Muon collider activities for the update of the European Strategy for Particle Physics in Trieste

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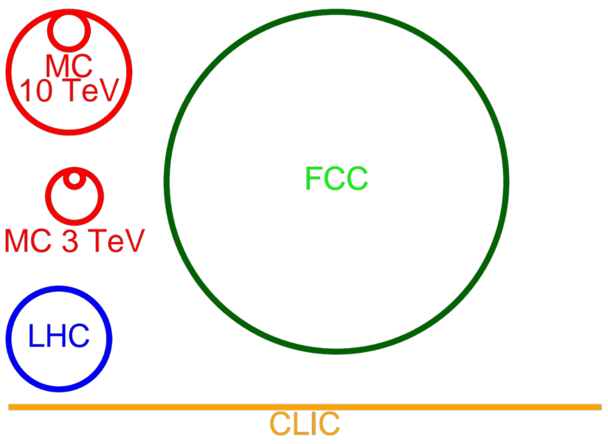
Trieste, 20 November 2024

Why a muon collider?

- A muon collider is a tool to provide leptonic collisions at multi-TeV center-of-mass energies in a relatively compact circular machine:
  - all collision energy is available to the hard-scattering process;
  - energy and momentum of the colliding particles are precisely known;
  - final states are in general "cleaner" w.r.t. hadronic machines.

A muon collider combines precision physics and high discovery potential.

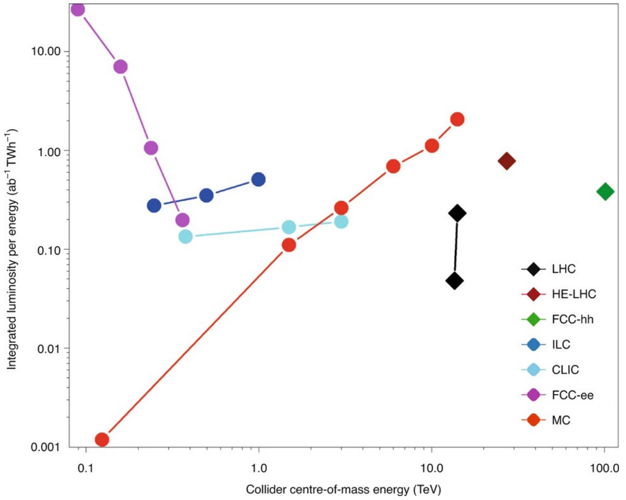
footprints for different high-energy facilities



- Muon colliders are compact: cost effective and possibly more sustainable.

annual integrated luminosity per consumed electric power as a function of the center-of-mass energy

K.R. Long et al., Nat. Phys. 17, 289 (2021)



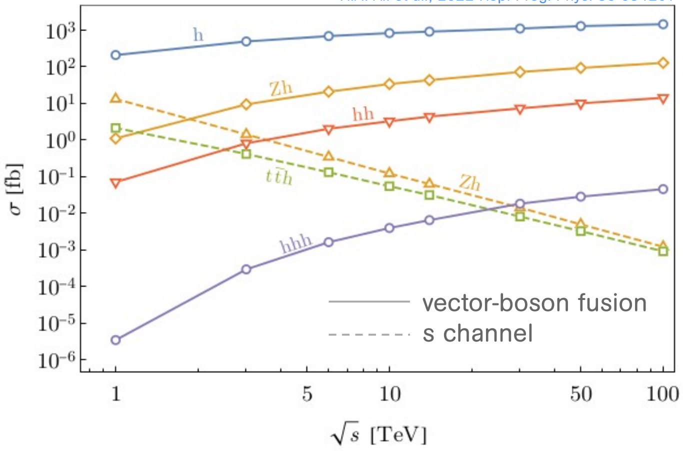
- Muon colliders are power-efficient at high collision energies.

A broad physics program

- Multi-TeV lepton collisions enable a broad physics program:
  - direct and indirect searches for new physics;
  - precise Standard Model measurements in an unexplored energy regime;
  - Higgs boson couplings to fermions and bosons and trilinear and quartic self-couplings of the Higgs boson (λ_3, λ_4)
    - ➔ determination of the Higgs potential: $V(h) = \frac{1}{2} m_h^2 h^2 + \lambda_3 v h^3 + \frac{1}{4} \lambda_4 h^4 .$

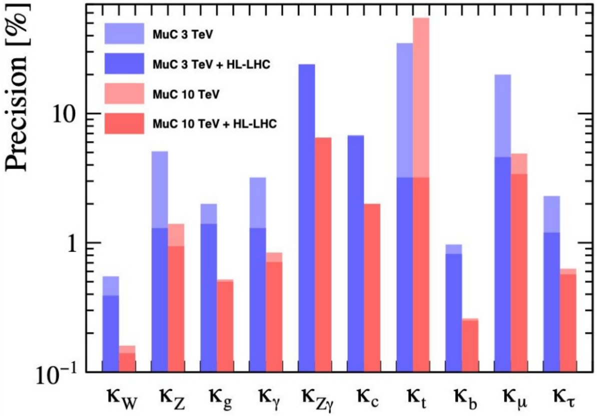
Higgs boson production cross sections

H.A. Ali et al., 2022 Rep. Prog. Phys. 85 084201

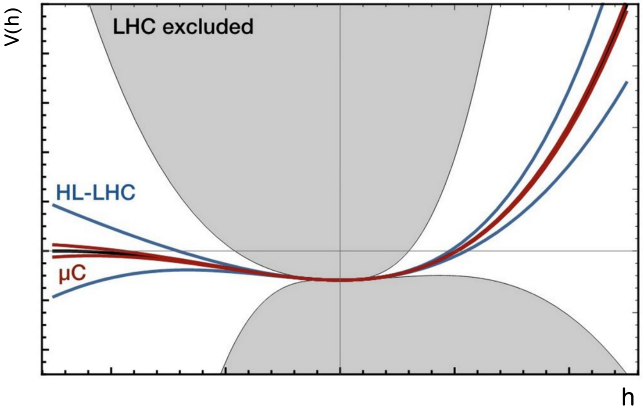


Higgs boson couplings

M.C. et al., Annu. Rev. Nucl. Part. Sci. 74 (2024) 233



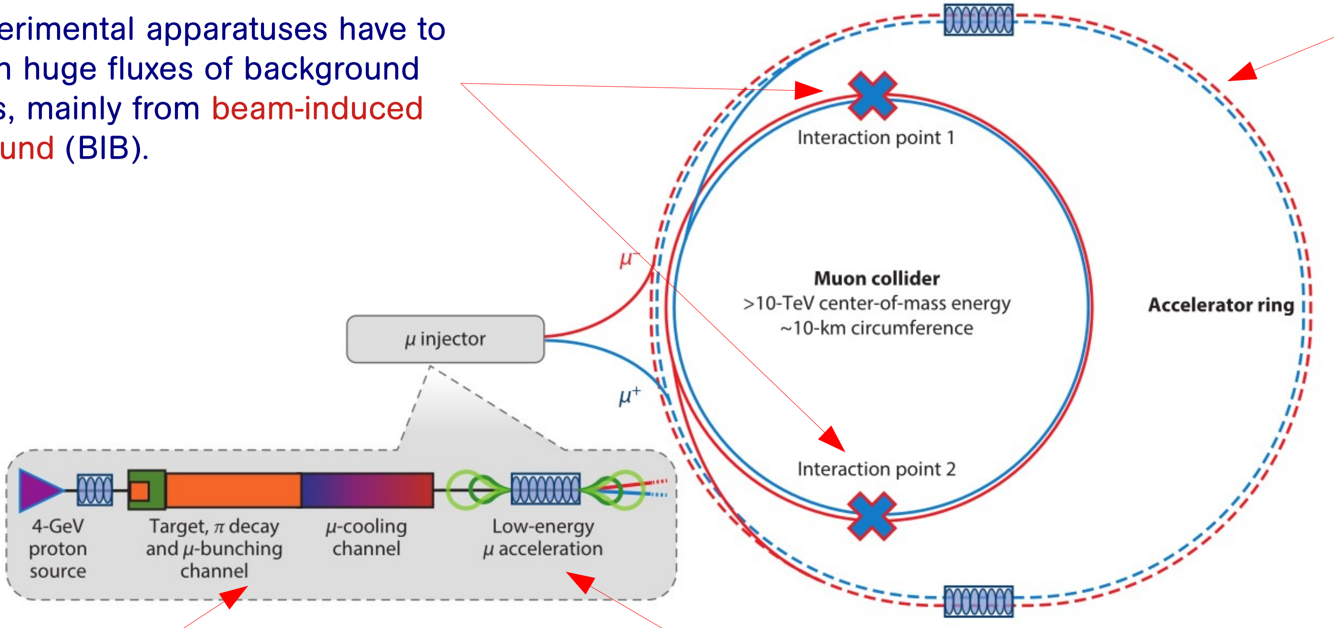
Higgs boson potential shape



The challenges of a muon collider

The experimental apparatuses have to deal with huge fluxes of background particles, mainly from beam-induced background (BIB).

High levels of machine background: all machine elements need to be properly shielded (a 750-GeV beam with 2×10^{12} μ/bunch is expected to radiate on average 0.5 kW/m).



Neutrino flux

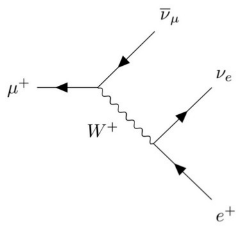
Intense and highly collimated neutrino beams, emerging at the earth surface even very far from the muon collider complex, may be responsible for a severe ionization radiation hazard for the population and the environment.

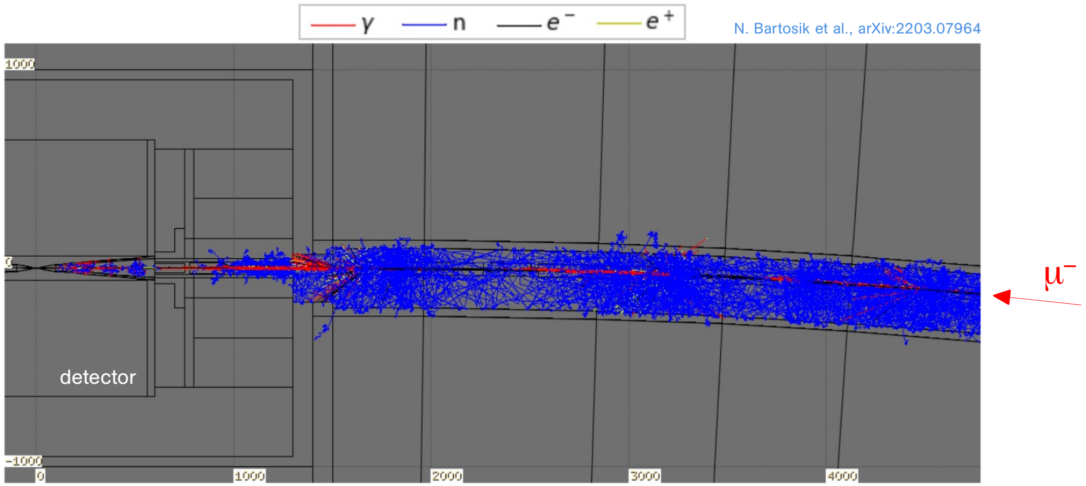
The muon beam production and "cooling", i.e. the reduction of the initial transverse phase-space volume by more than $O(10^5)$, represent the crucial stage of the facility.

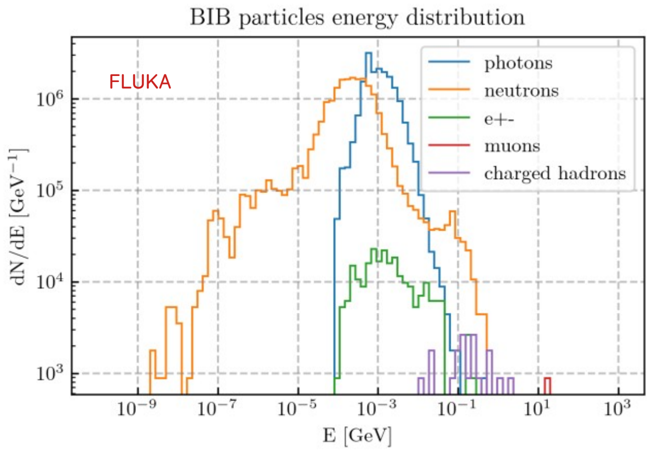
Muon beams must be prepared and accelerated as quick as possible to exploit the relativistic time dilation in the lab system (for a 5 TeV beam t_μ = 105 ms in the lab).

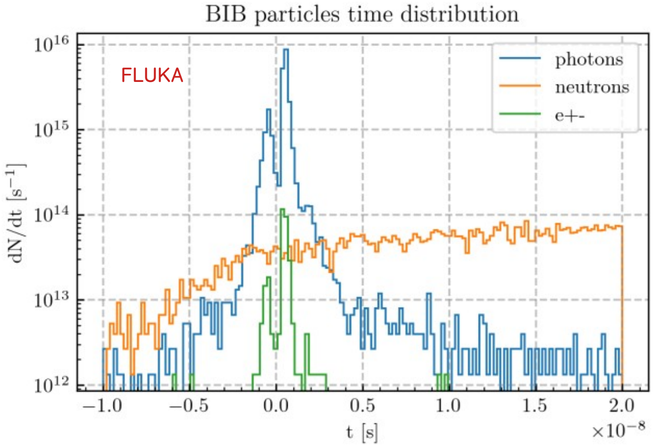
Design fully driven by the muon lifetime.

Background from muon decays





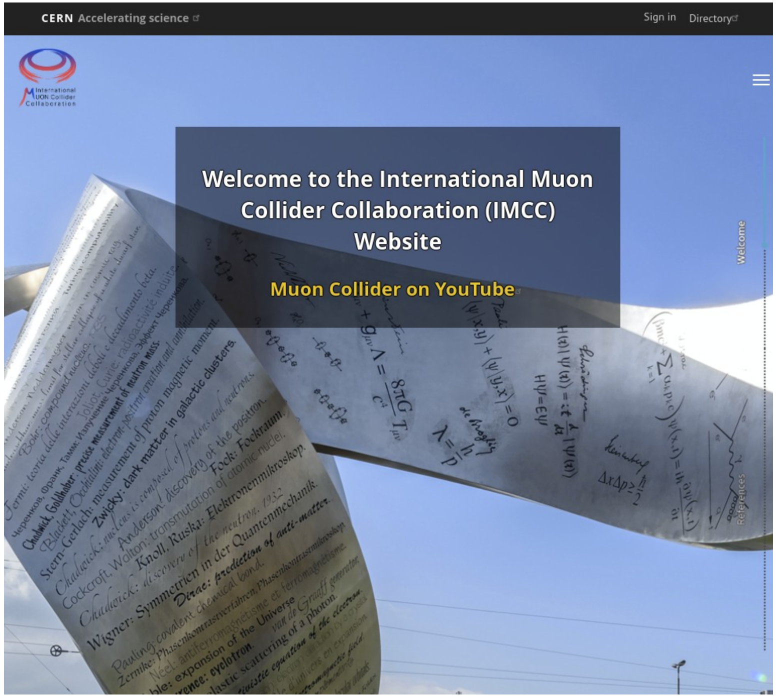




- Beam-induced background (BIB) from muon decay products interacting with the machine components and the shields inside the detector (nozzles):
  - soft particles and mostly out of time w.r.t. the bunch crossing:
  - $\sim 10^8$ photons, $\sim 10^7$ neutrons, and $\sim 10^5$ electrons/positrons enter the detector at every bunch crossing in the time window [-1, 15] ns.
- Extensively studied with MARS15 and FLUKA.

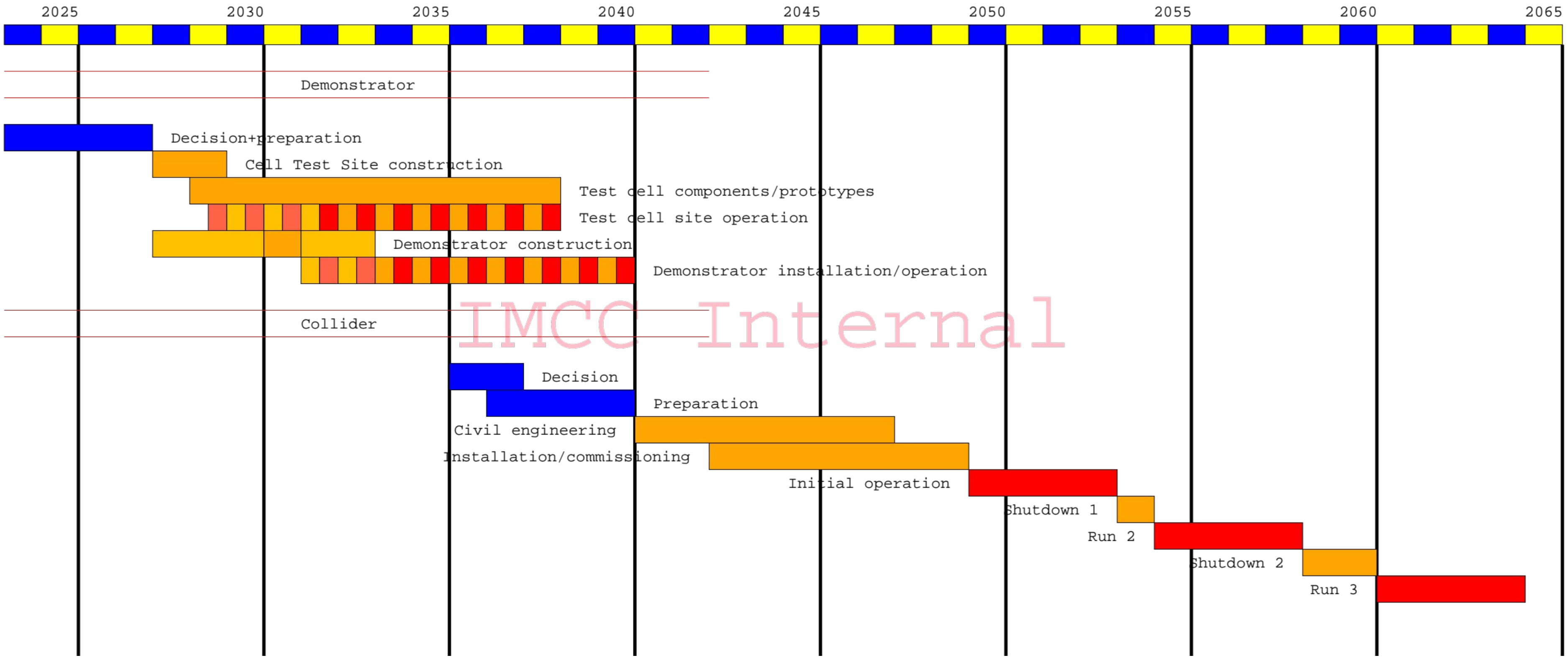
International picture

- The R&D studies for a muon collider are coordinated by the International Muon Collider Collaboration (IMCC), established at CERN in 2022 as a result of the recommendations of the ESPP 2020 update:
  - IMCC main goals:
    - assess and develop the muon collider concept for a ∼10 TeV facility;
    - identify potential sites to implement the collider;
    - develop an initial muon collider stage that can start operation around 2050;
    - develop an R&D roadmap towards the collider.
- Fruitful collaboration with the U.S. HEP community from the very beginning: the studies of IMCC began where the U.S. Muon Accelerator Program (2010-2014) left off.
- Outcome of Snomass 2021 in U.S. very favorable to muon collider: P5 final report recommends pursuing R&D on a machine with "partonic center of mass energy" of 10 TeV and above and encourages the U.S. HEP community to join the IMCC (ongoing integration process).



muoncollider.web.cern.ch

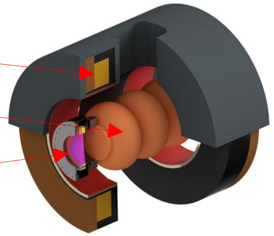
Tentative timeline for a 10 TeV muon collider



D. Schulte, IMCC Demonstrator Workshop, FNAL, Oct. 30-Nov. 1, 2024

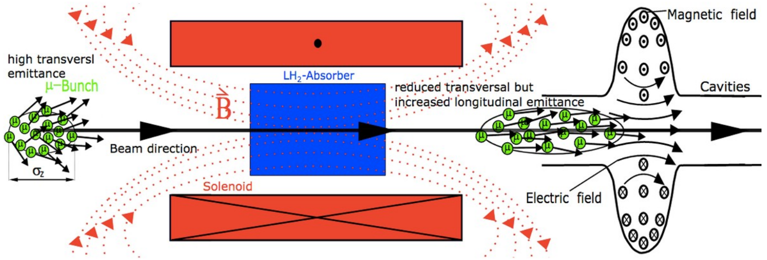
Muon cooling demonstrator

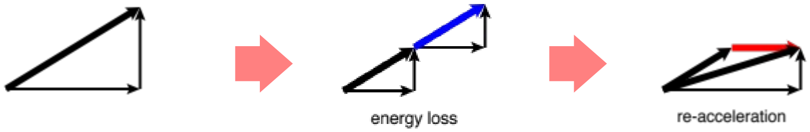
- First step towards a muon collider is to build a demonstrator facility
  - ➔ to demonstrate 6D reduction of muon beam emittance by a factor of 2 with the ionization cooling
  - to test the cooling cell technology to be employed in the muon collider in an operational environment:
    - HTS magnets at 20 K, cooled by LH_2;
    - warm, multi-cell, high-gradient radio frequencies;
    - LH_2 and LiH absorbers;



  - to study and test the production target:
    - high-power materials;
    - horn magnets;
  - to develop new beam monitoring instrumentation.
- Depending on the available resourced the muon beam could be accelerated for muon and neutrino physics.

ionization cooling principle



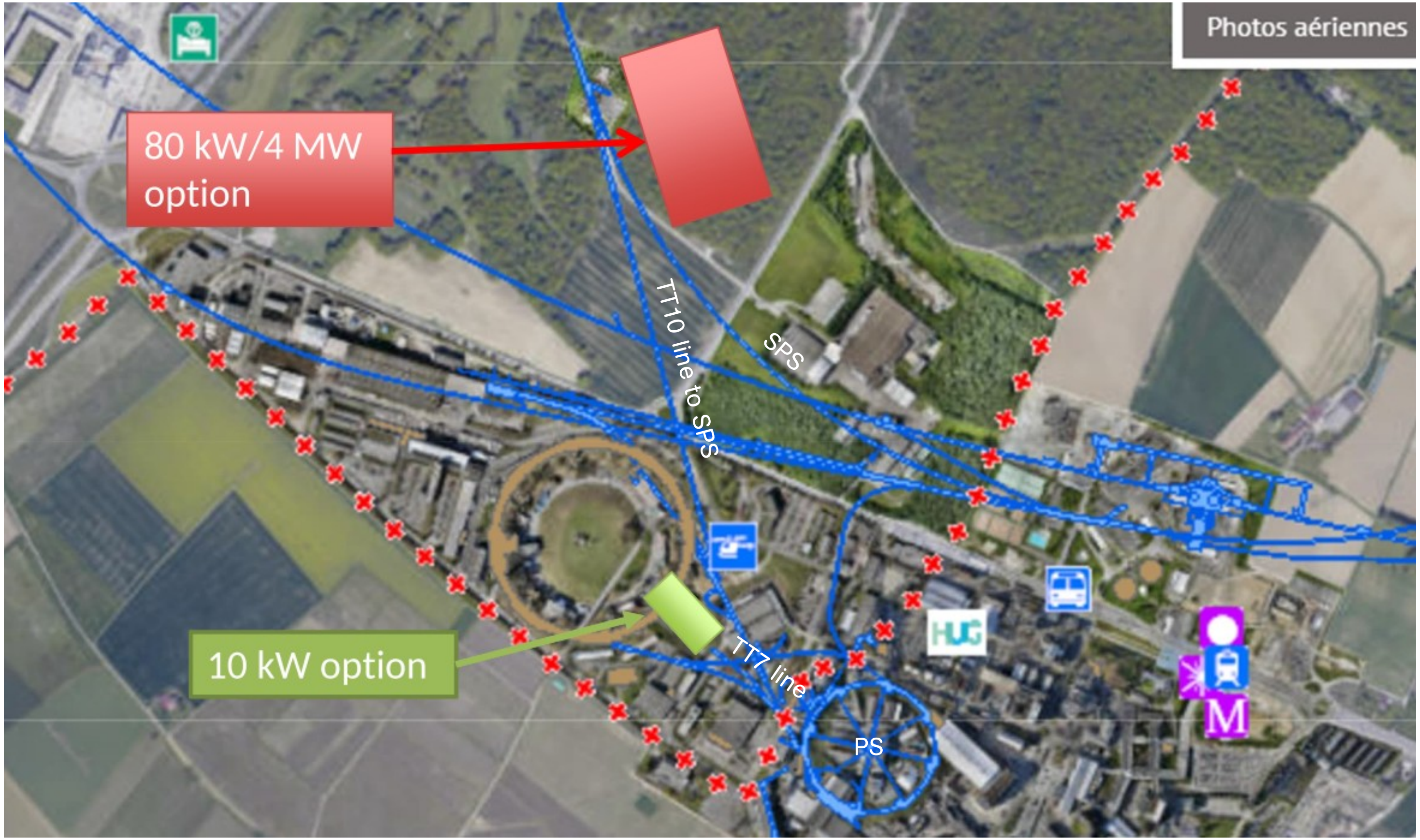


Muons have large transverse momenta at production.

Crossing an absorber, muons loose energy in longitudinal and transverse directions.

Muon acceleration in the longitudinal direction.

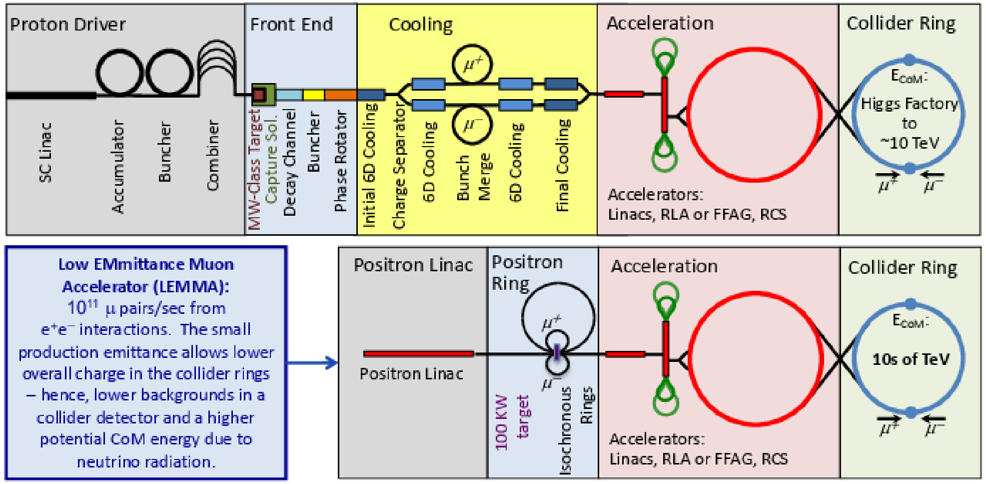
Possible sites for a demonstrator at CERN



R. Losito, IMCC Demonstrator Workshop, FNAL, Oct. 30-Nov. 1, 2024

Muon collider activities in Italy

- After MAP's shutdown in 2014, international interest in a muon collider has been revived thanks to the efforts of INFN:
  - proposal by P. Raimondi et al. of an alternative method for producing muons (LEMMA, Low EMittance Muon Accelerator) based on the process $e^+e^- \rightarrow \mu^+\mu^-$.



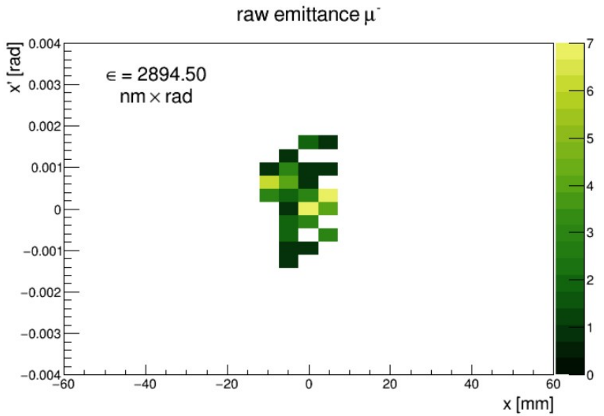
- In 2021, a CSN1 project dedicated to muon collider studies RD_MUCOL started, which currently counts 113 collaborators (24.6 FTE), engaged in:
  - R&D of magnets and radio frequencies for the accelerator;
  - detector R&D;
  - physics and detector studies.

- From 2023, participation of several Italian groups in the European project MuCol (HORIZON-INFRA-2022-DEV-01), which is mainly dedicated to machine studies and R&D, but also includes a work package dedicated to the detector:
  - Trieste is responsible for one of the Tasks of the Work Package "Detector and Physics performance": evaluation of the detector performance at different collision energies with major physics processes.

Muon collider activities in Trieste (2018-2020)

- Trieste has been involved in the R&D studies for the Muon Collider from the very beginning.
- LEMMA testbeams in 2018:
  - study of muon pair production from $e^+e^- \rightarrow \mu^+\mu^-$:

    N. Amapane et al., "Study of muon pair production from positron annihilation at threshold energy", 2020 JINST 15 P01036



- Inputs to the 2020 ESPP update:
  - detector and physics ($H \rightarrow b\bar{b}$) studies at a 1.5 TeV muon collider with full simulation including the beam-induced background
    - ➔ this was the first demonstration that it is possible to efficiently reconstruct events and obtain competitive physics measurements under the severe background conditions of a muon collider.

    N. Bartosik at al., "Detector and Physics Performance at a Muon Collider", 2020 JINST 15 P05001

	$\sqrt{s}$ [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

full simulation study (1.5 TeV row)

projections (3.0 and 10 TeV rows)

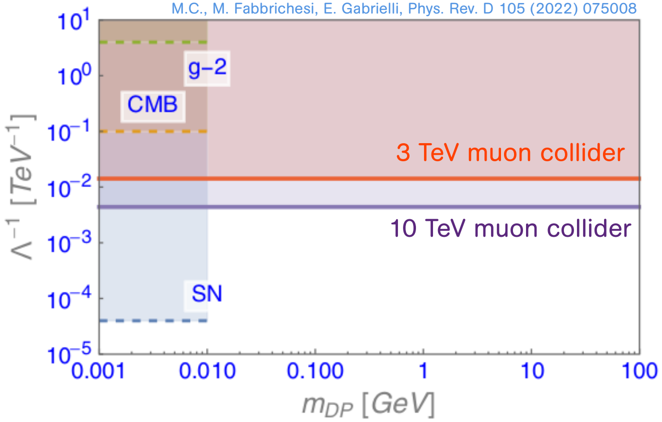
Muon collider activities in Trieste (2021-2023)

- Inputs to the U.S. Snowmass 2021:
  - full-simulation studies of the sensitivity of a 3 TeV muon collider on the production cross sections of the Higgs boson in the $b\bar{b}$, WW, ZZ, μμ, γγ channels and of two Higgs bosons (trilinear self-coupling):

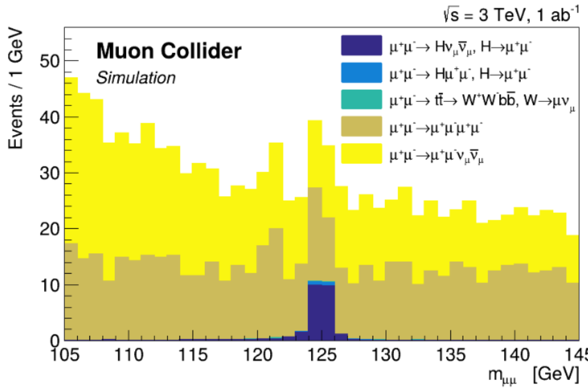
    P. Andreetto et al., “Aspects of Higgs Physics at a √s=3 TeV Muon Collider with detailed detector simulation”, submitted to EPJC (arXiv:2405.19314)
  - search for a dark photon or ALP with a monophoton signature at 3 and 10 TeV:

    M.C., M. Fabbrichesi and E. Gabrielli, “Monochromatic single photon events at the muon collider”, Phys. Rev. D 105, 075008 (2022)

95% CL limits on DP effective coupling to muons



H → μμ at 3 TeV
(A. Montella, Master’s Degree Thesis)



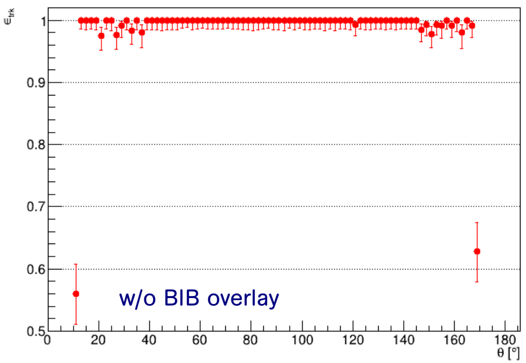
$\sqrt{s}$ = 3 TeV, 1 ab^{-1}		channel	$\sigma_{\rm eff}$ [fb]	$\epsilon_{\rm sel}$ [%]	$N_{\rm evt}$	$\Delta\sigma_H/\sigma_H$ [%]
$H \to b\bar{b}$	S:	$b\bar{b}$	308	19.3	59500	0.75
	B:	$\mu^+\mu^- \to q_h\bar{q}_hX$ ($q_h = b, c$; $X = \nu_\mu\bar{\nu}_\mu, \mu^+\mu^-$)	584	11.2	65400	
$H \to WW^*$	S:	$q\bar{q}'\mu\nu_\mu$	17.3	14.1	2430	2.9
	B:	$\mu^+\mu^- \to q\bar{q}'\mu\nu_\mu$	5020	0.05	2600	
$H \to \gamma\gamma$	S:	$\gamma\gamma$	0.91	43.9	396	7.6
	B:	$\mu^+\mu^- \to \gamma\gamma\nu_\mu\bar{\nu}_\mu$	82.0	1.1	442	
		$\mu^+\mu^- \to \ell^+\ell^-\gamma$ ($\ell = e, \mu$)	159	0.06	31	
		$\mu^+\mu^- \to \ell^+\ell^-\gamma\gamma$ ($\ell = e, \mu$)	4.41	0.3	11	
$H \to ZZ^*$	S:	$q\bar{q}\mu^+\mu^-$	0.35	15.9	55	17
	B:	$\mu^+\mu^- \to q\bar{q}\mu^+\mu^-$	5.67	0.69	39	
$H \to \mu^+\mu^-$	S:	$\mu^+\mu^-$	0.12	21.6	26	38
	B:	$\mu^+\mu^- \to \mu^+\mu^-\nu_\mu\bar{\nu}_\mu$	11.1	5.74	637	
		$\mu^+\mu^- \to \mu^+\mu^-\mu^+\mu^-$	297.4	0.16	476	
$HH \to b\bar{b}b\bar{b}$	S:	$b\bar{b}b\bar{b}$	0.28	27.5	77	33
	B:	$\mu^+\mu^- \to q_h\bar{q}_hq_h\bar{q}_hX$ ($q_h = b, c$; $X = \nu_\mu\bar{\nu}_\mu, \mu^+\mu^-$)	4.1	17.7	724	
		$\mu^+\mu^- \to H(b\bar{b})q_h\bar{q}_hX$ ($q_h = b, c$; $X = \nu_\mu\bar{\nu}_\mu, \mu^+\mu^-$)	2.8	24.7	698	

→ $0.81 < \kappa_{\lambda 3} < 1.44$ at 68% C.L.

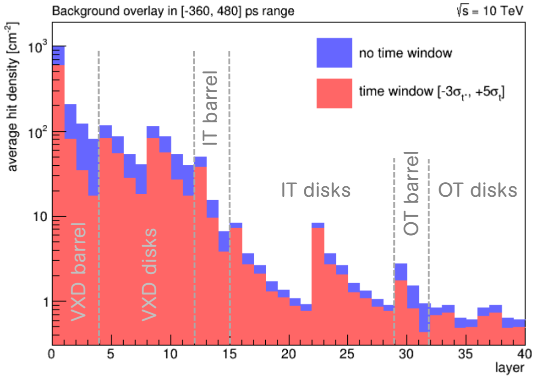
Current muon collider activities in Trieste

- Trieste is contributing to detector studies with full simulation in collaboration with the other Italian groups:
  - concept design of a new detector for 10 TeV μμ collisions: MUSIC (MUon System for Interesting Collisions);
  - revision and tuning of the reconstruction algorithms of main physics objects in the presence of machine backgrounds;
  - performance studies and characterization of the new detector.

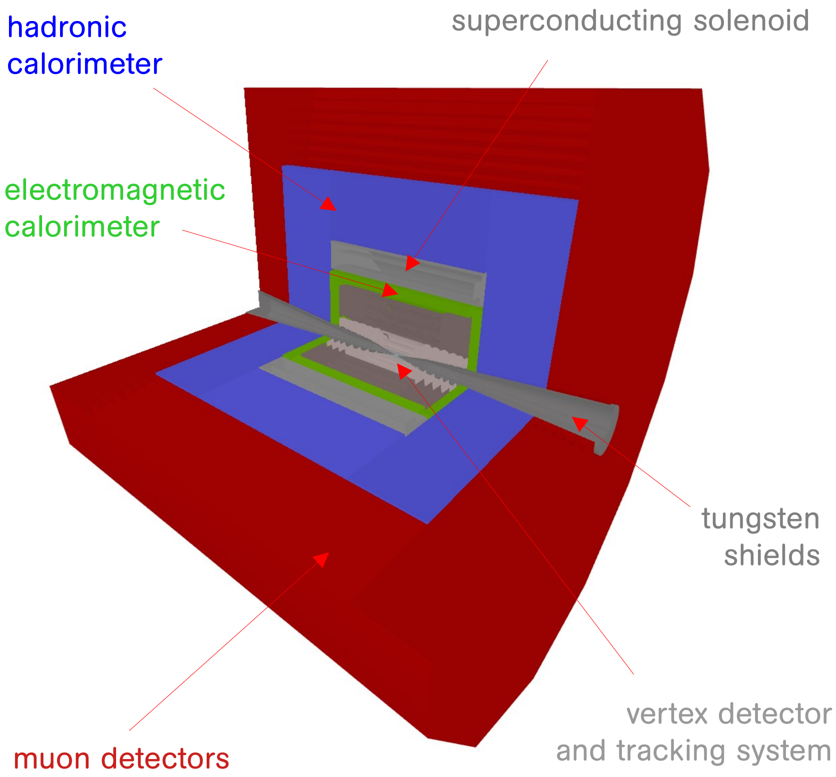
tracking efficiency for 10 GeV muons



average hit density of BIB hits in the tracker



MUSIC detector

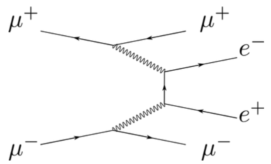


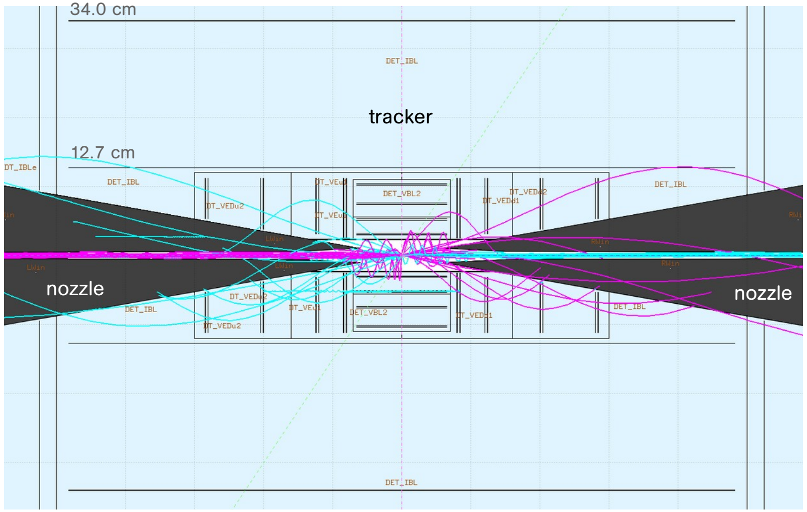
Plans for the next ESPP update

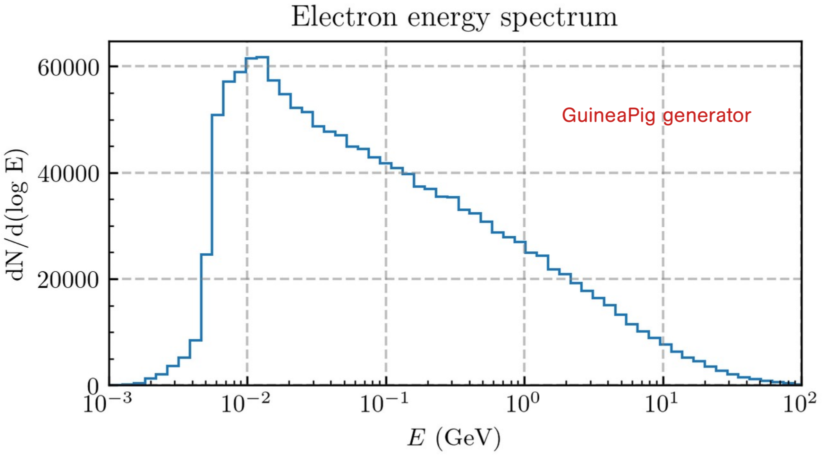
- Activities for the next ESPP update are mainly focused on a muon collider at $\sqrt{s}$ = 10 TeV.
- Completion of the MUSIC detector performance assessment
  - ➔ results will be submitted to the ESSP update as a common IMCC report.
- Higgs physics studies with full simulation including machine backgrounds (both beam-induced background and incoherent e^+e^- pair production):
  - $H \to b\bar{b}$;
  - $H \to WW$ (Giulia Liberalato Master's Degree thesis);
  - $H \to \gamma\gamma$;
  - $HH \to b\bar{b}b\bar{b}$ ➔ sensitivity on the Higgs boson trilinear self-coupling.

Backup

Bkg from incoherent e^+e^- pair production

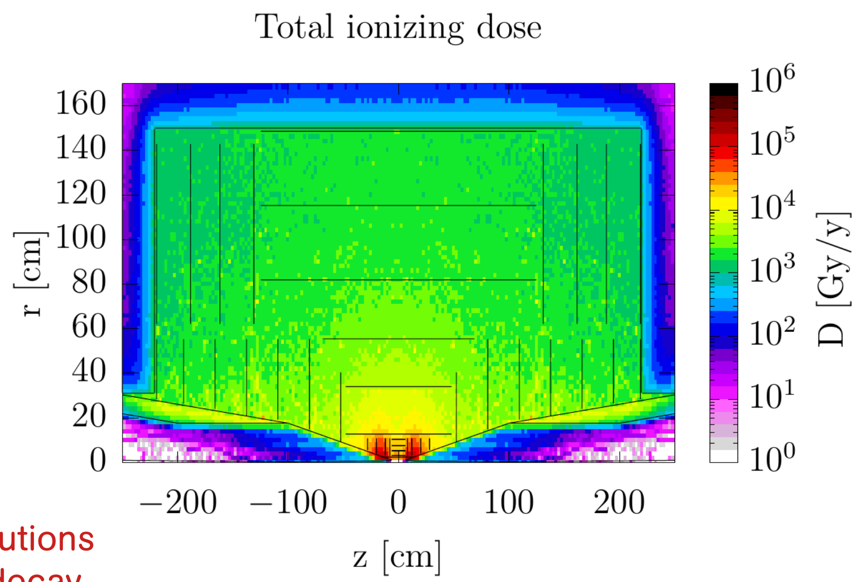


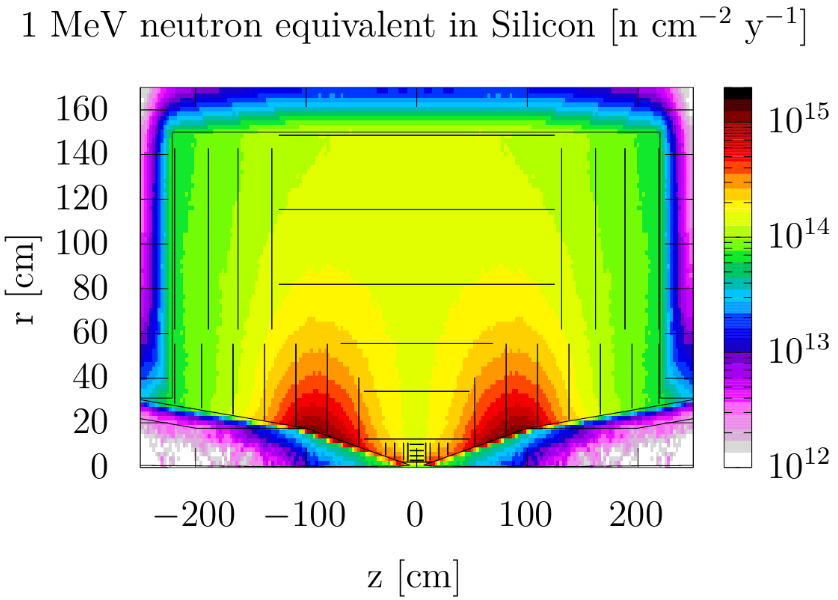




- Background from incoherent e^+e^- pairs produced at bunch crossing:
  - relatively high-energy $e^\pm$, which enter the detector at the interaction point in time with the bunch crossing;
  - photons ($\sim 10^6$), neutrons ($\sim 10^5$), and electrons/positrons ($\sim 10^5$);
  - affects mainly the vertex detector and the inner tracker layers.
- The solenoidal B field helps in confining most of the $e^\pm$ in the innermost region close to the beampipe.

Radiation environment at √s = 10 TeV



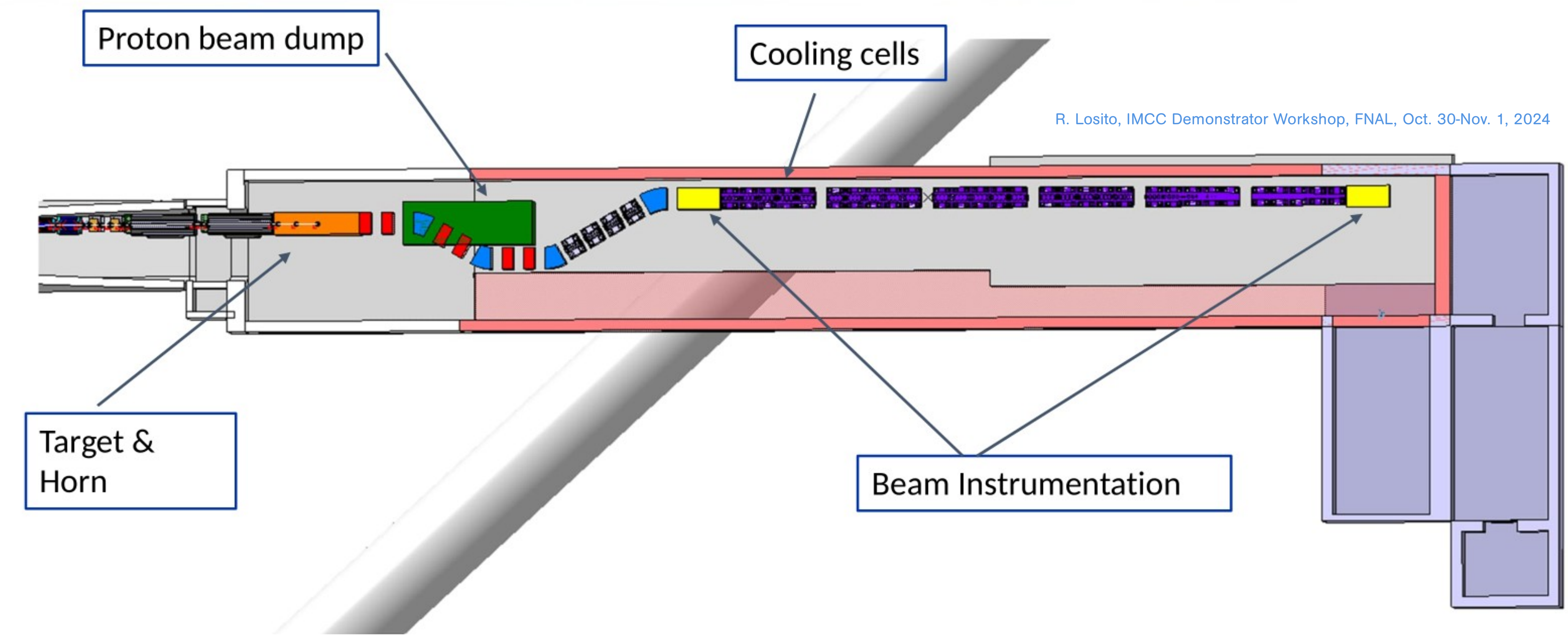


Only contributions from muon-decay background.

Assumptions:
- collision energy: 10 TeV;
- collider circumference: 10 km;
- beam injection frequency: 5 Hz;
- days of operation per year: 140.

	Maximum Dose (Mrad)		Maximum Fluence (1 MeV-neq/cm^2)	
	R= 22 mm	R= 1500 mm	R= 22 mm	R= 1500 mm
Muon Collider (3 TeV)	10	0.1	10^{15}	10^{14}
HL-LHC	100	0.1	10^{15}	10^{13}
Muon Collider (10 TeV)	20	0.2	3×10^{14}	10^{14}

Current CERN demonstrator layout



Higgs boson couplings at future colliders

S. Dawson et al., Report of the Topical Group on Higgs Physics for Snowmass 2021: The Case for Precision Higgs Physics, arXiv:2209.07510

Higgs Coupling (%)	HL-LHC	ILC250 + HL-LHC	ILC500 +HL-LHC	ILC1000 + HL-LHC	FCC-ee + HL-LHC	CEPC240 + HL-LHC	CEPC360 +HL-LHC	CLIC380 + HL-LHC	CLIC3000 +HL-LHC	μ(10TeV) + HL-LHC	μ125 +HL-LHC	FCC-hh +FCCee/FCCeh
hZZ	1.5	.22	.17	.16	.17	.074	.072	.34	.22	.33	1.3	.12
hWW	1.7	.98	.20	.13	.41	.73	.41	.62	1	.1	1.3	.14
$hb\bar{b}$	3.7	1.06	.50	.41	.64	.73	.44	.98	.36	.23	1.6	.43
$h\tau^+\tau^-$	3.4	1.03	.58	.48	.66	.77	.49	1.26	.74	.55	1.4	.44
$hgg.$	2.5	1.32	.82	.59	.89	.86	.61	1.36	.78	.44	1.7	.49
$hc\bar{c}$	-	1.95	1.22	.87	1.3	1.3	1.1	3.95	1.37	1.8	12	.95
$h\gamma\gamma$	1.8	1.36	1.22	1.07	1.3	1.68	1.5	1.37	1.13	.71	1.6	.29
$h\gamma Z$	9.8	10.2	10.2	10.2	10	4.28	4.17	10.26	5.67	5.5	9.8	.69
$h\mu^+\mu^-$	4.3	4.14	3.9	3.53	3.9	3.3	3.2	4.36	3.47	2.5	.6	.41
$ht\bar{t}$	3.4	3.12	2.82	1.4	3.1	3.1	3.1	3.14	2.01	3.2	3.4	1.0
Γ_{tot}	5.3	1.8	.63	.45	1.1	1.65	1.1	1.44	.41	.5	2.7	

Higgs self-coupling λ_3 at future colliders

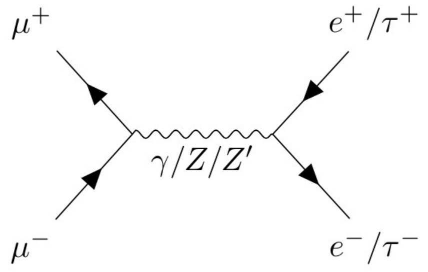
S. Dawson et al., Report of the Topical Group on Higgs Physics for Snowmass 2021: The Case for Precision Higgs Physics, arXiv:2209.07510

collider	Indirect-h	hh	combined
HL-LHC [78]	100-200%	50%	50%
ILC_{250}/C^3-250 [51, 52]	49%	–	49%
ILC_{500}/C^3-550 [51, 52]	38%	20%	20%
$CLIC_{380}$ [54]	50%	–	50%
$CLIC_{1500}$ [54]	49%	36%	29%
$CLIC_{3000}$ [54]	49%	9%	9%
FCC-ee [55]	33%	–	33%
FCC-ee (4 IPs) [55]	24%	–	24%
FCC-hh [79]	-	3.4-7.8%	3.4-7.8%
μ(3 TeV) [64]	-	15-30%	15-30%
μ(10 TeV) [64]	-	4%	4%

Example of Z' searches

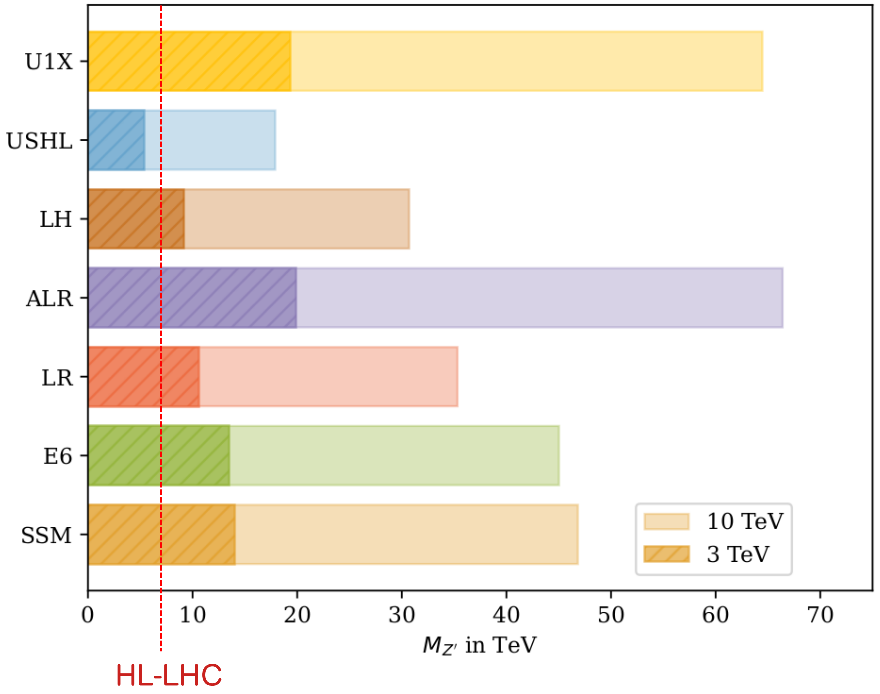
- New Z' bosons can be probed directly up to $M_{Z'} \sim \sqrt{s}$, but indirect searches extend much beyond:
  - example of a phenomenological study exploring the reach of a muon collide for additional neutral gauge bosons that couple to the standard model: K. Korshynska et al., arXiv:2402.18460.

- Indirect discovery potential for a new Z' boson coupled to the standard model in the final states ee and ττ:

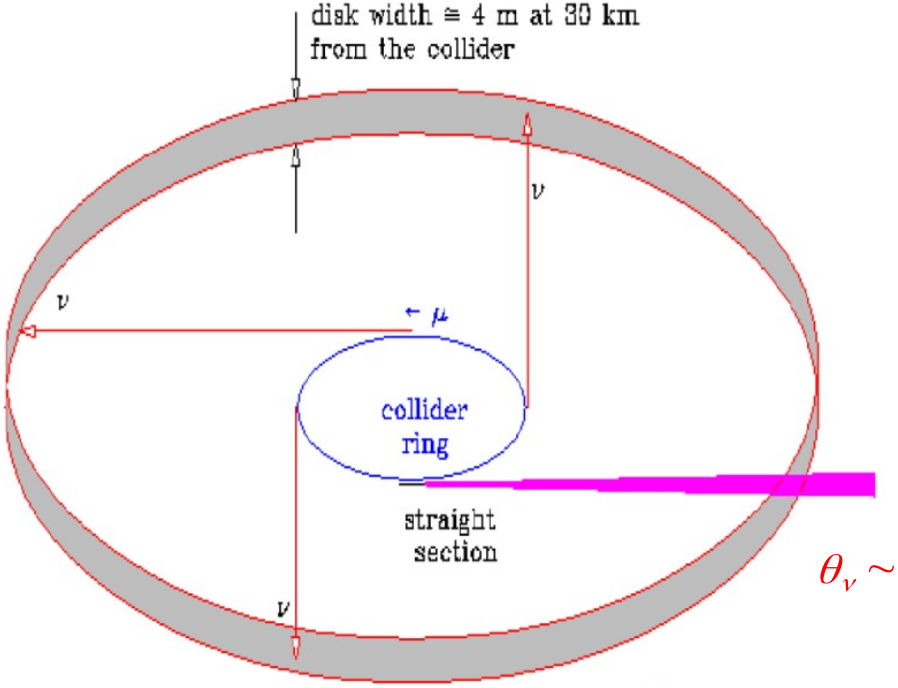


  - assumed 1 ab^{-1} at $\sqrt{s}$ = 3 TeV and 10 ab^{-1} at $\sqrt{s}$ = 10 TeV;
  - off-peak analysis based on observables of the final state leptons.

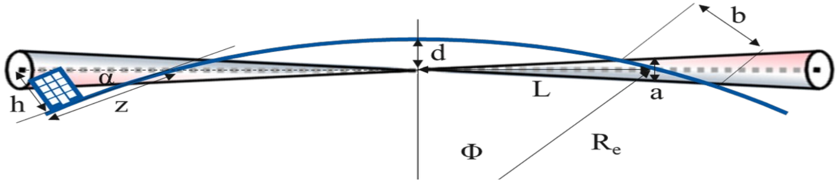
Z' exclusion limits at 95% C.L.



Neutrino flux

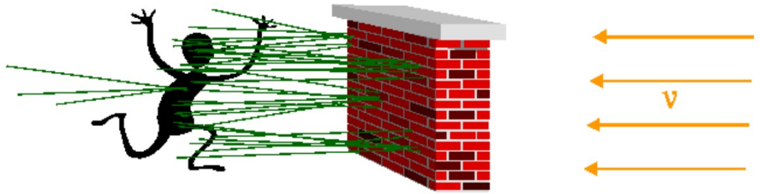


B.J. King, arXiv:hep-ex/0005006v1



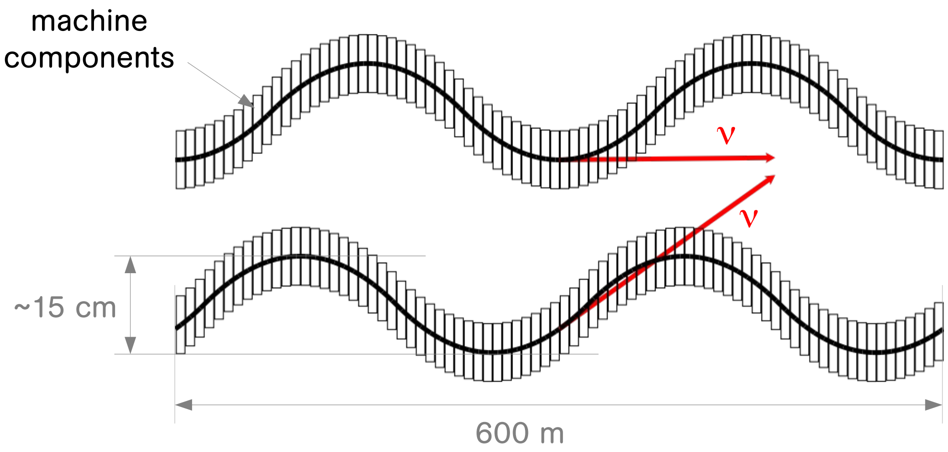
$$\theta_\nu \sim \frac{10^{-4}}{E_\mu\,[TeV]}$$

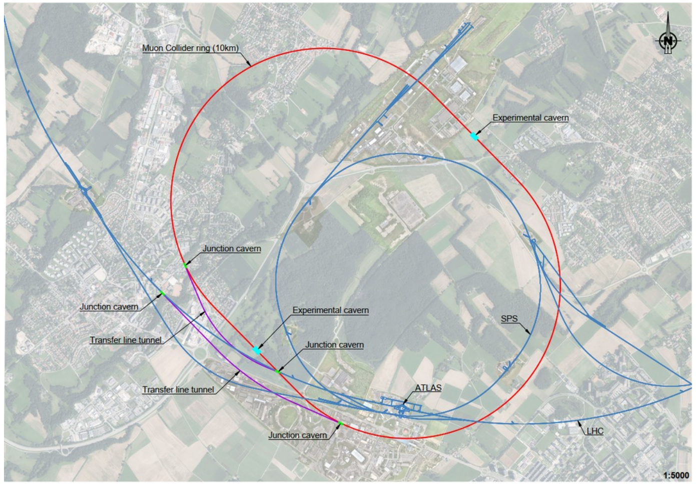
- Intense and highly collimated ν fluxes, emerging on the earth surface even very faraway from the muon collider complex, may activate in the long run the materials they cross:
  - arc sections → radiation disk;
  - straight sections → radiation hot spots.



$$\langle dose \rangle \sim \frac{E_\mu^3}{d}$$

Neutrino flux mitigation





- The final goal is to keep the radiation field at a negligible level (i.e. below 10 mSv/year), where the neutrino beams reach the Earth surface.
- MAP studies demonstrated that up to 3 TeV depth (~300 m at 3 TeV) and beam movements with optics adjustments might be sufficient.
- For a 10-TeV machine additional mitigation measures are necessary:
  - beam wobbling at a frequency of a few months by means of a mechanical mover system of the accelerator components to spread the neutrino flux;
  - a well-thought site selection: a team at CERN carried out a geological, environmental, land and radiological analysis of the area to assess the impact of a muon collider in the LHC tunnel.

International Muon Collider Collaboration

IEIO	**CERN**
FR	**CEA-IRFU**
	CNRS-LNCMI
	Mines St-Etienne
DE	DESY
	Technical University of Darmstadt
	University of Rostock
	KIT
UK	**RAL**
	UK Research and Innovation
	University of Lancaster
	University of Southampton
	University of Strathclyde
	University of Sussex
	Imperial College London
	Royal Holloway
	University of Huddersfield
	University of Oxford
	University of Warwick
	University of Durham
	University of Birmingham
	University of Cambridge

IT	**INFN**
	INFN, Univ., Polit. Torino
	INFN, Univ. Milano Biocca
	INFN, Univ. Padova
	INFN, Univ. Pavia
	INFN, Univ. Bologna
	INFN Trieste
	INFN, Univ. Bari
	INFN, Univ. Roma 1
	ENEA
	INFN Frascati
	INFN, Univ. Ferrara
	INFN, Univ. Roma 3
	INFN Legnaro
	INFN, Univ. Milano Bicocca
	INFN Genova
	INFN Laboratori del Sud
	INFN Napoli
Mal	**Univ. of Malta**
EST	**Tartu University**
PT	**LIP**

SE	**ESS**
	University of Uppsala
NL	**University of Twente**
FI	**Tampere University**
LAT	**Riga Technical University**
CH	**PSI**
	University of Geneva
	EPFL
BE	**Univ. Louvain**
AU	**HEPHY**
	TU Wien
ES	**I3M**
	CIEMAT
	ICMAB
China	***Sun Yat-sen University***
	IHEP
	Peking University
	Inst. Of Mod. Physics, CAS
KO	**Kyungpook National University**
	Yonsei University
	Seoul National University
India	***CHEP***

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

Signed MoC, ***requested MoC***, contributor