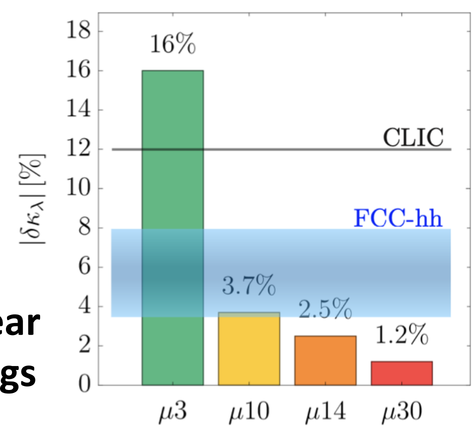
Exclusion contour for a scalar singlet of mass mϕ mixed with the Higgs boson with strength sin γ

Higgs coupling sensitivities k-framework

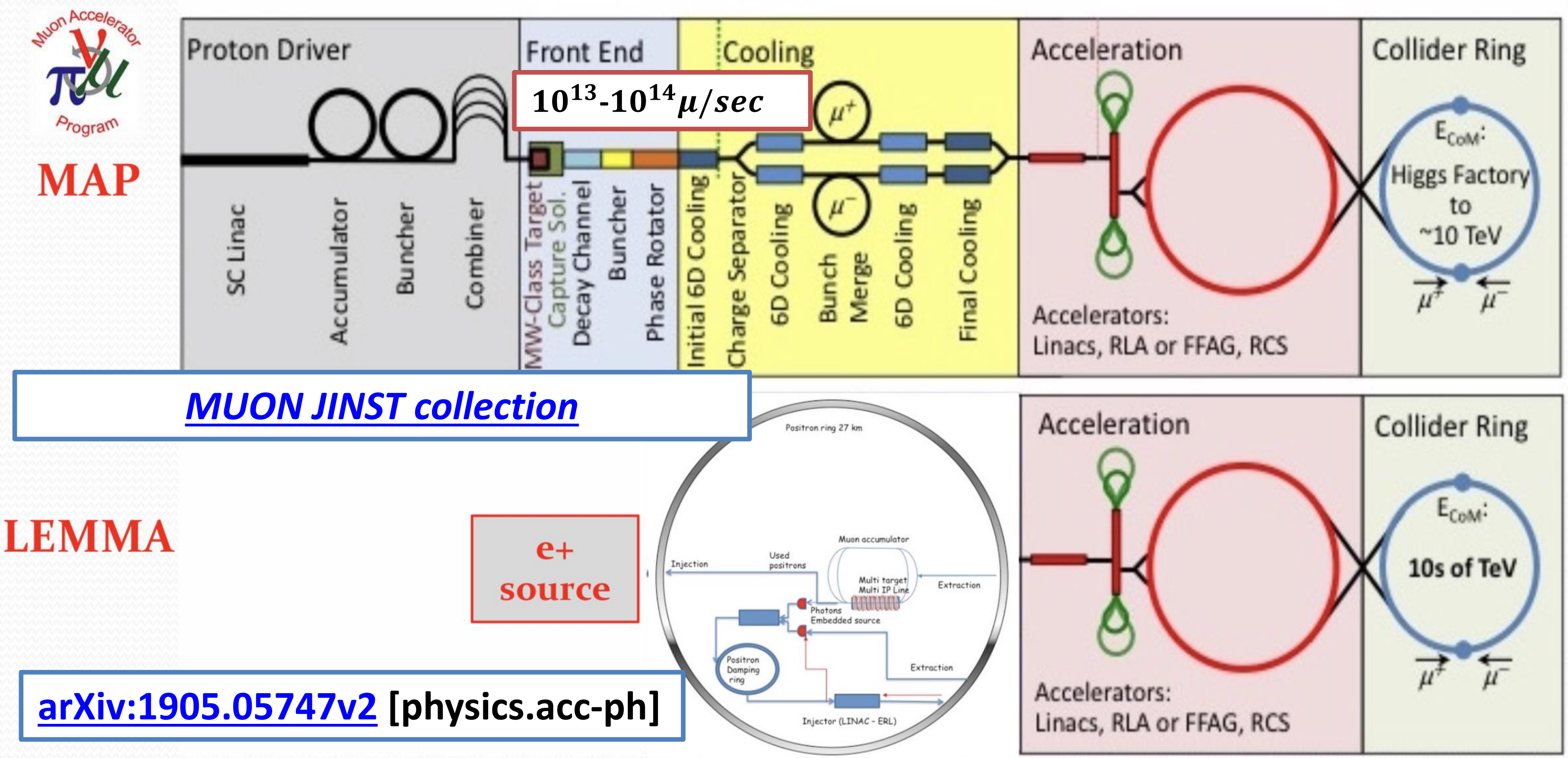
	HL-LHC	HL-LHC +10 TeV	HL-LHC +10 TeV + *ee*
κ_W	1.7	0.1	0.1
κ_Z	1.5	0.4	0.1
κ_g	2.3	0.7	0.6
κ_γ	1.9	0.8	0.8
κ_c	-	2.3	1.1
κ_b	3.6	0.4	0.4
κ_μ	4.6	3.4	3.2
κ_τ	1.9	0.6	0.4
$\kappa_{Z\gamma}^*$	10	10	10
κ_t^*	3.3	3.1	3.1

* No input used for μ collider

Higgs trilinear self-couplings



proton (MAP) vs positron driven muon source



MUON JINST collection

arXiv:1905.05747v2 [physics.acc-ph]

LEMMA: main idea
Low EMittance Muon Accellerator

M. Antonelli and P. Raimondi, Snowmass Report (2013) - INFN-13-22/LNF Note

POSITRON DRIVEN MUON SOURCE : direct μ pairs production

Muons produced from $e^+e^- \rightarrow \mu^+\mu^-$ at the $\mu^+\mu^-$ threshold @ $\sqrt{s} \approx$ **0.212 GeV**

Asymmetric collisions maximize the $\mu^+\mu^-$ pairs production cross section and minimize the $\mu^+\mu^-$ beam angular divergence and energy spread

- ➔ **45 GeV positron beam impinging on a target** (e^- at rest)
- ➔ $\mu^+\mu^-$ produced **@ ~22 GeV** with low transverse emittance with $\gamma(\mu) \approx$**200** and μ laboratory **lifetime** of about **500 μs**

Aimed at obtaining high luminosity with relatively small $\mu^\pm$ fluxes thus reducing background rates and activation problems due to high energy $\mu^\pm$ decays

Extremely promising

1) muon produced with low emittance ➔ “no/low cooling” needed
2) muon produced already boosted with low energy spread

But difficult

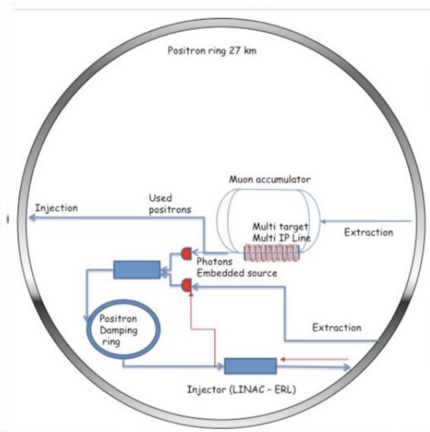
1) **Low** production **cross section**: maximum $\sigma(e^+e^- \rightarrow \mu^+\mu^-) \sim 1\ \mu$b
2) **Low** prodution **efficiency** ($\sim 9\times 10^{-8}$ μ per e^+ using a 3 mm Be target)
3) **Bremsstrahlung** (high Z → Z^2) & **multiple scattering** ($\sqrt{X_0}$) in production target
4) **High heat load** and **stress** in μ production target
5) **Synchrotron power** O(100 MW) 🡰 available 45 GeV positron sources

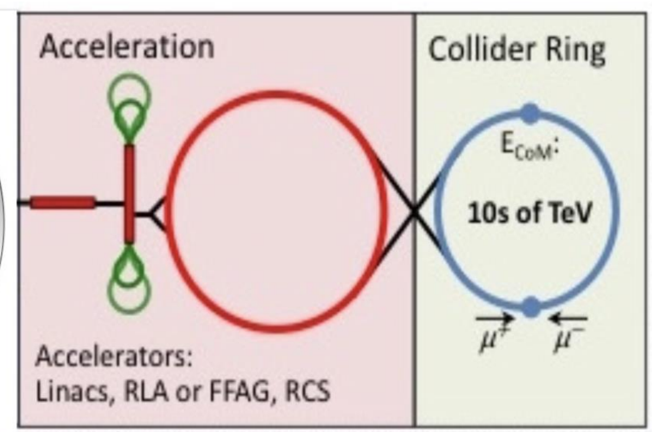
➔ **need consolidation** to overcome technical limitations to reach higher muon intensities
➔ **LEMMA pre-CDR plan** presented to INFN GE by Alessandro Variola October 2019

LEMMA

arXiv:1905.05747

e+ source





Alternative idea

Camilla Curatoro e Luca Serafini

Appl. Sci. **2022**, *12*(6), 3149;
https://doi.org/10.3390/app12063149

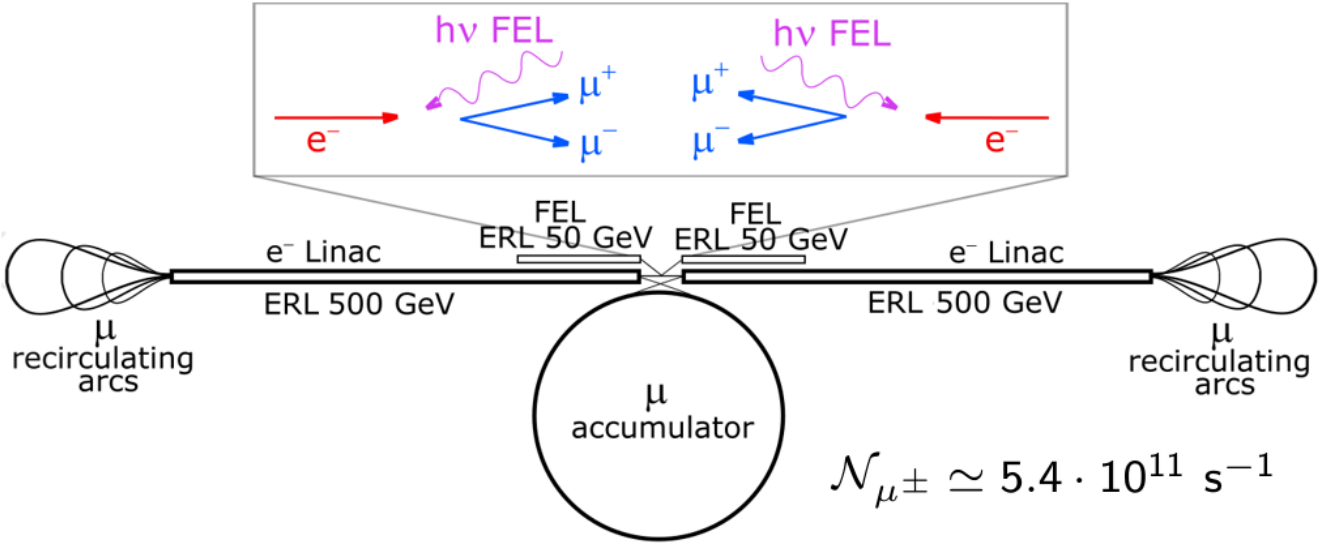
Electrons and **X**-rays to **M**uon **P**airs (**EXMP**)

C. Curatolo and L. Serafini Appl. Sci. 12(6), 3149 (2022)

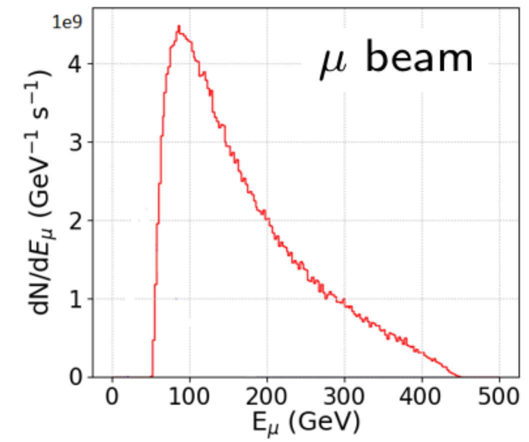
$$E_e = 500\ \text{GeV},\ h\nu = 60\ \text{keV},\ E_{CM} \simeq \sqrt{4E_e h\nu + M_e^2} = 346\ \text{MeV}$$

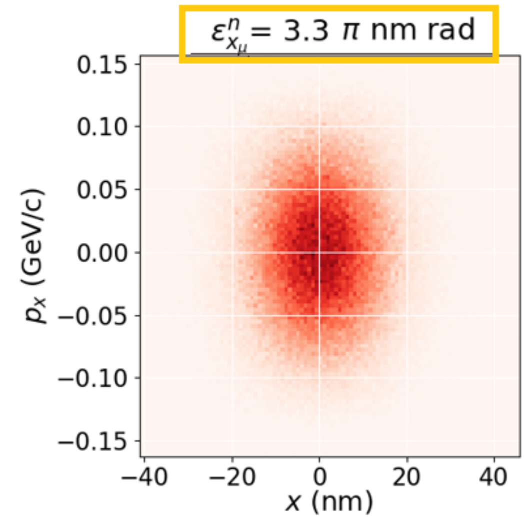
Photon energy in ERF $h\nu' \simeq 2h\nu\gamma_e = 120$ GeV

- no target → no target handling, no cooling needed
- no beam-beam, no ring → very tight focus allowed

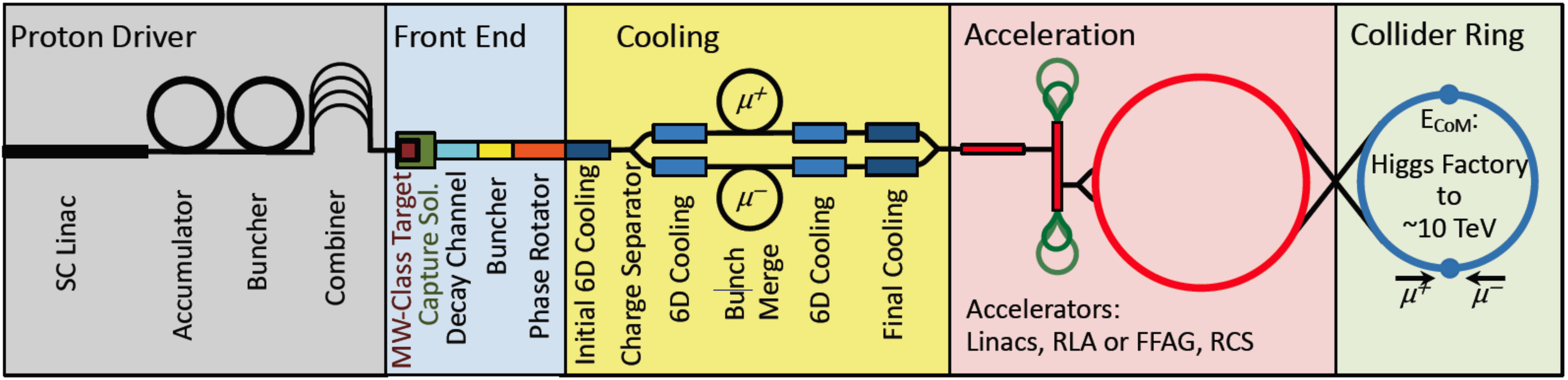


$$\mathcal{N}_{\mu^\pm} \simeq 5.4 \cdot 10^{11}\ \text{s}^{-1}$$





Proton-driven Muon Collider Concept



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

International Design Study facility

Proton driver production as baseline

- **Focus on two energy ranges:**

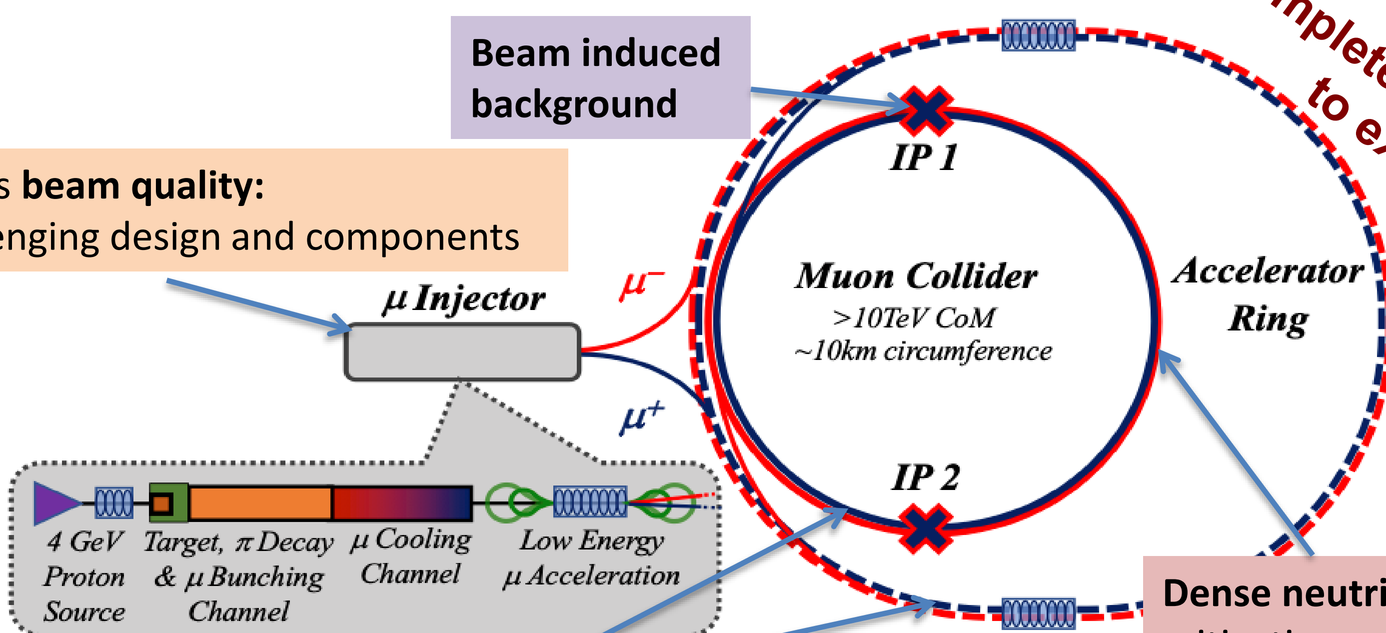
3 TeV technology ready for construction in 10-20 years

10+ TeV with more advanced technology

10+ TeV completely new regime to explore!

Beam induced background

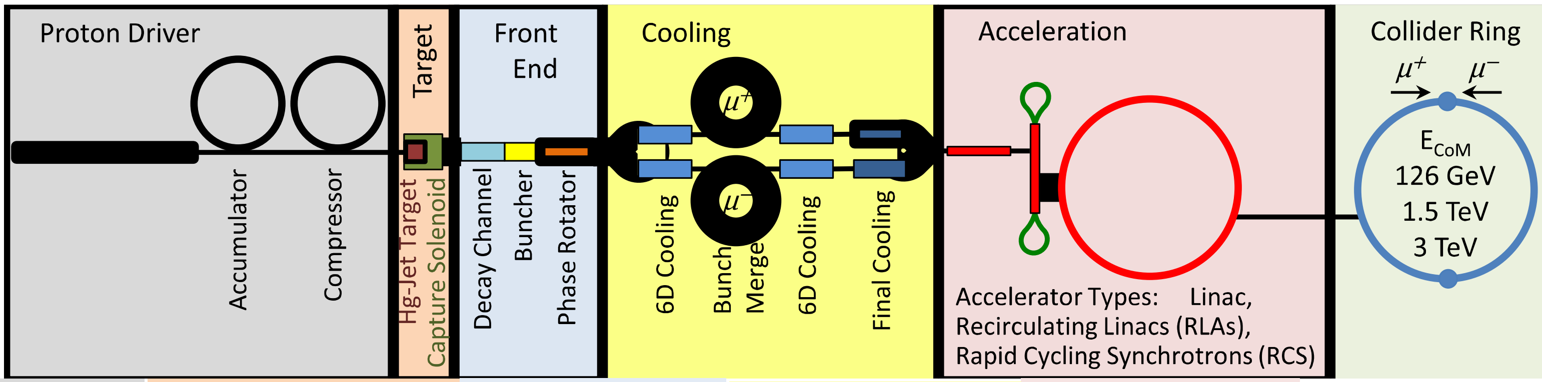
Drives **beam quality:** challenging design and components



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

MAP to International Design Study



- Based on 6-8 GeV Linac Source
- H- stripping requirements similar to neutrino ones

- high power target
- π production in high-field solenoid

- RF cavities bunch & phase rotate $\mu^{\pm}$ into bunch train

- Ionization cooling 6D
- MICE

- Fast acceleratio n
- Use RF and SC

- $\mu^{\pm}$ decay background
- Critical Machine Detector Interface

Luminosity and parameters goals

Target integrated luminosities

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

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

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

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

Note: currently consider 3 TeV and either 10 or 14 TeV

- Tentative parameters achieve goal in 5 years
- FCC-hh to operate for 25 years
- Might integrate some margins
- Aim to have two detectors

Now study if these parameters lead to realistic design with acceptable cost and power

Tentative target parameters
Scaled from MAP parameters

Comparison:
CLIC at 3 TeV: 28 MW

Parameter	Unit	3 TeV	10 TeV	14 TeV
L	$10^{34}\ cm^{-2}s^{-1}$	1.8	20	40
N	10^{12}	2.2	1.8	1.8
f_r	Hz	5	5	5
P_{beam}	MW	5.3	14.4	20
C	km	4.5	10	14
<B>	T	7	10.5	10.5
ε_L	MeV m	7.5	7.5	7.5
σ_E / E	%	0.1	0.1	0.1
σ_z	mm	5	1.5	1.07
β	mm	5	1.5	1.07
ε	µm	25	25	25
$\sigma_{x,y}$	µm	3.0	0.9	0.63

Muon Collider Luminosity Scaling

Fundamental limitation
Requires emittance preservation and advanced lattice design
Applies to MAP scheme

$$\mathcal{L} \propto \gamma \langle B \rangle \sigma_\delta \frac{N_0}{\epsilon \epsilon_L} f_r N_0 \gamma$$

High energy

High field in collider ring

Large energy acceptance

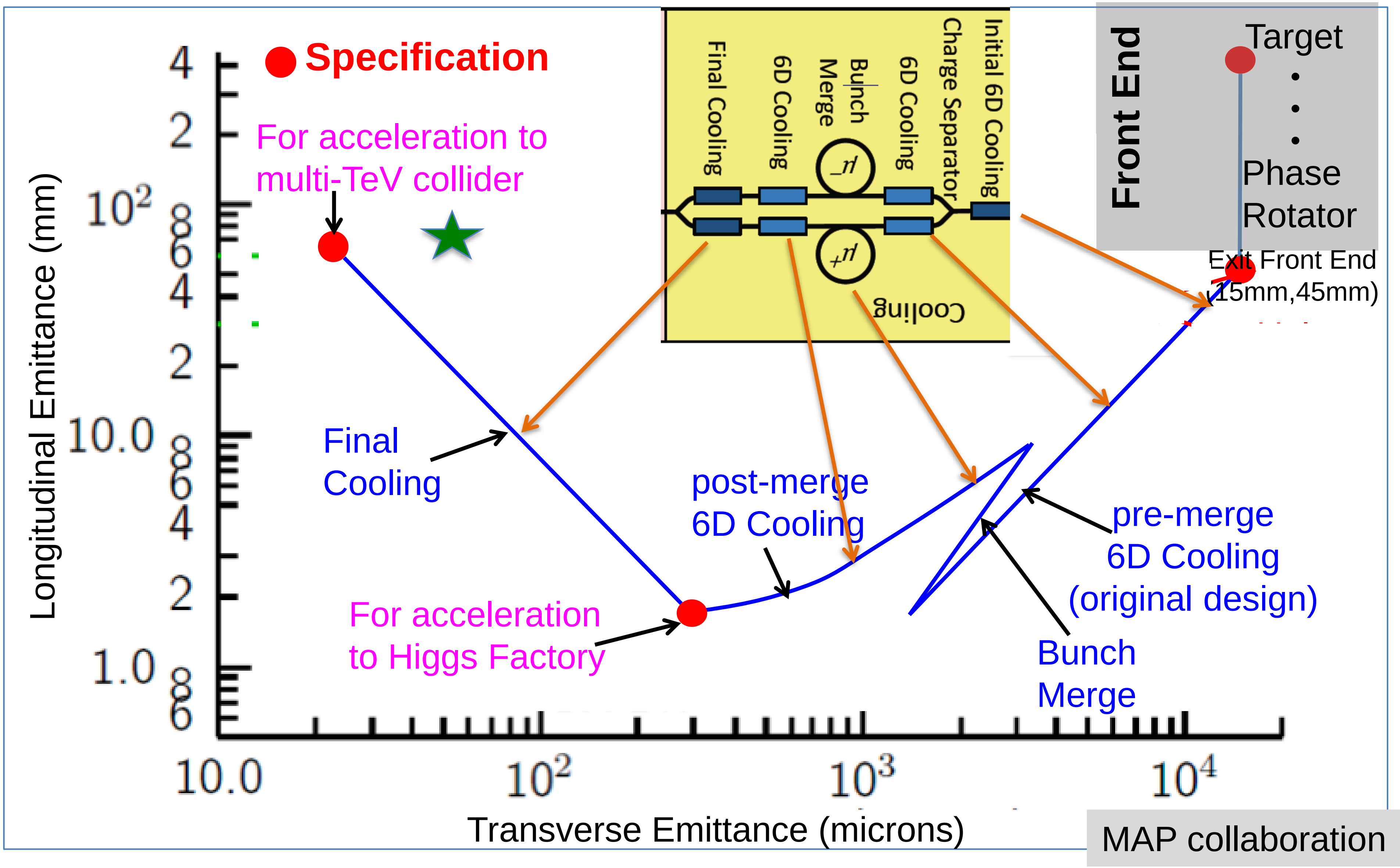
Dense beam

High beam power

Luminosity per power increases with energy
Provided technologies can be made available

Constant current for required luminosity scaling

Cooling: Emittance Path



International Design Study facility

- IMCC started officially on July 3rd 2020: Web site
- Several institutions are collaborating, US via the Snowmass process
- Muon collider is part of European Accelerator R&D Roadmap Yellow Report
- A lot of contributions submitted to the Snowmass process

https://arxiv.org/abs/2203.07256

International Muon Collider Collaboration

March 15, 2022
https://muoncollider.web.cern.ch

Muon Collider Physics Summary

Submitted to the Proceedings of the US Community Study
on the Future of Particle Physics (Snowmass 2021)

https://arxiv.org/abs/2203.07964

International Muon Collider Collaboration

March 16, 2022
https://muoncollider.web.cern.ch

Simulated Detector Performance at the Muon Collider

Submitted to the Proceedings of the US Community Study
on the Future of Particle Physics (Snowmass 2021)

https://arxiv.org/abs/2203.07224

International Muon Collider Collaboration

March 15, 2022
https://muoncollider.web.cern.ch

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

Submitted to the Proceedings of the US Community Study
on the Future of Particle Physics (Snowmass 2021)

https://arxiv.org/abs/2203.08033

International Muon Collider Collaboration

April 1, 2022
https://muoncollider.web.cern.ch

A Muon Collider Facility for Physics Discovery

Submitted to the Proceedings of the US Community Study
on the Future of Particle Physics (Snowmass 2021)

https://arxiv.org/abs/2203.07261

International Muon Collider Collaboration

March 15, 2022
https://muoncollider.web.cern.ch

The physics case of a 3 TeV muon collider stage

Submitted to the Proceedings of the US Community Study
on the Future of Particle Physics (Snowmass 2021)

Accelerator R&D Roadmap
Bright Muon Beams and Muon Colliders

International Design Study Collaboration GOAL

In time for the next European Strategy for Particle Physics Update, aim to **establish whether the investment into a full CDR and a demonstrator is scientifically justified**

The Panel endorsed this ambition and concludes that:

- the MC presents enormous potential for fundamental physics research at the energy frontier

➔ it is the future direction toward high-energy, high-luminosity lepton collider

➔ it can be an option as next project after HL-LHC (i.e. operation mid2040s)

- at this stage the panel did not identify any showstopper in the concept and sees strong support of the feasibility from previous studies

- it identified important R&D challenges

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

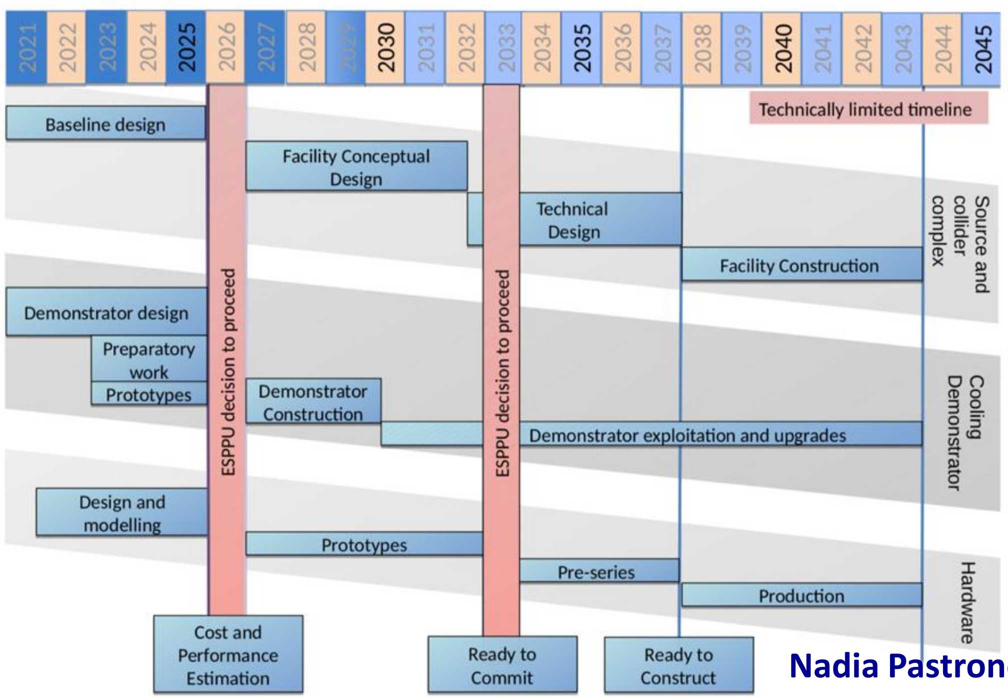
Accelerator R&D Roadmap

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**

Intense preparation and review activities in 2021:
3 Community Meetings (May, July, October) and
a dedicated Muon Collider Physics and Detector Workshop

presented to CERN Council in December and
published https://arxiv.org/abs/2201.07895
now under implementation by LDG + Council…



Technically limited timeline

A 3 TeV muon collider could be ready by 2045, as reviewed by the Roadmap

Plan

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

Label	Begin	End	Description	Aspirational [FTEy]	Aspirational [kCHF]	Minimal [FTEy]	Minimal [kCHF]
MC.SITE	2021	2025	Site and layout	15.5	300	13.5	300
MC.NF	2022	2026	Neutrino flux mitigation system	22.5	250	0	0
MC.MDI	2021	2025	Machine-detector interface	15	0	15	0
MC.ACC.CR	2022	2025	Collider ring	10	0	10	0
MC.ACC.HE	2022	2025	High-energy complex	11	0	7.5	0
MC.ACC.MC	2021	2025	Muon cooling systems	47	0	22	0
MC.ACC.P	2022	2026	Proton complex	26	0	3.5	0
MC.ACC.COLL	2022	2025	Collective effects across complex	18.2	0	18.2	0
MC.ACC.ALT	2022	2025	High-energy alternatives	11.7	0	0	0
MC.HFM.HE	2022	2025	High-field magnets	6.5	0	6.5	0
MC.HFM.SOL	2022	2026	High-field solenoids	76	2700	29	0
MC.FR	2021	2026	Fast-ramping magnet system	27.5	1020	22.5	520
MC.RF.HE	2021	2026	High Energy complex RF	10.6	0	7.6	0
MC.RF.MC	2022	2026	Muon cooling RF	13.6	0	7	0
MC.RF.TS	2024	2026	RF test stand + test cavities	10	3300	0	0
MC.MOD	2022	2026	Muon cooling test module	17.7	400	4.9	100
MC.DEM	2022	2026	Cooling demonstrator design	34.1	1250	3.8	250
MC.TAR	2022	2026	Target system	60	1405	9	25
MC.INT	2022	2026	Coordination and integration	13	1250	13	1250
			Sum	445.9	11875	193	2445

Scenarios

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

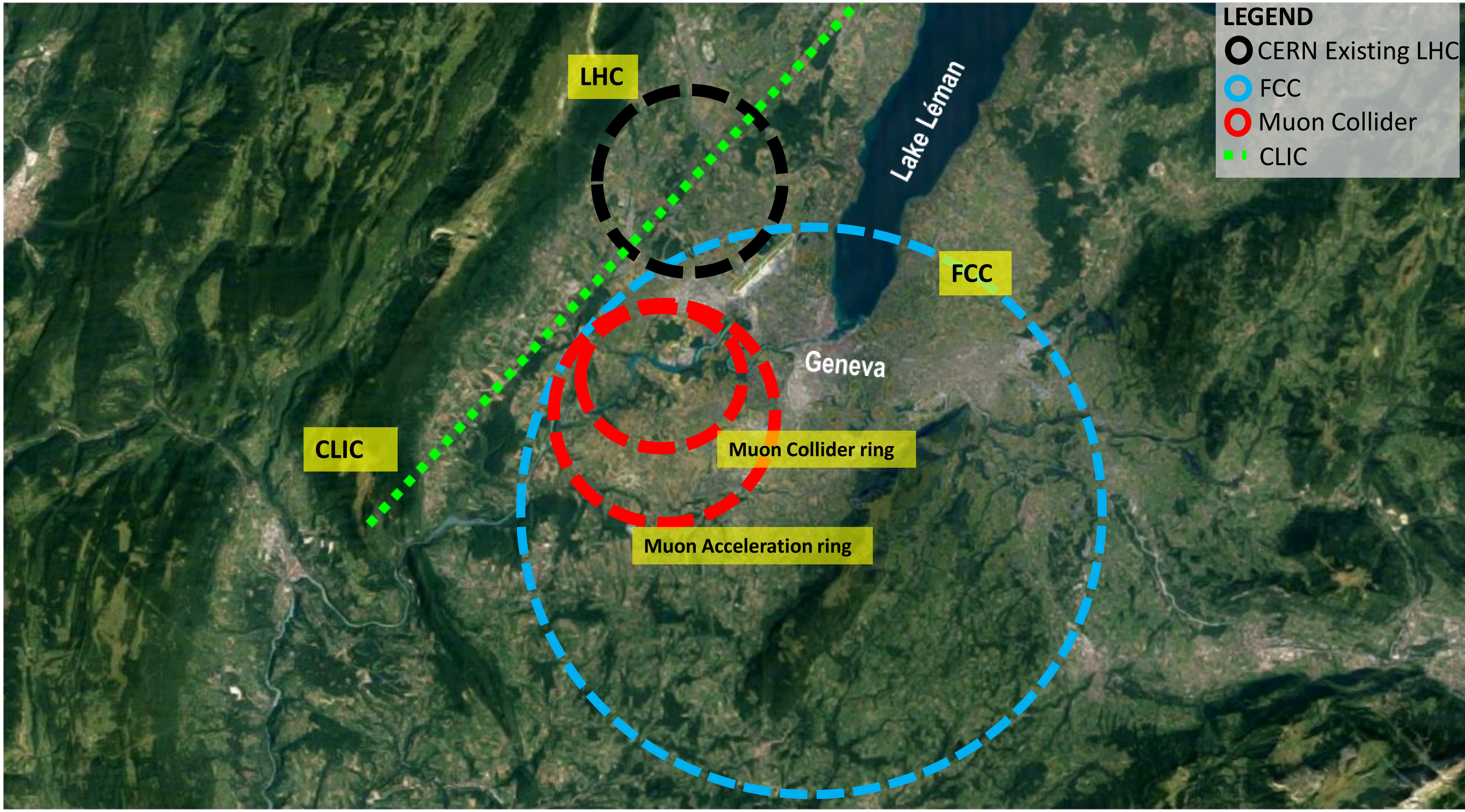
~70 Meu/5 years

INFN and the International Community

CONTEXT:

- **Laboratory Directors' Group (LDG)** **initiated a muon collider collaboration July 2, 2020**
- CERN Medium Term Plan 2021-2025 - dedicated budget line – 2MCHF/year
- **International Design Study based at CERN → MoC signed by INFN July 2021**
  the project encompasses physics, machine, detector and Machine Detector Interface
- European LDG **Accelerator R&D Roadmap → presented to December Council 2021**
  dedicated Muon Beams Panel - but also synergies in High field magnets, RF and ERL
- European ECFA **Detector R&D Roadmap → presented to December Council 2021**
  Muon collider @ 10 TeV is one of the targeted facilities emerging from the EPPSU
- US SnowMass Muon Collider Forum **since 2021** *share ideas and studies across frontiers*
- Snowmass/P5 process in the US → **ready by 2023**
- Submission of HORIZON-INFRA-2022-DEV-01-01 EU project for Design Study **April 2022**
  Research infrastructure concept development → **supported by TIARA**

Footprint of future colliders @ CERN

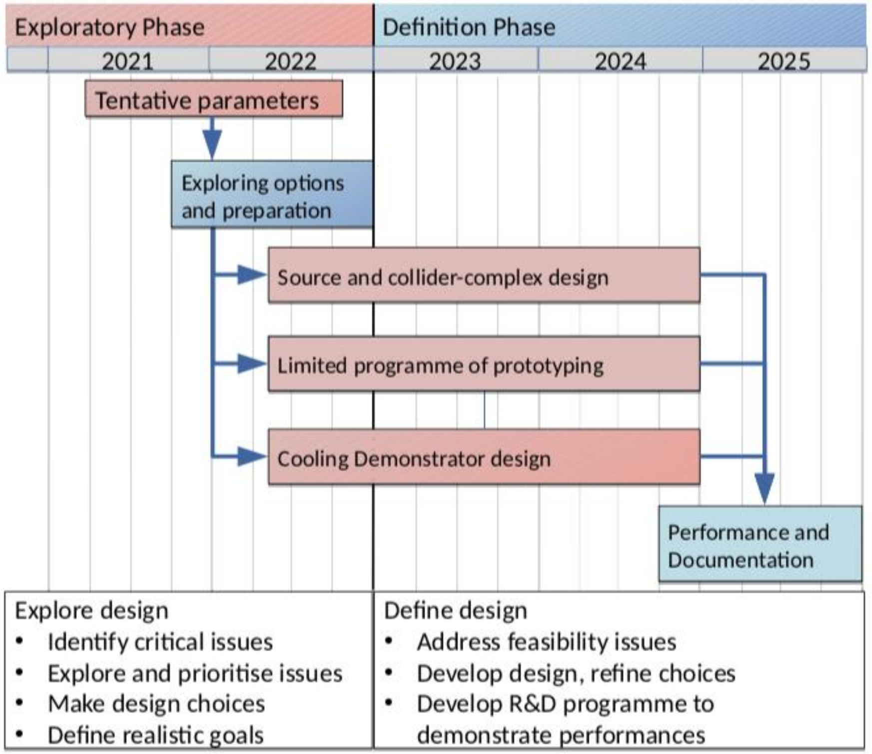


Key Challenge Areas

- **Physics potential** evaluation, including **detector concept and technologies**
- Impact on the environment
  - **Neutrino flux mitigation** and its impact on the site (first concept exists)
  - **Machine Induced Background** impact the detector, and might limit physics
- **High-energy systems** after the cooling (acceleration, collision, ...)
  - Fast-ramping magnet systems **NEW!!**
  - High-field magnets (in particular for 10+ TeV) **NEW!!**
- **High-quality muon beam production NEW!!**
  - Special RF and high peak power
  - Superconducting solenoids
  - Cooling string demonstration (cell engineering design, demonstrator design)
- **Full accelerator chain**
  - e.g. proton complex with H- source, compressor ring ➔ test of target material

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

Plan for next 5 years



- **End-to-end design with all systems**
- **Key performance specifications**
- **Evidence to achieve luminosity goal:**
  – beam parameters, collective effects, tolerances …
- **Evidence that the design is realistic:**
  – performance specification supported by technology
  – key hardware performances
  – radiation protection, impact and mitigation of losses
  – cost and power scale, site considerations
- **A path forward**
  – Test facility
  – Component development
  – Beam tests
  – System optimisation

MUon collider STrategy network – MUST

INFN – CERN (+BINP) – CEA – IJCLAB – KIT – PSI – UKRI – (USA not beneficiary)

May 1, 2021 – April 30, 2024

Task 5.1

….

It will serve as the common ground for a growing international muon-collider collaboration

MUST will support to establish an international collaboration and develop an optimized R&D roadmap towards a future muon collider, including the definition of optimum test facilities and possible intermediate steps

1 January 2022 - 31 December 2025 EU RISE project

aMUSE further provides an excellent platform for an ambitious EU-US network to advance the development of muon beams.

Objectives WP3 – leader: Donatella Lucchesi

- Study techniques of unstable particles beam cooling muon beams at different energies, aiming to validate the simulation with experimental tests
- High energy muon beams: determine the optimal interaction region configuration by studying the beam induced background and new detector technologies able to handle it
- Design and simulate detector for different centre of mass energies
- Evaluate the radiation hazards related to the neutrino flux emitted by the muon beams.

Key R&D challenges

Mark Palmer

Key R&D Challenges

	Issues	Status
Target	• Multi-MW Targets • High Field, Large Bore Capture Solenoid	• Ongoing >1 MW target development • Challenging engineering for capture solenoid
Front End	• Energy Deposition in FE Components • RF in Magnetic Fields (see Cooling)	• Current designs handle energy deposition
Cooling	• RF in Magnetic Field • High and Very High Field SC Magnets • Overall Ionization Cooling Performance	• MAP designs use 20 MV/m → 50 MV/m demo • >30 T solenoid demonstrated for Final Cooling • Cooling design that achieves most goals
Acceleration	• Acceptance • Ramping System • Self-Consistent Design	• Designs in place for accel to 125 GeV CoM • Magnet system development needed for TeV-scale • Self-consistent design needed for TeV-scale
Collider Ring	• Magnet Strengths, Apertures, and Shielding • High Energy Neutrino Radiation	• Self-consistent lattices with magnet conceptual design up to 3 TeV • > ~5 TeV – ν radiation solution required
MDI/Detector	• Backgrounds from μ Decays • IR Shielding	• Further design work required for multi-TeV • Initial physics studies at 1.5 TeV promising

Design Study activities: EU project

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

Total EU budget requested 3 Meu

Since 2022 INFN-Accelerator is joining Muon Collider studies on technologies (Magnets - RF – prototyping) starting on this project

Design study critical items requiring dedicated studies:

- combination of very large number of protons into each short pulse for muon production
- proton beam impact on the target and the surrounding solenoid
- achievement of small final beam emittance in the muon cooling system
- cost and power effective acceleration of the muon beams in the RCSs
- focusing of the beam in the collision point
- impact of muon beam decay on the facility, in particular the collider ring
- impact of beam-induced background on the detector performance
- potential environmental impact of the collider

EU DESIGN STUDY PROPOSAL WORKSHOP April 12, 2022
Please register at: https://indico.cern.ch/event/1143753/

EU project: WP

WP 2: Physics and Detector Requirements

Leader D. Lucchesi Univ. PD + INFN (M. Casarsa) + many + + Univ. PV associated

Link to the physics and detector studies, to provide a database with Beam-Induced Background (BIB) to the physics community and maintain a simplified model of the detector for physics studies. Based on feedback from the physics community, it will provide feedback and guidance to the accelerator design.

WP 3: The Proton Complex

Leader ESS-CERN-UU

key challenge of the proton complex design, the accumulation of the protons in very high-charge bunches and determine the required basic parameters of the complex.

WP 4: The Muon Production and Cooling

Leader STFC-CERN+ UK

Production of the muons by the proton beam hitting a target and the subsequent cooling

WP 5: The High-energy Complex

Leader CEA(Antoine Chance)-CERN-STFC-INFN (F. Collamati – RM1-TO) only MDI

Acceleration and collision complex of the muons. Interaction Region and Machine Detector Interface.

EU project: WP

WP 6: Radio Frequency Systems

Leader CEA(C. Marchand)+INFN(D. Giove- MI - LNL)-CERN++++

Radio Frequency (RF) systems of the muon cooling and the acceleration complex.

WP 7: Magnet Systems

Leader CERN(L. Bottura)-CERN+++ INFN(GE, MI, BO) + Univ. BO associated

Most critical magnets of the muon collider. In particular focus on the solenoids of the muon production and cooling, which are specific to the muon collider. The fast-ramping magnet system, which has ambitious requirements on power flow and power efficiency and limits the energy reach of the collider,

WP 8: Cooling Cell Integration

Leader CERN(R. Losito)+Univ. MI (L. Rossi)-STFC-INFN(M. Statera – mag. e D. Giove – RF)

Design of the muon cooling cell, which is a unique and novel design and which faces integration challenges: interact to address the challenges of the muon collider concept.

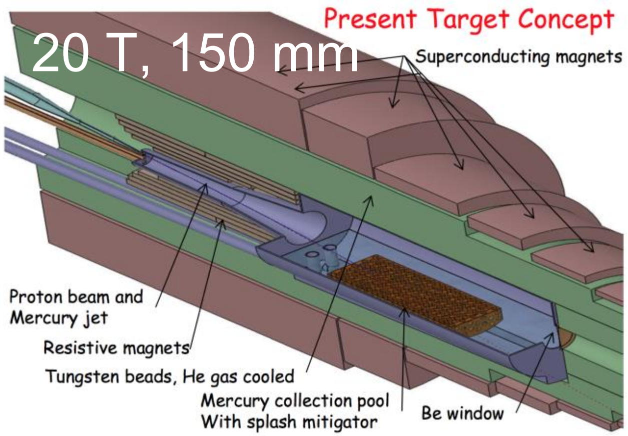
Summary of IMC RF systems

https://www.dropbox.com/s/2e71dj9bzomglwm/MC_RF%20Summary%20Draft.xlsx?dl=0

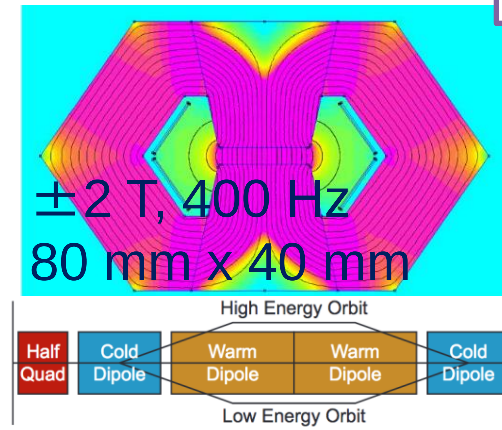
System			Driver			Front-End	Cooling			Acceleration			Collider	TOTAL	CLIC
Sub-system			Driver Linac H- (SPL like)		Accum &Comp	Capture& Bunching	Initial	6D (2 lines)	Final (2 lines)	Injector Linac	RLAs (2stages)	RCS (3stages)	Ring	IMC	Acceleration
Reference expert			F.Gerigk		?	D.Neuffer	C.Rogers	D.Stratakis	C.Rogers	A.Bogacz		S.Berg	E.Gianfelice		
	Energy	GeV/c	0.16	5	5	0.255	0.255	0.255	0.255	1.25	62.5	1500	1500		1500
Beam (system exit)	# bunches (μ+ or μ-)	#	40 mA		1	12	12	1	1	1	1	1	1		312
	Charge/bunch	E12			500	3.57	2.56	7.21	4.39	3.73	3.17	2.22	2.20		3.72E-03
	Rep Freq	Hz	5	5	5	5	5	5	5	5	5	5	5		50
	Norm Transv Emitt	rad-m				1.5E-02	3.0E-03	8.3E-05	2.5E-05	2.5E-05	2.5E-05	2.5E-05	2.5E-05		660/20E-06
	Beam dimens. (H/V) in RF	mm	?	?	?	?	?	?	?	?	?	?	?		1?
	Norm Long Emitt	rad-m				4.5E-02	2.4E-02	1.8E-03	7.0E-03	7.0E-03	7.0E-03	7.0E-03	7.0E-03		
	Pulse/Bunch length	m	2.2 ms		0.6 (2ns)	1.1E+01	1.1E+01	9.2E-02	9.2E-02	4.6E-02	2.3E-02	2.3E-02	5.0E-03		4.4E-05
	Power (μ+ and μ-)	W	6.40E+04	2.2E+06	2.0E+06	1.8E+04	1.3E+04	3.0E+03	1.8E+03	7.6E+03	3.2E+05	5.4E+06	5.3E+06		2.8E+07
RF cavities	Technology		NC Linac4	SC	SC	NC	NC	NC Vacuum	NC	SC	SC	SC	SC		NC High Grad
	Number of cavities	#	23	244	2	120	367	7182	32	52	360	2694	?	11076	149000
	RF length	m	46	237	1	30	105	1274	151	82	1364	2802	?	6092	30000
	Frf	MHz	352	704	44	326to493	325	325-650	20-325	325	650-1300	1300	800	4 to 1300	12000
	Grf	MV/m	1-3.7	19 - 25	2	20	20 to 25	19-28.5	7.2-25.5	20	25 to 38	35	?	1 to 38	100
	Aperture	mm	28	80		?	?	?	?	300	150	75	120	28 to 300	2.75
	Magnetic Field	T	0	0		2	3T	1.7-9.6	1.5-4	0	0	0	0	0 to 9.6	0
	Installed RF field	MV	169	5700	4	434	2618	30447	1836	1640	50844	98062	250	1.92E+05	3.00E+06
	Beam Energy gain	MeV	160	4840	0	0	0	0	0	1250	62500	1437000	0	1.51E+06	1.50E+06
	Recirculations	#	1	1		1	1	1	1	1	4.5 to 5	13 to 23	1000	1 to 1000	1
	RF Power/pulse (η=0.6)	MW	25	220	3.E-01	99	429	1172	43	52	360	2024	1.98E-02	4425	1.2E+07
RF power sources	Technology		klystron	klystron						Klytron-IOT					Two Beam
	Cavities/Power Source	#	23	244		4				1 to 2	1 to 2				2
	RF Pulse (fill+beam) estim.	ms	2.20	2.20	3.20	0.10	0.10	0.10	0.10	0.03	0.06	0.73	14.80		0.142
	Prf/Power Source	MW	11.7	1.93						1	1				15
	Total Power Sources	#	17	244		30				52	341			?	1638
	Installed Peak RF Power	MW	34	275		164	515	1407	52	52	341	2429	2.38E-02	5269	2.46E+04
	Average RF power (η=0.6)	MW	0.27	2.13	0.01	0.05	0.21	0.59	0.02	0.01	0.11	14.88	0.00	18.28	143
	Wall plug power (η=0.6)	MW	0.45	3.55	0.01	0.08	0.36	0.98	0.04	0.01	0.18	24.81	0.00	30.46	289

Magnet Demands

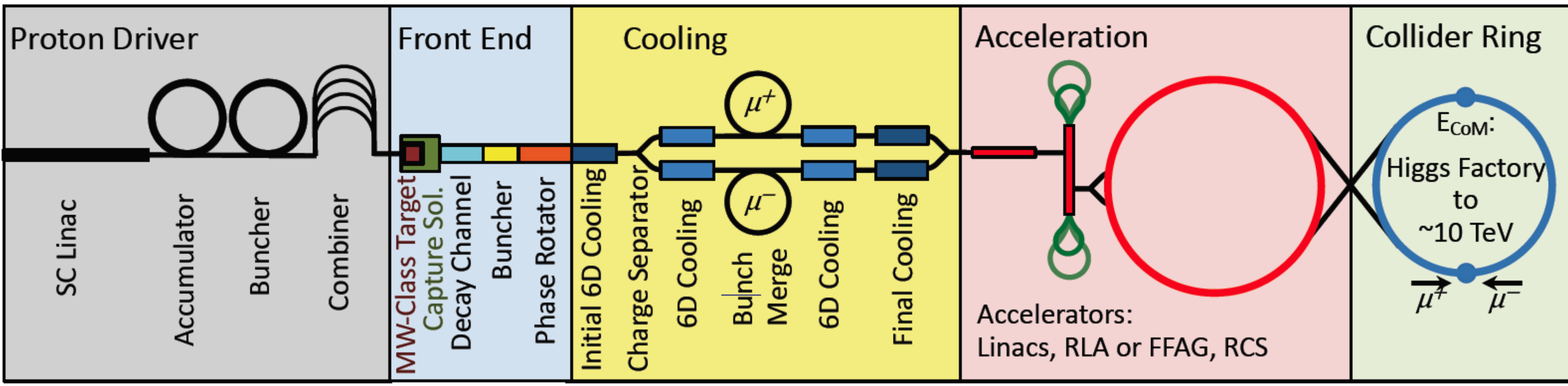
Luca Bottura



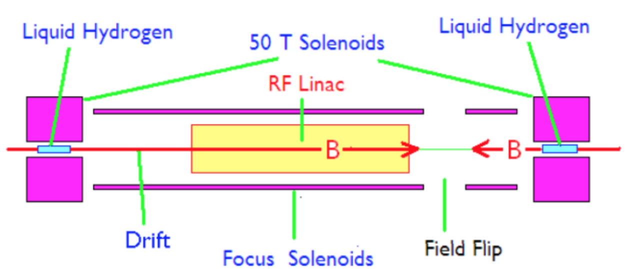
High-field and large aperture target solenoid with heavy shielding to withstand heat (100 kW/m) and radiation loads



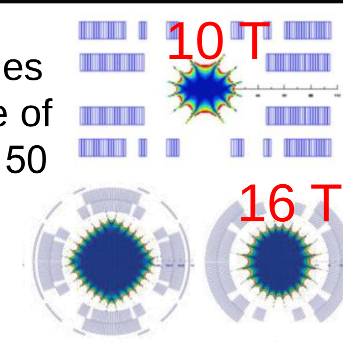
Combination of DC SC magnets (10 T) and AC resistive magnets (±2T)



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



Magnet preliminary Summary

Luca Bottura et al

Complex	Magnet	Field Gradient (T) / (T/m)	Field rate (T/s)	Aperture (mm)	Length (m)	Heat load (kW/m)	Candidate Technologies
Target and Capture	Solenoid	20	N/A	150	1	100	Hybrid (SC+resistive) All-SC (LTS+HTS)
Cooling	Solenoid	2…14 40…60	N/A	1000…50 50	1 0.5	TBD TBD	All SC (LTS+HTS)
Accelerator	NC Dipole	± 2	500 10,000	80x40	5	TBD	SC (LTS) DC + NC AC SC (LTS) DC + SC (HTS) AC FFAG
Collider	Dipole	10…16	N/A	150	15	0.5	Nb_3Sn or Nb-Ti+HTS
	Quadrupole	250…300	N/A	150	10	TBD	Nb_3Sn or Nb-Ti+HTS

Magnet R&D impact on Science and Society

Luca Bottura

- R&D on the magnet technology necessary for a muon collider has multiple implications for other fields of science, industry and society. Below some relevant examples:
  - The *target solenoid* requires large fields (15 T) in a large bore (2 m), in the range of field and geometry relevant for a full-body MRI of the next generation[1], or solenoid magnets for fusion[2]
  - Ultra-high field solenoids (40…60 T) with modest bore (50 mm) as required by the *final cooling stage* share the challenges of magnets for high-field science[3-5], as well as solenoids for NMR spectroscopy [6]
  - The fast-ramped magnets planned in the acceleration stage (4 T field swing, 400 Hz) are relevant to the development of rapid cycled synchrotrons for intense beams, nuclear physics, medical applications, and accelerator-driven reactors and transmutation systems [7]
  - Energy and power management for the fast ramped magnets in the accelerator complex, typically tens of MJ on the time scale of 1 ms, i.e. tens of GW, share challenges with pulsed power conversion for high-field magnets, as well as energy storage and power management for the power grid
  - Large aperture dipoles and quadrupoles for the collider will profit from the stress-management techniques developed for High-Field Magnets

Impact - References

[1] “The most powerful MRI scanner in the world delivers its first images!”, Press Release,2021, https://www.cea.fr/english/Pages/News/premieres-images-irm-iseult-2021.aspx

[2] P. Libeyre, et al., “From manufacture to assembly of the ITER central solenoid”, Fus. Eng. Des., 146(a) (2019), pp. 437-440

[3] High Magnetic Field Science and Its Application in the United States, Current Status and Future Directions, National Academies Press, 2013, ISBN: 978-0-309-38778-1

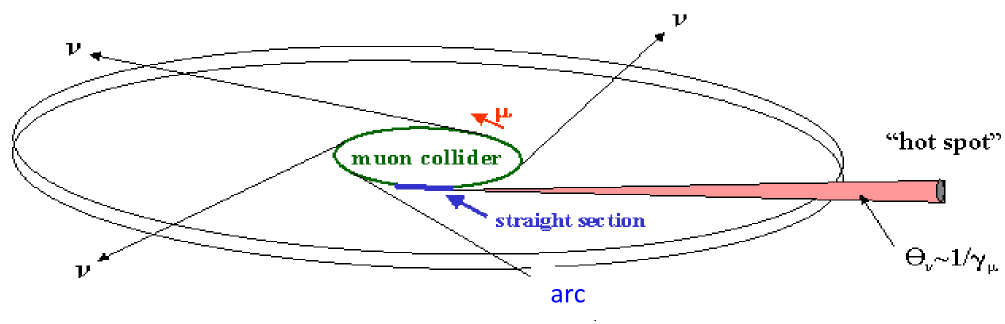
[4] Final Report Summary - EMFL (Creation of a distributed European Magnetic Field Laboratory), EU Grant agreement ID: 262111, 2014, https://cordis.europa.eu/project/id/262111/reporting

[5] S. Hahn, et al., “45.5-Tesla Direct-Current Magnetic Field Generated with a High-Temperature Superconducting Magnet”, Nature, 570 (2019) pp. 496–499

[6] “Bruker Announces World's First 1.2 GHz High-Resolution Protein NMR Data”, Press Release, 2019, https://ir.bruker.com/press-releases/press-release-details/2019/Bruker-Announces-Worlds-First-12-GHz-High-Resolution-Protein-NMR-Data/default.aspx

[7] Y. Fuwa, et al., “Design of Multi-MW Rapid Cycling Synchrotron for Accelerator Driven Transmutation System”, Proc. IPAC 2018, (2018), pp. 1057-1059

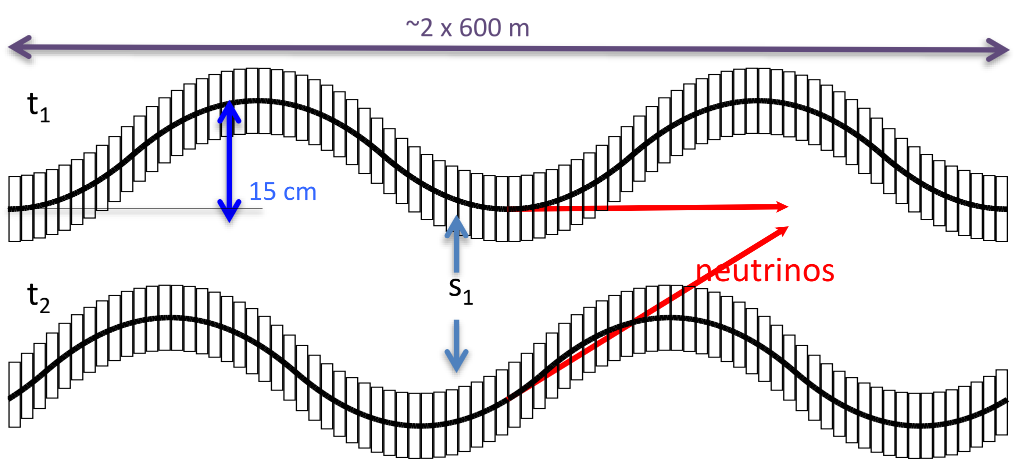
Neutrino Flux Mitigation



Legal limit 1 mSv/year
MAP goal < 0.1 mSv/year
Our goal: arcs below threshold for legal procedure < 10 μSv/year
LHC achieved < 5 μSv/year

3 TeV, 200 m deep tunnel is about OK

Need mitigation of arcs at 10+ TeV:
idea of Mokhov, Ginneken to move beam in aperture
our approach: move collider ring components, e.g. vertical bending with 1% of main field



Opening angle ± 1 mradiant

14 TeV, in 200 m deep tunnel comparable to LHC case

Need to study mover system, magnet, connections and impact on beam

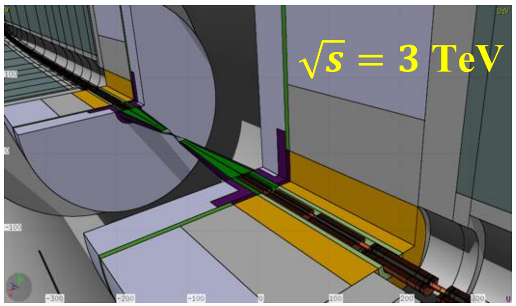
Working on different approaches for experimental insertion

Machine Detector Interface

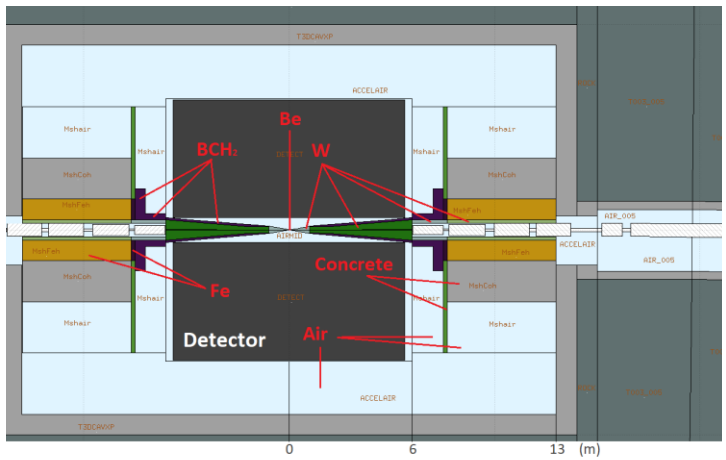
Advanced assessment of beam-induced background at a muon collider

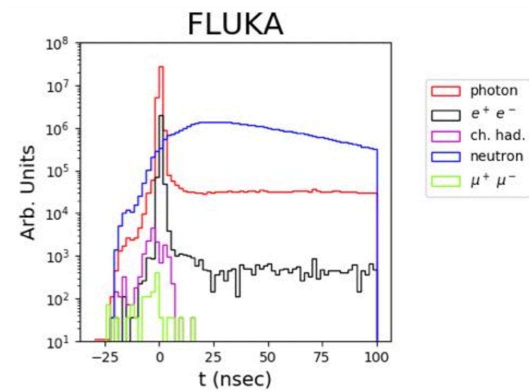
F. Collamati, C. Curatolo, D. Lucchesi, A. Mereghetti, P. Sala *et al.* 2021 *JINST* **16** P11009

Study Beam-Induced Background @ $\sqrt{s} = 1.5$ and 3 TeV, using MAP lattice – nozzle optimized at 1.5 TeV



LineBuilder + FLUKA simulation



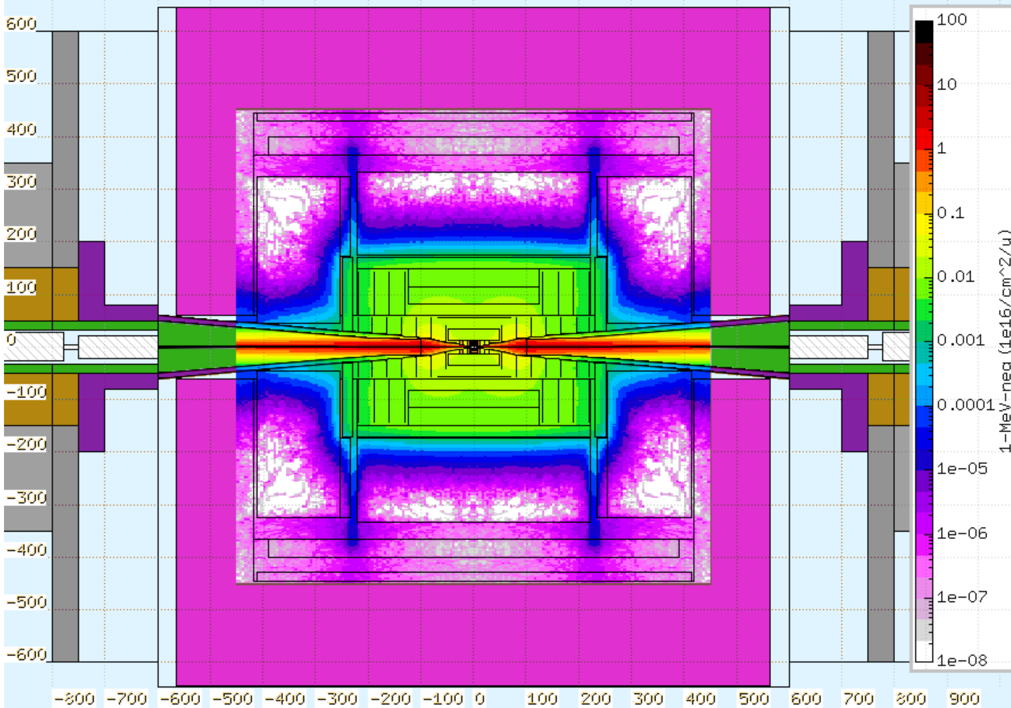


First MDI Kick-off meeting @ November 2021

➔ **first lattice and MDI studies @ 10 TeV by CERN**

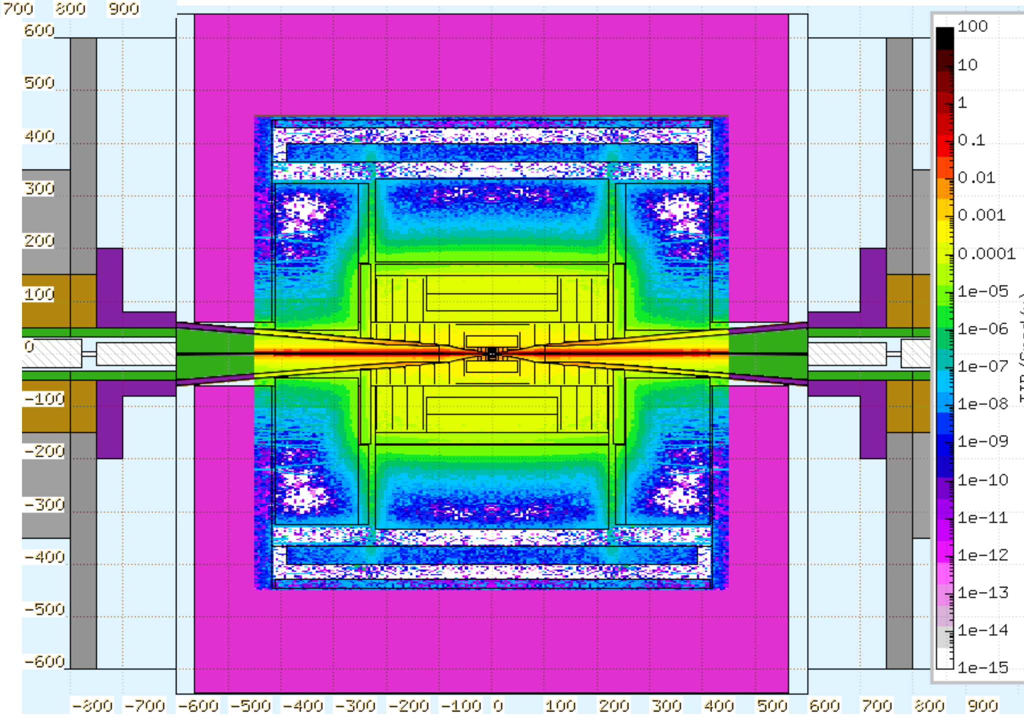
MDI WG: *C.Carli, A. Lechner,* ***CERN****, N. Mokhov, S.Jindariani,* ***FNAL****, D.Lucchesi, N.Pastrone,* ***INFN***

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



1 MeV n_{eq} fluence/year @ 3 TeV

TID/year @ 3 TeV



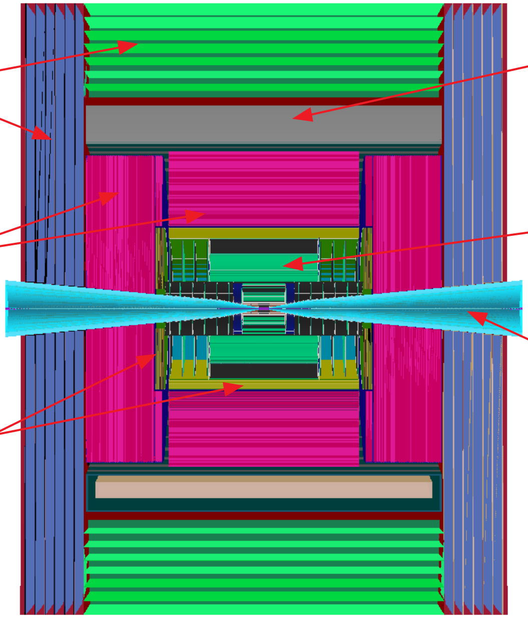
Camilla Curatolo, Paola Sala

Detector studies @ $\sqrt{s}$ =1.5 TeV

arXiv:2203.07964 Simulated Detector Performance at the Muon Collider
arXiv:2203.07224 Promising Technologies and R&D Directions for the Future Muon Collider Detectors

Synergies with AIDAinnova EU project

- CLIC Detector technologies adopted with important tracker modifications to cope with BIB
- Detector design optimization at $\sqrt{s}$=1.5 (3) TeV



Vertex Detector (VXD)
- 4 double-sensor barrel layers 25x25µm^2
- 4+4 double-sensor disks 25x25µm^2

Inner Tracker (IT)
- 3 barrel layers 50x50µm^2
- 7+7 disks "

Outer Tracker(OT)
- 3 barrel layers 50x50µm^2
- 4+4 disks "

Electromagnetic Calorimeter (ECAL)
- 40 layers W absorber and silicon pad sensors, 5x5 mm^2

Hadron Calorimeter (HCAL)
- 60 layers steel absorber & plastic scintillating tiles, 30x30 mm^2

R&D Detector:
CRILIN in corso **LNF**
LGAD resistivi **TO**
mu_picosec **PV**
HCAL-gas **BA**
Cristalli FE
Bersagli LNL-RM1/3

TO BE IMPROVED
TUNED at higher $\sqrt{s}$

B = 3.57 T to be studied and tuned

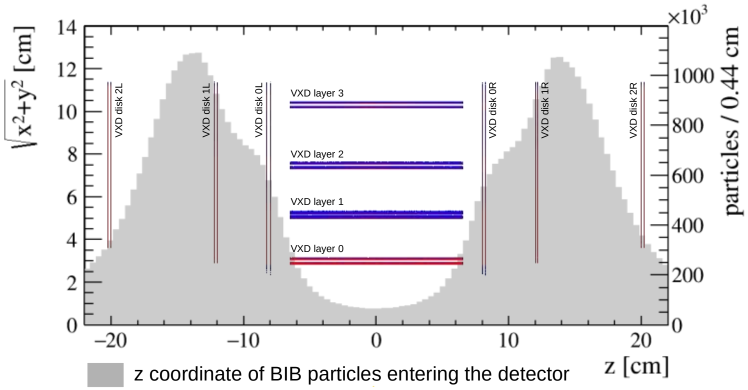
Full simulation available on public repository

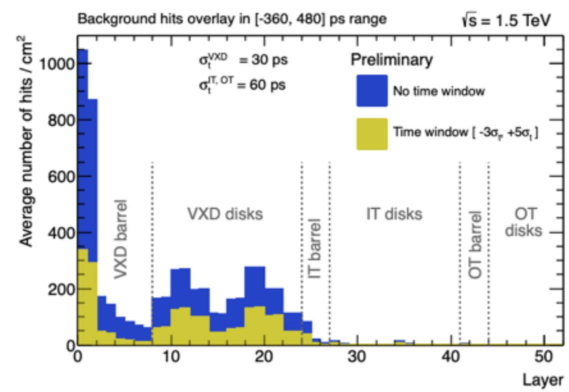
Quite advanced conceptual design for 1.5 TeV and 3 TeV
➔ More R&D on technologies required @ 10+ TeV

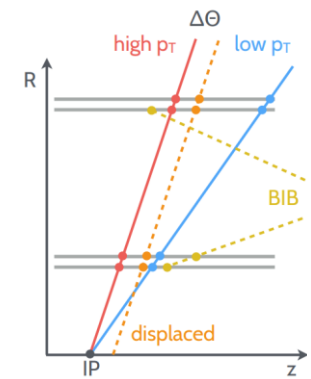
Tracker detector @ 1.5 TeV

Nazar Bartosik, Massimo Casarsa et al.

Max radiation tolerance NIEL: 0.5x 10^{16} neq/cm²/year
Max radiation tolerance TID: 300 Mrad/year







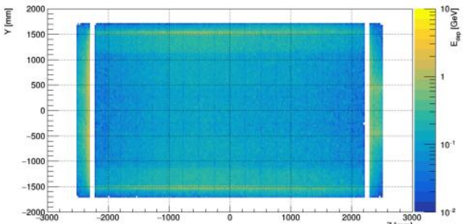
- Vertex detector properly designed to not overlap with the BIB hottest spots around IR
- Timing window applied to reduce hits from out-of-time BIB
- Granularity optimized to ensure ≲ 1% occupancy
- Realistic digitization in progress ➔ BIB suppression based on cluster shape
- If primary vertex could be known before ➔ effective angular matching of hit doublets
- To be tuned in presence of secondary vertices or long-lived particles

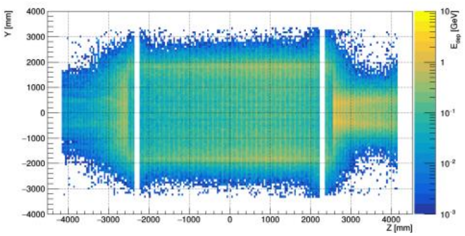
Calorimeters and Muon detectors

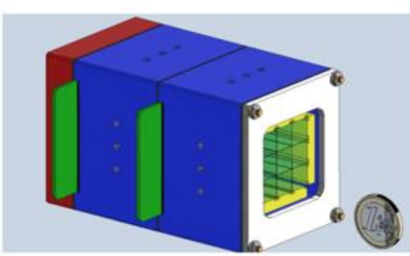
timing and longitudinal measurements play a key role in the BIB suppression

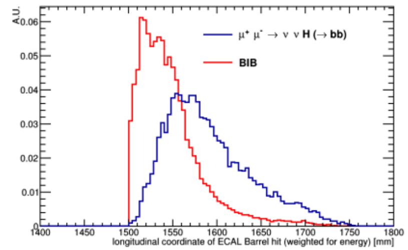
Calorimeters

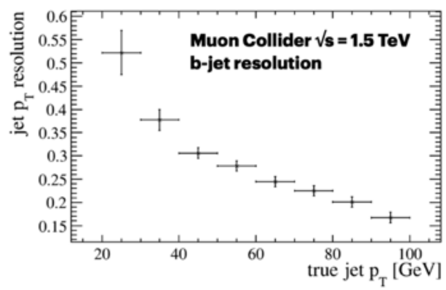
BIB deposits large amount of energy in both ECAL and HCAL

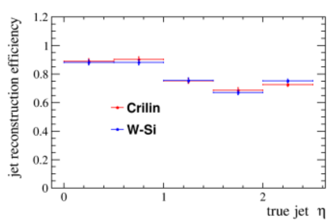


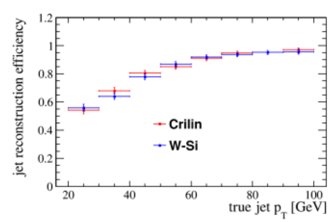










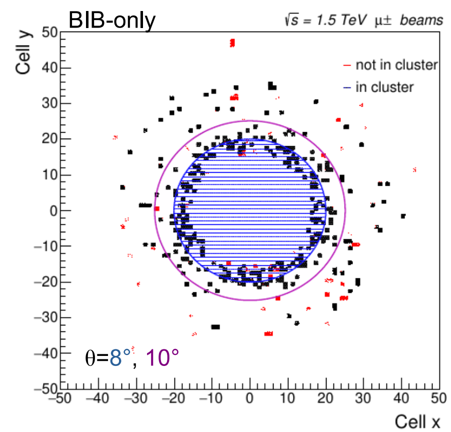


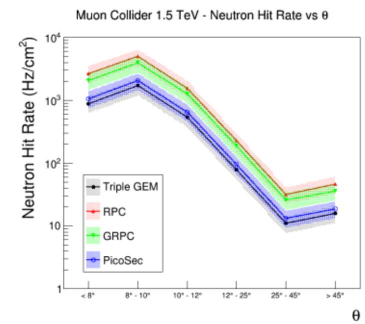
Lorenzo Sestini, Ivano Sarra et al.

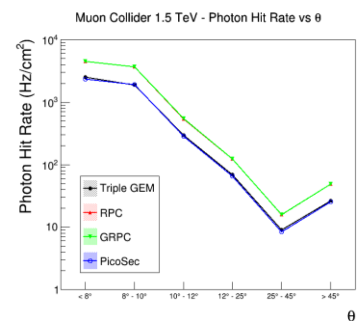
Muon System

Low BIB contribution, concentrated in the low-radius endcap region

C. Aimè, C. Riccardi, P. Salvini, Ilaria Vai, N. Valle







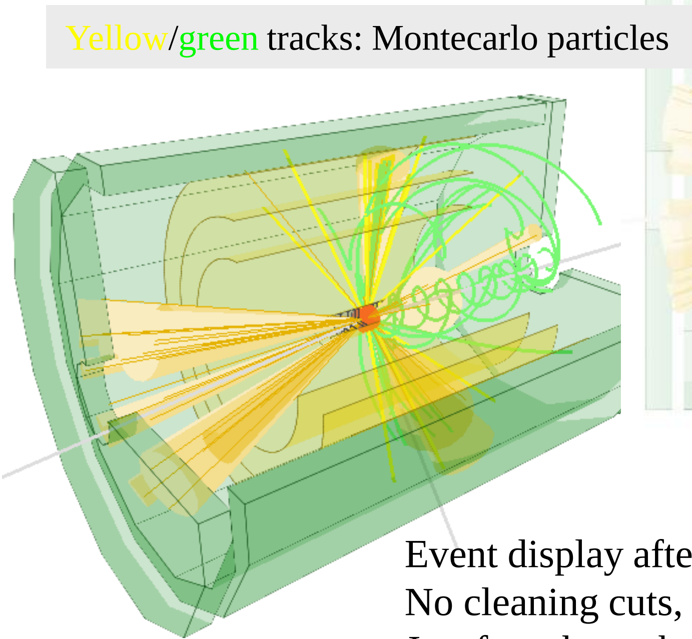
Investigating new technologies for R&D

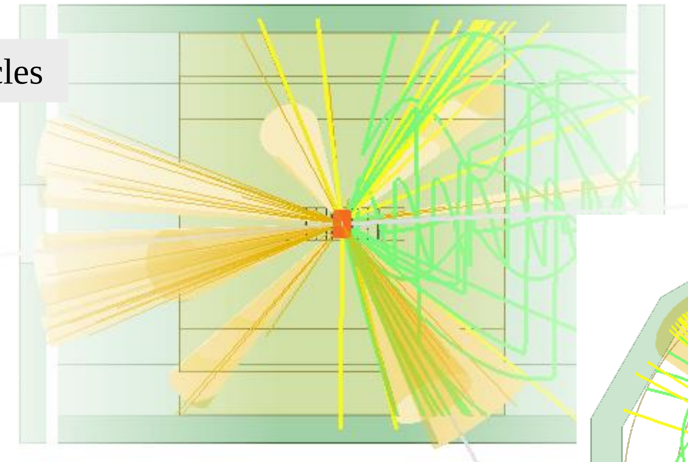
Innovative and computationally efficient event-reconstruction approaches are needed

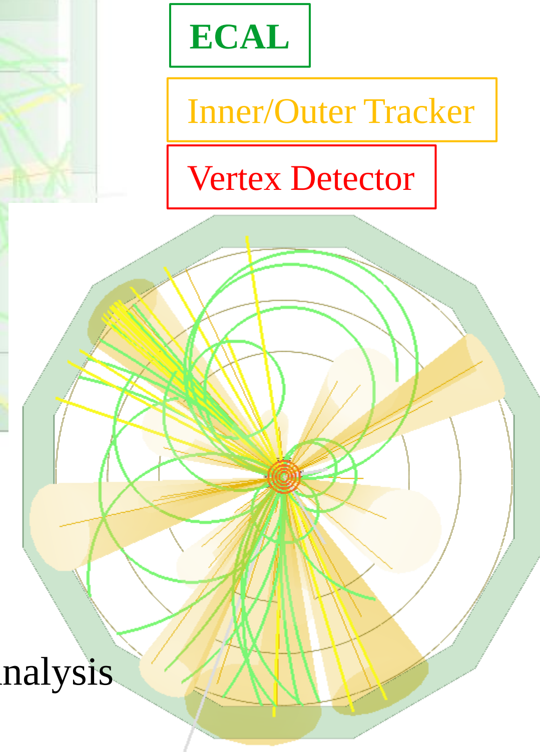
High Precision Measurements

Donatelle Lucchesi et al.

$\mu^+\mu^- \rightarrow Hx \rightarrow b\bar{b}x$ with Beam-Induced Background at 3 TeV







Event 1300, Run 13

Event display after the reconstruction
No cleaning cuts, no analysis requirements
Jets from beam background removed during the analysis

Different phyiscs benchmark simulated with Beam-Induced Background at 3 TeV to demonstrate feasibility and physics potential reach

[arXiv:2203.07261](https://arxiv.org/abs/2203.07261) The physics case of a 3 TeV muon collider stage
[arXiv:2203.07964](https://arxiv.org/abs/2203.07964) Simulated Detector Performance at the Muon Collider

Demonstrator and test facilities

Production and cooling complex novel and unique to the muon collider

- Many components are unconventional
  - ✓ e.g. high-gradient cavities in magnetic field with Be windows or filled with gas
  - ✓ massive use of absorbers in the beam path

- Novel technologies beyond MAP design can be considered
  - ✓ e.g. very short RF pulse to reduce breakdown probability

- Compact integration is required to maximise muon survival
  - ✓ complex lattice design optimisation

- Almost no experience with beam in these components, MICE has been a limited model (no RF, single muons)

⬇

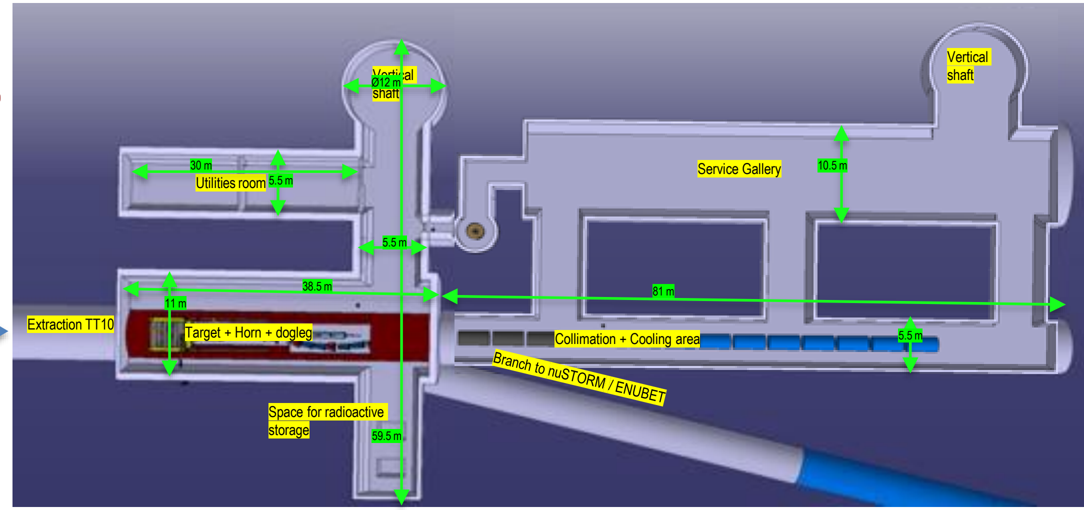
Test Facility is needed where muons are produced and cooled

Demonstrator and test facilities

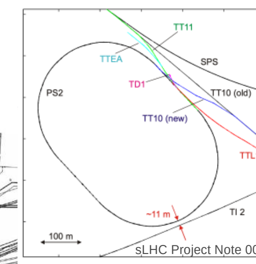
(Muon production) and Cooling Demonstrator @ CERN

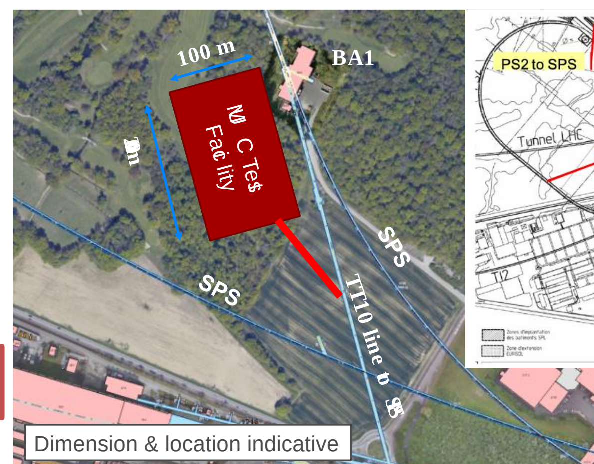
Strong synergies with nuSTORM and ENUBET

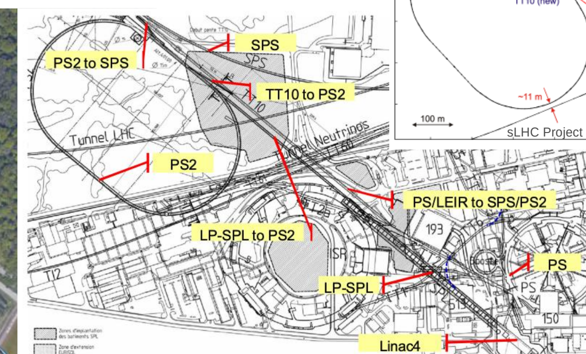
First attempt to design a site
Great opportunity to contribute



It could be close to TT10, and inject beam from PS
It would be on molasse,
no radiation to ground water







M. Benedikt, LHC Performance Workshop, Chamonix 2010
CERN-AB-2007-061

Test facilities for enabling tecnologies:
RF, Magnets, Target materials…..

Strong synergies with other future projects

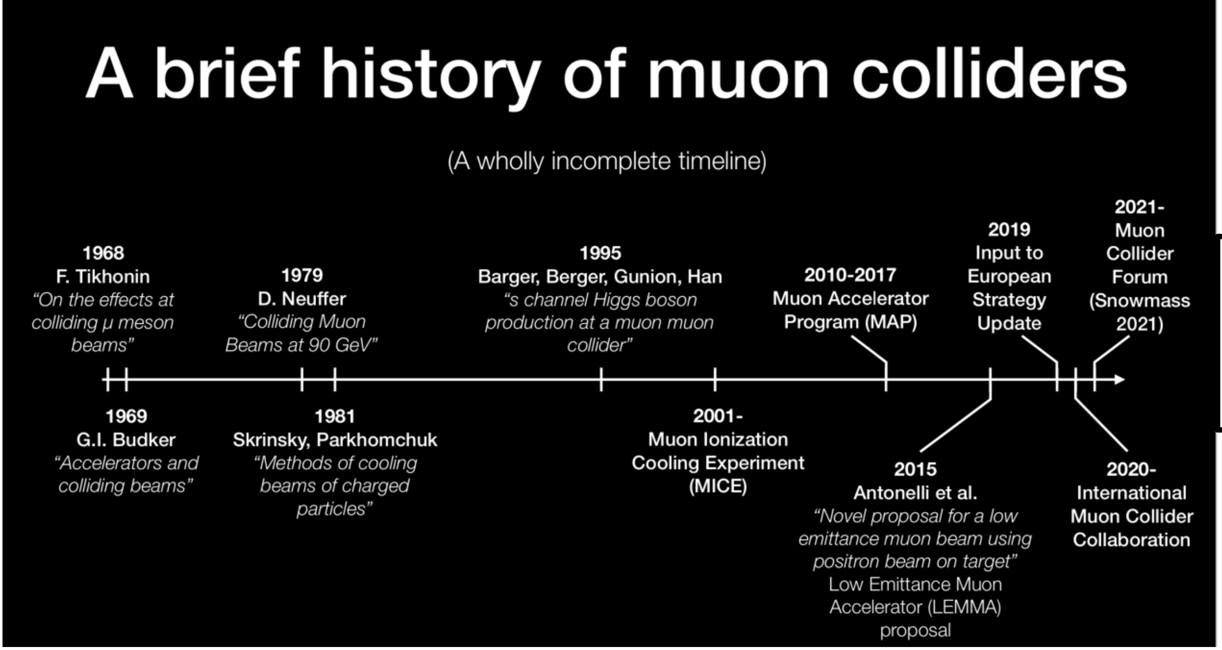
Conclusions e plans

International Collaboration GOALs:

- pre-conceptual design report with cost and power scale
- test facility conceptual design
- prepared R&D programme

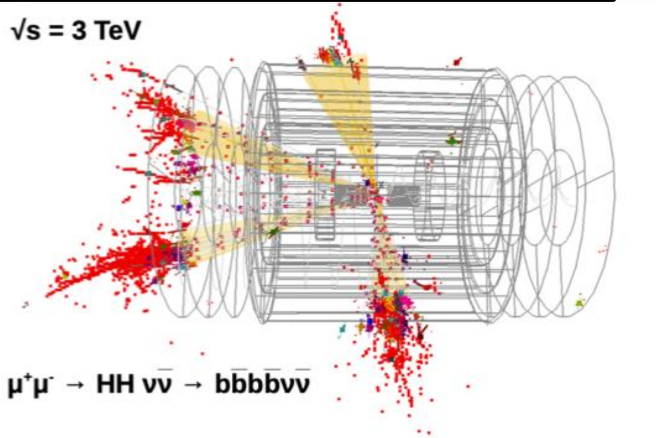
➔ **updated timeline: Muon collider $\sqrt{s} = 3$ TeV ready to take data after HL-LHC**

- **Design Study** work getting well organized in WG
  ➔ a good team on accelerator technology on board **NOW also @ INFN!**
- HORIZON-INFRA-2022-DEV-01-01 **EU project** almost ready to be submitted
  ➔ Beneficiaries: INFN, Univ. MI, Univ. PD Associated: Univ. BO, Univ. PV
- **Mandatory to consolidate resourses** mainly on accelerator
  ➔ **IMPORTANT INFN support – discussed with management in Nov. 2021**
- 2 new **PJAS @ CERN** started in March 2022 (50% on CMS)
- **5 SnowMass whitepapers** submitted March 2022 ➔ Frontiers papers to be submitted
  - arXiv:2203.08033 A Muon Collider Facility for Physics Discovery
  - arXiv:2203.07256 Muon Collider Physics Summary
  - arXiv:2203.07261 The physics case of a 3 TeV muon collider stage
  - arXiv:2203.07964 Simulated Detector Performance at the Muon Collider
  - arXiv:2203.07224 Promising Technologies and R&D Directions for the Future Muon Collider Detectors



International MUON Collider Collaboration

Design Study INFRADEV
EU project to be submitted
April 2022



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

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

Ready? GO!

Grazie!

specialmente a

M.E. Biagini, S. Guiducci, D. Lucchesi, M. Palmer, D. Schulte e molti altri

- **CERN website**
  https://muoncollider.web.cern.ch/
- **INFN Confluence website: full simulation**
  https://confluence.infn.it/display/muoncollider
- **International Design Study Indico @ CERN**
  https://indico.cern.ch/category/11818/
- **Muon Collider SnowMass Forum USA**
  https://indico.fnal.gov/event/47038/

Please subscribe at the

CERN e-group "muoncollider":

MUONCOLLIDER-DETECTOR-PHYSICS

MUST-phydet@cern.ch

MUONCOLLIDER-FACILITY

MUST-mac@cern.ch

64th ICFA Beam Dynamics Workshop on High Luminosity Factories eeFACT22
Frascati INFN National Laboratories September 12-15 2022
https://agenda.infn.it/event/21199/

extras

Community Meeting WG

Radio-Frequency (RF): *Alexej Grudiev (CERN), Jean-Pierre Delahaye (CERN retiree), Derun Li (LBNL), Akira Yamamoto (KEK)*

Magnets: *Lionel Quettier (CEA), Toru Ogitsu (KEK), Soren Prestemon (LBNL), Sasha Zlobin (FNAL), Emanuela Barzi (FNAL)*

High-Energy Complex (HEC): *Antoine Chance (CEA), J. Scott Berg (BNL), Alex Bogacz (JLAB), Christian Carli (CERN), Angeles Faus-Golfe (IJCLab), Eliana Gianfelice-Wendt (FNAL), Shinji Machida (RAL)*

Muon Production and Cooling (MPC): *Chris Rogers (RAL), Marco Calviani (CERN), Chris Densham (RAL), Diktys Stratakis (FNAL), Akira Sato (Osaka University), Katsuya Yonehara (FNAL)*

Proton Complex (PC): *Simone Gilardoni (CERN), Hannes Bartosik (CERN), Frank Gerigk (CERN), Natalia Milas (ESS)*

Beam Dynamics (BD): *Elias Metral (CERN), Tor Raubenheimer (SLAC and Stanford University), Rob Ryne (LBNL)*

Radiation Protection (RP): *Claudia Ahdida (CERN)*

Parameters, Power and Cost (PPC): *Daniel Schulte (CERN), Mark Palmer (BNL), Philippe Lebrun (CERN retiree and ESI), Mike Seidel (PSI), Vladimir Shiltsev (FNAL), Jingyu Tang (IHEP)*

Machine Detector Interface (MDI): ***Donatella Lucchesi*** *(University of Padova and INFN), Christian Carli (CERN), Anton Lechner (CERN), Nicolai Mokhov (FNAL),* ***Nadia Pastrone*** *(INFN), Sergo R Jindariani (FNAL)*

Synergy: *Kenneth Long (Imperial College), Roger Ruber (Uppsala University), Koichiro Shimomura (KEK)*

Test Facility (TF): *Roberto Losito (CERN), Alan Bross (FNAL), Tord Ekelof (Uppsala University)*

Physics & Detector:
Donatella Lucchesi *(Univ. Padova - INFN)*

WG 1: **Physics Potential:** Andrea Wulzer (EPFL&CERN) et al.
WG 2: **Detector performance (with several focus areas)**
WG 3: **Detector R&D and Software & Computing development**

Staged approach and workload

3 TeV collider: physics potential comparable to CLIC at 3 TeV

- option that could be realized much faster than a 10 TeV option:
  - It is cheaper, much more compact with a smaller power consumption
  - It can accept more compromises in technology performance

e.g. current ring magnets are comparable in performance to HL-LHC magnets

10 TeV collider

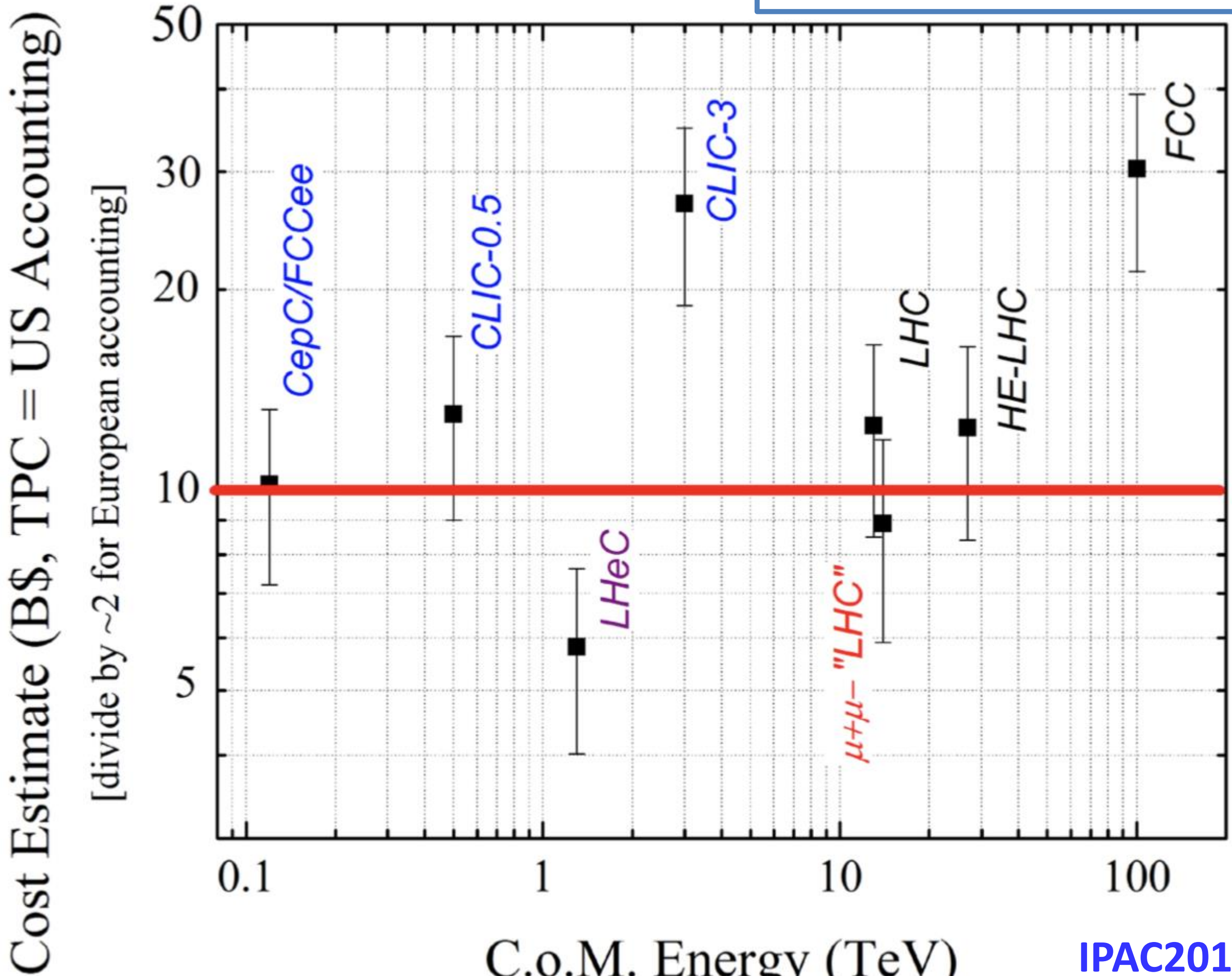
- could then be realized using almost all infrastructure from 3 TeV, but collider ring

- 3 and 10 TeV collider designs share all systems
  - except collider ring and 1.5 to 5 TeV accelerator rings
  - limited lattice design work – more work for MDI
- Some technology challenges are more important at 10 than at 3 TeV
  - higher dipoles fields in collider (O(15 T)) – stronger final focus quadrupoles (O(18-20 T))
  - shorter bunches in cavities of last accelerator ring
  - would like more performance accelerator ring systems to cut length and cost
- **Total additional effort seems acceptable given the importance**

Very rough cost estimate

NB: all $$ - "US Accounting" (divide by 2-2.4 at CERN)

Vladimir SHILTSEV, David NEUFFER (Fermilab)



IPAC2018 - MOPMF072

Muon Collider @ FNAL option

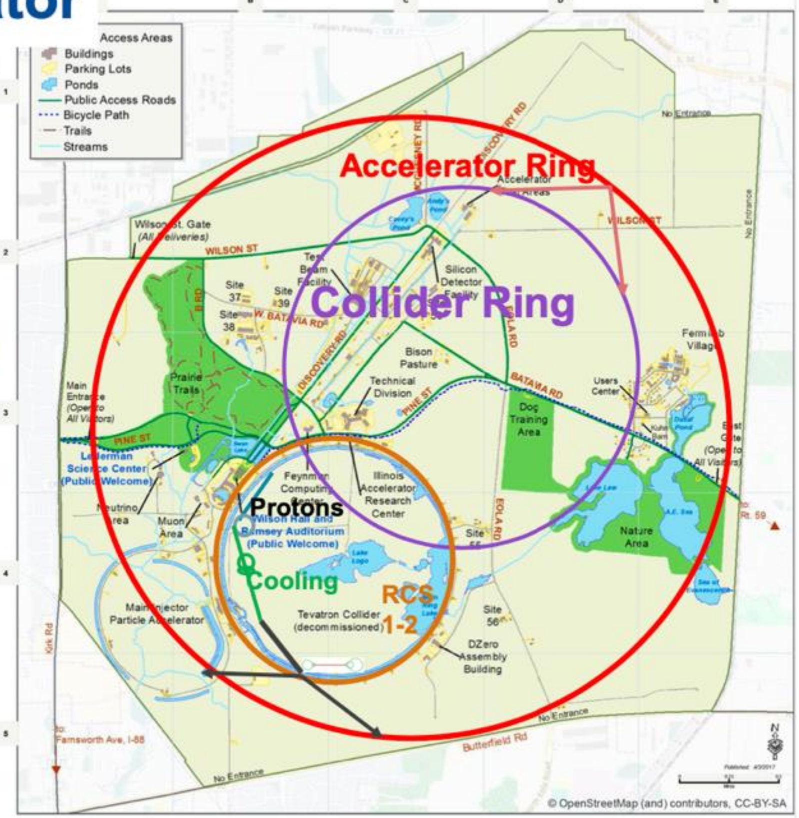
10 TeV collider requires ~16 T dipoles in RCS scenarios With rapid-cycling 2-4 T magnets

Site filler Accelerator

- **Proton Source**
  - **PIP-III→target**
- **μ Cooling**
- **Linac + RLA → 65 GeV**
- **RCS 1 and 2 → 1000 GeV**
  - **Tevatron-size**
- **RCS 3 → 5 TeV**
  - **Site filler accelerator**

10 TeV collider

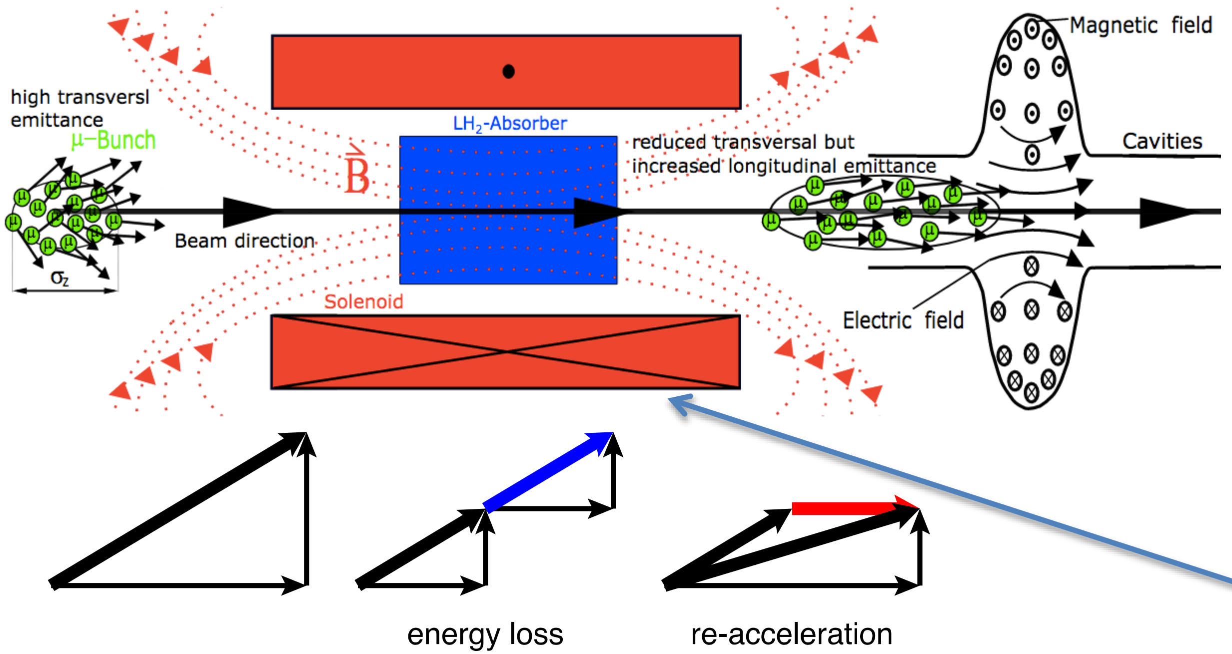
Collider Ring ~10 km

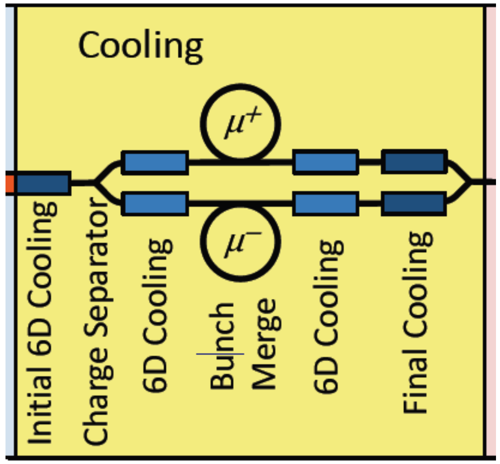


Fermilab

Fermilab new formed Future Colliders Group is actively exploring filler option

Final Cooling Challenge





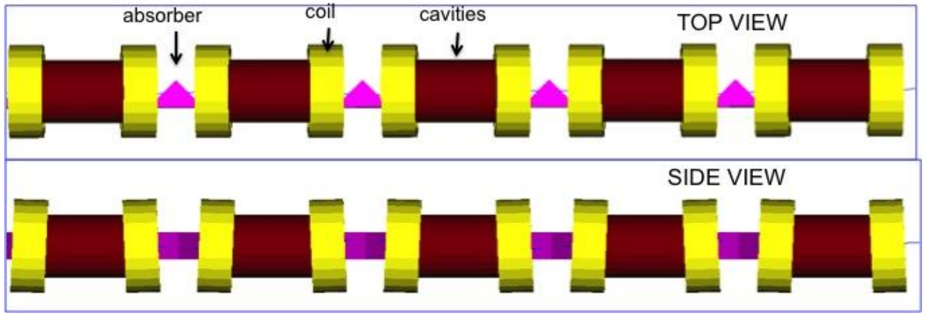
High field solenoids minimise beta-function and impact of multiple scattering

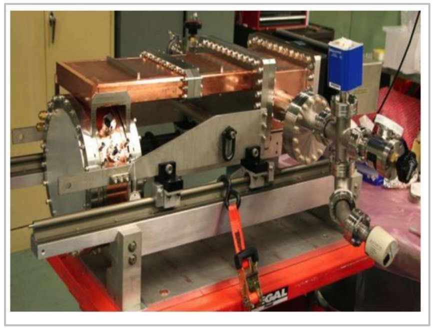
Energy loss = cooling

Multiple scattering = heating

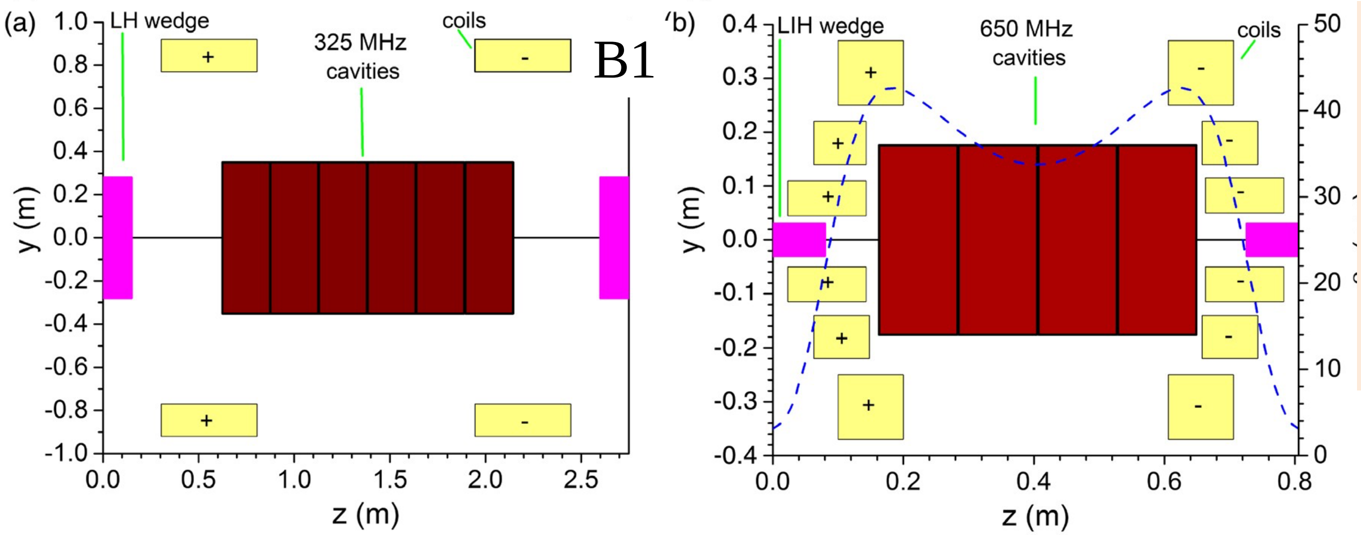
$$\frac{d\epsilon_\perp}{ds} = -\frac{1}{(v/c)^2}\frac{dE}{ds}\frac{\epsilon_\perp}{E} + \frac{1}{2}\frac{1}{(v/c)^3}\left(\frac{14\,\mathrm{MeV}}{E}\right)^2\frac{\beta\gamma}{L_R}$$

6D Cooling Cell Design





MuCool: >50 MV/m in 5 T
Two solutions
- H2-filled copper cavities
- Cavities with Be end caps

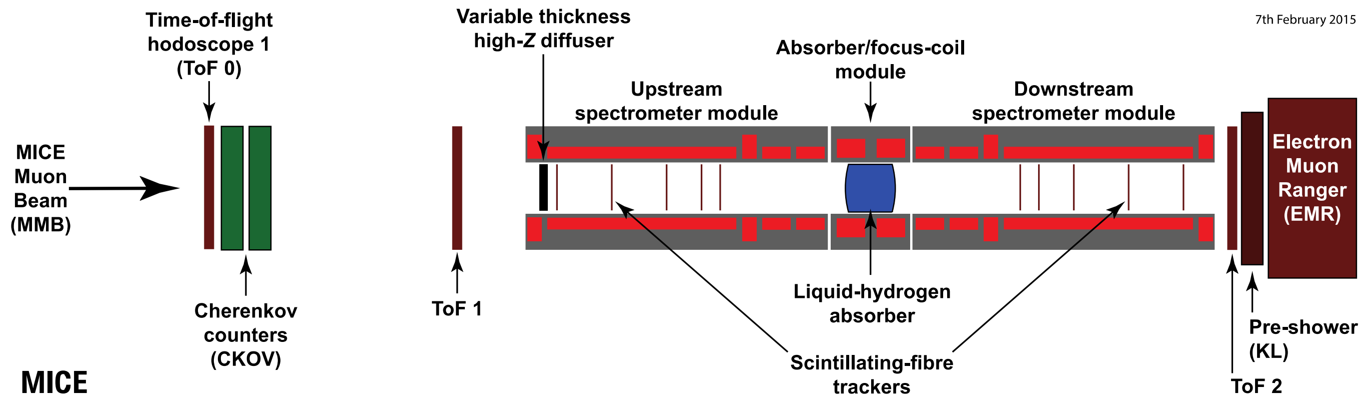


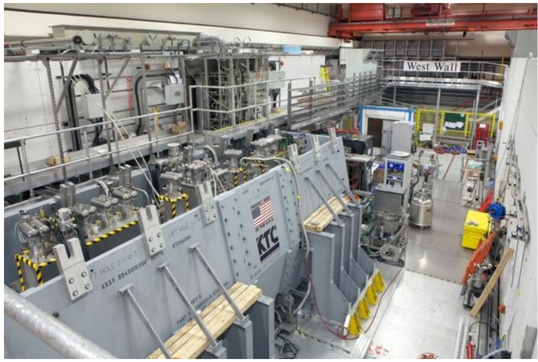
H**igh-gradient cavities in high magnetic field**

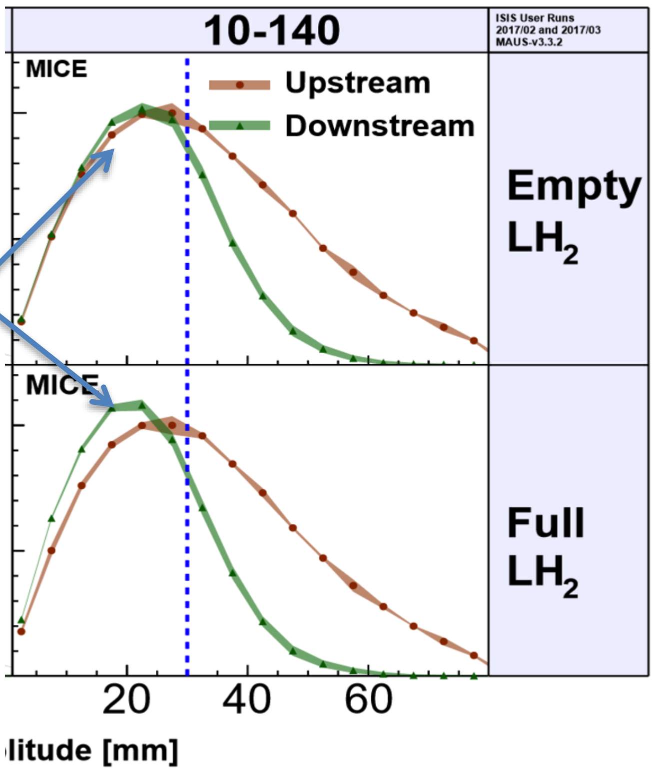
Tight integration of solenoids, RF, absorbers, instrumentation, cooling, vacuum, alignment, …

Will aim for further optimisation
This is the **unique** and **novel** system of the muon collider
Will need a **test facility**

MICE (in the UK)







Nature volume 578, pages 53-59 (2020)

More particles at smaller amplitude after absorber is put in place

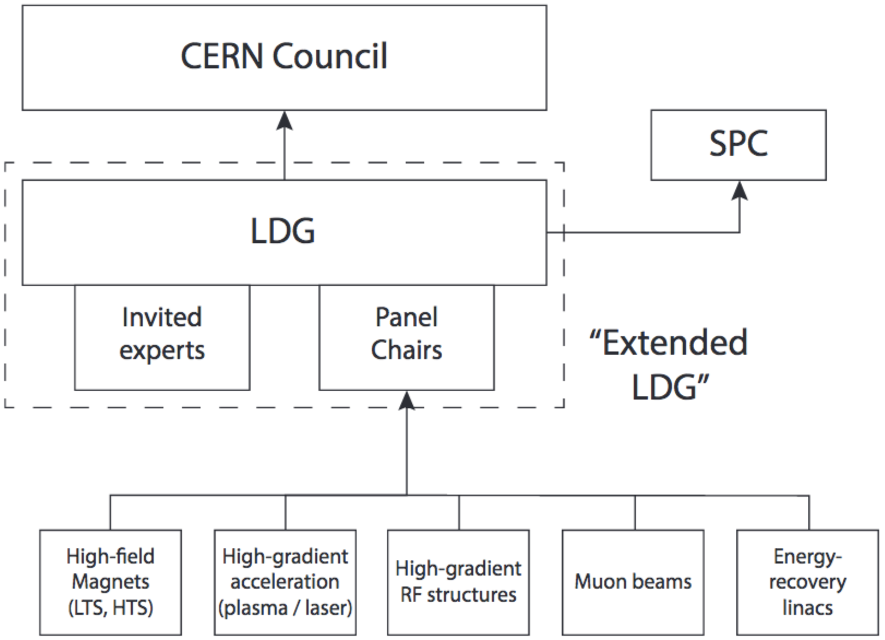
Principle of ionisation cooling has been demonstrated

More complete experiment with higher statistics, more than one stage required

Integration of magnets, RF, absorbers, vacuum is engineering

European Accelerator R&D Roadmap

Council charged Laboratory Directors Group (LDG) to deliver European **Accelerator R&D Roadmap** by the end of the year



Panels

- Magnets: P. Vedrine
- Plasma: R. Assmann
- RF: S. Bousson
- Muons: D. Schulte
- ERL: M. Klein

Muon Beam Panel members: Daniel Schulte (CERN, chair), Mark Palmer (BNL, co-chair), Tabea Arndt (KIT), Antoine Chance (CEA/IRFU) Jean-Pierre Delahaye (retired), Angeles Faus-Golfe (IN2P3/IJClab), Simone Gilardoni (CERN), Philippe Lebrun (European Scientific Institute), Ken Long (Imperial College London), Elias Metral (CERN), Nadia Pastrone (INFN-Torino), Lionel Quettier (CEA/IRFU), Tor Raubenheimer (SLAC), Chris Rogers (STFC-RAL), Mike Seidel (EPFL and PSI), Diktys Stratakis (FNAL), Akira Yamamoto (KEK and CERN)
Contributors: Alexej Grudiev (CERN), Donatella Lucchesi (INFN-Padua), Roberto Losito (CERN), Andrea Wulzer (EPFL, CERN, Padua)

Roles of panel members and European (other regions to be added) contact persons at https://muoncollider.web.cern.ch/organisation

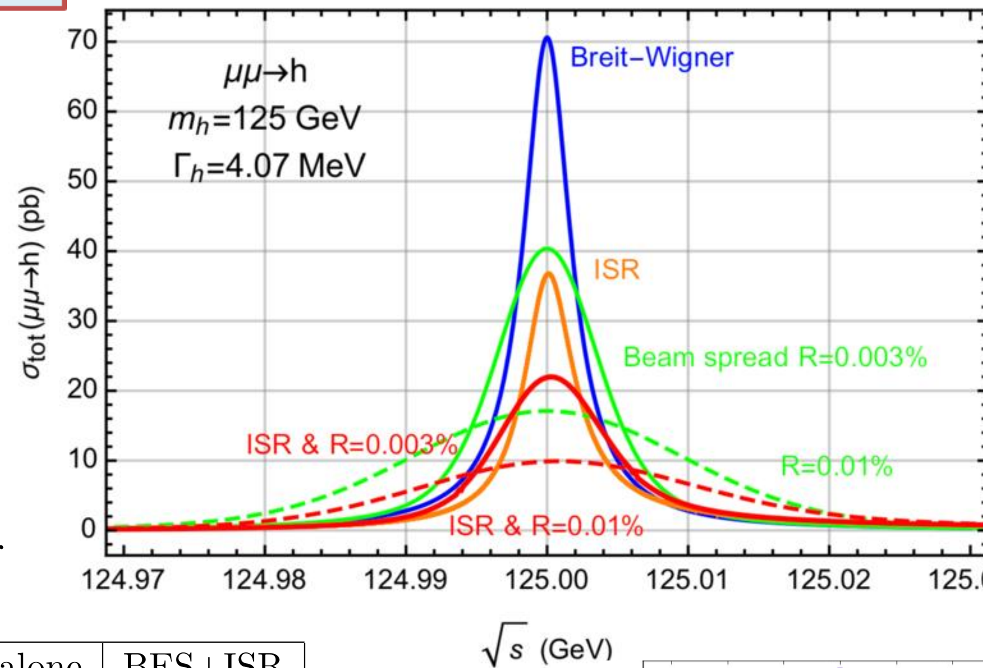
Lepton Colliders: μ vs e @ $\sqrt{s}$=125 GeV

Back on the envelope calculation:

$$\sigma(\mu^+\mu^- \to H) = \left(\frac{m_\mu}{m_e}\right)^2 \times\sigma(e^+e^- \to H) = \left(\frac{105.7MeV}{0.511\,MeV}\right)^2 \times\sigma(e^+e^- \to H)$$

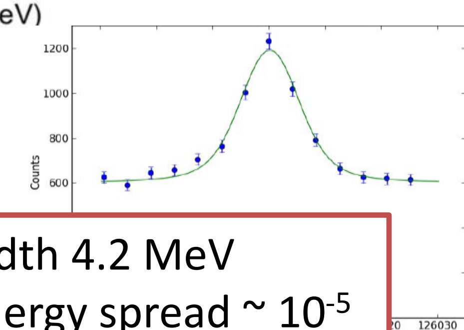
$$\sigma(\mu^+\mu^- \to H) = 4.3\times10^4\times\sigma(e^+e^- \to H)$$

More precise determination
by M. Greco et al. arXiv:1607.03210v2



R: percentage beam energy resolution, key parameter

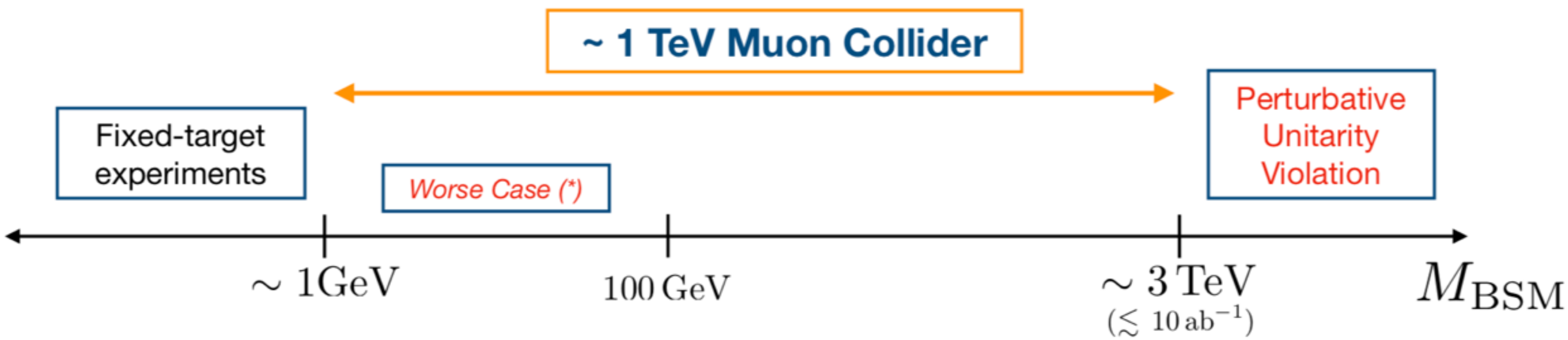
σ(BW)	ISR alone	R (%)	BES alone	BES+ISR
$\mu^+\mu^-$: 71 **pb**	37	0.01	17	10
		0.003	41	22
e^+e^-: 1.7 **fb**	0.50	0.04	0.12	0.048
		0.01	0.41	0.15



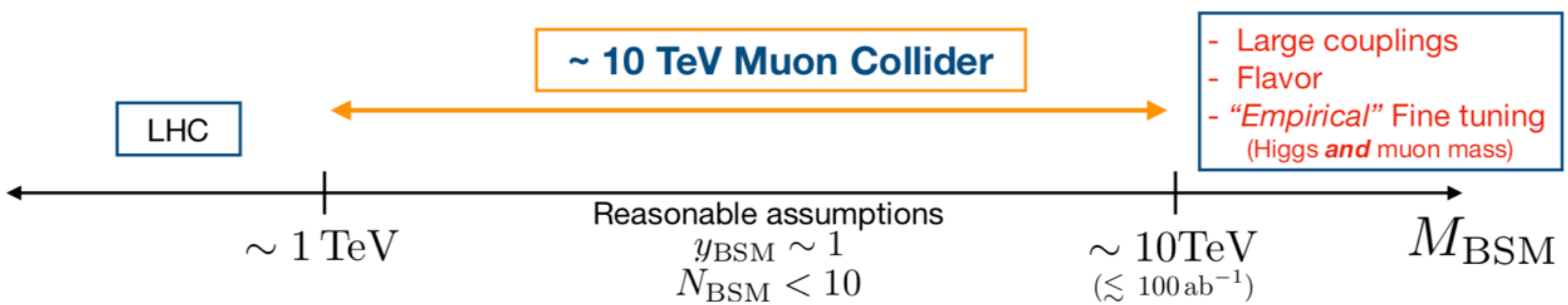
Higgs width 4.2 MeV
Beam energy spread ~ 10^{-5}

g-2 @ Muon Collider

- Singlet Models

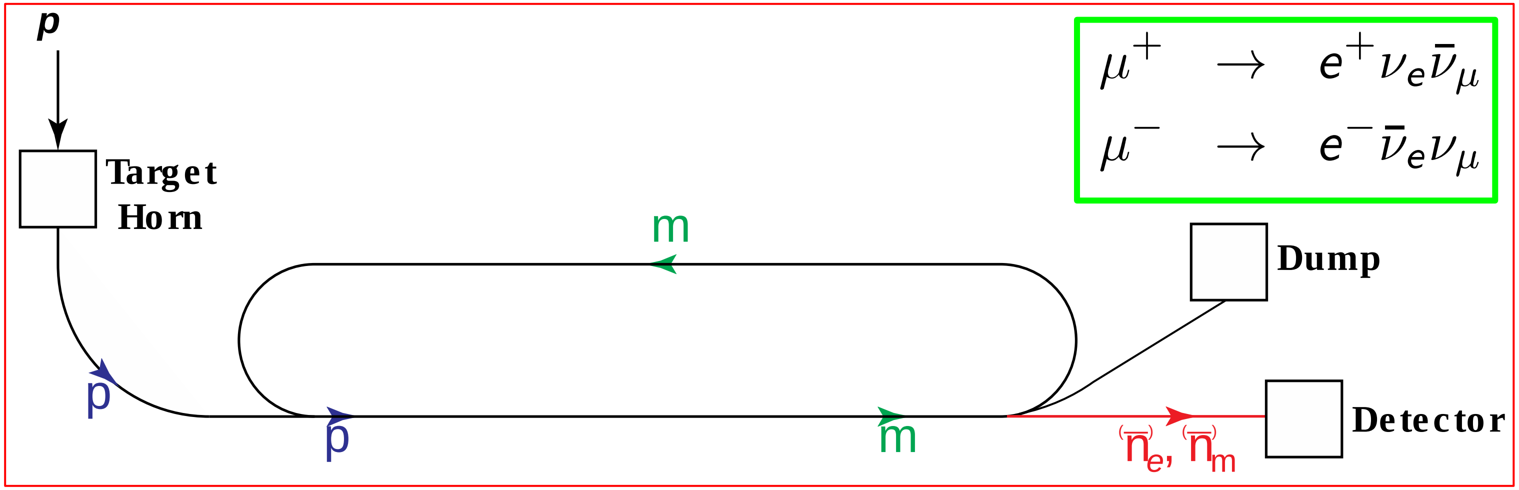


- High-Scale EW Models



nuSTORM: neutrino from stored muons

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



- **Scientific objectives**:
  1. %-level ($\nu_e N$) cross sections
     - Double differential
  2. Sterile-neutrino/BSM search
     - Beyond Fermilab SBN

- **Precise neutrino flux:**
  - **Normalisation: < 1%**
  - **Energy (and flavour) precise**

- ***π*⇢ *μ* injection pass:**
  - **"Flash" of muon neutrinos**