Workshop Nazionale
Milano 7-8 Aprile 2022

INFN ACCELERATORI

multi-TeV Muon Collider

RD_MUCOL @ CSN1

International MUON Collider Collaboration

Nadia Pastrone INFN TORINO

On behalf of **INFN** *groups in*:
LNF PD RM1 MI TO TS BO MIB FE PV LNL RM3 BA GE NA LNS

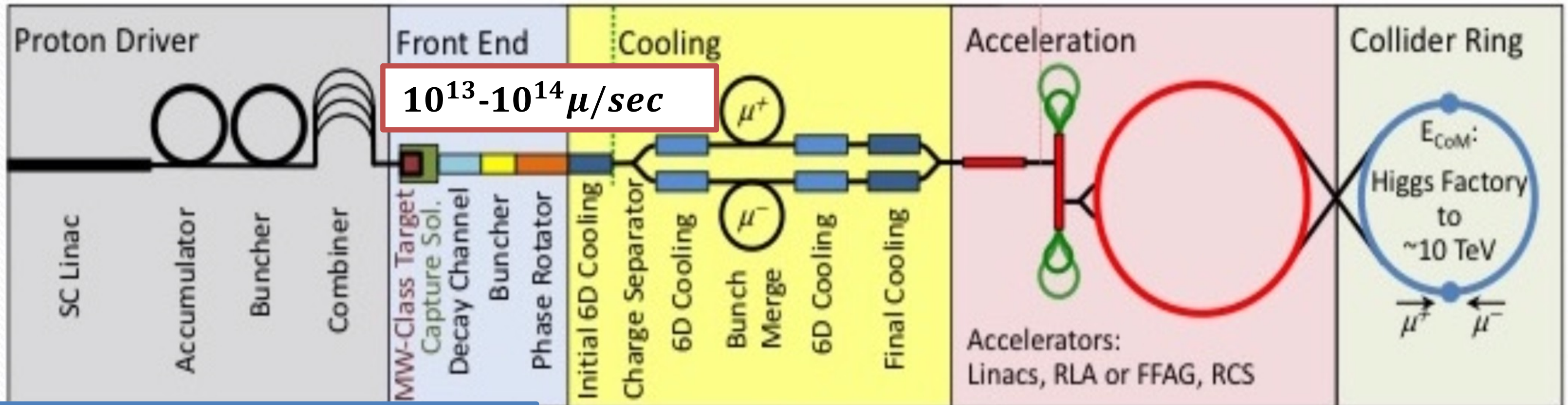
2016-2020: RD_FA @ CSN1 WP LEMMA Mario Antonelli (LNF PD RM1 MI PV FE TO TS)

Since 2021: RD_MUCOL @ CSN1 ~16+3 FTE / 90+20 phys/eng in 13 + 3 sections
Synergies in EU projects: aMUSE, AIDAinnova, I.FAST

Accelerator Tecnologies

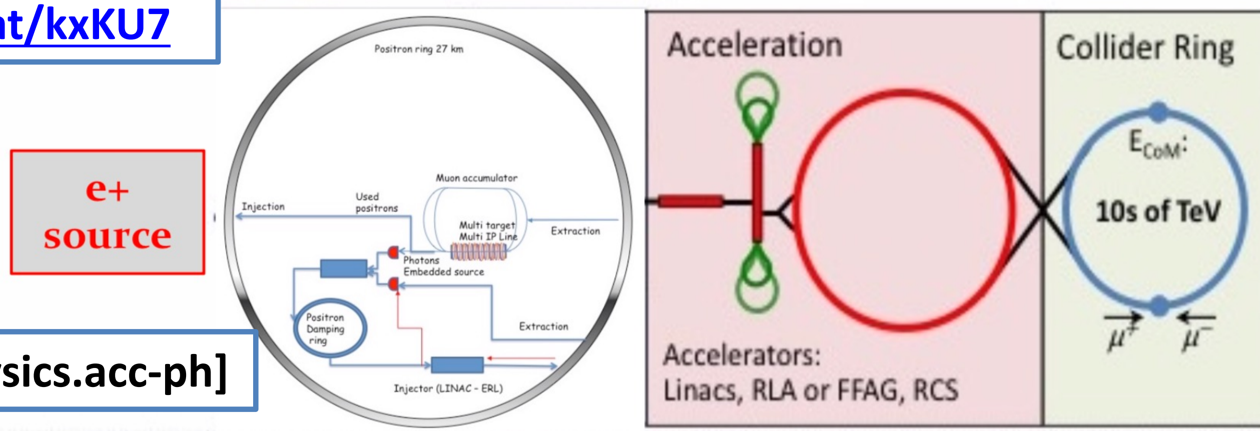
proton (MAP) vs positron (LEMMA) driven muon source

MAP



MUON JINST, shorturl.at/kxKU7

LEMMA



arXiv:1905.05747v2 [physics.acc-ph]

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

A long story…

- The **muon collider idea** was first introduced in **early 1980's** *[A. N. Skrinsky, D. Neuffer et al.,]*
- Idea further developed by a **series of world-wide collaborations**
- **US Muon Accelerator Program – MAP,** created in **2011,** was terminated in **2014**

  MAP developed a ***proton driver scheme*** *and addressed the feasibility of novel technologies required for Muon Colliders and Neutrino Factories* ***"Muon Accelerator for Particle Physics," JINST,*** *https://iopscience.iop.org/journal/1748-0221/page/extraproc46*
- **LEMMA (Low EMittance Muon Accelerator)** proposed in **2013** *[M. Antonelli e P. Raimondi]*

  a new end-to-end design of a ***positron driven scheme*** *presently under study by INFN-LNF et al. to overcome technical issues of initial concept* ➔ arXiv:1905.05747
- **CERN-WG on Muon Colliders** *[N.Pastrone chair]***:** September 2017- June 2020
- Padova Aries2 Workshop on Muon Colliders – July 2018
- **Input document** submitted to ESPPU: "Muon Colliders" arXiv:1901.06150 December 2018 (*)
- Various workshop/meeting to prepare for Granada (2019) and during ESPPU

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

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

LDG established in September 2017 the Muon Collider Working Group that states:

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

International Collaboration

International
MUON Collider
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

A unique facility

Jan 2021 **nature physics**

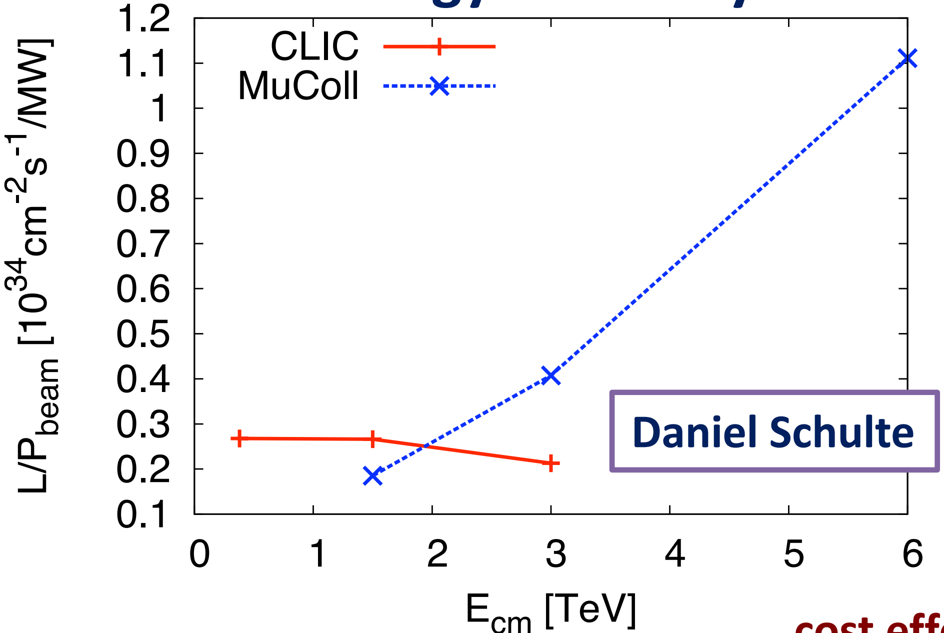
[Muon colliders to expand frontiers of particle physics](#)

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](#)

Energy Efficiency



Overwhelming physics potential:

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

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

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

Baseline facility

- **Focus on two energy ranges:**

3 TeV technology ready for construction in 10-20 years

10+ TeV with more advanced technology

ASSUMPTION/IP

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

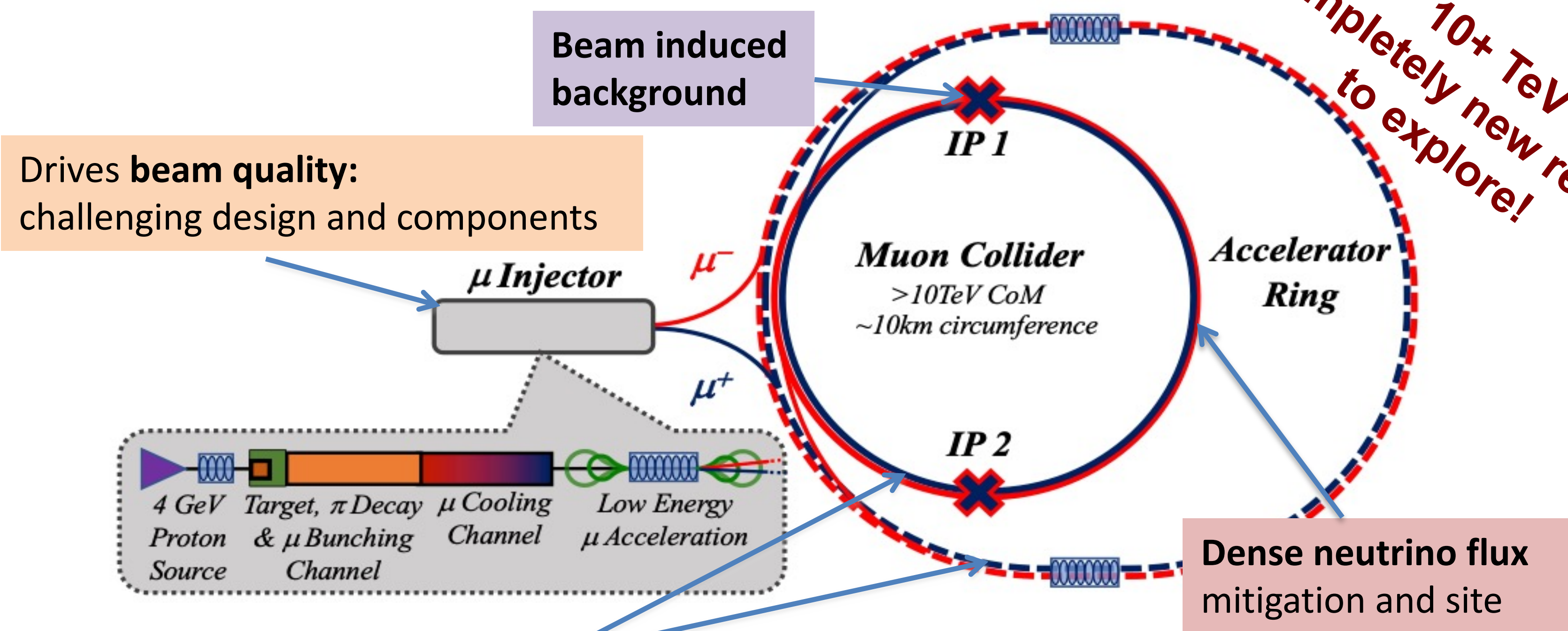
@ 3 TeV $1\ \text{ab}^{-1}$ /5 years

@ 10 TeV $10\ \text{ab}^{-1}$ /5 y

@ 14 TeV $20\ \text{ab}^{-1}$ /5 y

Proton driver production
Baseline @ International Design Study

10+ TeV completely new regime to explore!



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

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 no staging
Would only do 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

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 → ready to December Council 2021**
  dedicated Muon Beams Panel - but also synergies in High field magnets, RF and ERL
- European ECFA **Detector R&D Roadmap → ready 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 spring 2023**
- Submission of HORIZON-INFRA-2022-DEV-01-01 EU project for Design Study **April 2022**
  Research infrastructure concept development → **supported by TIARA**

Physics potential

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

Direct searches
Pair production, Resonances, VBF, Dark Matter, …

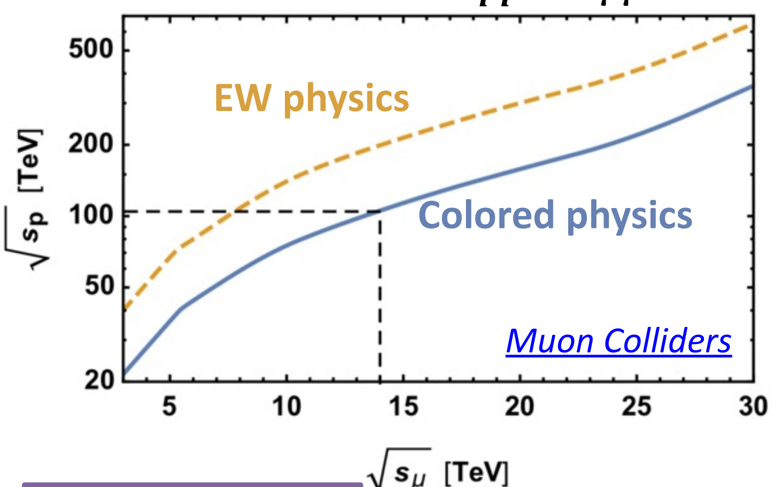
High-rate measurements
Single Higgs, self coupling, rare and exotic Higgs decays, top quarks, …

High-energy probes
Di-boson, di-fermion, tri-boson, EFT, compositeness, …

Muon physics
Lepton Flavor Universality, $b \to s\mu\mu$, muon g-2, …

Muon Collider can be the game changer!

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



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

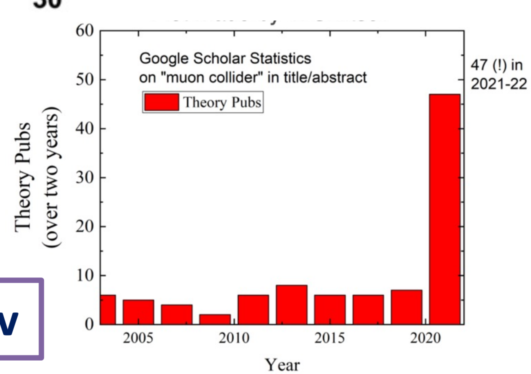
The Muon Smasher's Guide,
https://doi.org/10.48550/arXiv.2103.14043

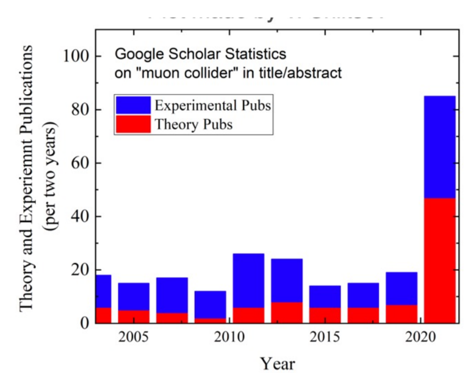
Strong and crucial synergies to design the machine and the experiment to reach the physics goals with energy and luminosity allowing % precision measurements

➔ **Physics benchmarks steer machine parameters and experiment design**

Andrea Wulzer

Vladimir Shiltev

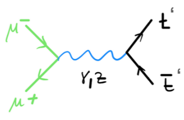




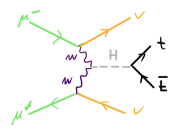
Physics: the essentials

Fabio Maltoni

O(10) TeV muon collider energy allows to have two colliders in one:



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



A completely new regime opening for a multi-TeV muon collider

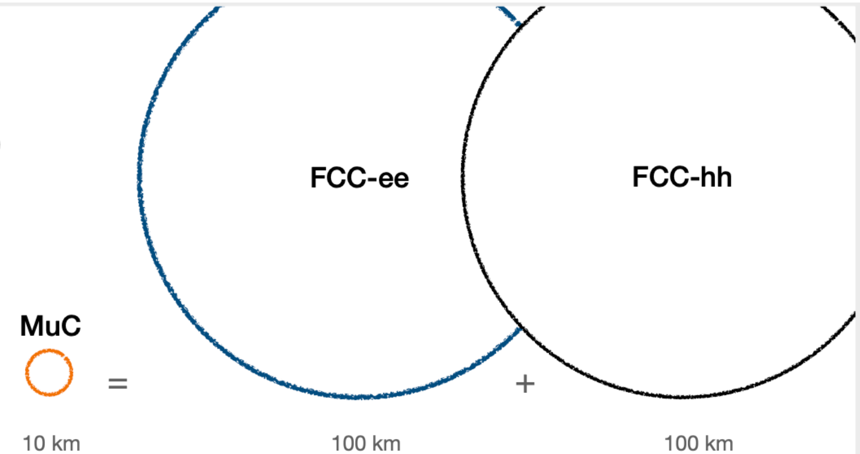
Different physics being probed in the two channels

A Multi-TeV Muon Collider is a space-time compact collider, energy upgradable, with the unique ability to act as a lepton collider as well as a VV collider

Muon collider physics

The essentials

1] O(10) TeV Energy small two-in-one collider:



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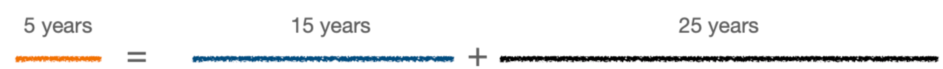
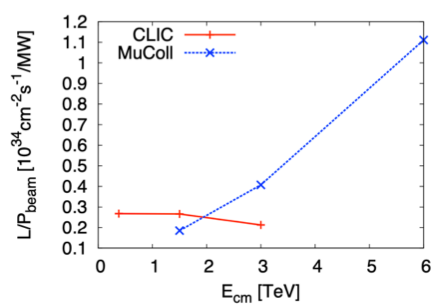
2] Luminosity growing with energy:



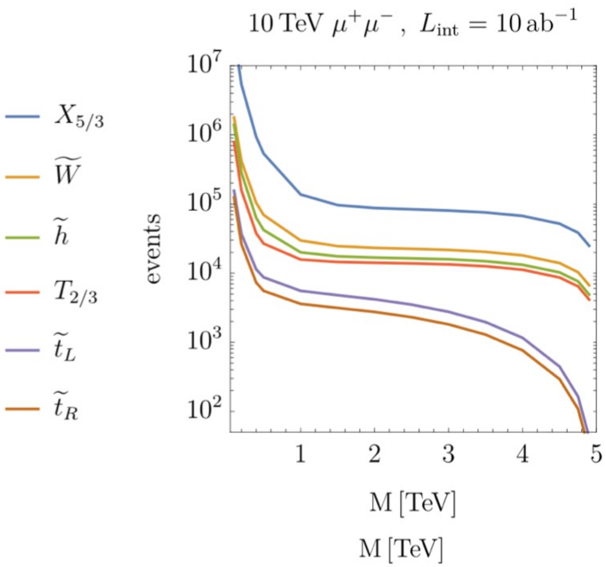


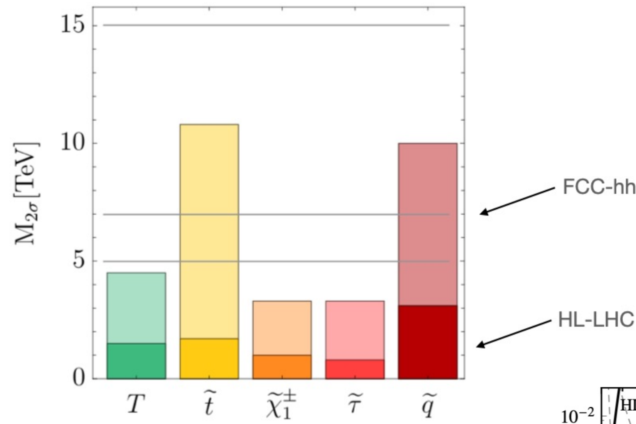
⇒**MuC is an SSTC = Space-Time Compact Collider**

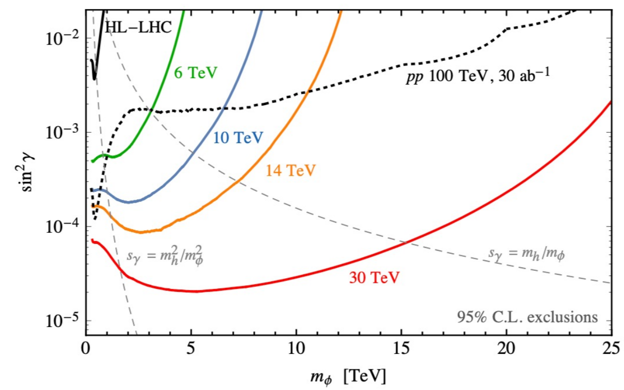
MuC10: 10 TeV, 10 iab, 10 times smaller and 10 times quicker than the FCC

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







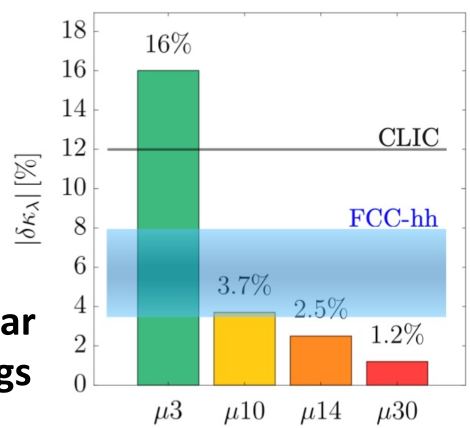
Exclusion contour for a scalar singlet of mass mϕ mixed with the Higgs boson with strength sin γ

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



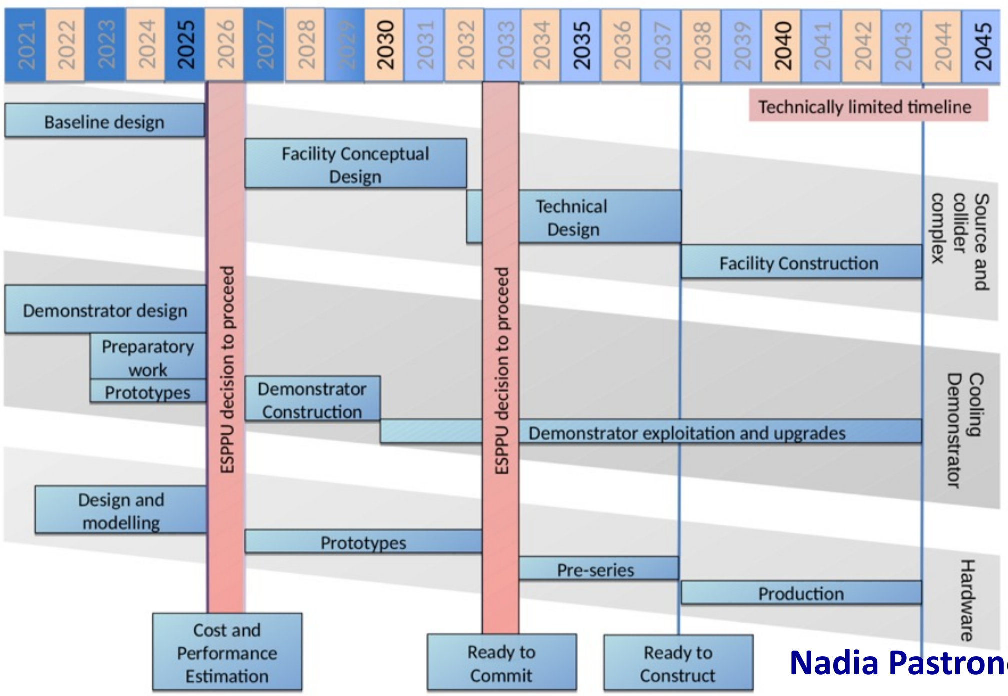
Accelerator R&D Roadmap

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

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

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

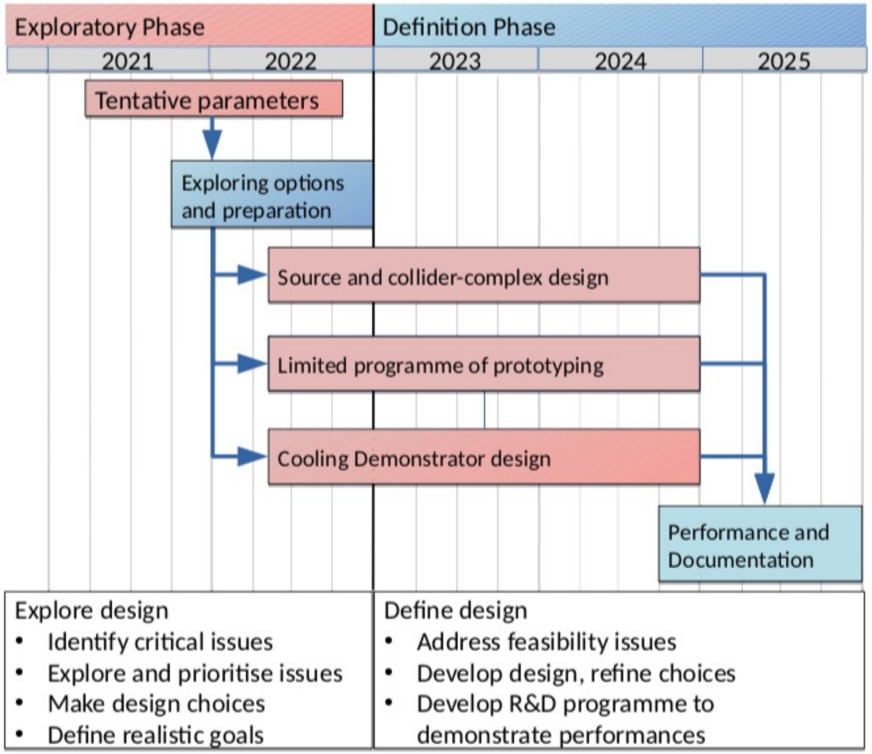
~70 Meu/5 years

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

aMUSE **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.

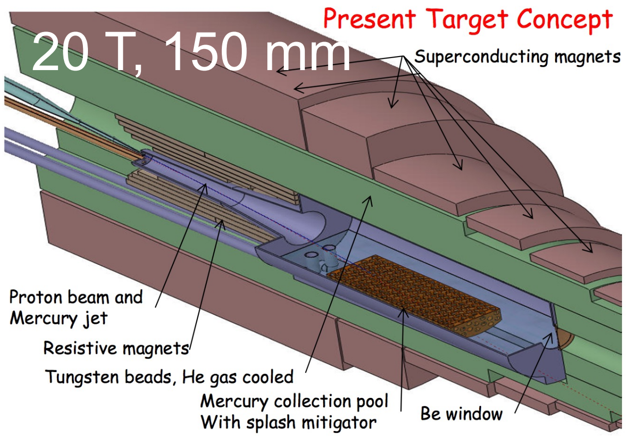
Summary of IMC RF systems

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

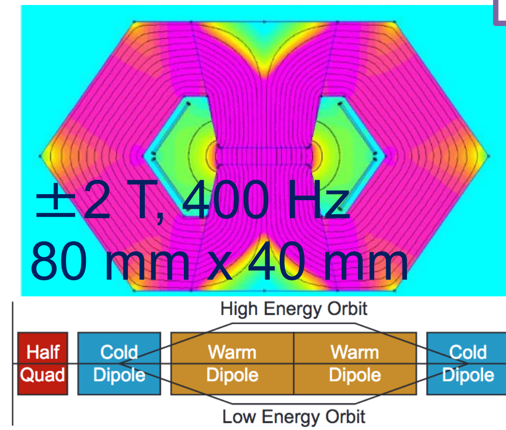
System			Driver			Front-End	Cooling			Acceleration			Collider	TOTAL	CLIC
Sub-system			Driver Linac H- (SPL like)		Accum &Comp	Capture& Bunching	Initial	6D (2 lines)	Final (2 lines)	Injector Linac	RLAs (2stages)	RCS (3stages)	Ring	IMC	Acceleration
Reference expert			F.Gerigk		?	D.Neuffer	C.Rogers	D.Stratakis	C.Rogers	A.Bogacz		S.Berg	E.Gianfelice		
Beam (system exit)	Energy	GeV/c	0.16	5	5	0.255	0.255	0.255	0.255	1.25	62.5	1500	1500		1500
	# 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

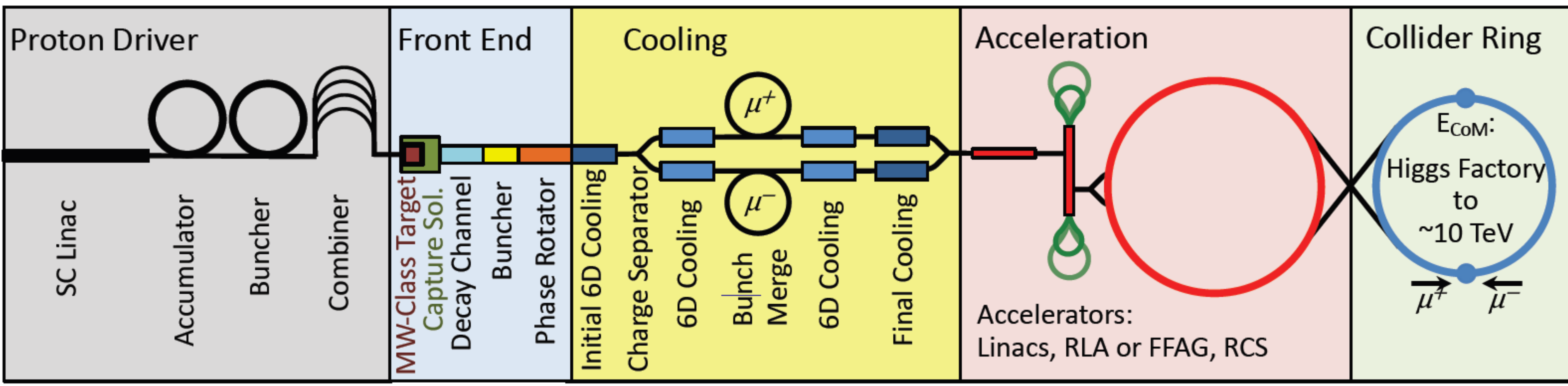
Luca Bottura



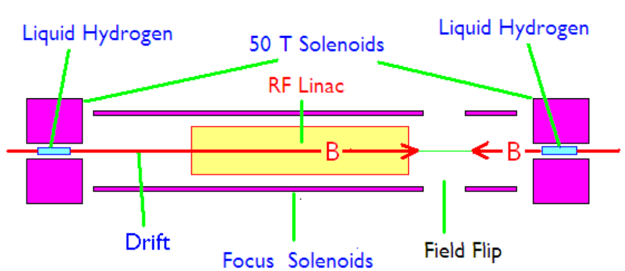
High-field and large aperture target solenoid with heavy shielding to withstand heat (100 kW/m) and radiation loads



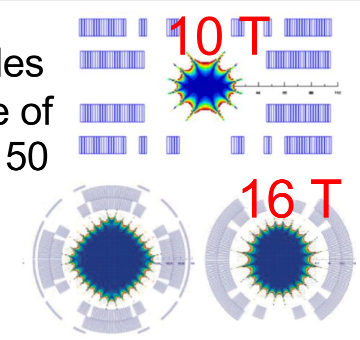
Combination of DC SC magnets (10 T) and AC resistive magnets (±2T)



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

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

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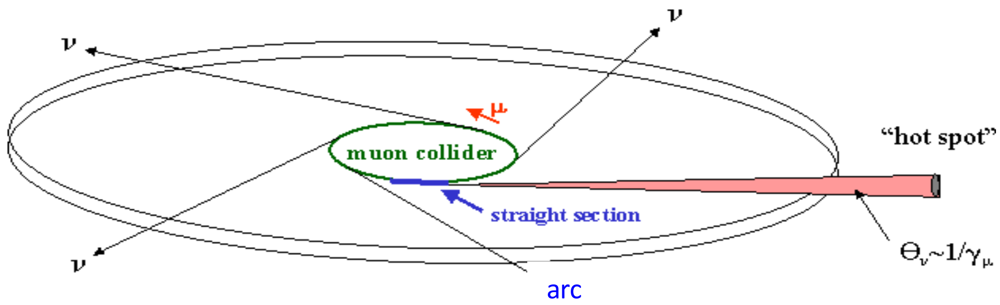
[5] S. Hahn, et al., “45.5-Tesla Direct-Current Magnetic Field Generated with a High-Temperature Superconducting Magnet”, Nature, 570 (2019) pp. 496–499

[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

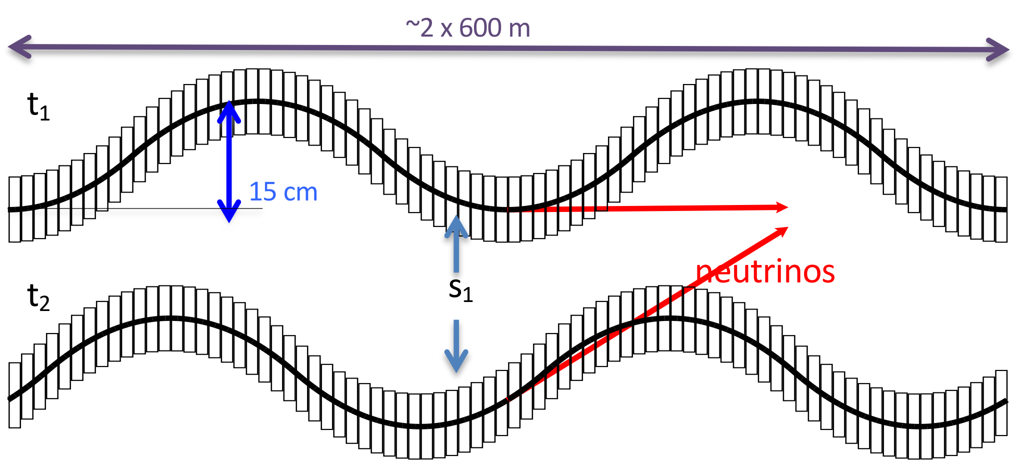
Neutrino Flux Mitigation



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

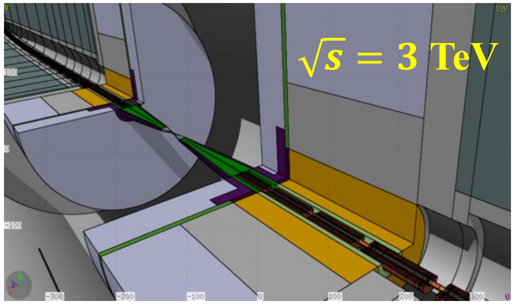
Need to study mover system, magnet, connections and impact on beam

Working on different approaches for experimental insertion

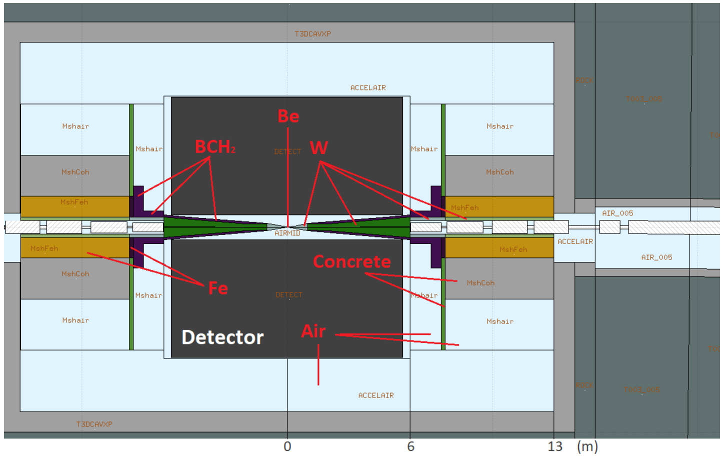
Machine Detector Interface

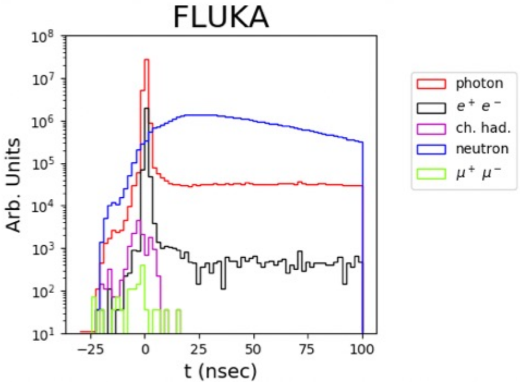
Advanced assessment of beam-induced background at a muon collider
F. Collamati, C. Curatolo, D. Lucchesi, A. Mereghetti, P. Sala *et al.* 2021 *JINST* **16** P11009

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



LineBuilder + FLUKA simulation



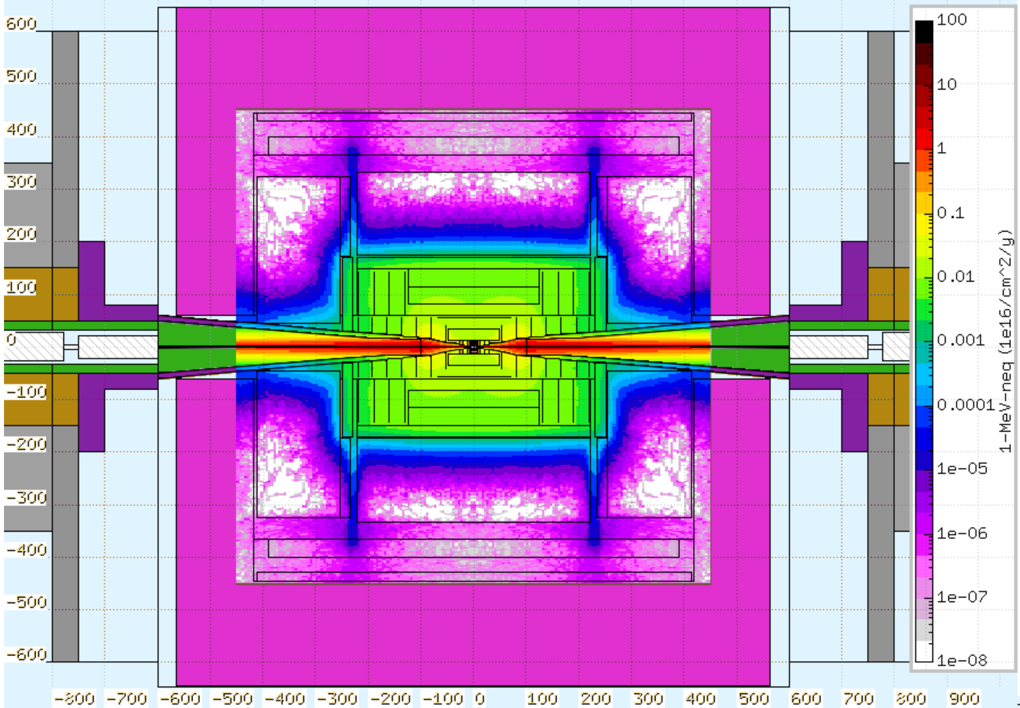


First MDI Kick-off meeting @ November 2021

➔ first lattice and MDI studies @ 10 TeV by CERN

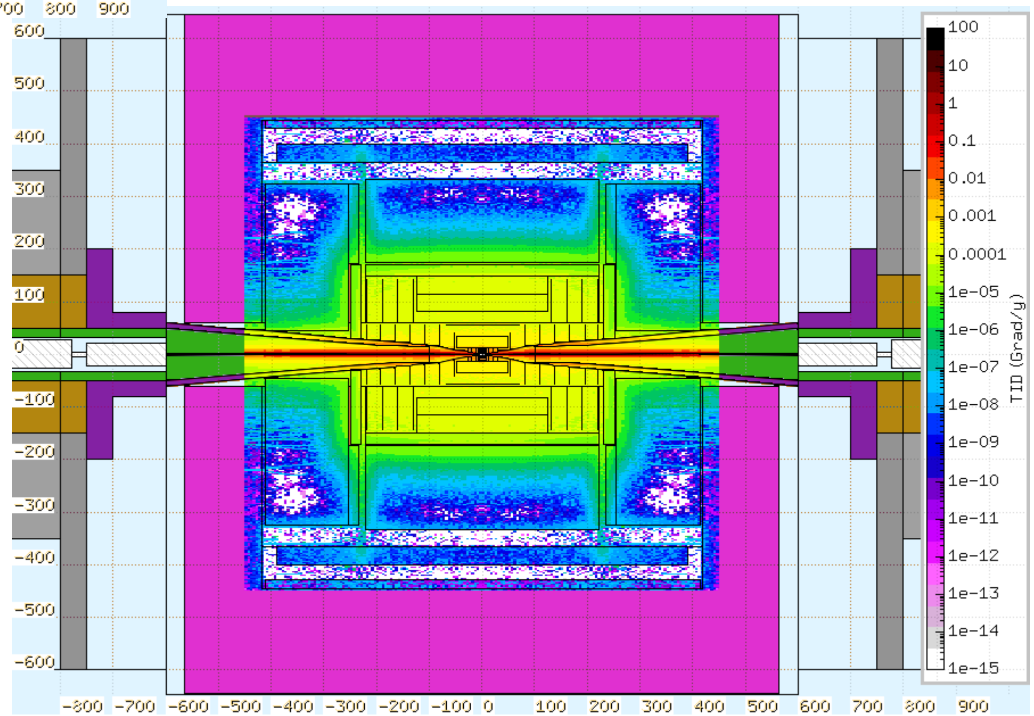
MDI WG: *C.Carli, A. Lechner,* ***CERN****, N. Mokhov, S.Jindariani,* ***FNAL****, D.Lucchesi, N.Pastrone,* ***INFN***

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



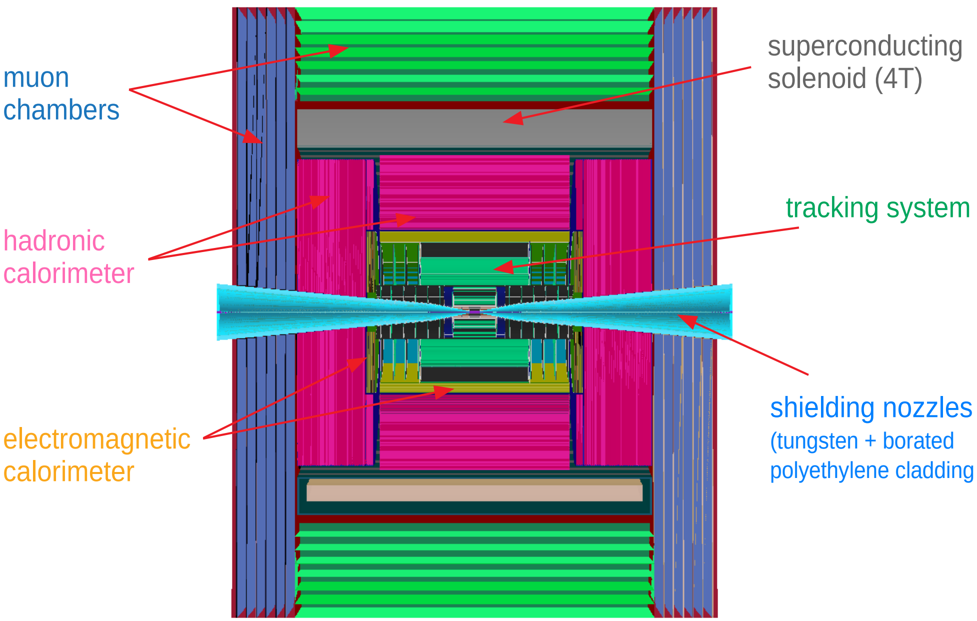
Camilla Curatolo, Paola Sala

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

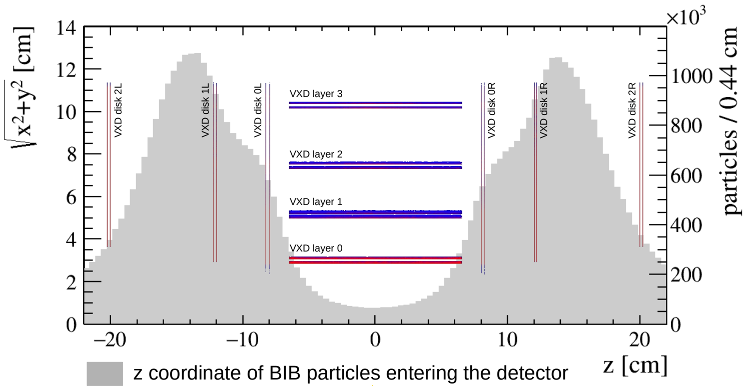
Full simulation available on public repository

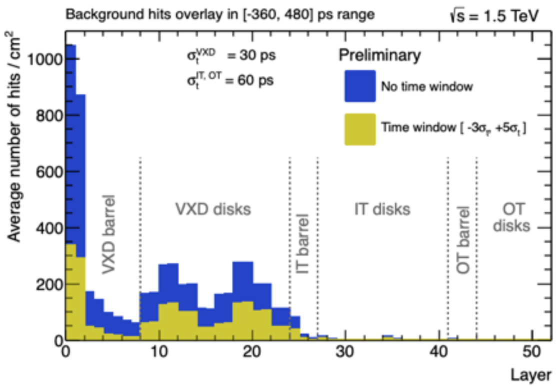
Quite advanced conceptual design for 1.5 TeV and 3 TeV
➔ More R&D on technologies required @ 10+ TeV

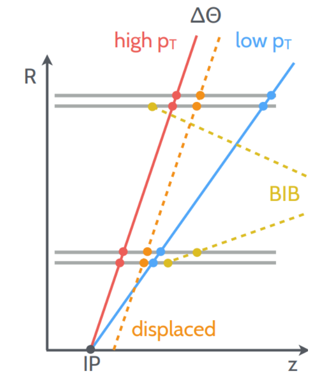
Tracker detector @ 1.5 TeV

Nazar Bartosik, Massimo Casarsa et al.

Max radiation tolerance NIEL: 0.5x 10^{16} neq/cm^2/year
Max radiation tolerance TID: 300 Mrad/year







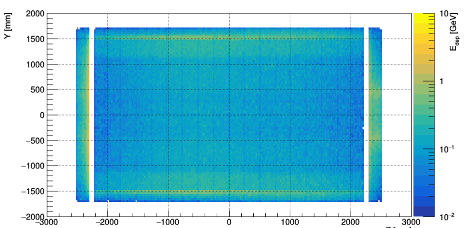
- Vertex detector properly designed to not overlap with the BIB hottest spots around IR
- Timing window applied to reduce hits from out-of-time BIB
- Granularity optimized to ensure $\lesssim$ 1% occupancy
- Realistic digitization in progress ➔ BIB suppression based on cluster shape
- If primary vertex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

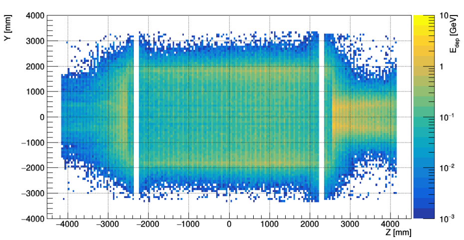
Calorimeters and Muon detectors

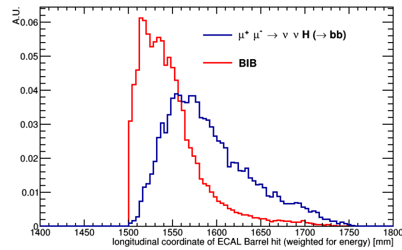
timing and longitudinal measurements play a key role in the BIB suppression

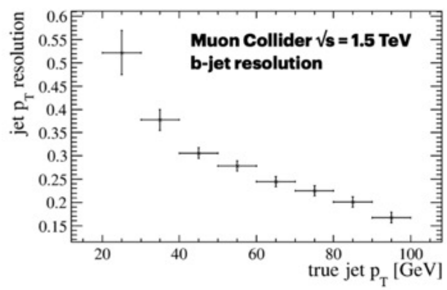
Calorimeters

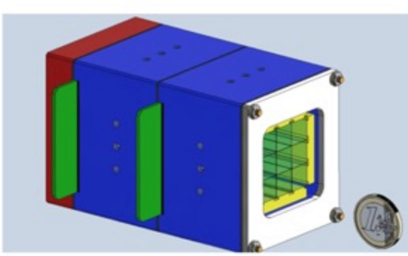
BIB deposits large amount of energy in both ECAL and HCAL

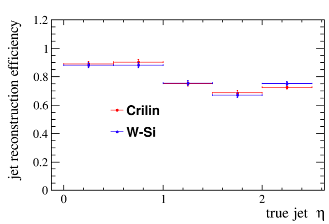


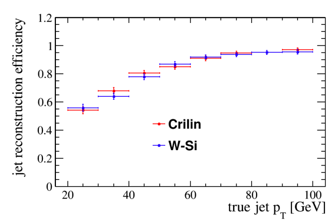










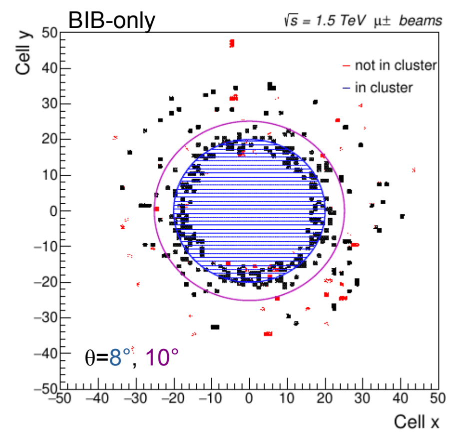


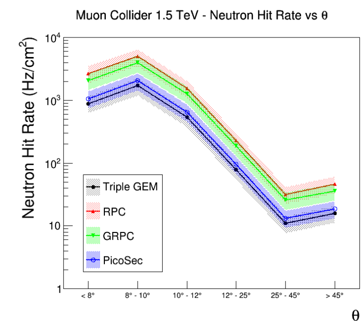
Lorenzo Sestini, Ivano Sarra et al.

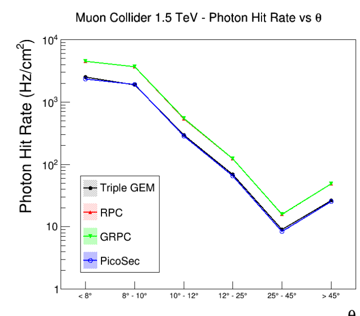
Muon System

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

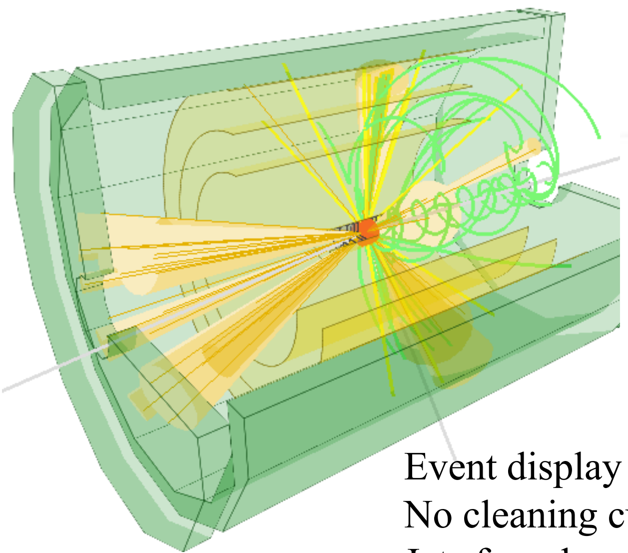
Innovative and computationally efficient event-reconstruction approaches are needed

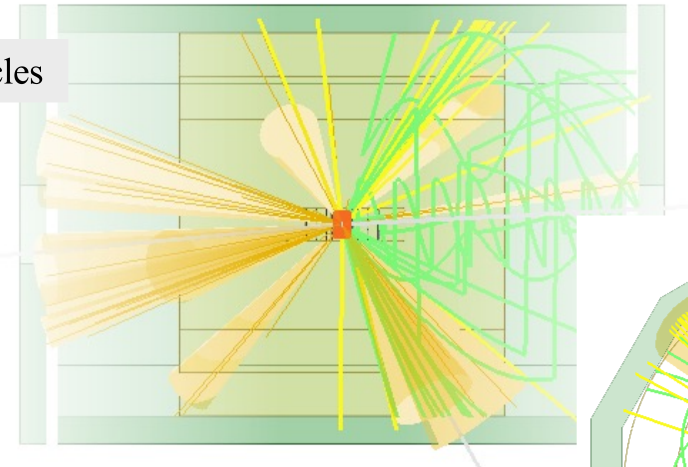
High Precision Measurements

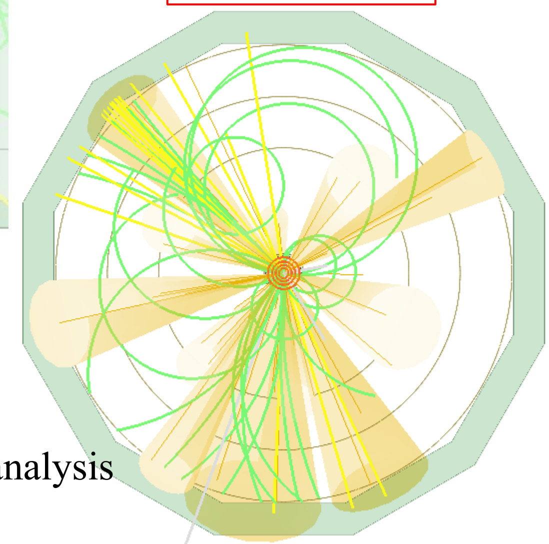
Donatelle Lucchesi et al.

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

Yellow/green tracks: Montecarlo particles







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

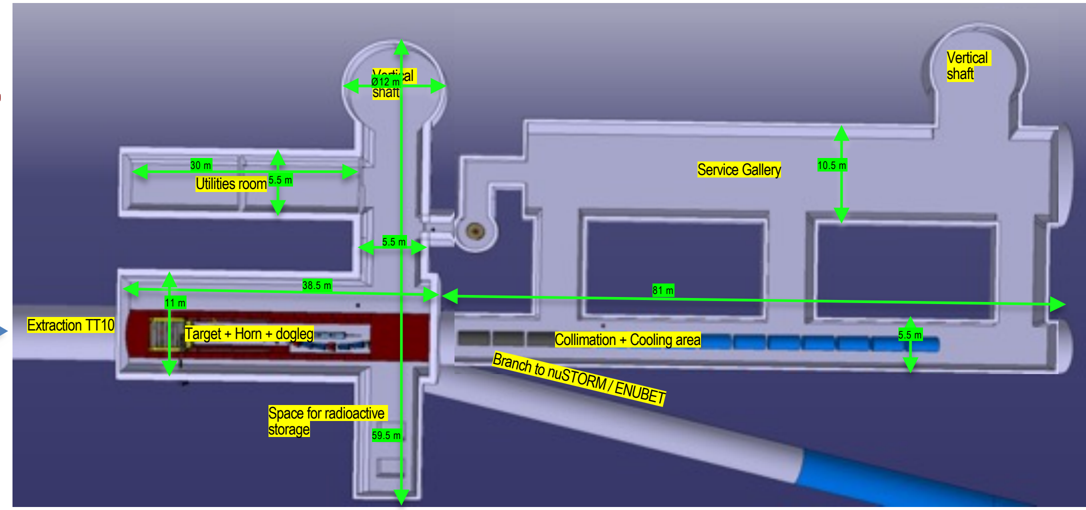
⬇

Test Facility is needed where muons are produced and cooled

Demonstrator and test facilities

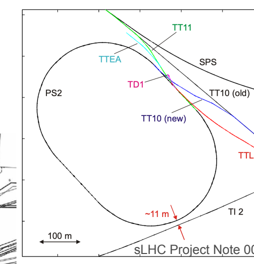
(Muon production) and Cooling Demonstrator @ CERN

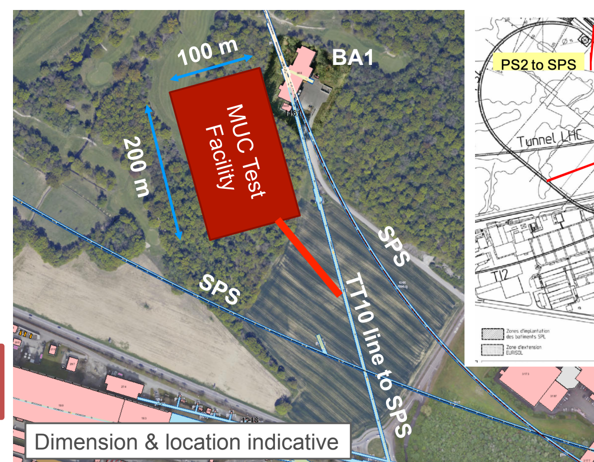
Strong synergies with nuSTORM and ENUBET

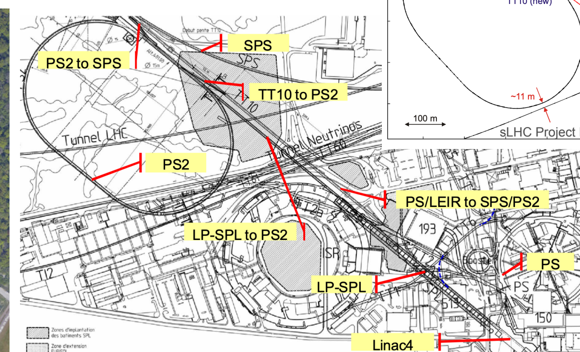


First attempt to design a site
Great opportunity to contribute

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

Still ongoing activities: LEMMA Source

- **Positron-based Muon Source – LEMMA**

Positron production and acceleration, muon targets, muon accumulation

– **Positron source studies** – collaboration with IJCL *+ A.Bacci, I.Drebot et al.* **MI**

also on crystal applications: *L.Bandiera, A.Mazzolari et al.* **FE**

➔ **agreement INFN-FE with IJCL** for intensity positron source – synergy with FCCee

– Material simulations and studies for positron and **muon production targets**

M.Antonelli, R.Li Voti, G.M. Cesarini et al. **RM1** *+ ….*

measurements and R&D planned using beam at LNF and CERN

➔ *S. Corradetti et al.* **LNL** *+ A. Passeri et al.* **RM3** graphite targets for LEMMA

production and surface tests – new facility @ RM1-SBAI and test beam MAMI

– Crystals for muon beam manipulation and merging – proposed by Alessandro Variola

L.Bandiera, A.Mazzolari et al. **FE different Si thickness and bending**

– CERN test beam to evaluate targets and emittance *J. Inst.* **15** P01036, 20

➔ new proposal to run at CERN in 2022➔ 2023 with improved set-up

+ N.Amapane, F. Anulli, A.Bertolin, M.Zanetti et al.

Resource plan towards a pre-CDR submitted by Alessandro Variola (October 2019)

need major consolidation to prove feasibility

to overcome technical limitations and reach higher muon intensities

LEMMA:

LowEMittanceMuonAccelerator

Marica Biagini et al.
LoI AF4 SnowMass21

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

- Based on muons production from a 45 GeV positron beam annihilating with the electrons of a target close to threshold for pair creation

  ➔ generating muon beams with low enough transverse emittance for a high energy collider

  ➔ muon pair boost for post-production capture and emittance minimization, drastically reducing the source transverse emittance and, coupled with a collider nano-beam scheme

  ➔ should allow reaching for the luminosity with a lower bunch intensity

- **Scheme under study**:

  ➔ positron bunches extracted to impinge on multiple targets in a dedicated straight section

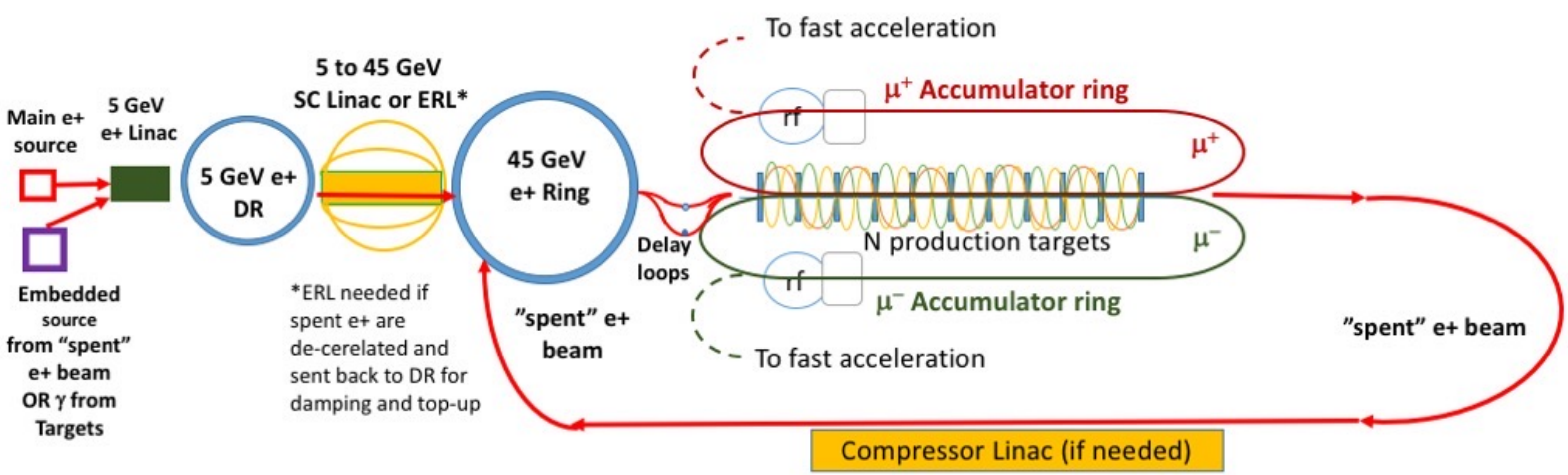
  ➔ muons are then collected in two Accumulation Rings (AR) and stored until the muon bunch has a suitable number of particles.

This scheme aims at releasing the impact of the average power on the targets and also reducing the number of positron needed from the source

LEMMA new scheme in brief

Alessandro Variola, Marica Biagini, Susanna Guiducci, Mario Antonelli, Manuela Boscolo et al.

- Positron for first fill produced by Main **e^+ source** (MPS) and accelerated to 5 GeV for damping in a 5 GeV **Damping Ring** (DR)
- Acceleration to 45 GeV in SC Linac or ERL and storage of 1000 e^+ bunches in **Positron Ring** (PR)
- **Extraction of e^+ bunches** to one or more muon production lines, while produced **muons are accumulated in two AR** and a muon bunch is "built" by several passages through the targets, to be then delivered to the **fast acceleration chain**
- Re-injection and damping in the PR @45 GeV of the spent e^+ beam to save on the number of needed e^+, the MPS and a possible γ-embedded source will provide the refilling of lost e^+
  Other option: send e^+ back to DR (through decelerating ERL) for damping and top-up



Attività Test Beam LEMMA

BA, PD, PV, RM1, TO

Reuse from previous LEMMA test beams:

- Muon Chambers (drift tubes) – 4+2 now fully commissioned
- Calorimeters

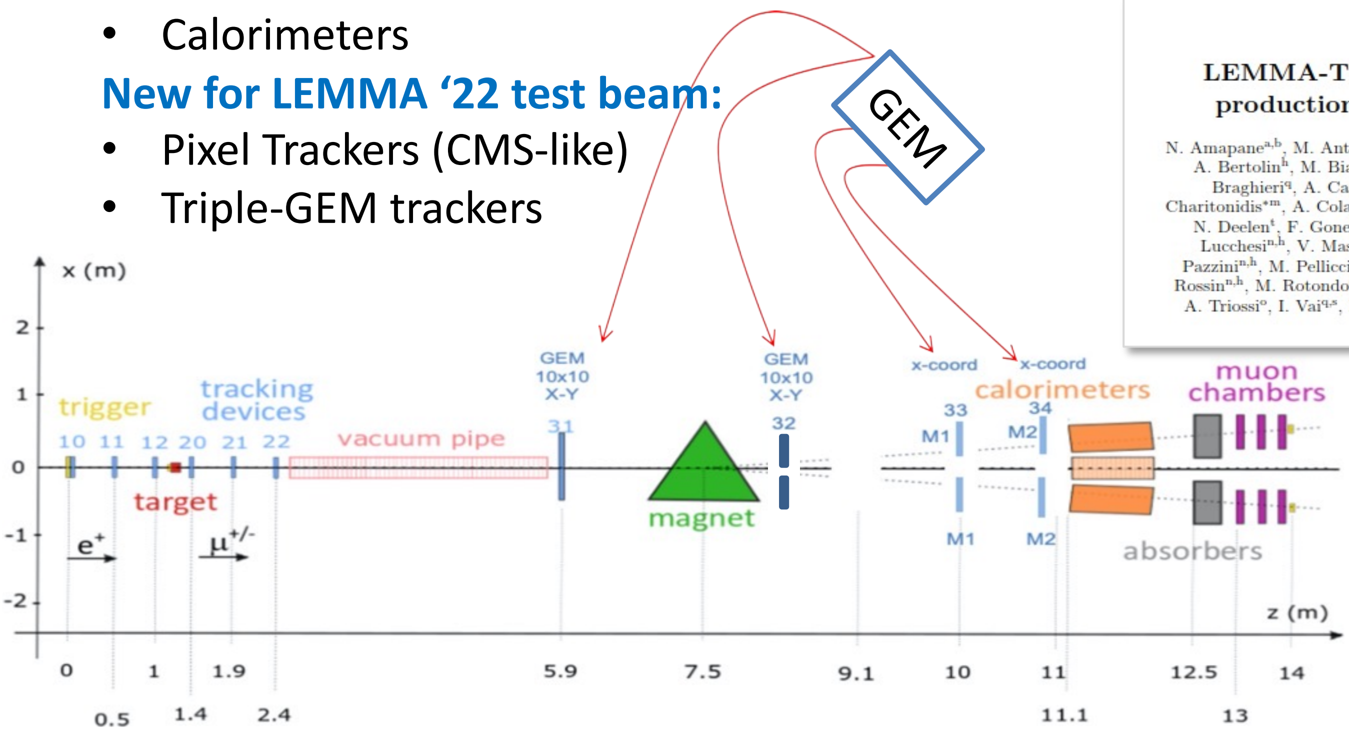
New for LEMMA '22 test beam:

- Pixel Trackers (CMS-like)
- Triple-GEM trackers

CERN-SPSC-2020-004

LEMMA-TB: an experiment to measure the production of a low emittance muon beam

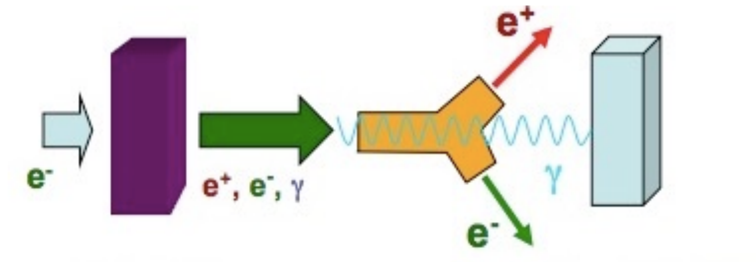
N. Amapane[a,b], M. Antonelli[c], F. Anulli[d], N. Bacchetta[h], N. Bartosik[b], M. Bauce[d], A. Bertolin[h], M. Bianco[m], C. Biino[b], O. R. Blanco-Garcia[c], M. Boscolo[c], A. Braghieri[q], A. Cappati[a,b], F. Casaburo[l,d], M. Casarsa[i], G. Cavoto[l,d], N. Charitonidis[*m], A. Colaleo[p], F. Collamati[d], G. Cotto[a,b], D.Creanza[p], C. Curatolo[h], N. Deelen[t], F. Gonella[h], S. Hoh[n,h], M. Iafrati[c], F. Iacoangeli[d], B. Kiani[b], D. Lucchesi[n,h], V. Mascagna[e,f], S. Mersi[m], A. Paccagnella[n,h], N. Pastrone[b], J. Pazzini[n,h], M. Pelliccioni[b], B. Ponzio[c], M. Prest[e,f], C. Riccardi[q,r], M. Ricci[c], R. Rossin[n,h], M. Rotondo[c], P. Salvini[q], O. Sans Planell[a,b], L. Sestini[h], L. Silvestris[p], A. Triossi[o], I. Vai[q,s], E. Vallazza[f], R.Venditti[p], S. Ventura[h], P. Verwilligen[p], P. Vitulo[q,r], and M. Zanetti.[n,h]



Positron source: beam tests @ MAMI B   Nov 2021

IPAC'21: L. Bandiera et al., "Intense Channeling Radiation as a tool for an hybrid crystal based positron source for future colliders"

Positron Source based on oriented crystals

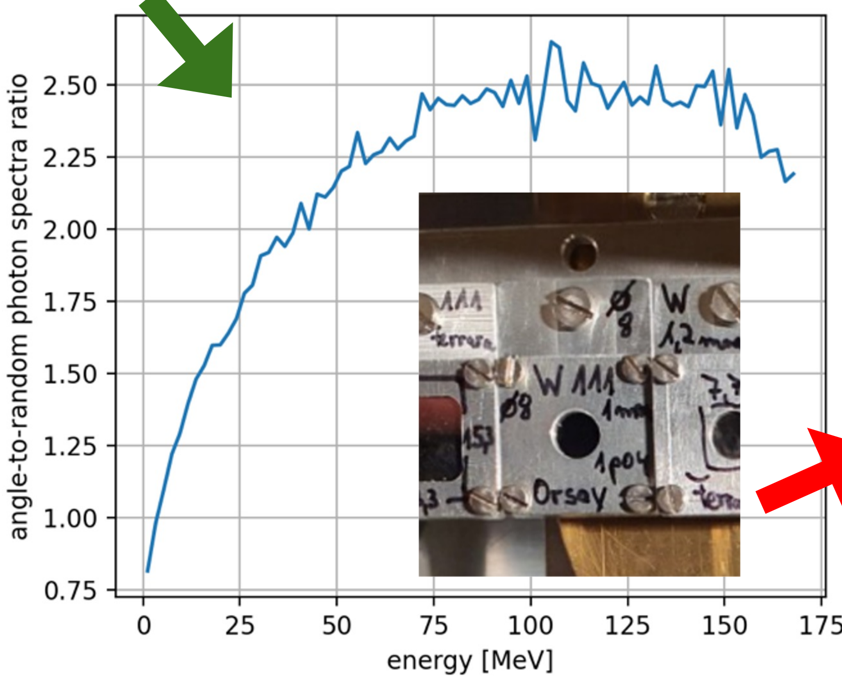


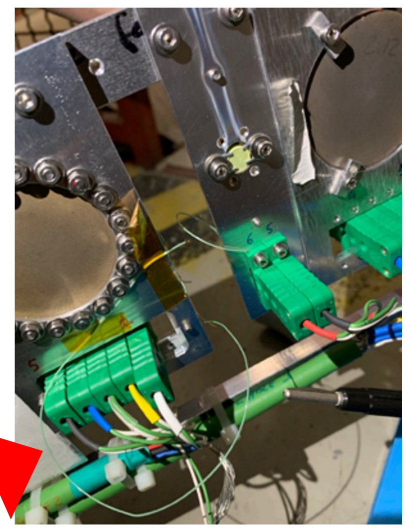
Thin crystal radiator **Thicker amorphus converter target**

By <u>INFN Ferrara and IJCLab teams</u>.

- Measurements of the energy spectra of the <u>electromagnetic radiation resulting from coherent interactions</u> between 855-MeV e^- and <u>oriented W</u>.
- Measurements of <u>heating of amorphous W</u> during irradiation with high-intensity e^- beam (~2 µA average current, 300 µs pulses

radiation enhancement when on axis





⇒ **Success!** Results of great interest for <u>positron-driven muon collider (and FCC-*ee*) R&D</u>

New beamtest sessions foreseen in 2022. Moreover, a PhD student from INFN Ferrara will join the IJCLab team in Spring/Summer to contribute to the 2022 measurements preparation

Alternative idea

Camilla Curatoro e Luca Serafini

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

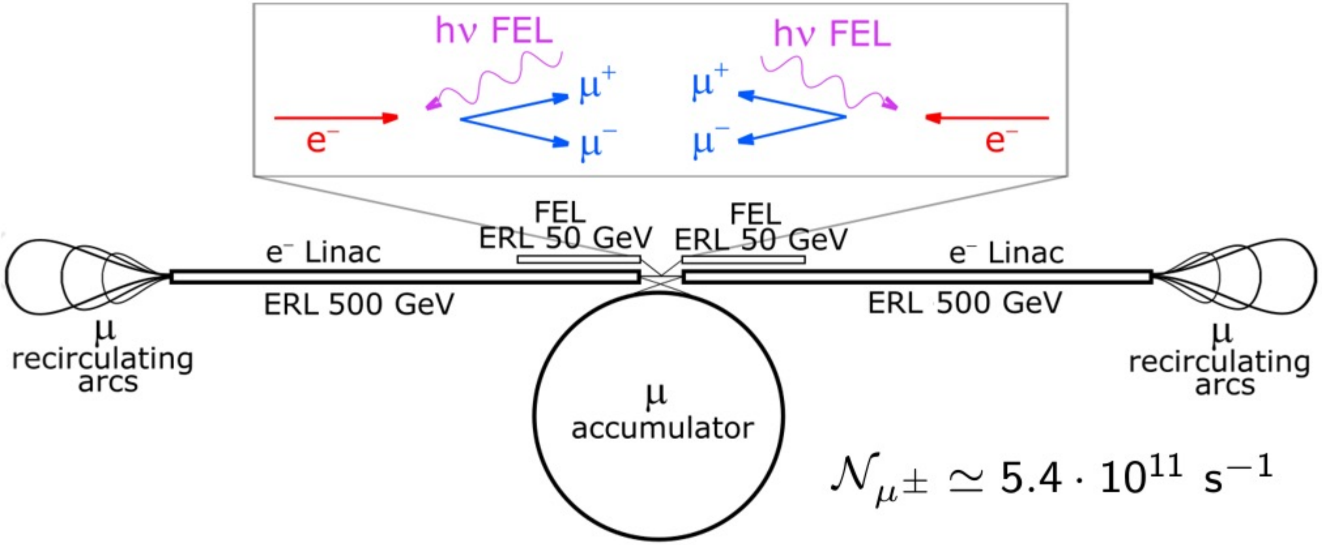
Electrons and **X**-rays to **M**uon **P**airs (**EXMP**)

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

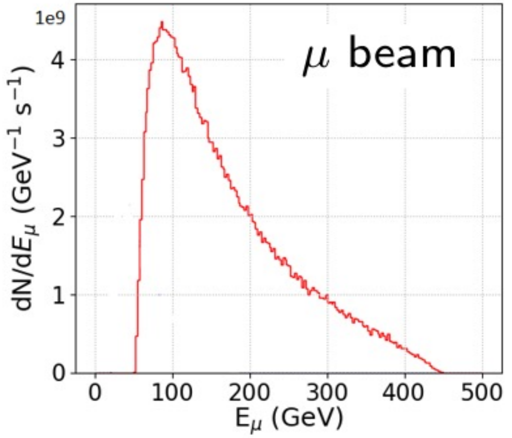
$$E_e = 500 \text{ GeV},\ h\nu = 60 \text{ keV},\ E_{CM} \simeq \sqrt{4E_e h\nu + M_e^2} = 346 \text{ MeV}$$

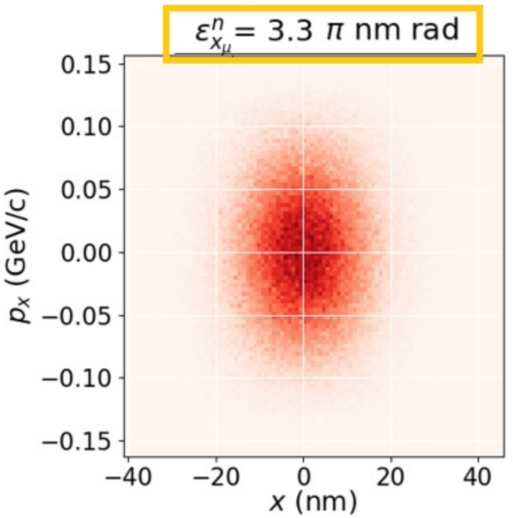
Photon energy in ERF $h\nu' \simeq 2h\nu\gamma_e = 120$ GeV

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



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





Conclusions e plans

International Collaboration GOALs:

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

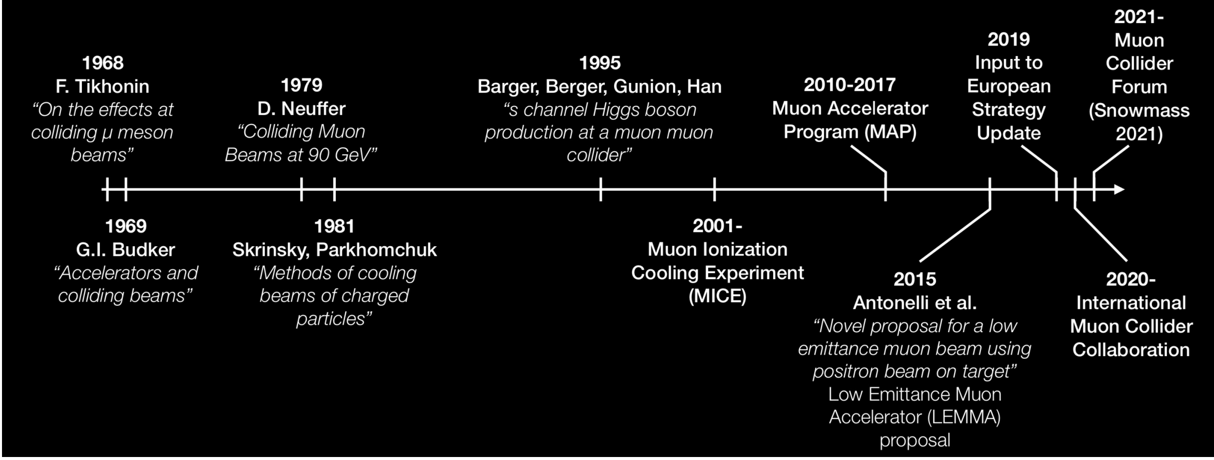
➔ **updated timeline: Muon collider $\sqrt{s} = 3$ TeV ready to take data after HL-LHC**

- **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

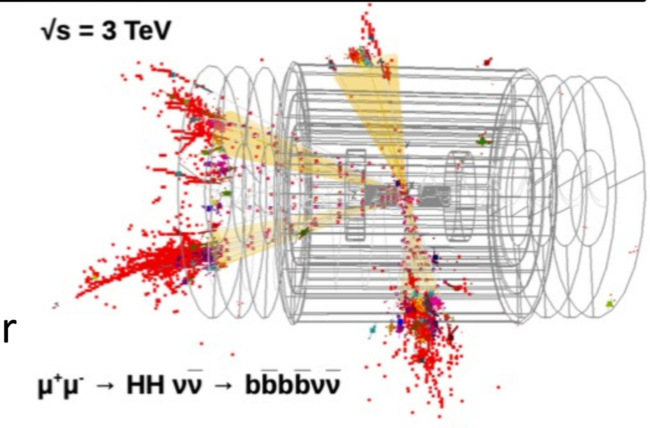
A brief history of muon colliders

(A wholly incomplete timeline)



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

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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

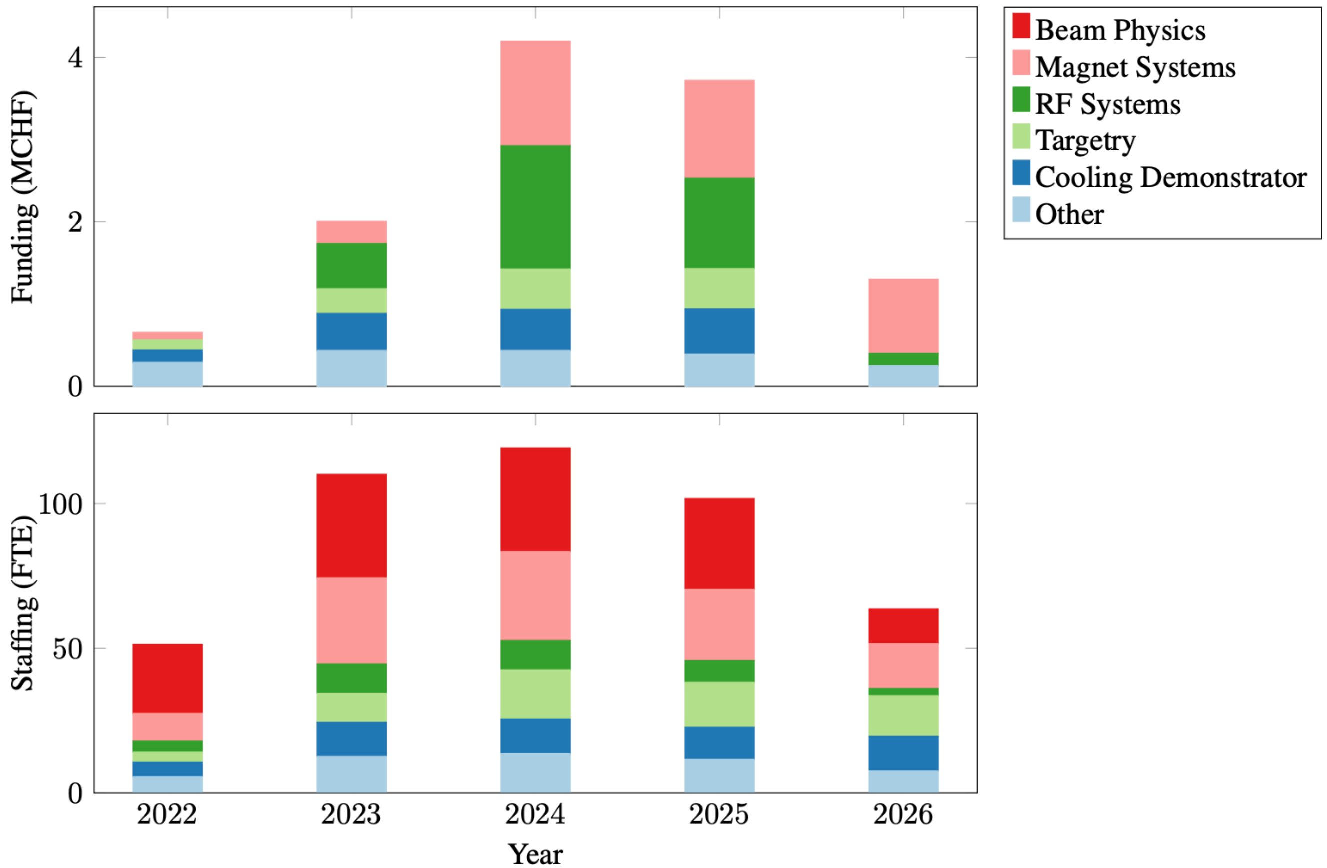
- could then be realized using almost all infrastructure from 3 TeV, but collider ring

- 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**

Conclusions

- Muon collider is most promising for future high-energy, high-luminosity lepton collisions
  ➔ Going well beyond CLIC at 3 TeV, the highest energy concept
- Could also be next project in Europe if Higgs factory is realised elsewhere
- So far no technical obstacle identified to realise 3 TeV by 2045
- Aspirational programme will deliver R&D programme
- Opportunities for important R&D exists
  - Fast ramping magnet systems
  - High-field solenoids
  - High-field normal-conducting RF
  - Integrated design of muon cooling system and demonstrator
- Synergies with other efforts (neutrino programme) can be exploited

Aspirational scenario



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

~70 Meu/5 years

MAP Budget/Effort Overview

Mark Palmer

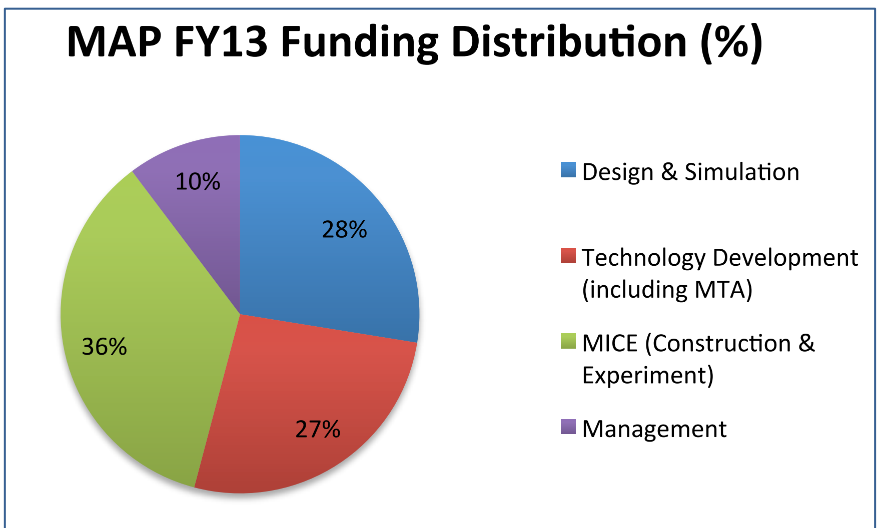
- Overview of FY12-FY17
  - Full program in FY12-14 (funding includes fully burdened labor)
  - Ramp-down with focus on MICE completion during FY15-17

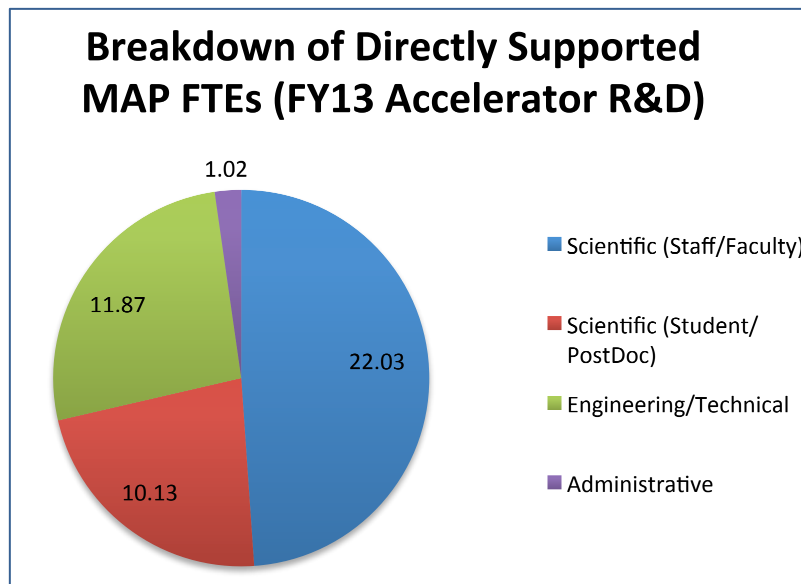
	FY12	FY13	FY14	FY15	FY16	FY17
US Funding (M$)	12.0	11.8	12.7	9.0	6.0	1.0

Reduced scope of effort

Snapshot of Effort Distribution During "full" program operation in FY13

- 23 Institutions Participating
- ~45 FTEs

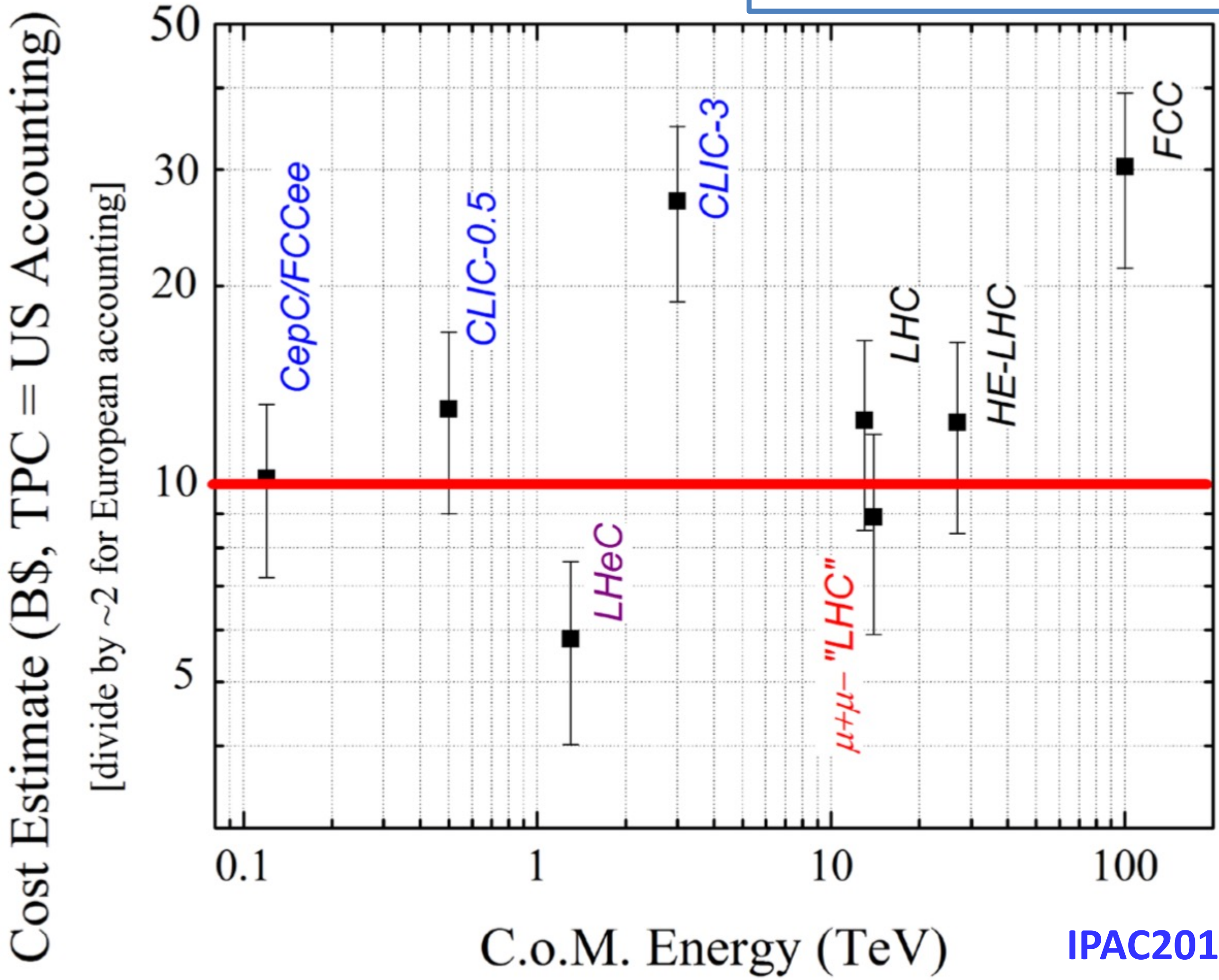




Very rough cost estimate

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

Vladimir SHILTSEV, David NEUFFER (Fermilab)



IPAC2018 - MOPMF072

Muon Collider @ FNAL option

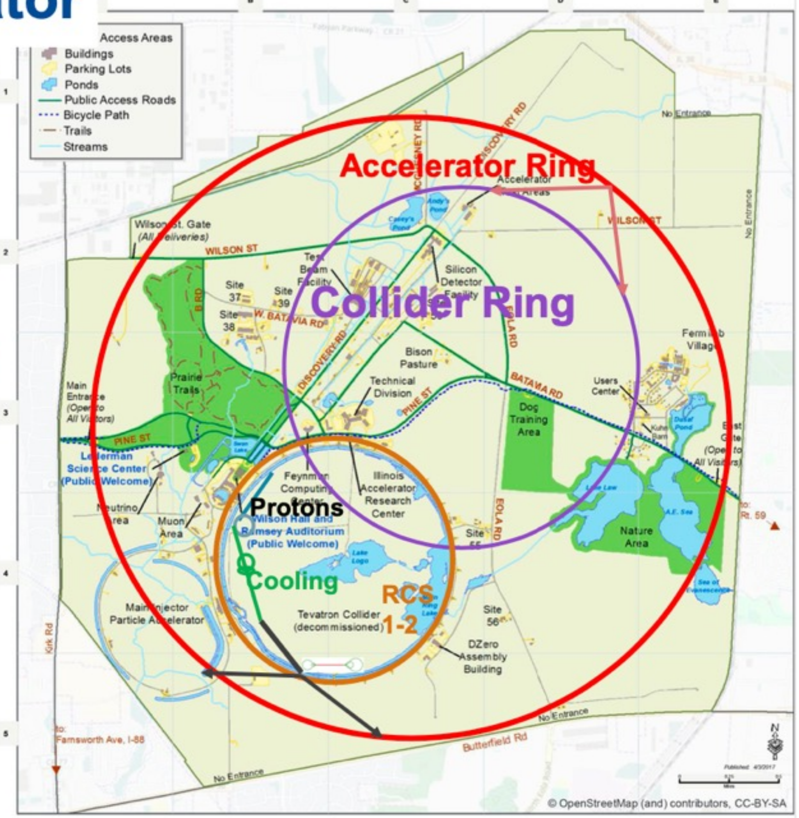
10 TeV collider
requires ~16 T dipoles
in RCS scenarios
With rapid-cycling
2-4 T magnets

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

Crista per sorgenti di positroni @ FE

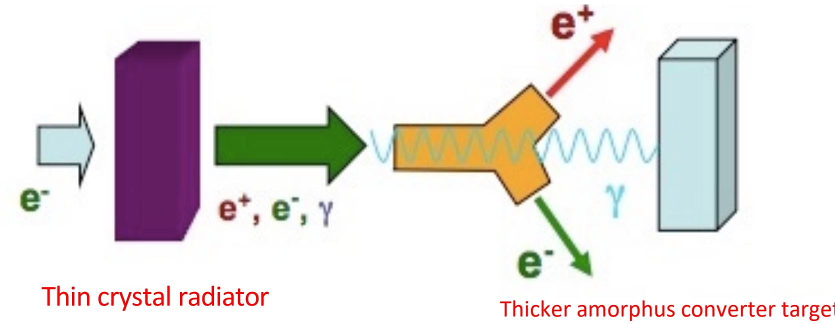
- Caratterizzati cristallograficamentecr cristalli di W tramite x-ray diffraction e Rutherford back scattering

- Assegnati due turni di tempo fascio a MAMI (5-8 Novembre; 22-27 Novembre) per l'irraggiamento sia dei radiatori cristallini che dei convertitori amorfi, per valutarne la resistenza. Lavoro in collaborazione con I. Chaikovska (IJCL): forte sinergia con le attività relative alla sorgente di positroni di FCCee

- Lo stato delle attività presentato in un intervento alla conferenza IPAC'21: L. Bandiera et al., "Intense Channeling Radiation as a tool for an hybrid crystal based positron source for future colliders"

- E' in preparazione un articolo scientifico

Sorgente di positroni basata su cristalli orientati



Problema principale nelle sorgenti di e+ ad alta intensità non è solo la resa, ma anche la deposizione di energia e la relativa PEDD (Peak Energy Deposition Density)

Principali vantaggi della sorgente a cristalli:

I. Aumento della generazione di fotoni grazie alla channeling radiation -> con aumento della produzione di coppie nel convertitore
II. Alto tasso di fotoni soft -> creazione e+ soft (decine di MeV) facilmente catturati dal Capture System
III. Diminuzione PEDD nel convertitore di almeno un ordine di grandezza