Muon Collider Project

Workshop on FCC-ee and Lepton Colliders
Frascati 22 - 24 January 2025

Donatella Lucchesi University and INFN of Padova

for the

International Muon Collider Collaboration

International MUON Collider Collaboration

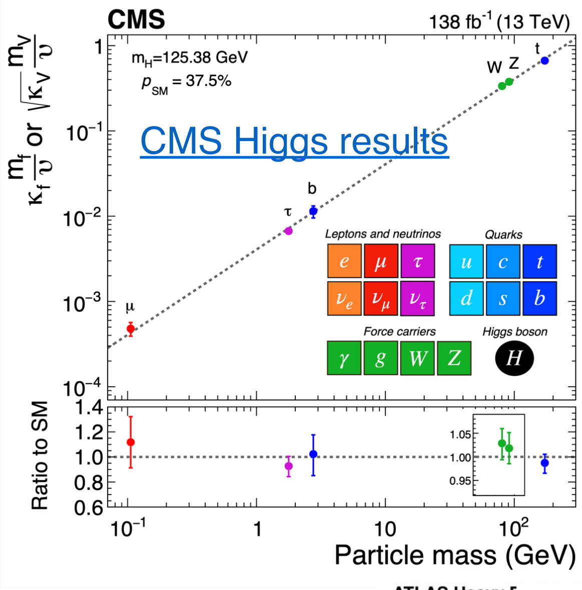
MuCol

INFN PADOVA

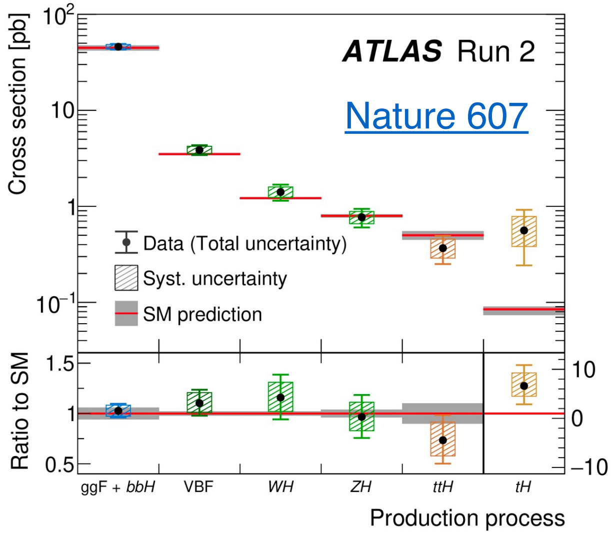
Università degli Studi di Padova

This project has received funding from the European Union's Research and Innovation programme under GAs No 101094300 and No 101004730.

If the lesson of the LHC is Higgs + nothing…



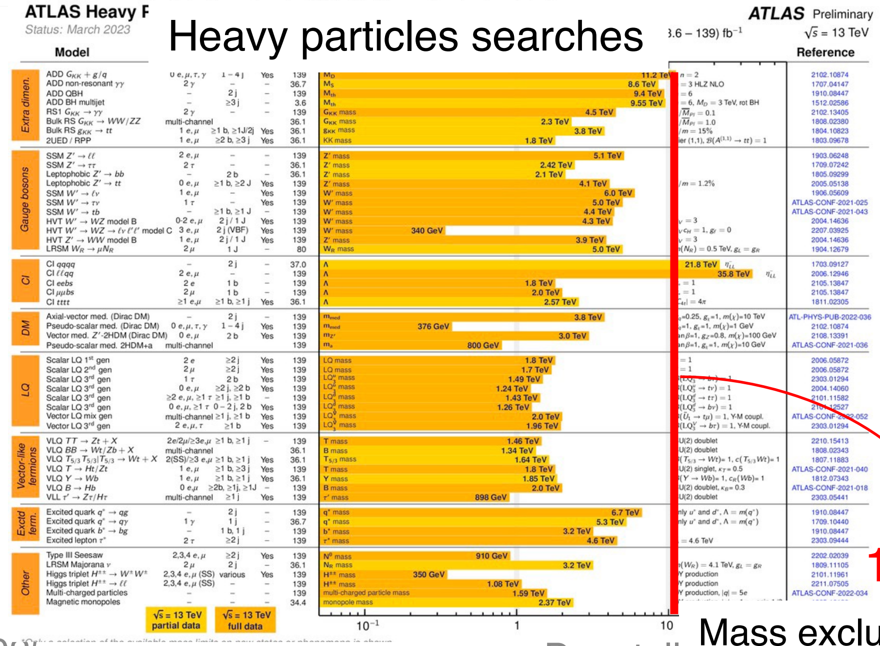
CMS Higgs results



Nature 607

Heavy particles searches

Models

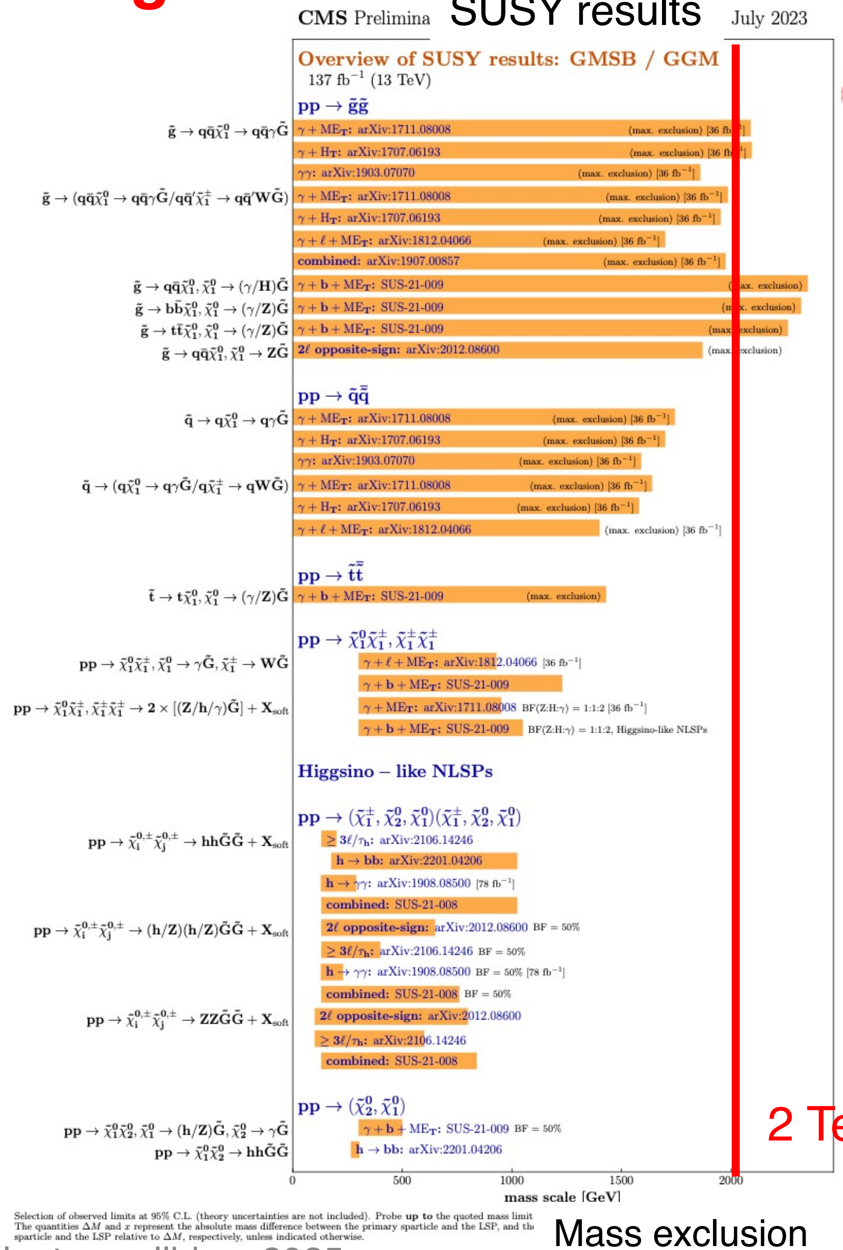


Atlas summary

10 TeV

Mass exclusion

SUSY results



2 TeV

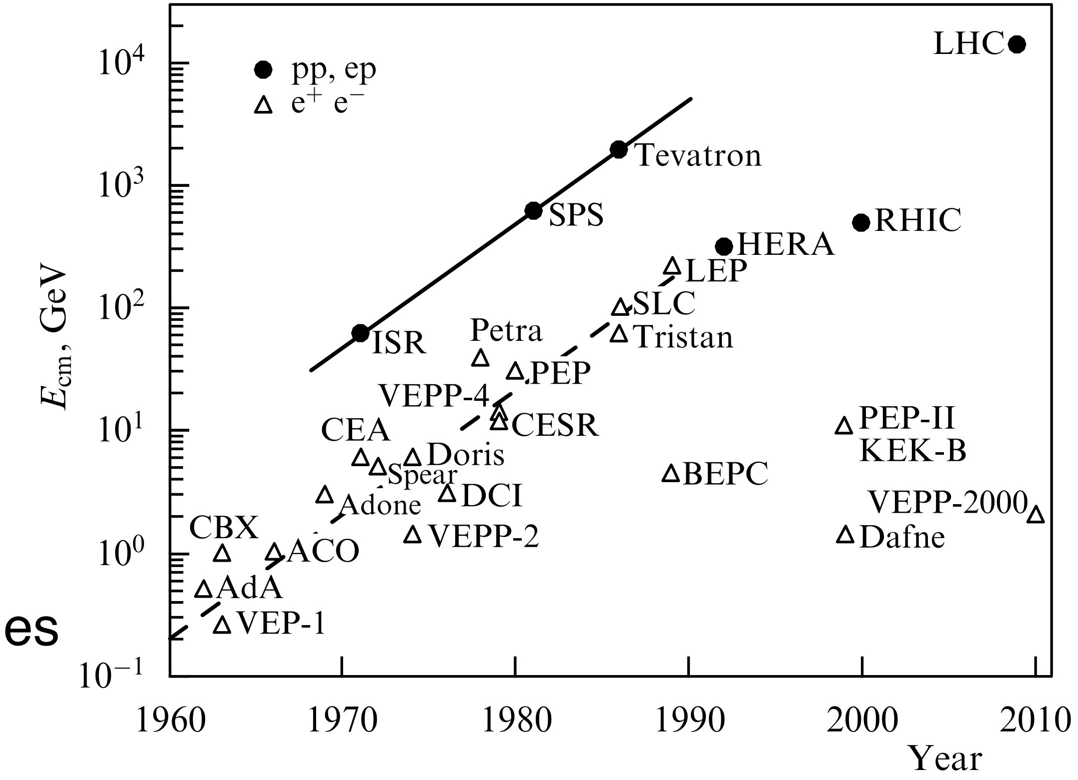
Mass exclusion

Is a Higgs factory sufficient to fully understand Higgs boson sector?

(it would be great to have a Higgs factory ready in few years…)

For the future, are record energies a luxury?

High energy has been successful for discoveries



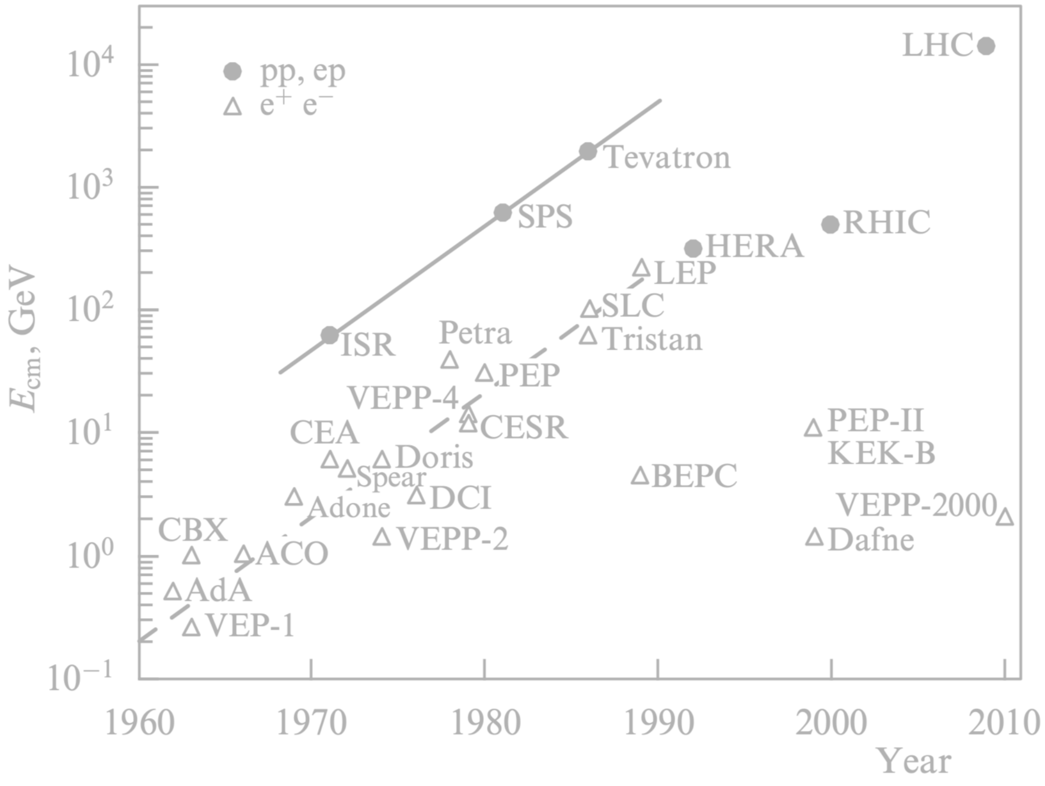
(V. Shiltsev, 2012)

Is a Higgs factory sufficient to fully understand Higgs boson sector?

NO

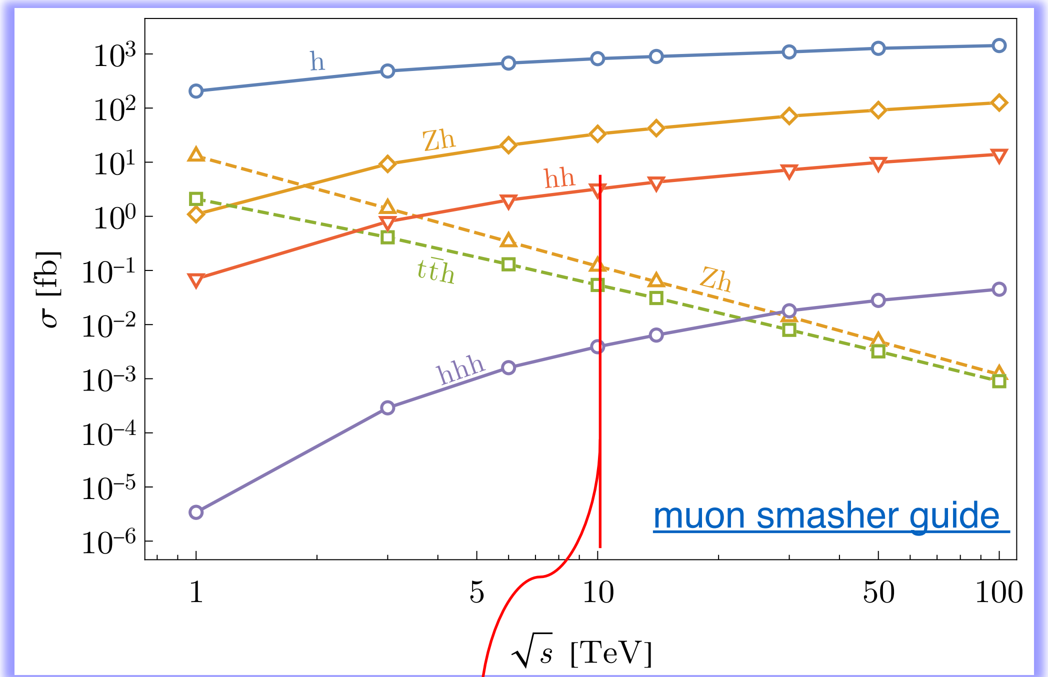
(it would be great to have a Higgs factory ready in few years…)

For the future, are record energies a luxury?

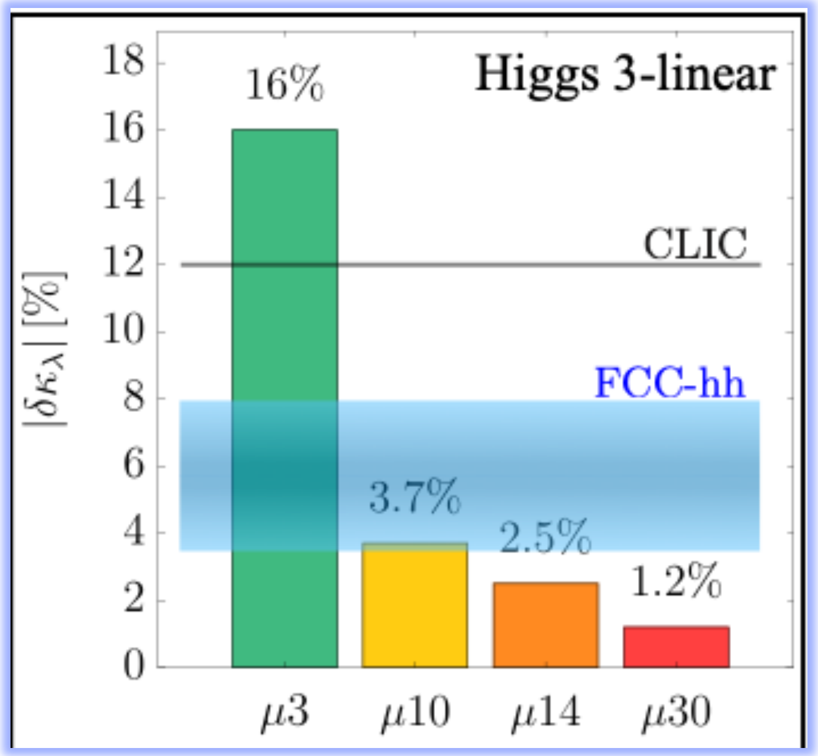


(V. Shiltsev, 2012)

Linear or any circular e^+e^- colliders will not produce di-Higgs boson sample large enough to measure the Higgs self-coupling parameter, crucial to determine Higgs potential.



$3.8 \cdot 10^4$ HH in 10 ab^{-1}



FCC-hh $\sqrt{s} = 100$ TeV, 2 experiments 30 ab^{-1} in ~20 years

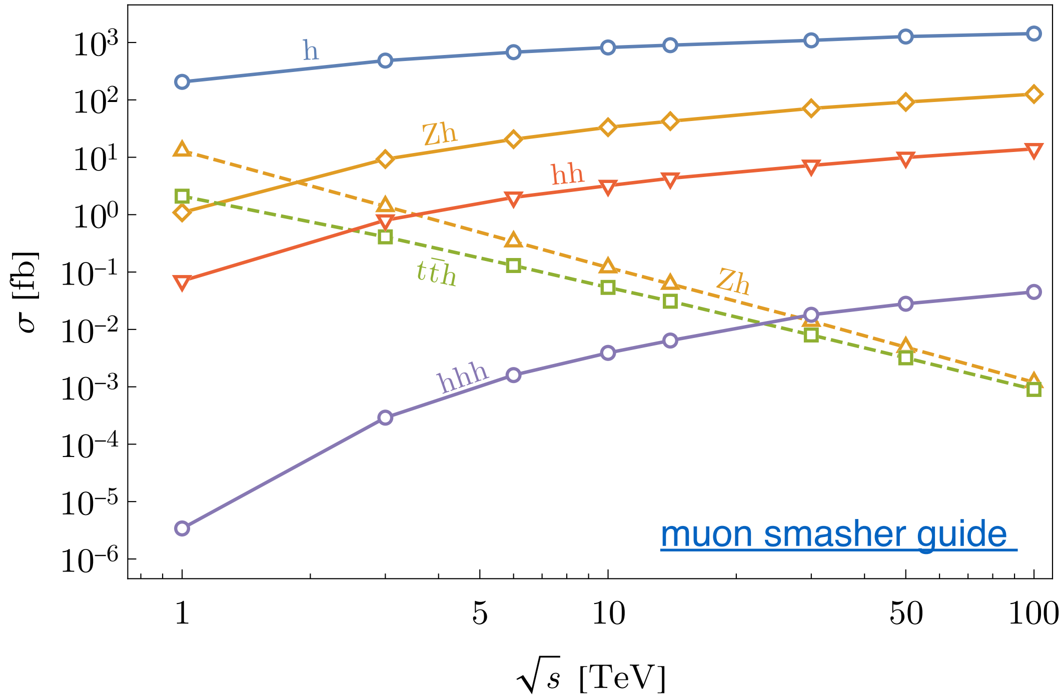
Higgs-pair production at a 100 TeV

MuC $\sqrt{s} = 10$ TeV, 1 experiment 10 ab^{-1} in ~5 years

Muon collisions at $\sqrt{s} = 10$ TeV guarantee the best precision.

Indeed, multi-TeV muon collisions produce significant number of single, double and triple Higgs bosons

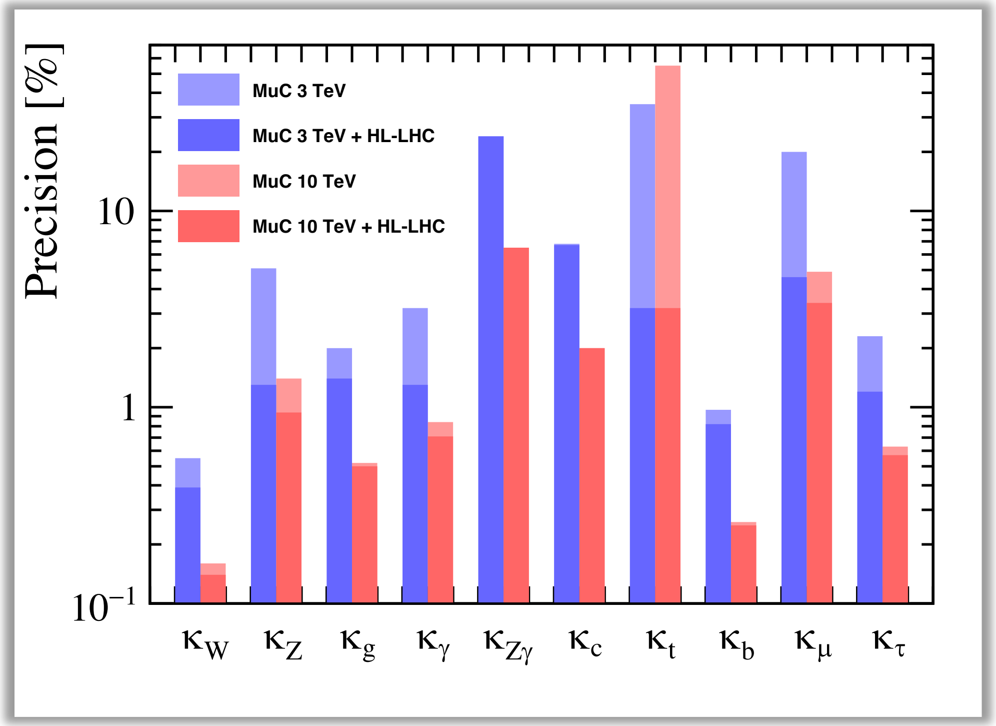
International MUON Collider Collaboration



	cross section [fb]		expected events	
	3 TeV	10 TeV	1 ab^{-1} at 3 TeV	10 ab^{-1} at 10 TeV
H	550	930	5.5×10^5	9.3×10^6
ZH	11	35	1.1×10^4	3.5×10^5
$t\bar{t}H$	0.42	0.14	420	1.4×10^3
HH	0.95	3.8	950	3.8×10^4
HHH	3.0×10^{-4}	4.2×10^{-3}	0.30	42

Higgs couplings to bosons and fermions

M. Forslund, P. Meade and M. Casarsa, D. Lucchesi, L. Sestini



Results obtained with parametric modeling of detector effects validated with detailed simulation including beam-induced background. See D. Zuliani presentation

Result of 10-parameter fit, K0 framework: 1σ sensitivities in %

Preliminary

	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
$\kappa_{Z\gamma}$	10	7.2	7.1
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
κ_t^*	3.3	3.1	3.1

* No input used for the MuC

e^+e^- at 250 GeV

Permille-level precision on Higgs couplings achievable when adding MuC, no BSM contribution.

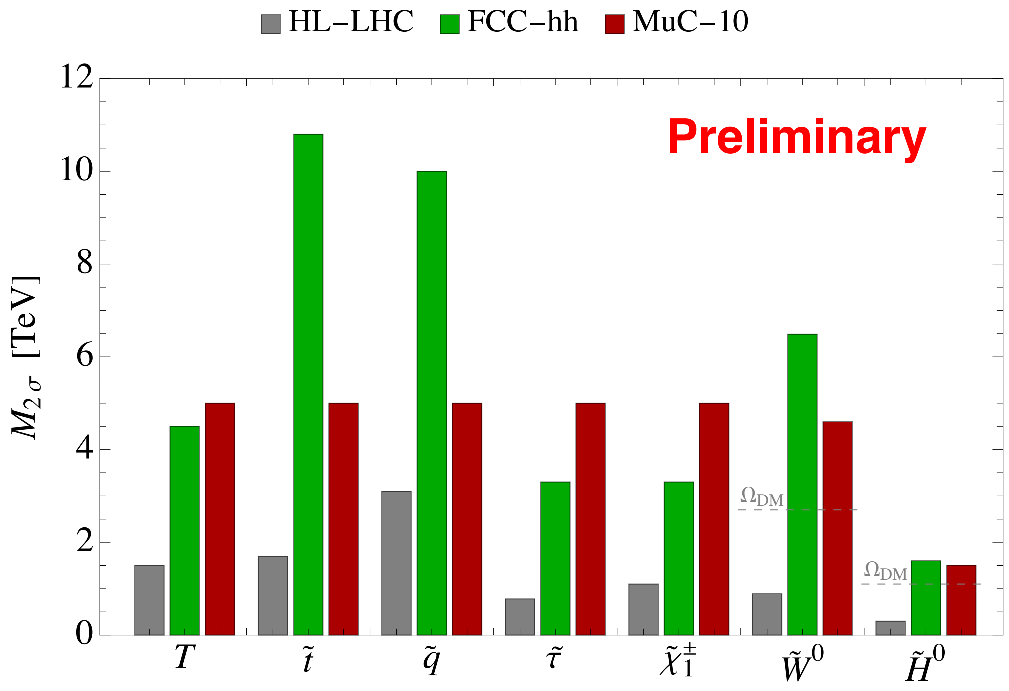
Strong Italian contribution

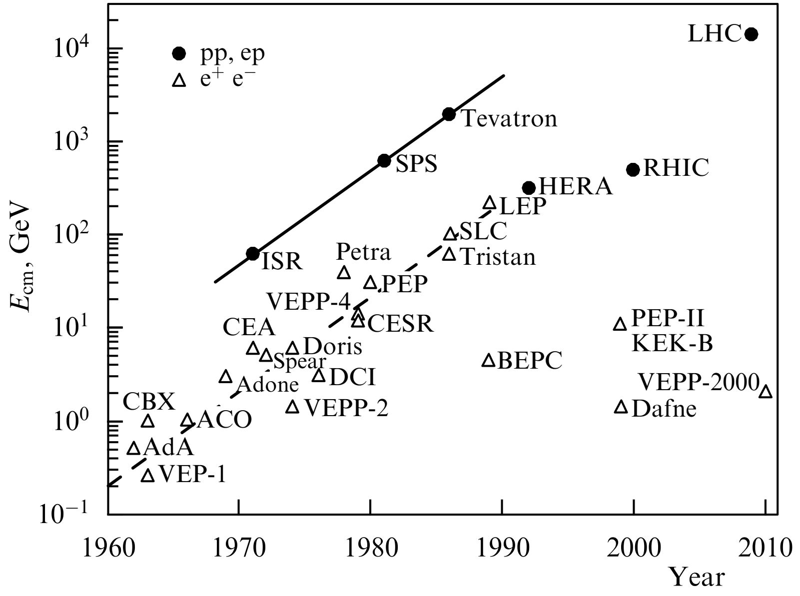
Is an e^+e^- Higgs factory sufficient?

(it would be great to have a Higgs factory ready in few years…) **NO**

Are record energies a luxury? **NO**

95%CL exclusion reach on mass of several BSM particles





(V. Shiltsev, 2012)

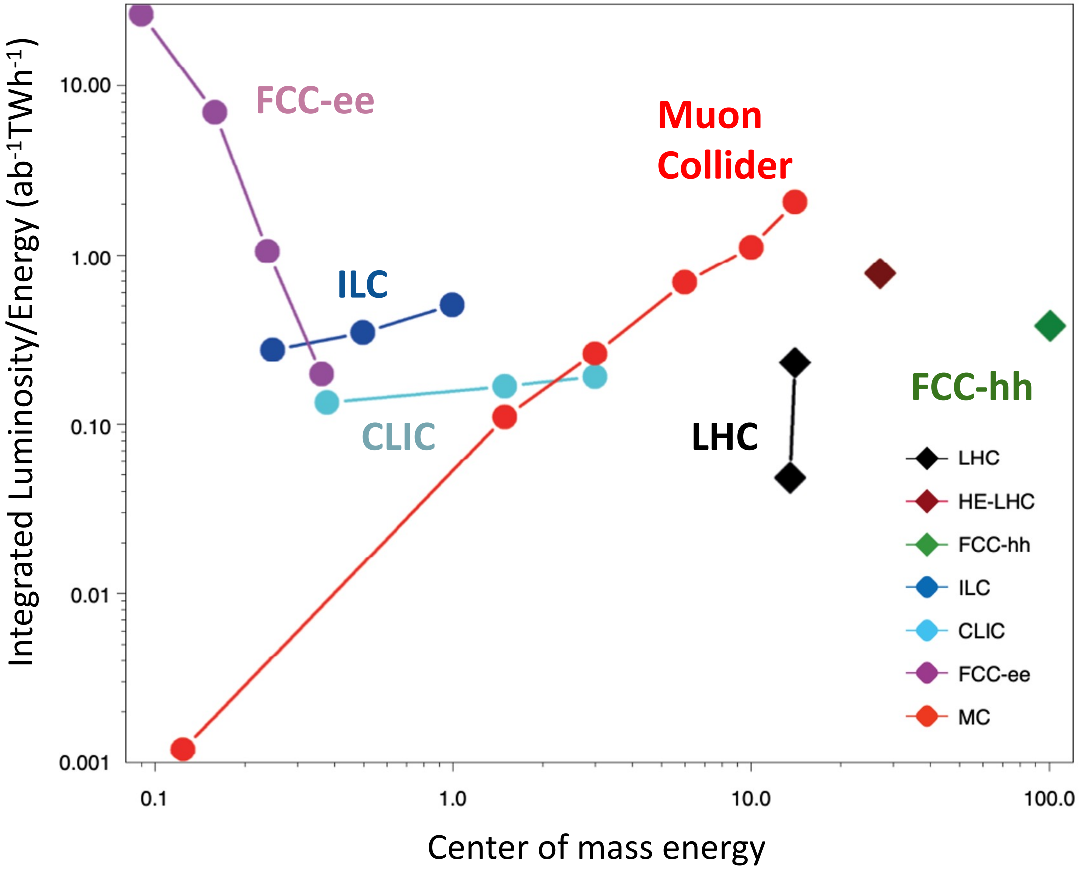
High energy has been successful for discoveries, it allows to investigate New Physics models

Details in Chiara Aimè presentation

High energies are “peculiar” at MuC

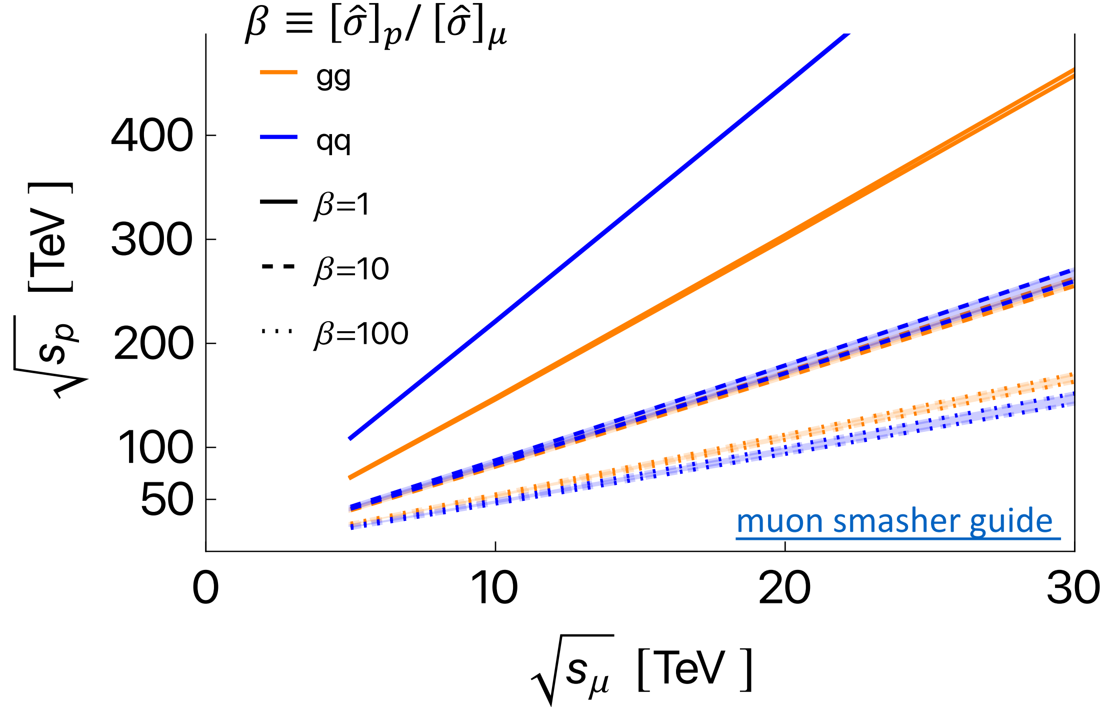
High luminosity and energy with reasonable wall plug power

F. Meloni [2007.15684](#) [2003.09084](#)



Muon vs Protons

Center of mass energy for equivalent cross sections of 2 → 2 scattering

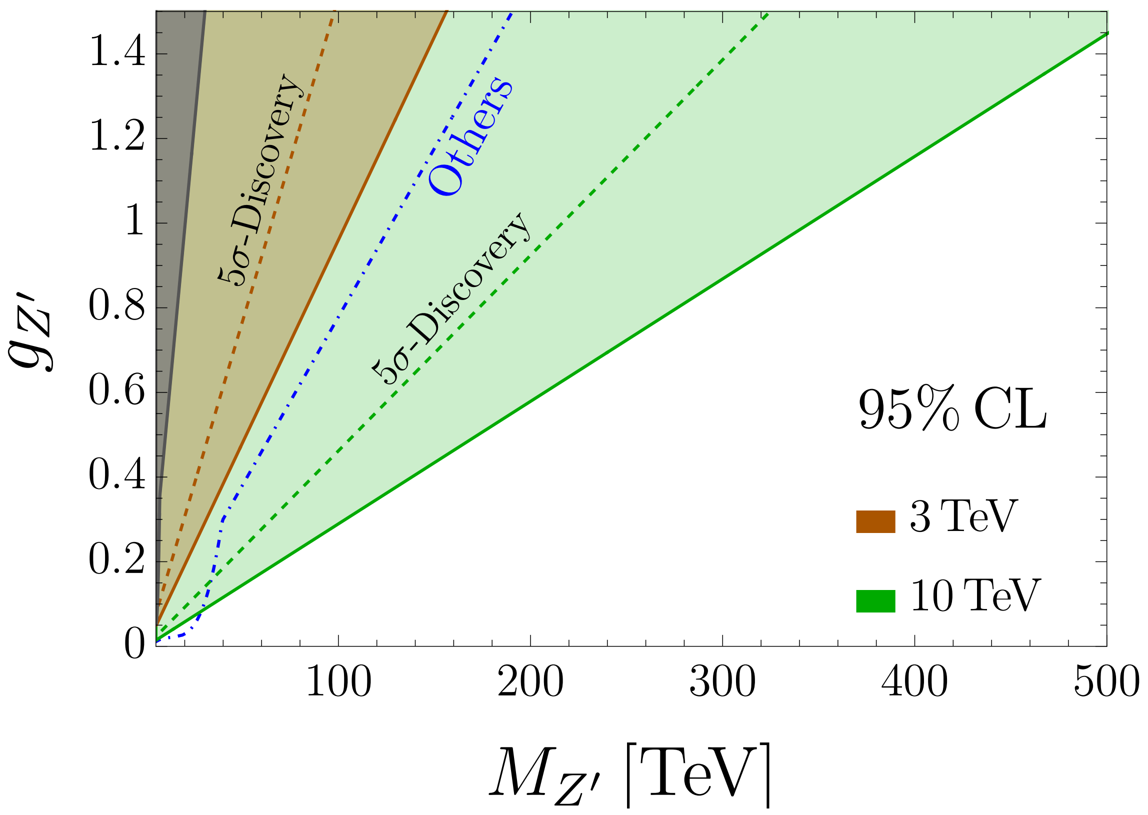


Muon Collider can go beyond 100 TeV pp

- $\sqrt{s} = 10$ TeV **is not the limit**, just a study point
- negligible background contribution respect to pp

The combination of high energy and high precision enhances sensitivity to new physics, reaching 100 TeV scale with 10 TeV muon collisions.
A 100 TeV hadron collider does not have direct access to such a scale due to the composite nature of proton.

Others: CLIC+FCC-ee+FCC-hh



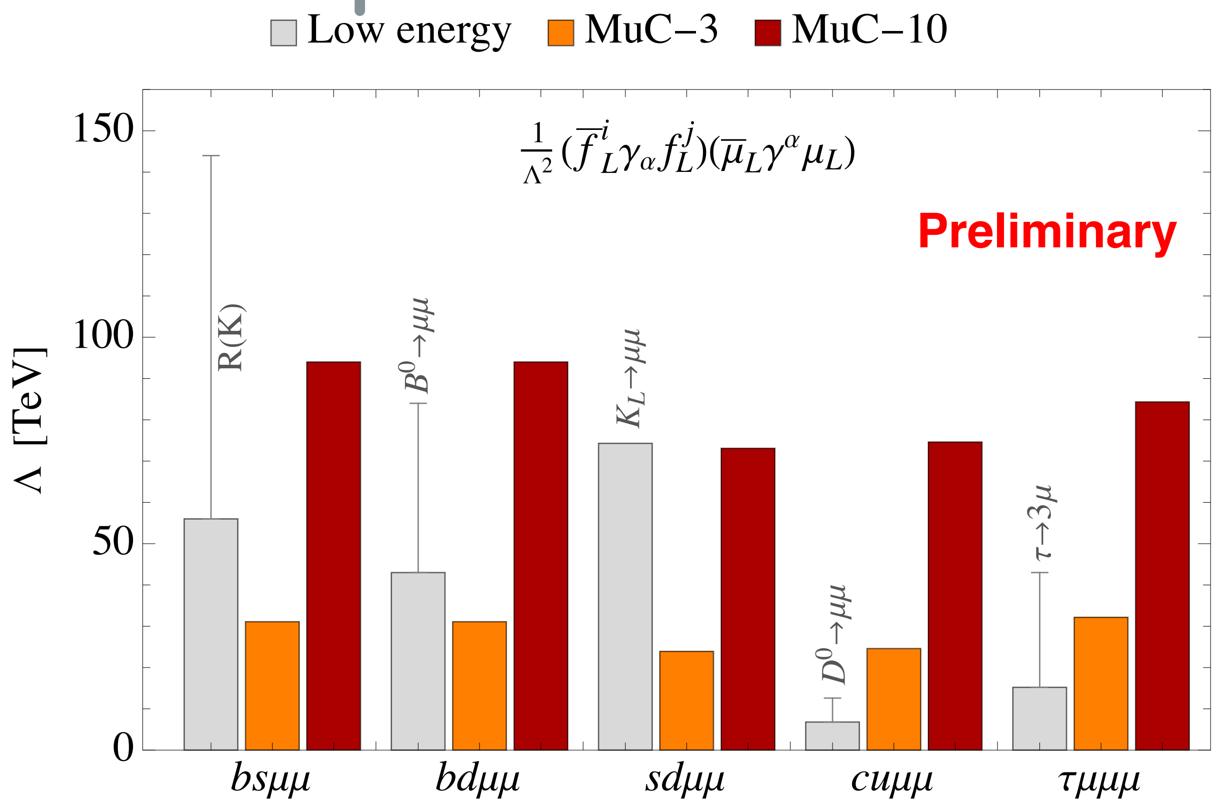
- Discovery up to 100 TeV for SM-like EW gauge couplings.
- Exclusion up to 500 TeV for the maximal value of the $g_{Z'}$ coupling.

More details in Chiara Aimè presentation

Flavor physics at 10 TeV muon collisions

Possible to search for $\mu^+\mu^- \to \bar{f}f$ or new particles that cause Lepton Flavor Violation.
Flavor transitions mediated by heavy new particles are enhanced at high energy.

Current results of LHCb, BelleII, NA62

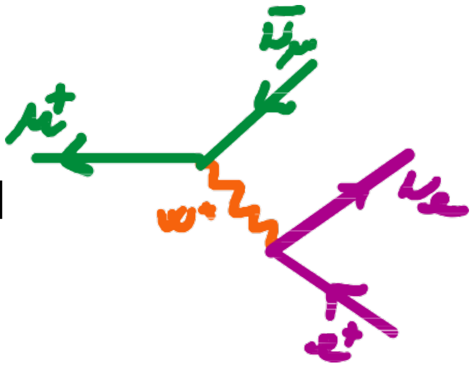


Realistic quark flavor and lepton identification and mis-identification efficiencies included.

A $\sqrt{s} = 10$ TeV muon collider reach on the effective scale, Λ, is comparable to prospects of dedicated experiments.

Neutrino beams! New opportunity to explore

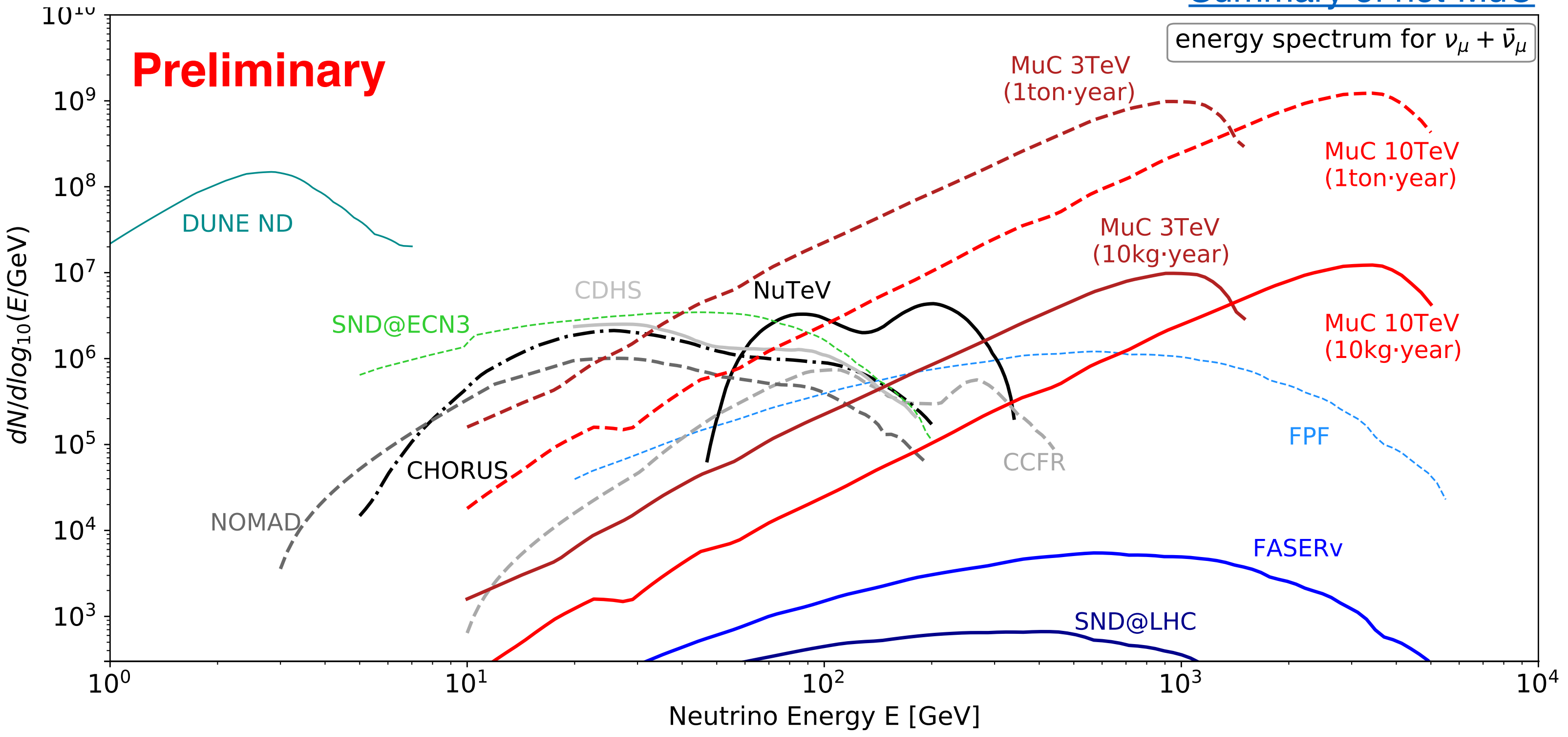
High energy, high intensity muons beams decays produce high energy, high intensity neutrino beams at the MuC interaction point usable for fixed target experiments.



$N_\nu = 9{\times}10^9$ per second per species

$N_\nu = 9{\times}10^{19}$ per year

Summary of not-MuC



Energy spectrum of neutrino interactions at forward detector

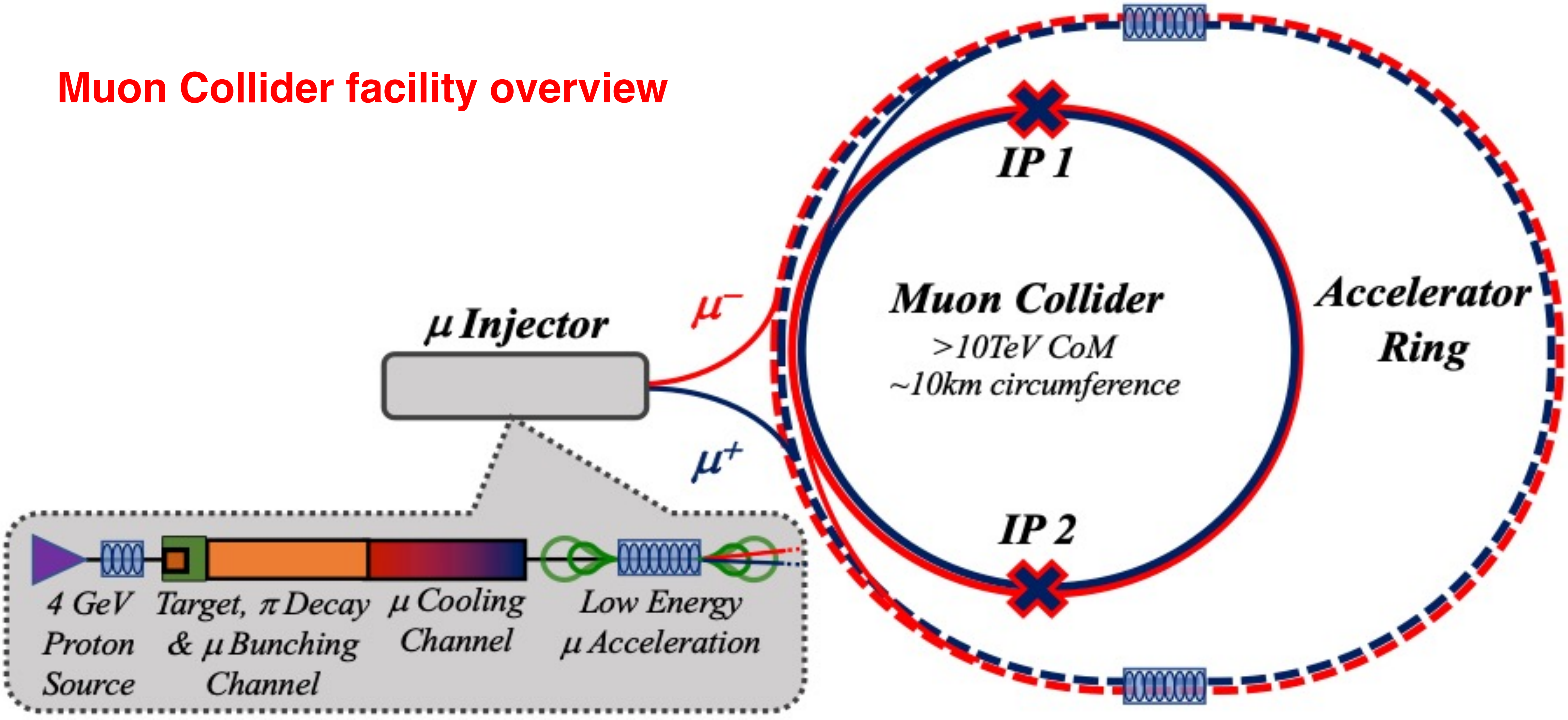
Assumptions:
- $\sqrt{s} = 10$ TeV
- single bunch $N_{\mu^\pm} = 1.8{\times}10^{12}$
- straight section $L = 10\ m$
- μ, ν constant angular spread 0.6 mrad

MuC is superior in statistics and beam energy definition.

Physics opportunities still to be fully explored.

Where would such measurements be possible?

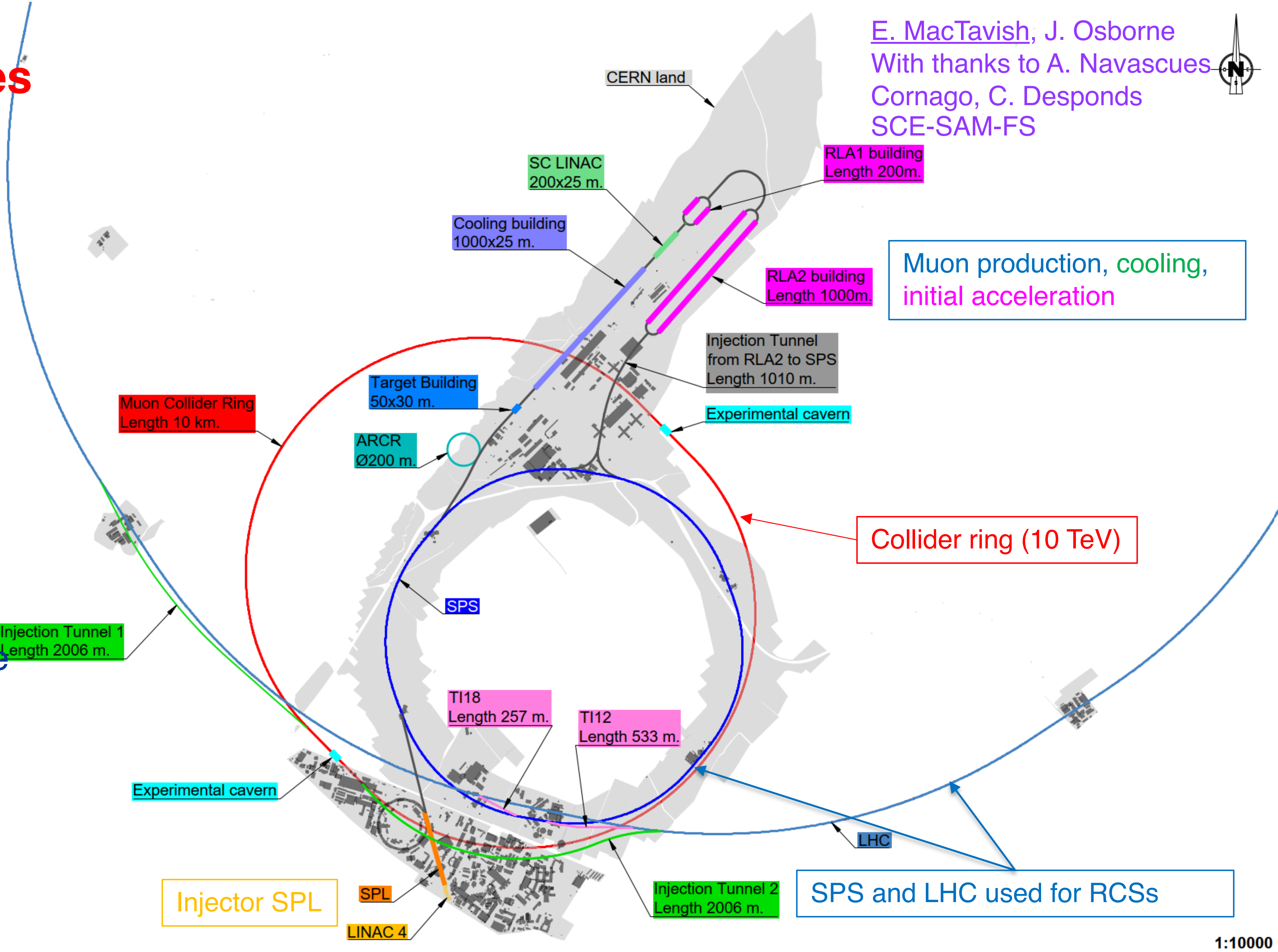
Muon Collider facility overview



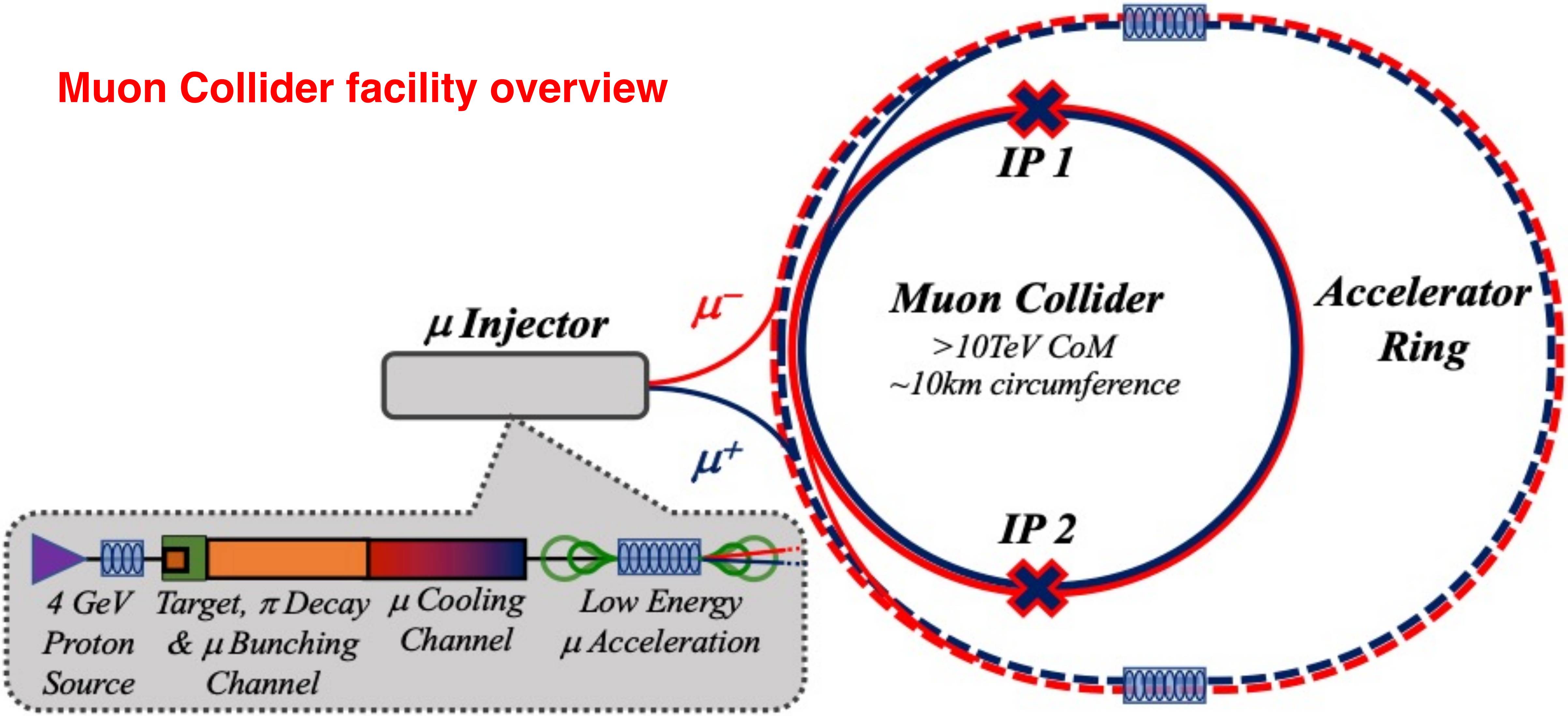
Exploratory Site Studies

- Initiates at LINAC 4
- Integrates existing SPL design
- Transfer to Prevessin via SPS
- Series of Cut & Cover construction on Prevessin Site
- Injection to SPS beneath existing buildings.
- Transfer via TI12 & TI18 into the LHC
- Injection from the LHC into the Collider Ring at equidistant points from the Experimental Cavern

E. MacTavish, J. Osborne
With thanks to A. Navascues Cornago, C. Desponds
SCE-SAM-FS

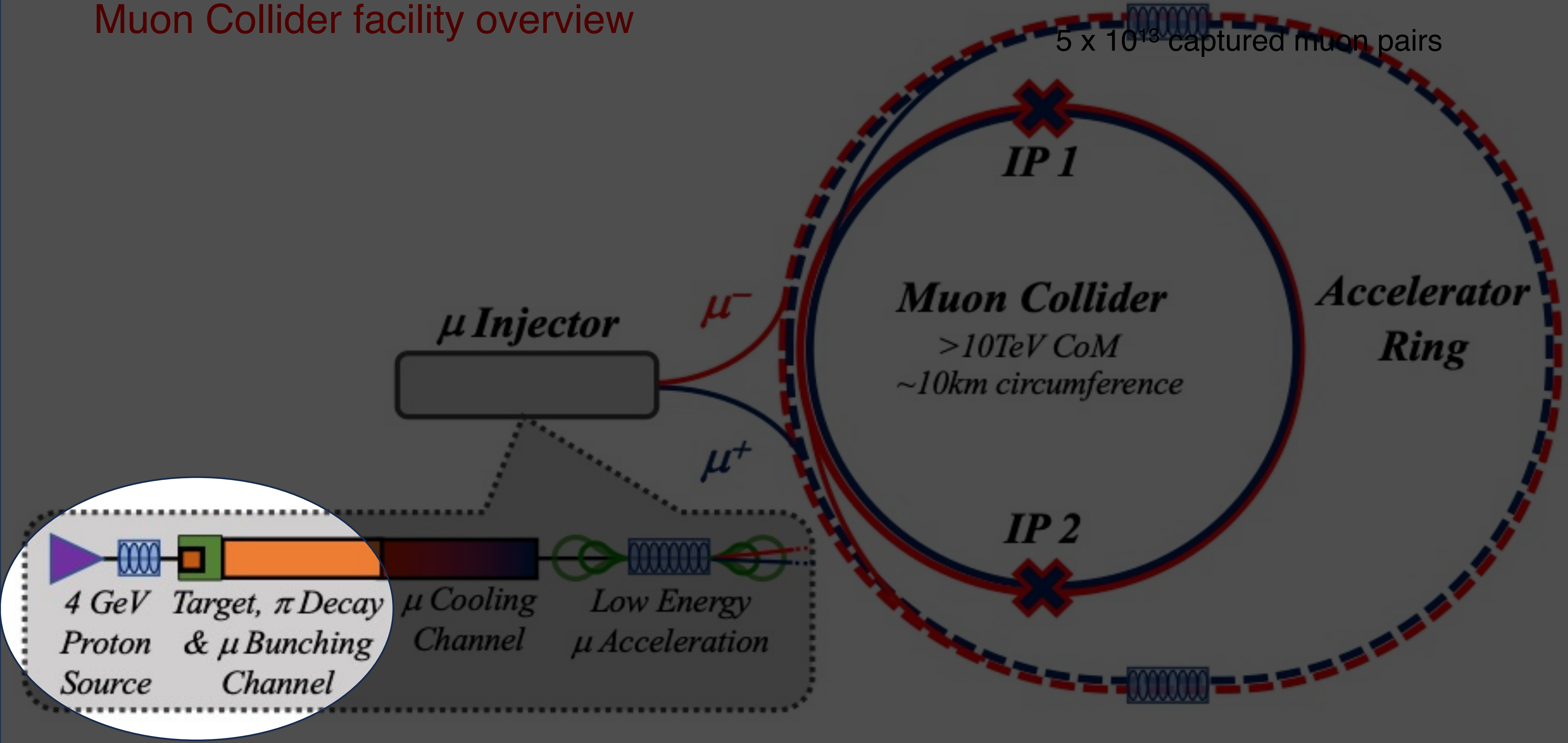


Muon Collider facility overview



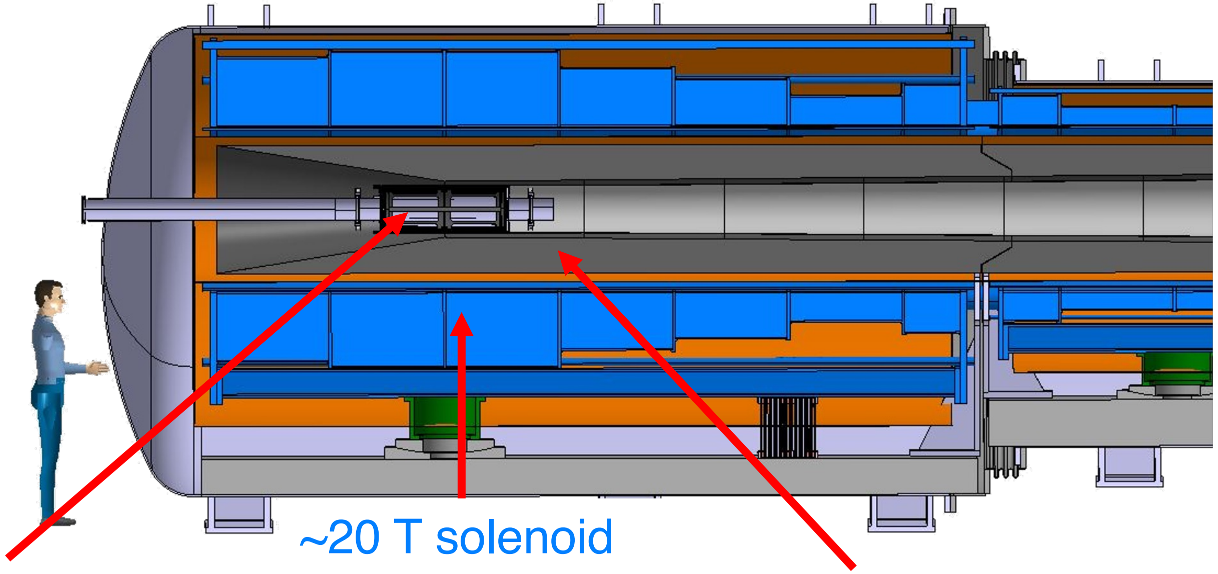
Muon Collider facility overview

5 x 10^{13} captured muon pairs



4-5 GeV proton beam
400 kJ x 5 Hz = 2 MW

5×10^{13} captured muon pairs



Graphite Target

~20 T solenoid to guide pions and muons

Tunsten shielding to protect magnet

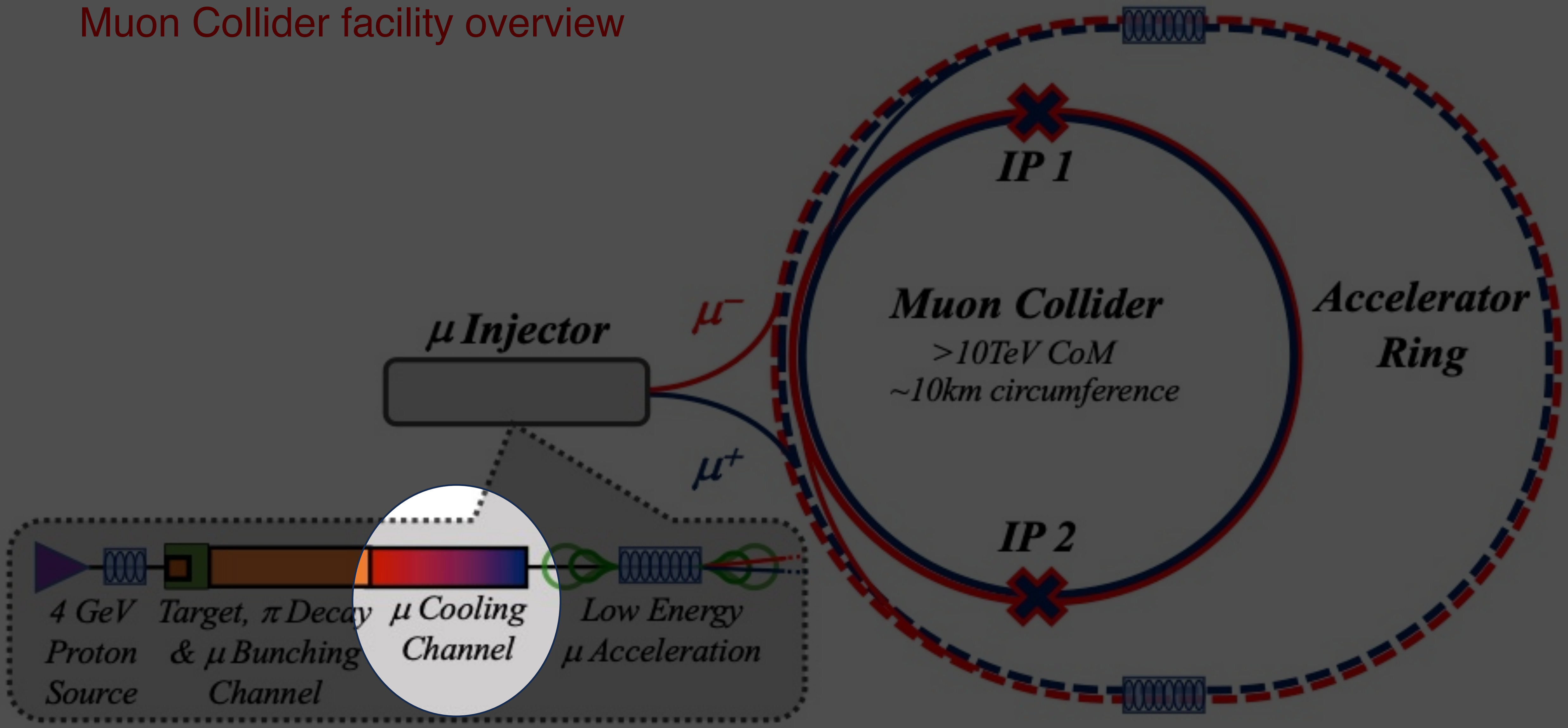
Main R&D

- Investigation of new target materials e.g. liquid target to arrive to 4 MW to have very high intensity muon beam
- 20 T target solenoid design including radiation shielding
- System integration

Synergies with neutrino and neutron facilities

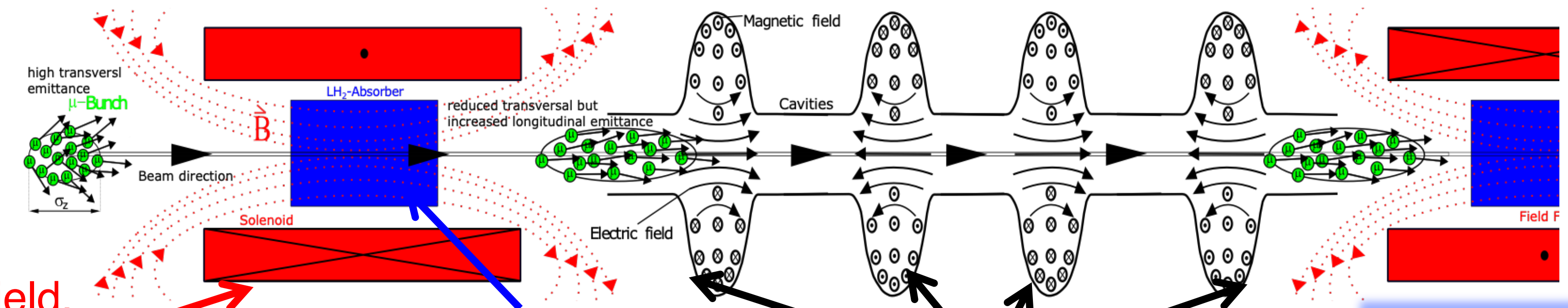
Italian interest and contributions

Muon Collider facility overview



Muon ionization cooling principle

Strong Italian contributions



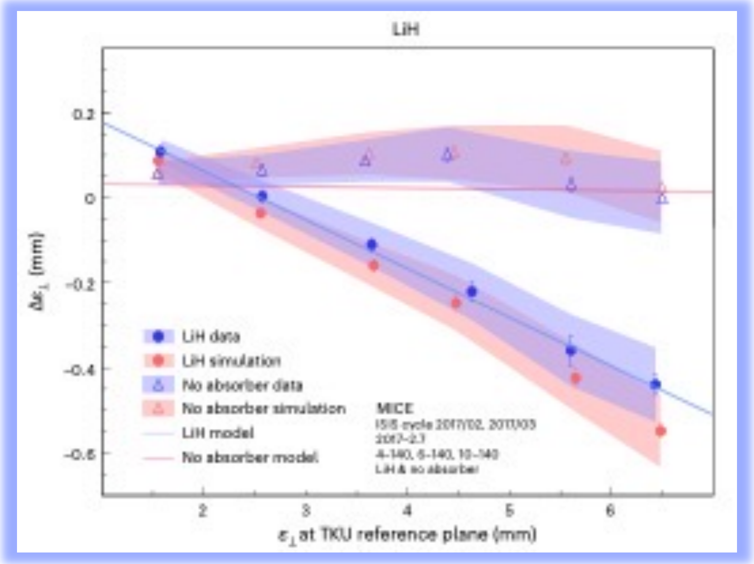
High-field, superconducting solenoid to minimize multiple scattering effect

Absorbers, Low Z material: Lithium hydride, liquid H

High-gradient normal-conducting RF cavities

Design and test of the different cells with muon beams one of the core activities of the **muon collider demonstrator program.**

Details on Roberto Losito presentation

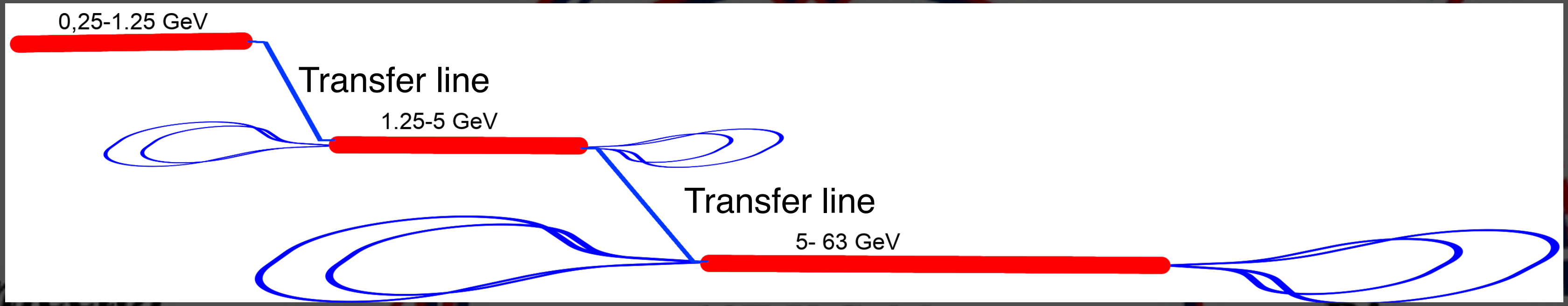


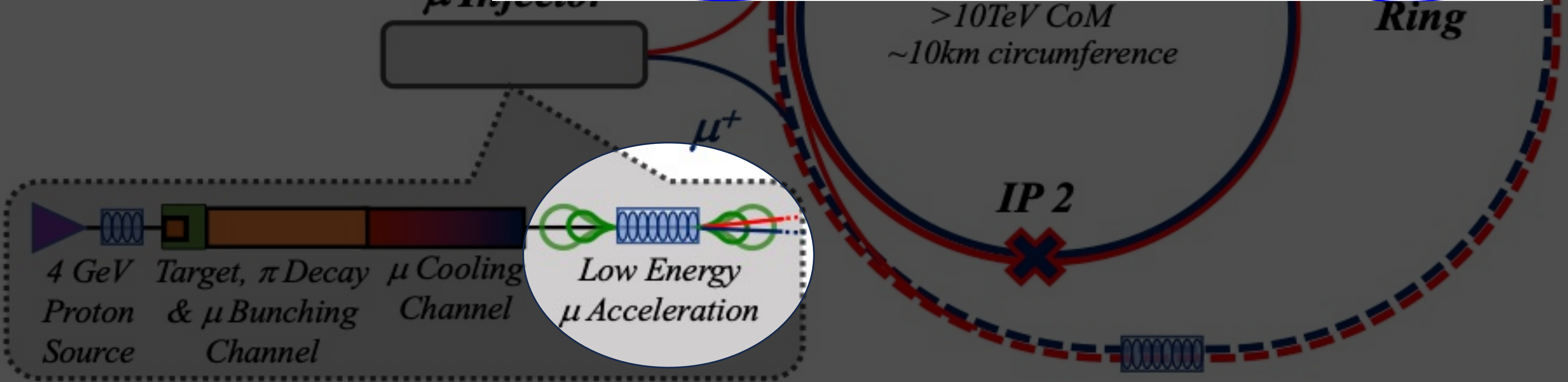
Simulation of transverse emittance well reproduced by MICE data

Muon Collider facility ov

Rapid acceleration is crucial:

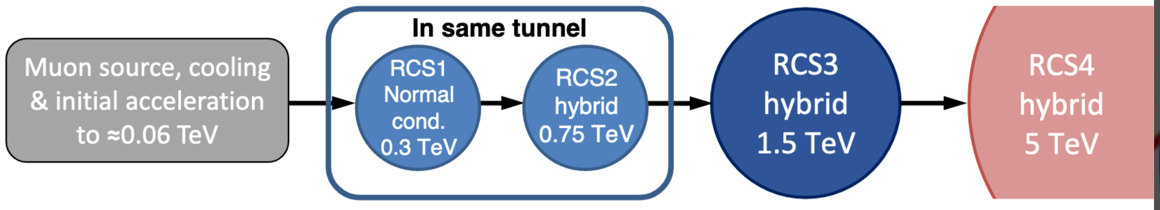
- Linac takes muons at 255 MeV and bring them to 1.25 GeV.
- Two stages of Recirculating Linac, RLA1 from 1.25 GeV to 5 GeV and RLA 2 from 5 GeV to 63 GeV.



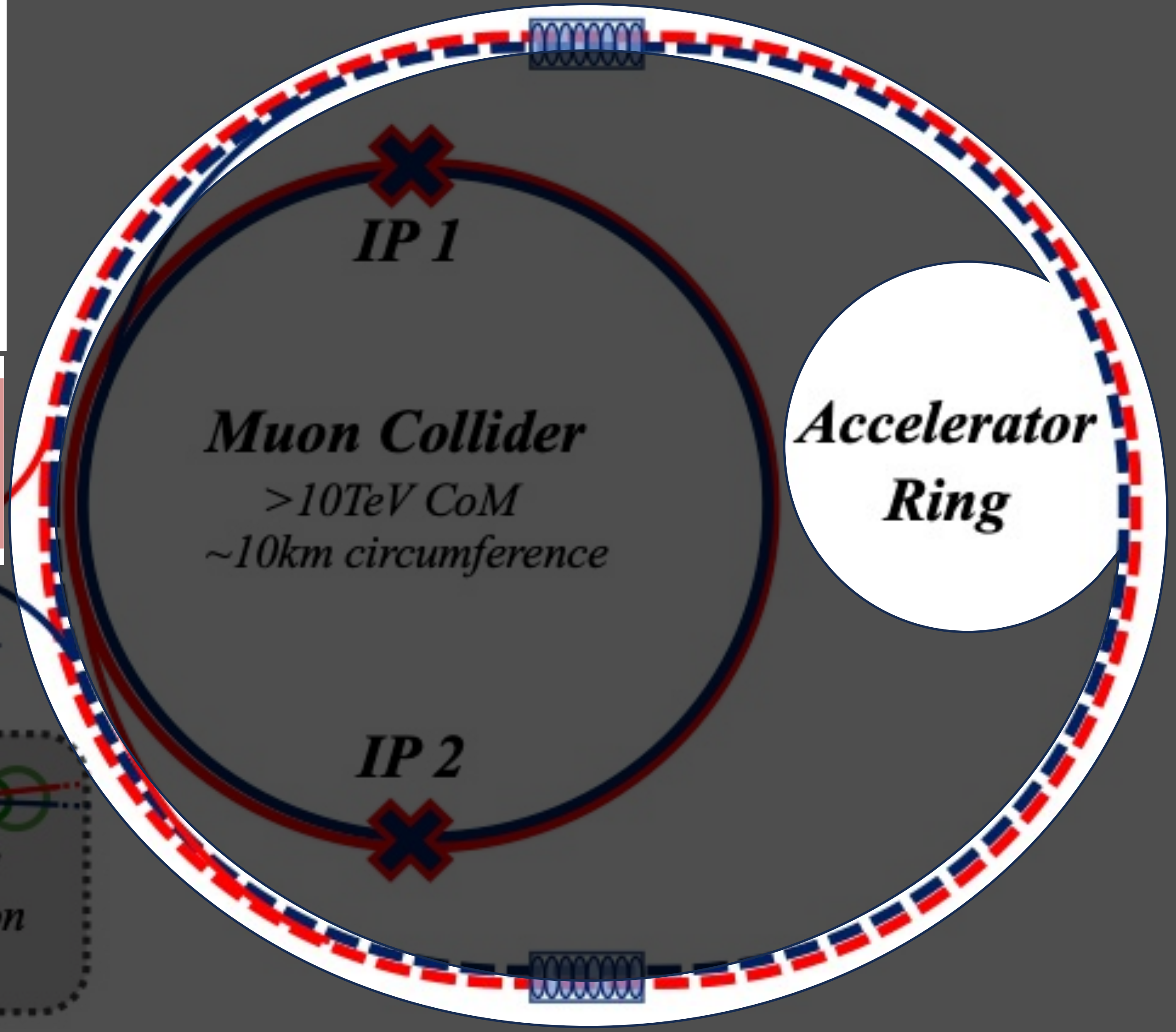


A μ^+ and μ^- bunch must be brought to 5 TeV.
Most promising schema: chain of rapid cycling synchrotrons (RCS) with repetition rate of 5 Hz.
Alternative: Fixed-Field Alternating Gradient.

Survival rate of 90% per RCS required → ultra-fast acceleration, E_{gain} ~10ish GeV per turn.



Study and R&D:
- Magnets
    - hybrid magnets have strong fixed-field, they are superconducting magnets interleaved with normal conducting magnets.
    - shapes of fast ramping magnet and design possible power converter.
- RF: determine the exact frequency



First design of $\sqrt{S} = 10$ TeV collider ring almost complete

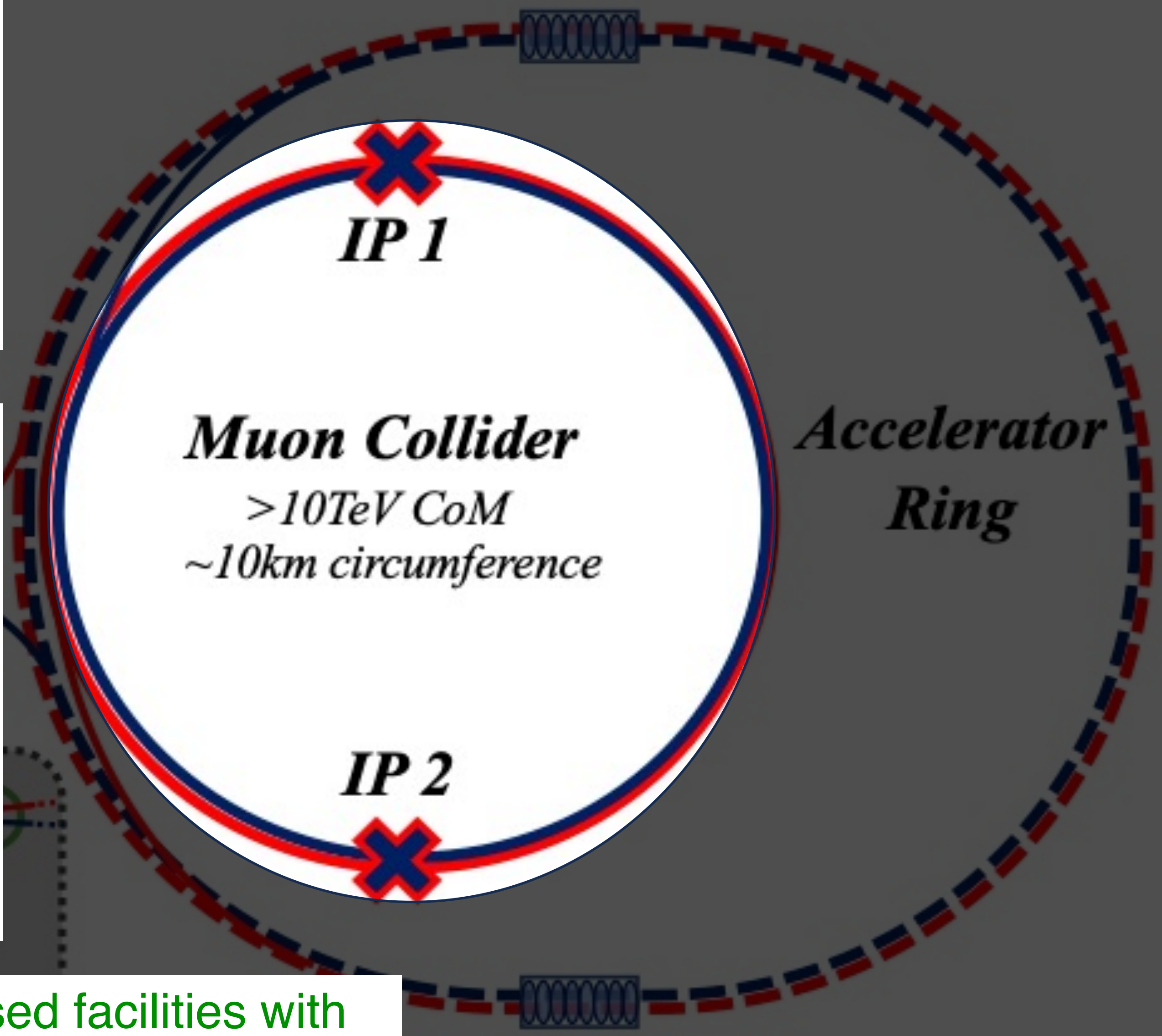
Main challenges to have high performance:

- Very small beta-function ~1.5 mm.
- Maintain short bunches.

Magnet: assumed 16 T HTS dipoles or 11 T Nb_3Sn.
Final focus based on HTS.

Study and R&D

- Study magnet limitations
  - stress, protection, etc. against bore diameter vs. magnetic field for different conductor material and temperature.

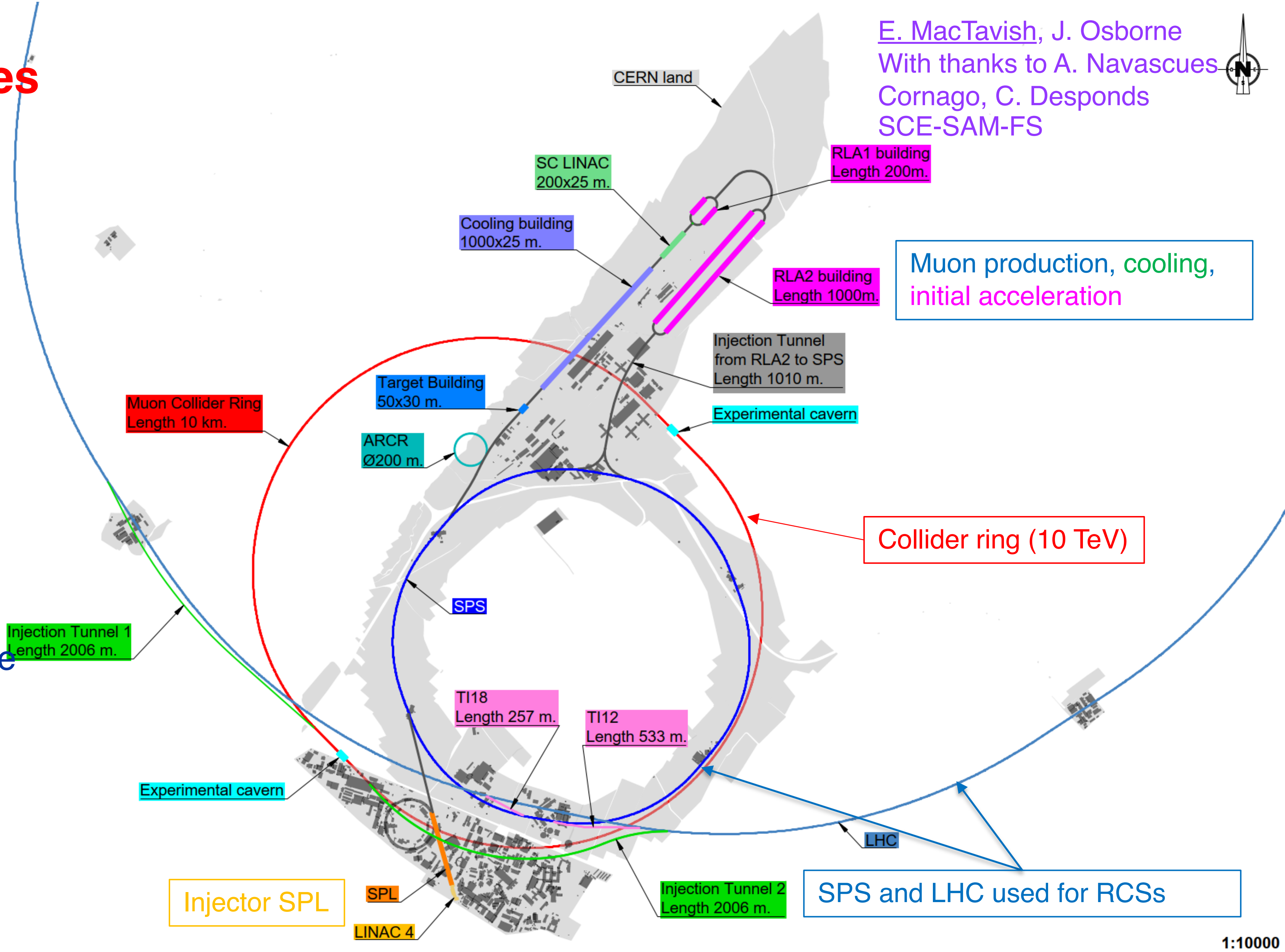


HTS magnets R&D synergic with others proposed facilities with relevant applications in no HEP activities, for example fusion.

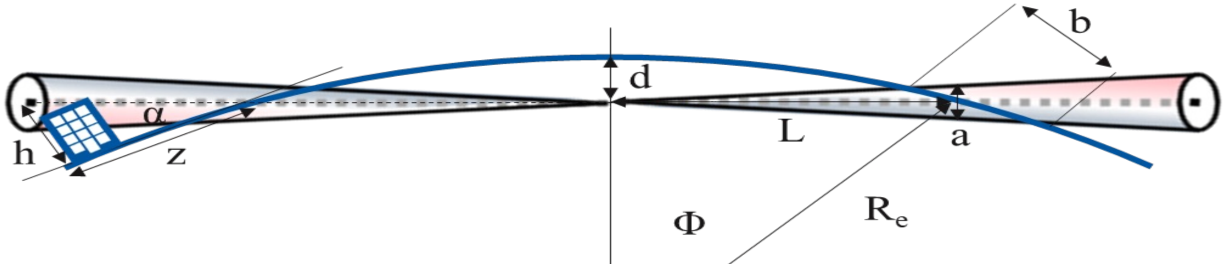
Exploratory Site Studies

E. MacTavish, J. Osborne
With thanks to A. Navascues Cornago, C. Desponds
SCE-SAM-FS

- Initiates at LINAC 4
- Integrates existing SPL design
- Transfer to Prevessin via SPS
- Series of Cut & Cover construction on Prevessin Site
- Injection to SPS beneath existing buildings.
- Transfer via TI12 & TI18 into the LHC
- Injection from the LHC into the Collider Ring at equidistant points from the Experimental Cavern

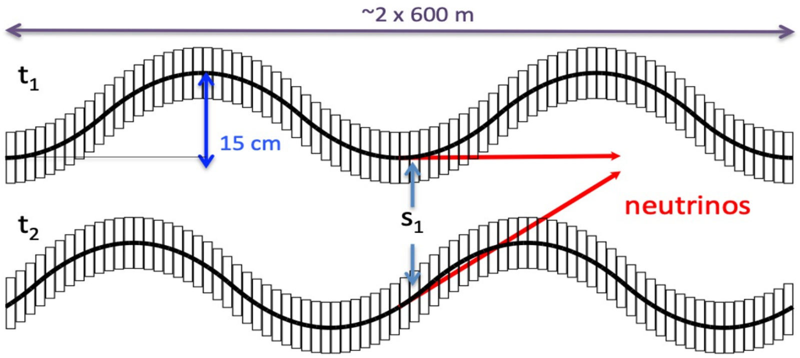


High energy high intensity neutrino flux could interact far away in material near the Earth's surface producing secondary particle showers.



Aim for negligible impact (~ LHC), possible in arc sections

- Almost done at $\sqrt{S} = 3$ TeV
- $\sqrt{S} = 10$ TeV radiation level go from acceptable to negligible moving collider ring components. Mover system designed.

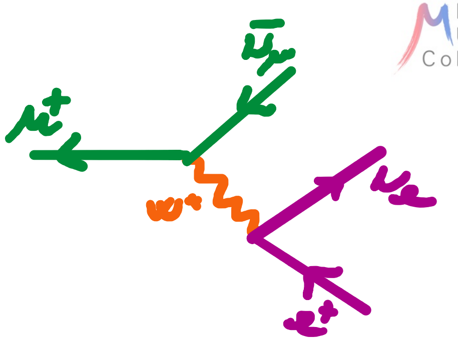


Straight sections strategies depend on the site location, a simple one foresees the two hot spots point toward mediterranean see and uninhabited area in Jura.

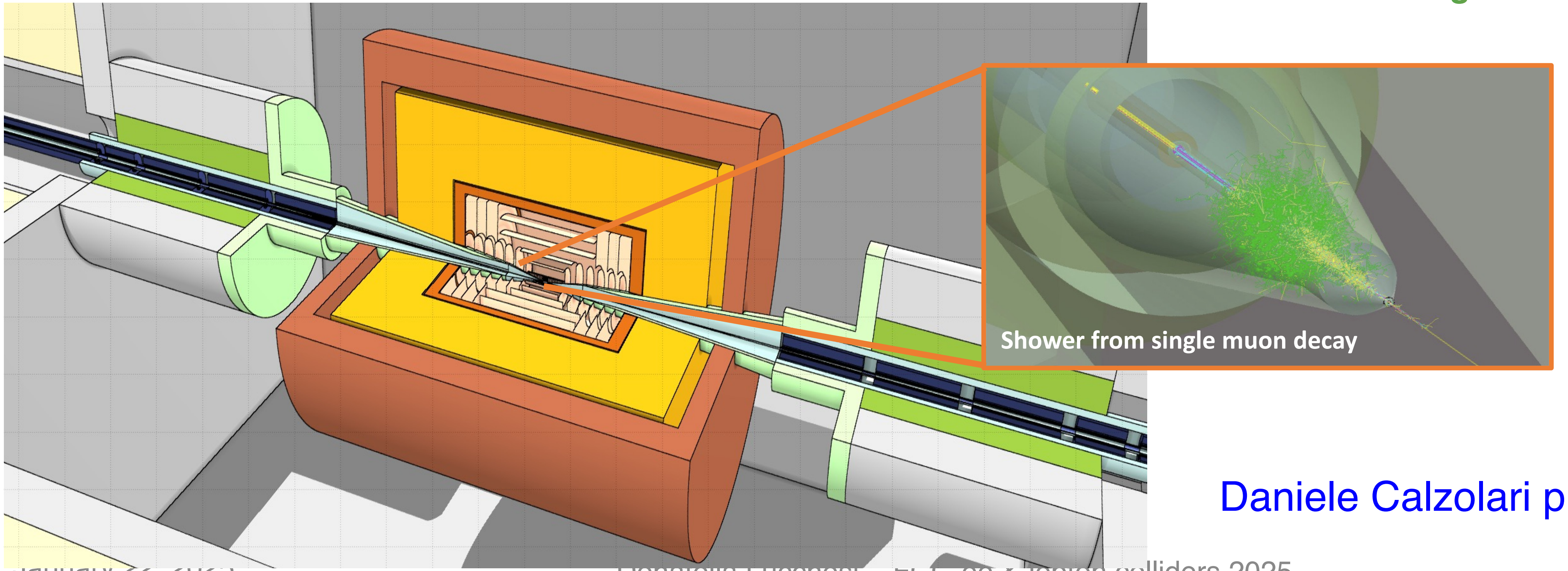
Machine Detector Interface (MDI)

Strategies to mitigate effects of high energy e^{+}/e^{-}at interaction region

- Optimize interaction region configuration
  - Two designs available for $\sqrt{s} = 3$ TeV (MAP-US) and $\sqrt{s} = 10$ TeV
- Locate absorbers around the interaction point
  - Optimized absorber at 3 TeV by using advanced machine learning
  - Improved absorbers design for $\sqrt{s} = 10$ TeV

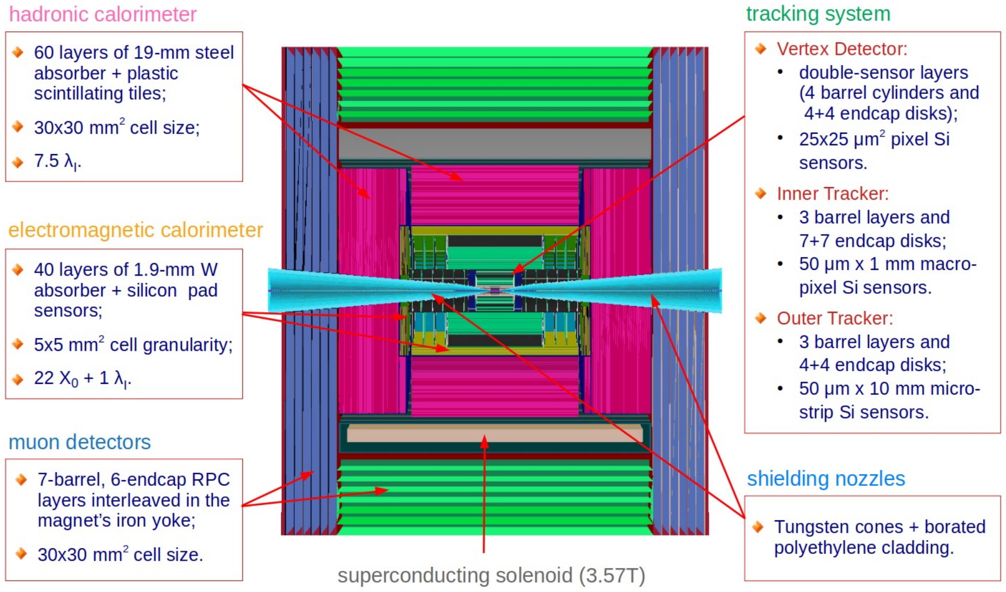


Strong Italian contribution



Daniele Calzolari presentation

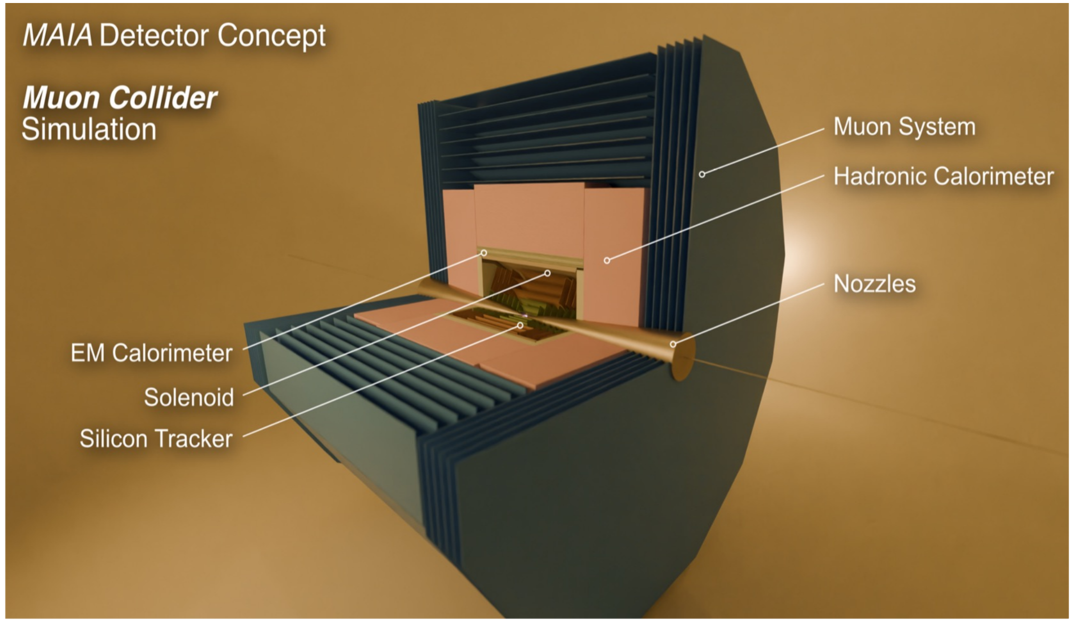
Strong Italian contribution

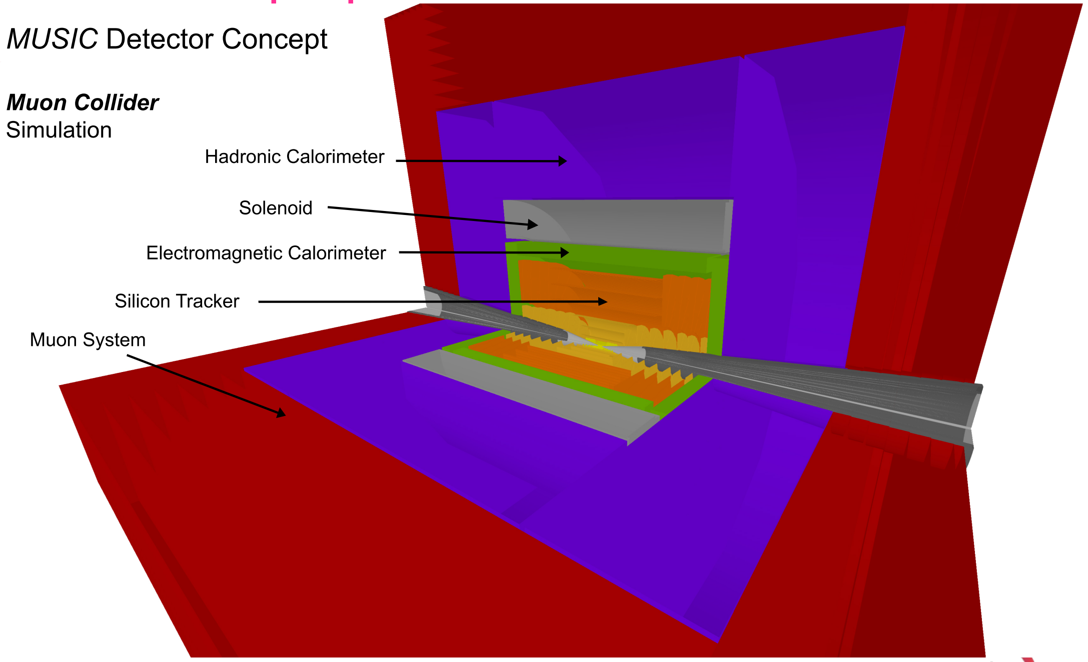


Detector concept at $\sqrt{S} = 3$ TeV was adapted from the CLICdet

Davide Zuliani presentation

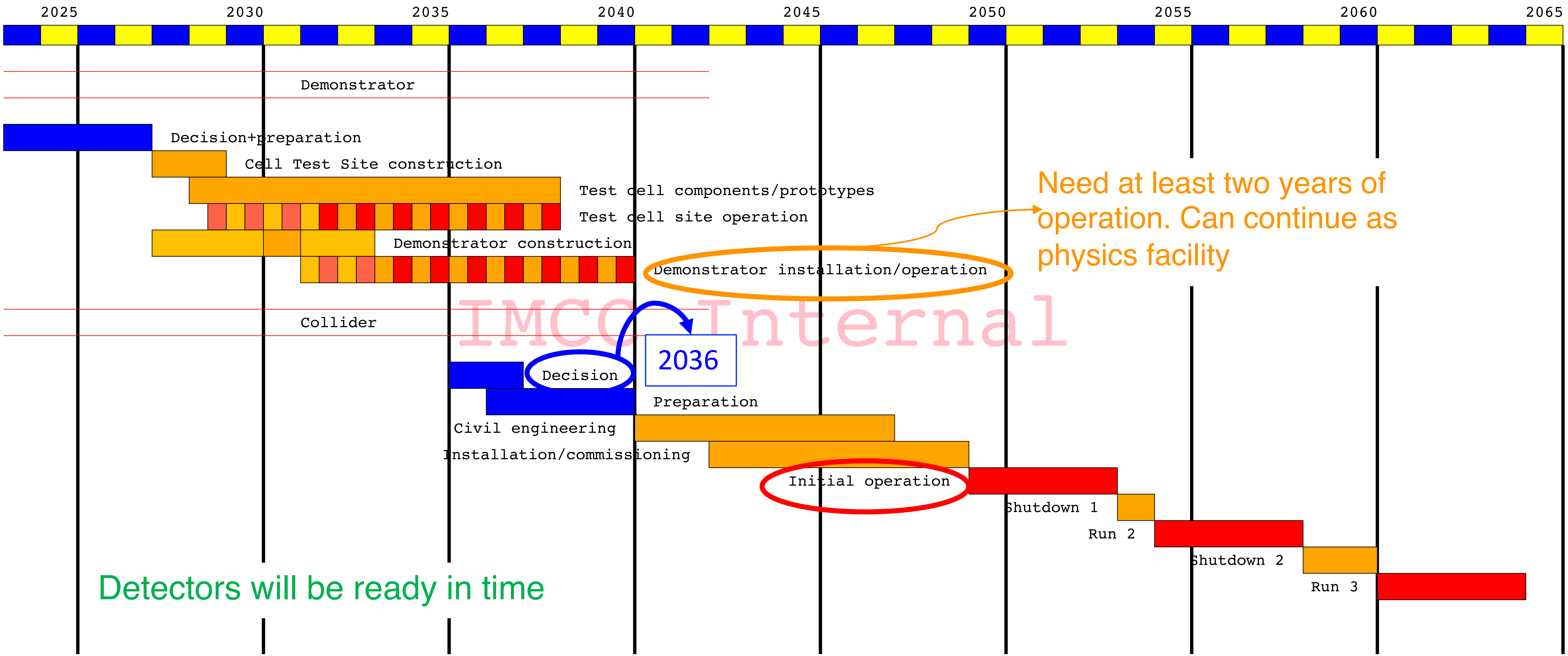
At $\sqrt{S} = 10$ TeV two different detectors are proposed





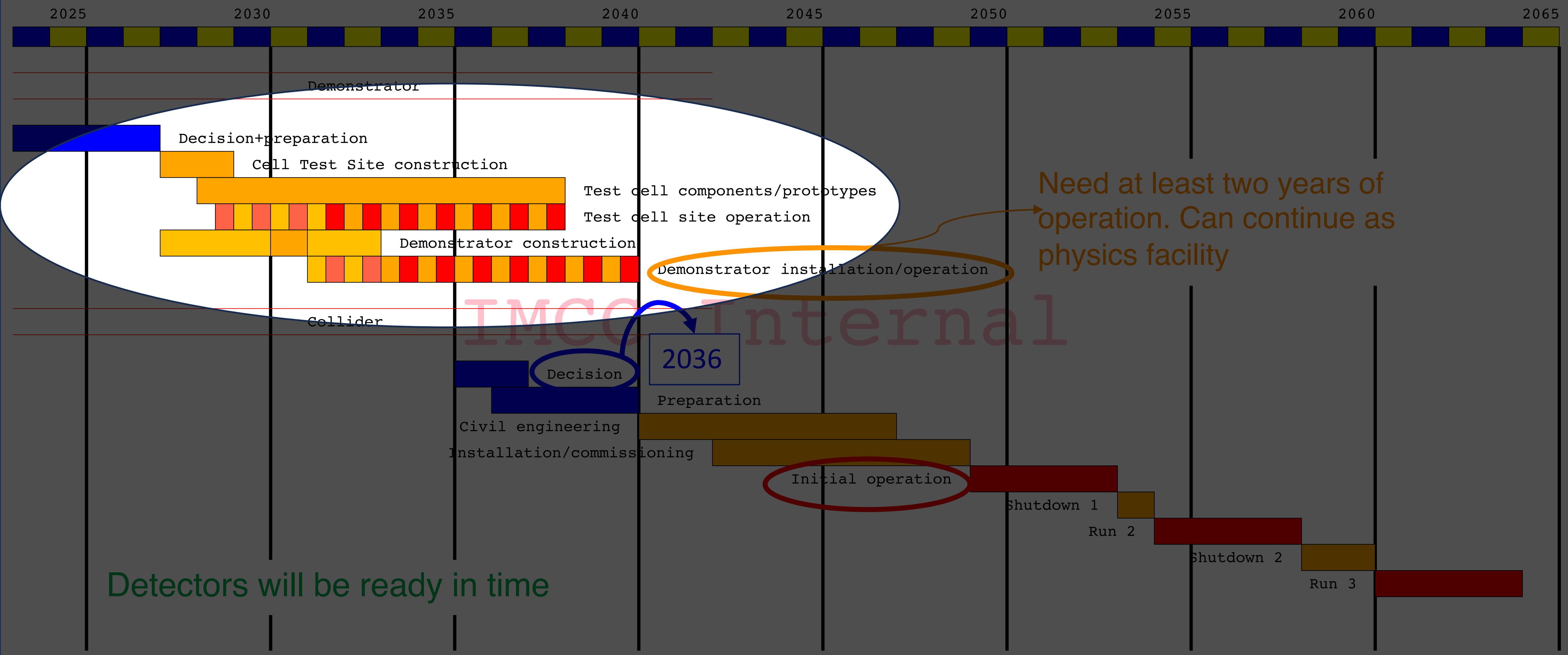
When all of that can happen?

IMCC Internal means it will be reviewed soon



Detectors will be ready in time

IMCC Internal means it will be reviewed soon



Muon collider demonstrator program

Establish a facility where the MuC specific R&D can be done, it could evolve in a high intensity muon beam facility at CERN.

Major activities could be included in the program

1. Muon production targets
   a. Test different materials
   b. Test materials in high magnetic field

   → Requirements: proton beam & solenoid
2. Radiofrequencies
   a. Test the functionalities in magnetic field
      In progress with INFN & Italian entity participation
3. Cooling cells
   a) Design, construct and test single cell and multiple cells functionalities
      In progress with INFN & Italian entity participation

   (2, 3) → Cooperation and synergy between CERN and other laboratories
4. Integrate various sub-systems, test cooling prototype with multiple cells with muon beam.

It requires substantial investments, and if MuC will not proceed in Europe?

It requires substantial investments, if MuC will not proceed in Europe?

International MUON Collider Collaboration

The facility could evolve in a high intensity muon beam and neutrino facility at CERN.

Currently CERN muon beams have intensity of $3{\cdot}10^8$/spill, with a cooling facility the intensity could be comparable to PSI and J-PARC ($3{\cdot}10^{12}$) but with $\mu^+$and μ^- beams.

Muon facility can be used:

- Physics measurements, for example study Charge Lepton Flavor Violation processes and dark matter searches coupled to muon.
- Muography including detector testing.
- Technology advancement, muon-catalyzed fusion.
- …

Neutrino facility will allow physics measurements with NuStorm
Low-energy neutrino beam can be used for high-precision measurements of cross-sections in the energy range below 1 GeV/c, where experimental data are currently very limited.

In addition, it could constitute a facility to train young people in accelerator technology developments

Summary

International
MUON Collider
Collaboration

The potential of Muon Collider facility has been presented, highlighting its transformative impact on advancing particle physics.

Significant progress achieved by the International Muon Collider Collaboration in recent years has been outlined, with no fundamental showstoppers identified.

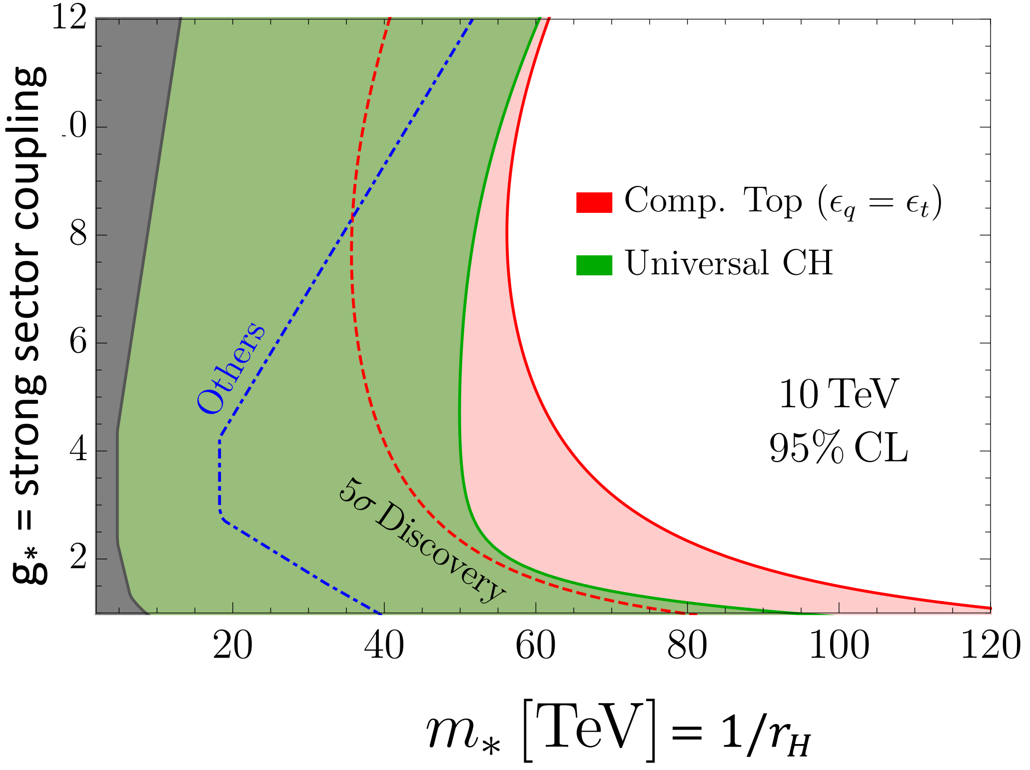
Next critical R&D steps required to enable facility construction have been clearly identified.

The experimental demonstrator program toward the muon collider should continue, adequate funding is essential.

Additional material

The combination of high energy and high precision enhances sensitivity to new physics, reaching 100 TeV scale with 10 TeV muon collisions.
A 100 TeV hadron collider does not have direct access to such a scale due to the composite nature of proton.

Others: CLIC+FCC-ee+FCC-hh

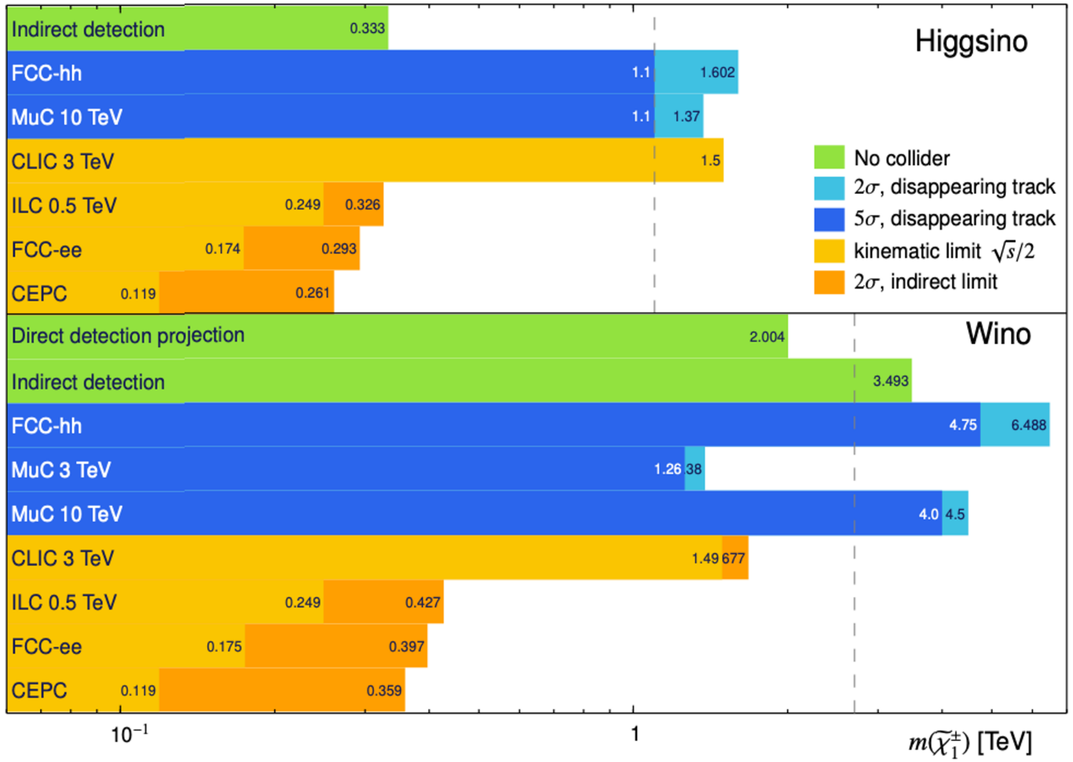


Sensitivity to Higgs compositeness
r_H: Higgs radius

Great reach in the search for New Physics testing several models

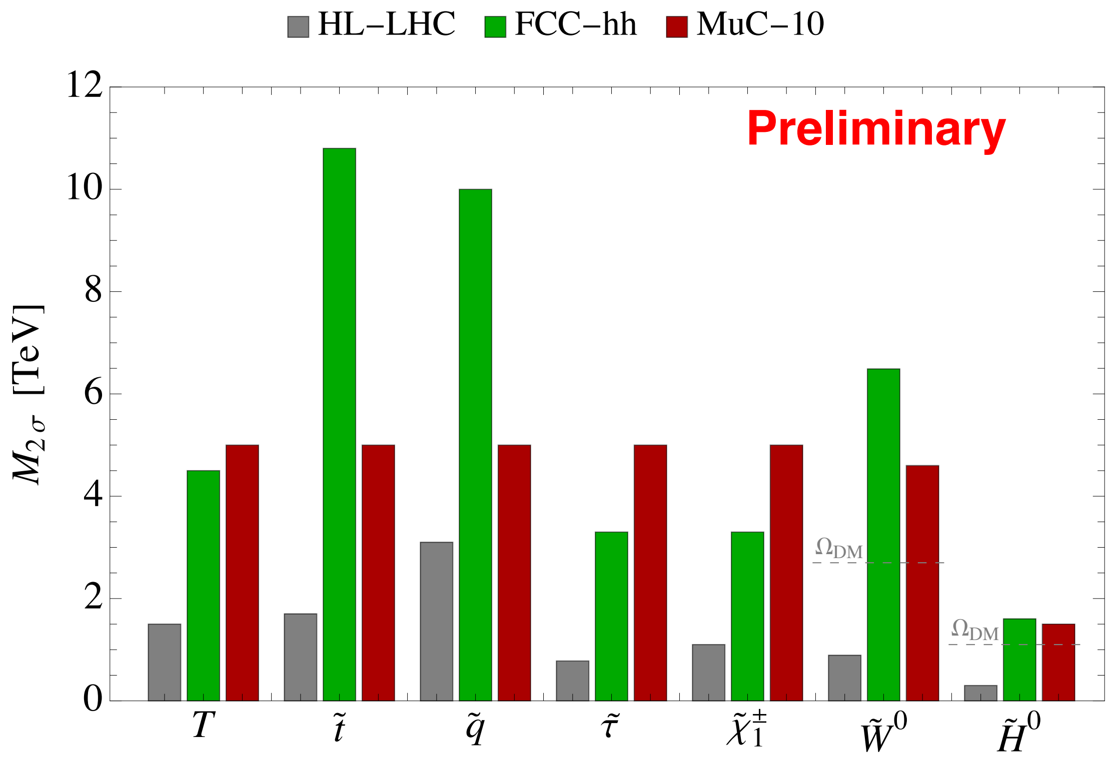
MSSM model

Low energy spectrum: chargino, $\tilde{\chi}^{\pm}$,+1(2) neutral particle(s) for $\widetilde{W}(\widetilde{H})$



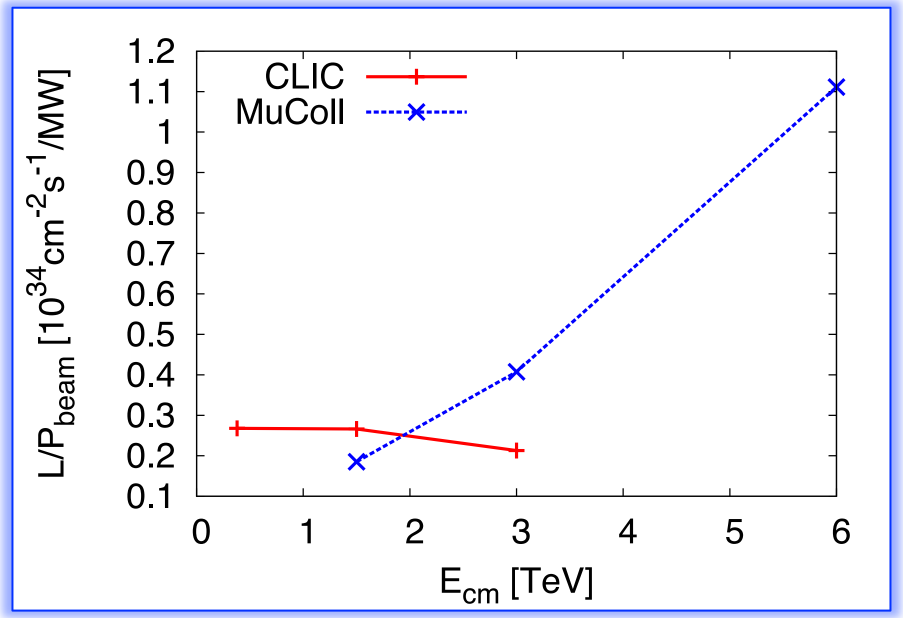
Disappearing track, detailed detector and background simulation

95%CL exclusion reach on the mass of several BSM particles

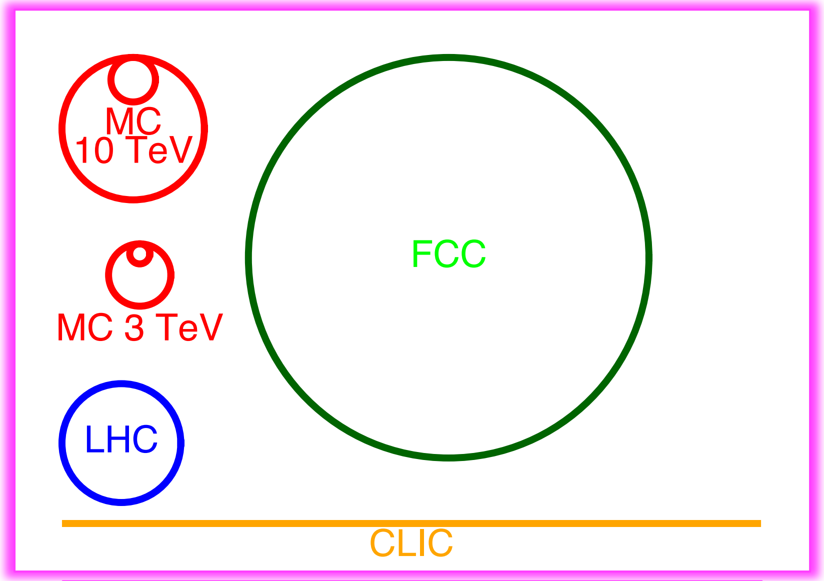


Why muons

Muons do not suffer too much from synchrotron radiation in the considered energy range



High center of mass energy & high luminosity & power efficient machine



luminosity increase per beam power vs. E_{CM}

A sustainable accelerator complex

Compact → cost effective

Main parameters of the facility

Energy staging: Start at lower center-of-mass energy, e.g. $\sqrt{S}$= 3 TeV or more suited energy, move later at higher energy

Luminosity staging: Start $\sqrt{S}$=10 TeV with low luminosity, upgrade later to high luminosity as in HL-LHC

Expected integrated luminosity in 5 years one experiment

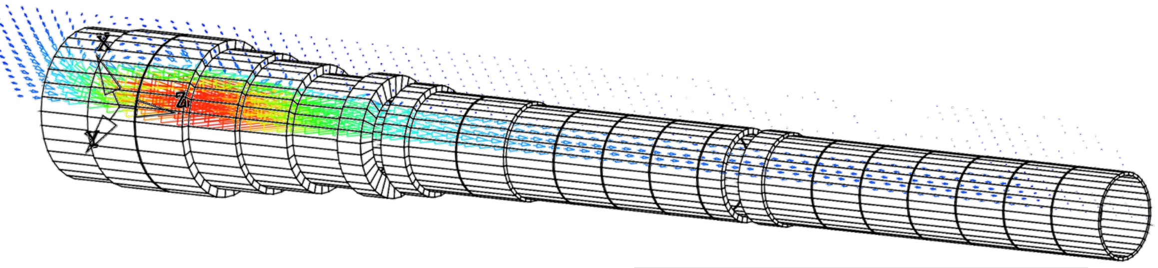
$\sqrt{s}$ = 3 TeV 1 ab^{-1}

$\sqrt{s}$ = 10 TeV 10 ab^{-1}

Parameter	Symbol	unit	Scenario 1		Scenario 2	
			Stage 1	Stage 2	Stage 1	Stage 2
Centre-of-mass energy	E_{cm}	TeV	3	10	10	10
Target integrated luminosity	$\int \mathcal{L}_{\mathrm{target}}$	ab^{-1}	1	10	10	
Estimated luminosity	$\mathcal{L}_{\mathrm{estimated}}$	$10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$	2.1	21	tbc	14
Collider circumference	C_{coll}	km	4.5	10	15	15
Collider arc peak field	B_{arc}	T	11	16	11	11
Luminosity lifetime	N_{turn}	turns	1039	1558	1040	1040
Muons/bunch	N	10^{12}	2.2	1.8	1.8	1.8
Repetition rate	f_{r}	Hz	5	5	5	5
Beam power	P_{coll}	MW	5.3	14.4	14.4	14.4
RMS longitudinal emittance	$\varepsilon_{\parallel}$	eVs	0.025	0.025	0.025	0.025
Norm. RMS transverse emittance	$\varepsilon_{\perp}$	µm	25	25	25	25
IP bunch length	σ_z	mm	5	1.5	tbc	1.5
IP betafunction	β	mm	5	1.5	tbc	1.5
IP beam size	σ	µm	3	0.9	tbc	0.9

Target Technologies

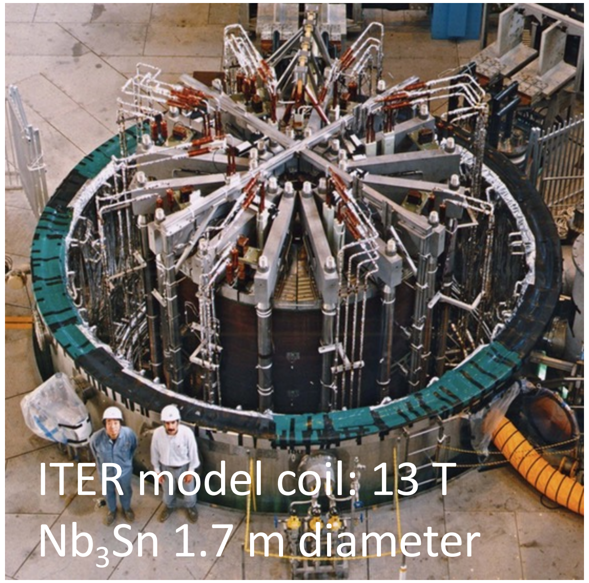
Target solenoid design ongoing
Either large bore 20 T HTS or 15 T LTS with 5 T insert



HTS target solenoid: 20 T, 20 K

A Portone, P. Testoni,
J. Lorenzo Gomez, F4E

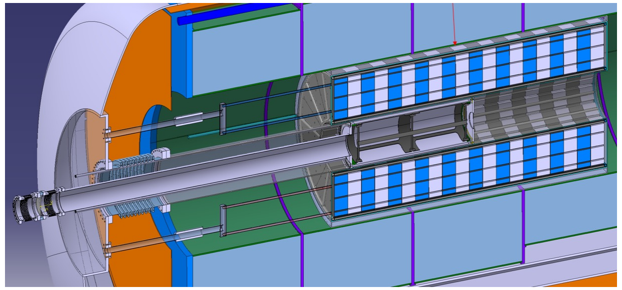
Our work is relevant for fusion



ITER model coil: 13 T
Nb_3Sn 1.7 m diameter

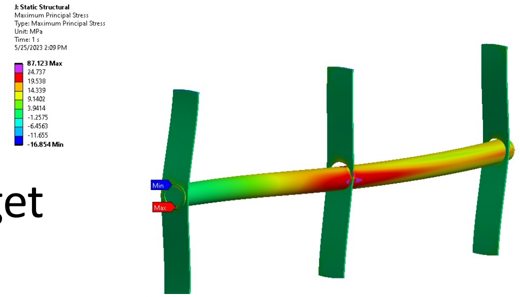
FLUKA studies:
2 MW target: stress in target, shielding, vessel OK
Need to have closer look at window
Cooling OK

Integration

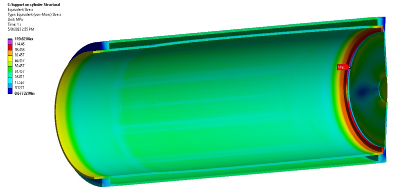


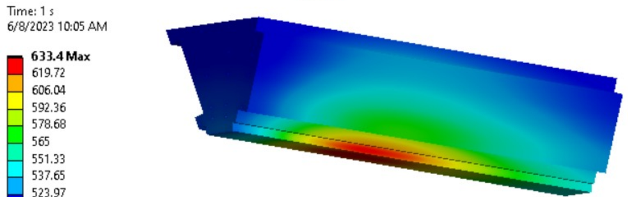
Cooling, vacuum, mechanics, …

Target



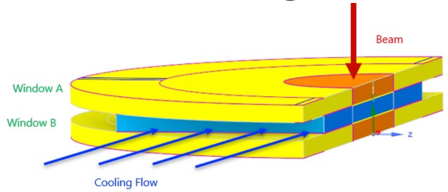
Vessel



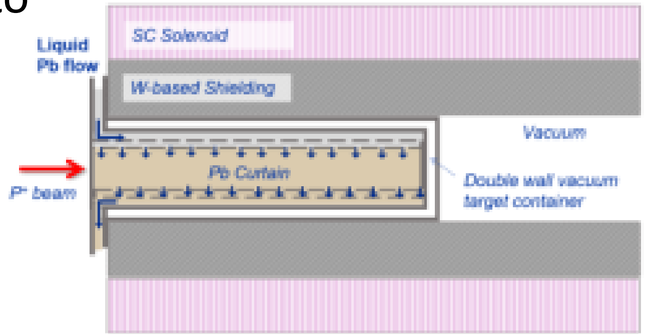


Tunsten shielding

Window



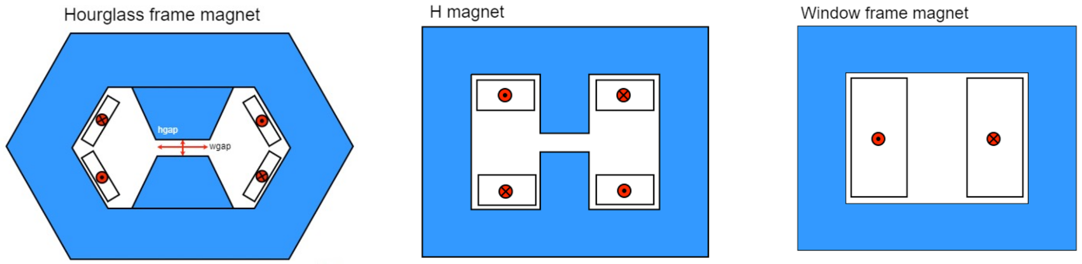
Liquid metal target
Serious alternative to graphite



Fast-ramping Magnet System

Efficient energy recovery for resistive dipoles (O(100MJ))

Synchronisation of magnets and RF for power and cost



5.07 kJ/m — 5.65…7.14 kJ/m — 5.89 kJ/m

FNAL 300 T/s HTS magnet

Could consider using HTS dipoles for largest ring

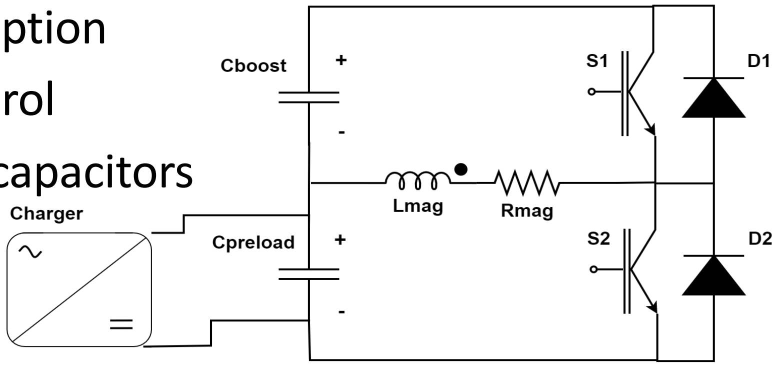
Simple HTS racetrack dipole could match the beam requirements and aperture for static magnets

Differerent power converter options investigated

Commutated resonance (novel)

Attractive new option

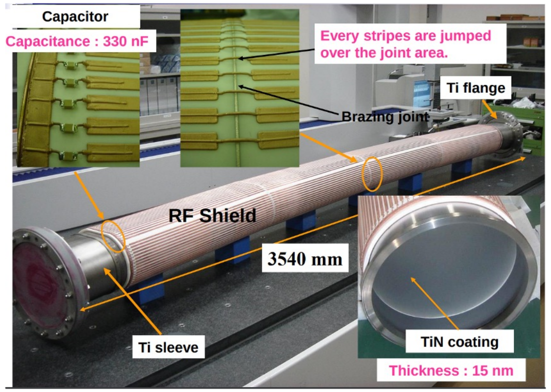
- Better control
- Much less capacitors



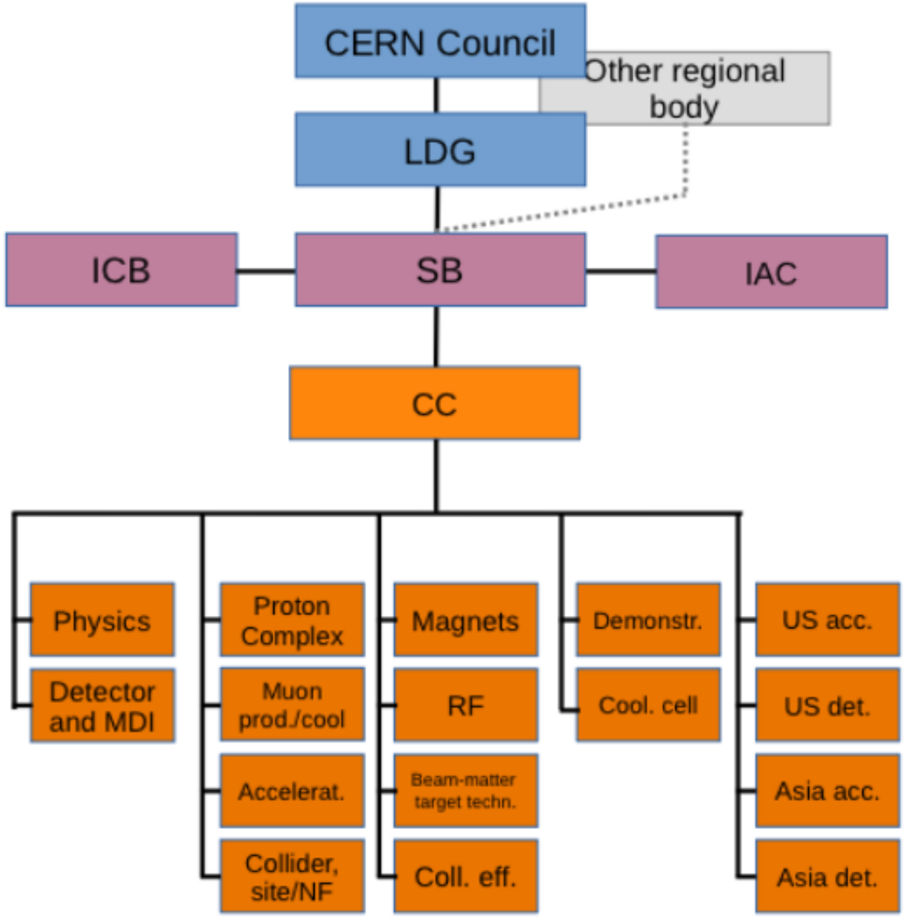
Beampipe study

Eddy currents vs impedance

Maybe ceramic chamber with stripes



IMCC organization



IMCC was founded in 2021

- Reports to CERN Council
- Anticipate it will also report to DoE and other funding agencies