$\mu^+\mu^-$ colliders

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on behalf of the International Muon Collider Collaboration

Horizons in Accelerators, Particle/Nuclear Physics and Laboratory-Based Quantum Sensors for HEP/NP
ICTS-TIFR, Bengaluru, India – November 14-17, 2022

Outline

- The International Muon Collider Collaboration:
  - goals, plans and a tentative work timeline.

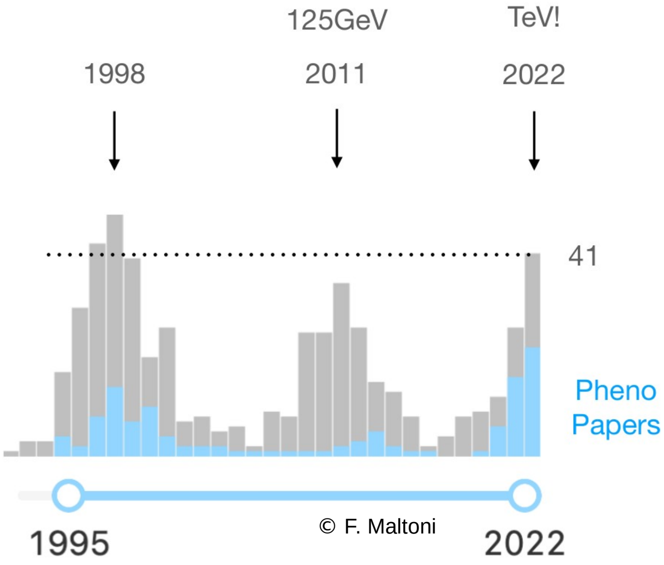
- Concept design of a 10-TeV muon collider:
  - overview of the main components of the accelerator complex and the related technical challenges;
  - detector operation conditions and a glance to some preliminary physics results.

- Conclusions.

Historical recap

- Milestones:
  - US Muon Accelerator Program (MAP): main focus on key elements of the accelerator complex for colliders at center of mass energies of 125 GeV and 1.5 TeV
    - → JINST Volume "Muon Accelerators for Particle Physics".
  - Muon Ionization Cooling Experiment (MICE) in UK: proof of principle of the ionization cooling
    - → Nature 578, 58 (2020).
  - Low Emittance Muon Accelerator (LEMMA) in Italy: studies for an alternative technique to produce muons based on the process $e^+e^- \to \mu^+\mu^-$
    - → Nucl. Instrum. Meth. A 807, 101 (2016).
  - 2020 Update of the European Strategy for Particle Physics (ESPPU): recommended R&D on muon beams
    - → "ESPP - Accelerator R&D Roadmap", arXiv:2201.07895.
  - US Snowmass 2021: very strong interest of the US HEP community in muon colliders
    - → "Muon Collider Forum Report", arXiv:2209.01318.

number of papers on muon collider



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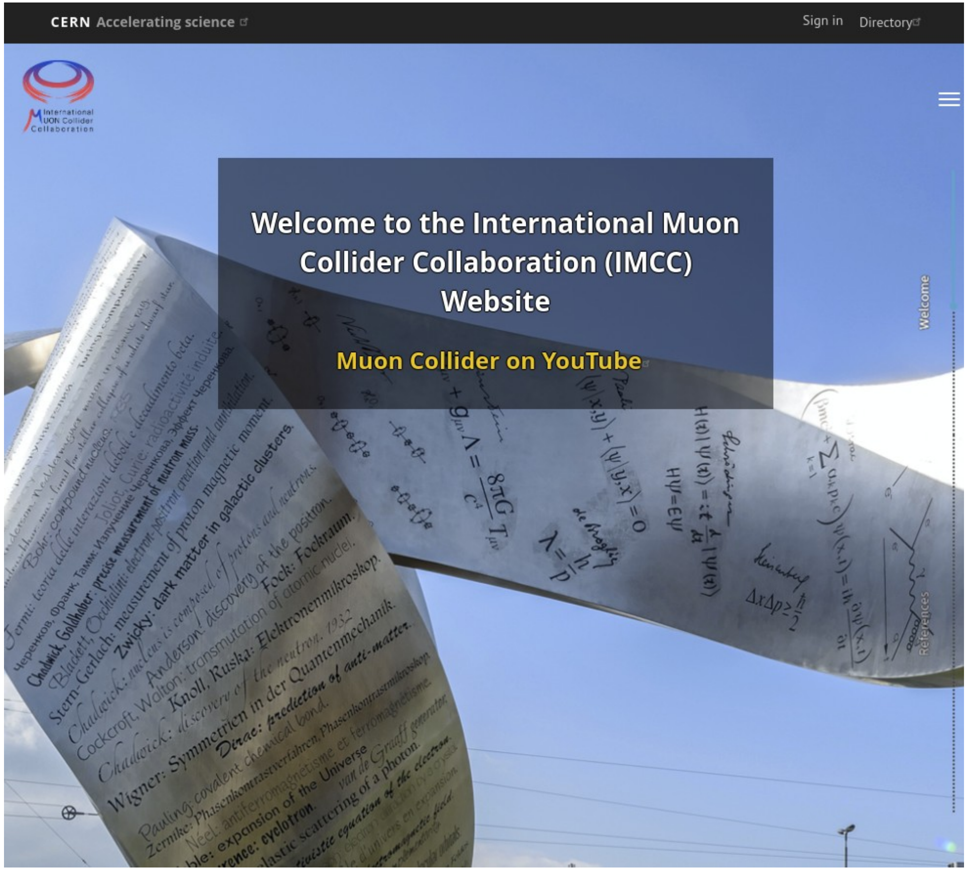
International Muon Collider Collaboration



Welcome to the International Muon Collider Collaboration (IMCC) Website

Muon Collider on YouTube

muoncollider.web.cern.ch

- Following the recommendation of the Update of the European Strategy for Particle Physics, an International Muon Collider Collaboration (IMCC) has been formed at CERN to foster and coordinate the muon collider R&D efforts.
- IMCC main goals for the next ESPP Update:
  - assessing the potential of a muon collider;
  - defining an R&D plan towards the collider;
  - explore possible synergies with other fields.
- Two options currently considered with focus on high energy and high luminosity:
  - a 10+ TeV machine;
  - a possible intermediate stage (e.g., 3 TeV).

IMCC members and design study partners

IEIO	**CERN**
FR	**CEA-IRFU**
	CNRS-LNCMI
DE	DESY
	Technical University of Darmstadt
	University of Rostock
	KIT
IT	**INFN**
	INFN, Univ., Polit. Torino
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	INFN, Univ. Pavia
	INFN, Univ. Bologna
	INFN Trieste
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	INFN, Univ. Roma 1
	ENEA

UK	**RAL**
	UK Research and Innovation
	University of Lancaster
	University of Southampton
	University of Strathclyde
	University of Sussex
	Imperial College
	Royal Holloway
	University of Huddersfield
	University of Oxford
	University of Warwick
	University of Durham
SE	**ESS**
	University of Uppsala
PT	LIP
NL	**University of Twente**

FI	**Tampere University**
US	**Iowa State University**
	Wisconsin-Madison
	BNL
China	***Sun Yat-sen University***
	IHEP
	Peking University
EST	***Tartu University***
LAT	**Riga Technical Univers.**
AU	**HEPHY**
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ES	***I3M***
CH	**PSI**
	University of Geneva
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IT	INFN Frascati
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	INFN, Univ. Roma 3
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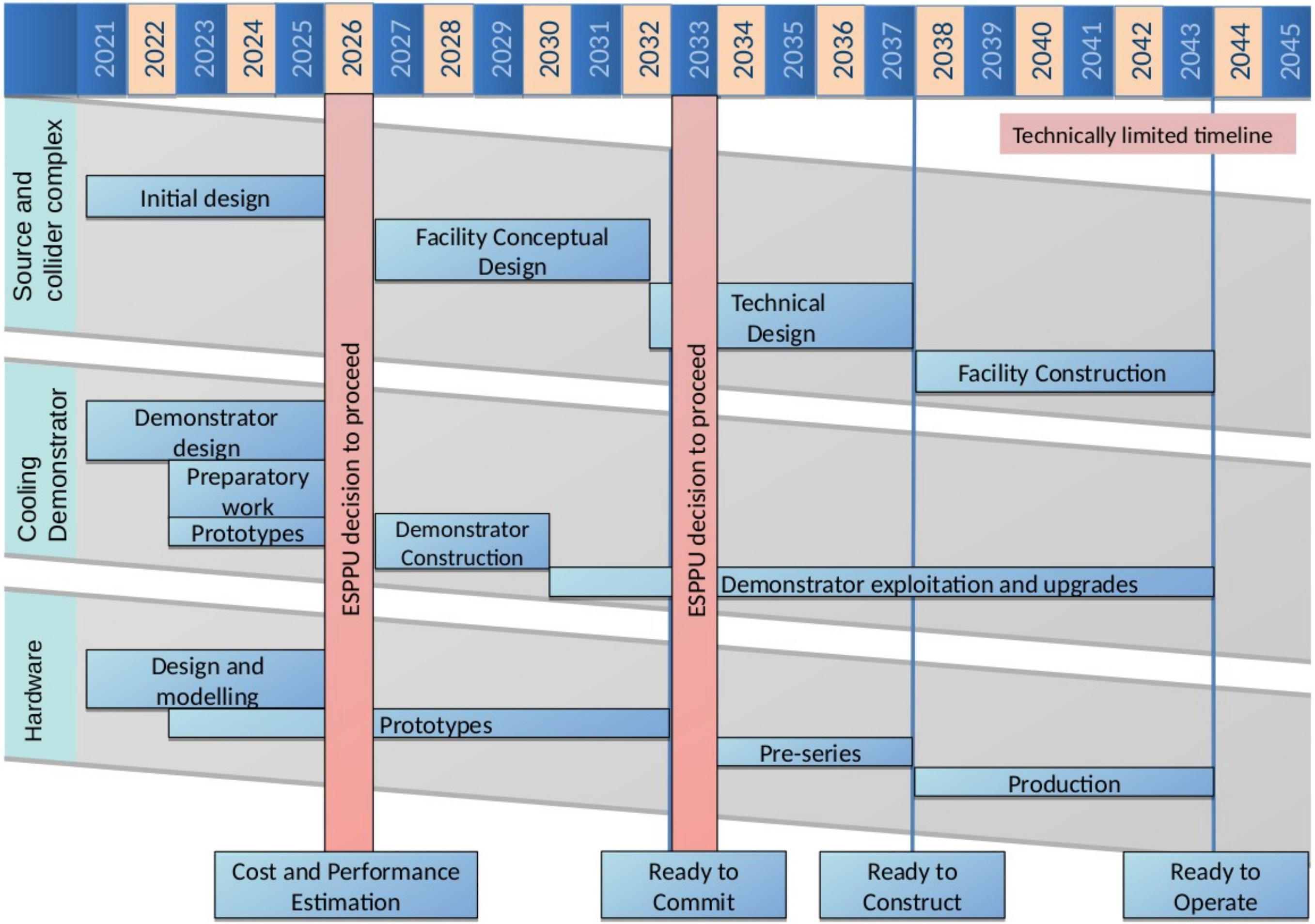
	INFN, Univ. Milano Bicocca
	INFN Genova
	INFN Laboratori del Sud
	INFN Napoli
US	FNAL
	LBL
	JLAB
	Chicago
Japan	Akira Yamamoto
	Akira Sato
	Toru Ogitsu

Tentative timeline for a 3-TeV collider

D. Stratakis *et al.*, arXiv:2203.08033



2021 2022 2023 2024 2025 2026 2027 2028 2029 2030 2031 2032 2033 2034 2035 2036 2037 2038 2039 2040 2041 2042 2043 2044 2045

Technically limited timeline

Source and collider complex

Initial design

Facility Conceptual Design

Technical Design

Facility Construction

Cooling Demonstrator

Demonstrator design

Preparatory work

Prototypes

Demonstrator Construction

Demonstrator exploitation and upgrades

Hardware

Design and modelling

Prototypes

Pre-series

Production

ESPPU decision to proceed

ESPPU decision to proceed

Cost and Performance Estimation

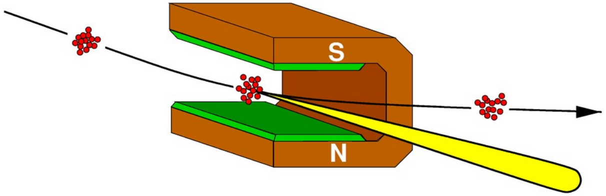
Ready to Commit

Ready to Construct

Ready to Operate

Why to collide muons?

Basically, to get collisions at center-of-mass energies of several TeVs with leptons.



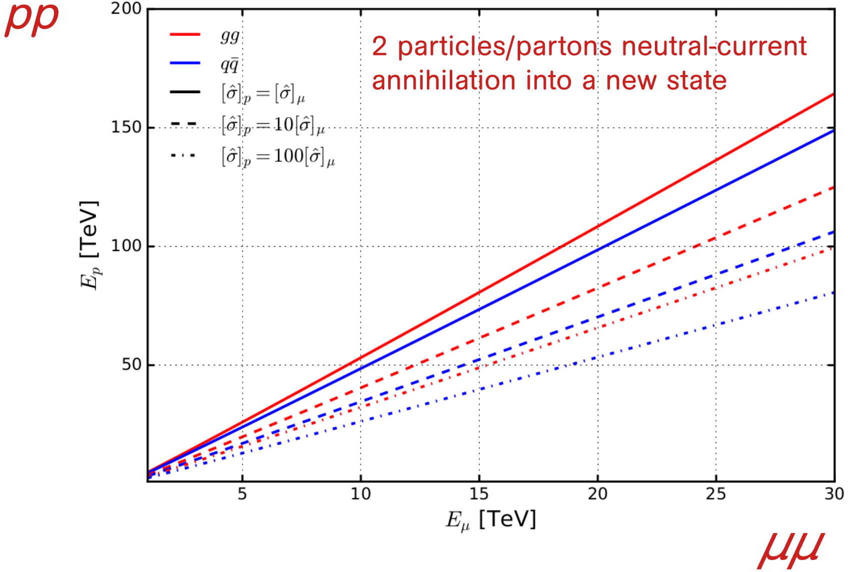
$$P_{synchrotron} \propto \frac{E^4}{m^4 R^2}$$

- Being ~207 times heavier than electrons, muons are less sensitive to synchrotron radiation losses when curved in the field of dipole magnets:

$$\left(\frac{m_\mu}{m_e}\right)^4 = 1.8 \cdot 10^9.$$

- Muons can be accelerated to multi-TeV energies in relatively compact rings with all the advantages of circular machines.

Advantages of leptonic collisions



A. Costantini et al., JHEP 09 (2020) 080

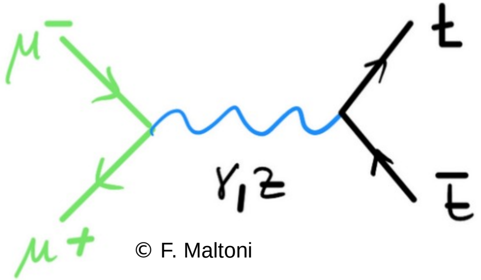
2 particles/partons neutral-current annihilation into a new state

- Unlike protons used at LHC, muons are fundamental point-like particles:
  - all collision energy is available to the hard-scattering process;
  - the energy and momentum of the colliding muons are precisely known;
  - final states are in general “cleaner”.

A muon collider combines precision physics and discovery reach.

Muon collider are vector boson collider

Multi-TeV muon colliders are effectively vector boson colliders!



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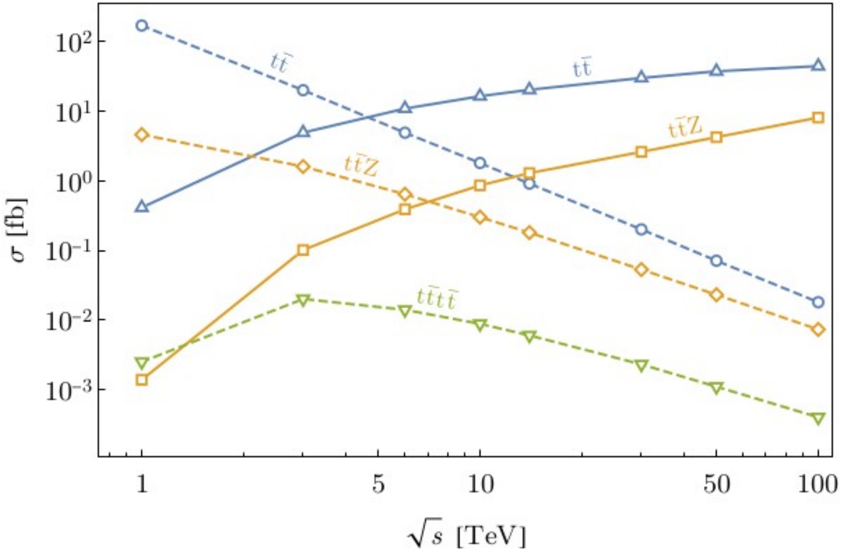
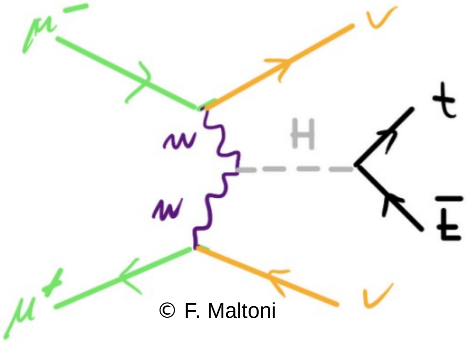
$$\sigma(s) \sim \frac{1}{s}$$

H.A. Ali et al., arXiv:2103.14043





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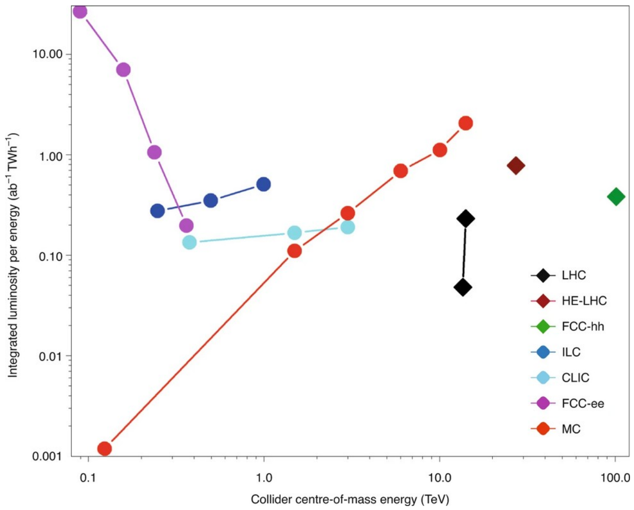
$$\sigma(s) \sim \frac{1}{M} \log^n\left(\frac{s}{M}\right)$$

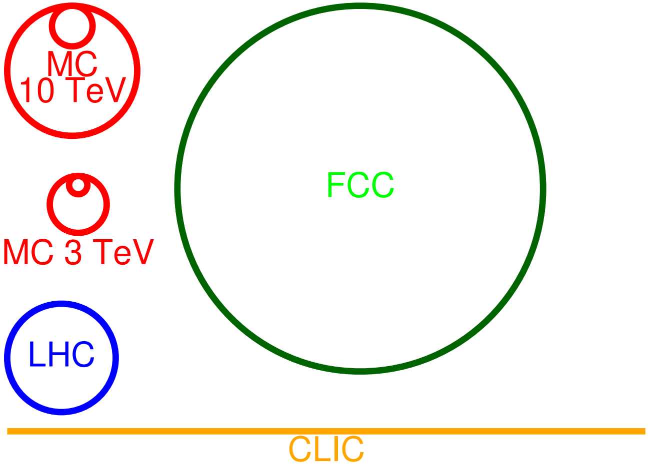
Sustainability

- At the highest collision energies a muon collider is the most power-efficient machine.

- No severe beam-strahlung effects like in e^+e^- linear colliders: expected a beam energy spread of $dE/E < 10^{-3}$ up to 14 TeV.

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





- A muon collider facility may be built with a relatively smaller footprint w.r.t. to other future accelerators.

Likely to be cost effective and more sustainable.

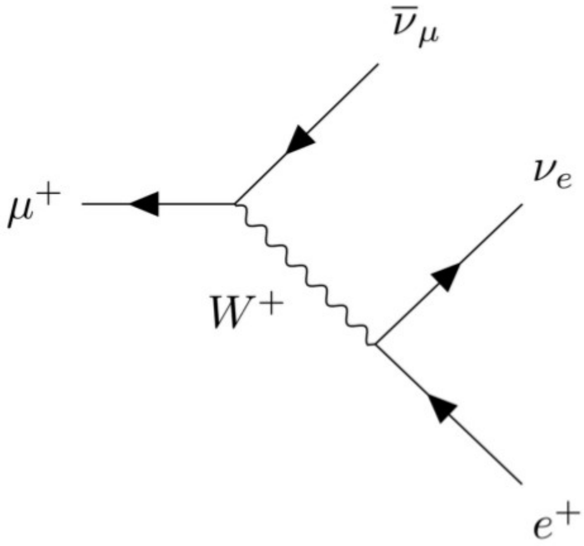
Initial target parameters

Parameter	Unit	3 TeV	10 TeV	14 TeV	CLIC @ 3 TeV
L	10^{34} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$	1.8	20	40	2 (6)
N	10^{12}	2.2	1.8	1.8	
f_r	Hz	5	5	5	
P_{beam}	MW	5.3	14.4	20	28
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	

- Initial parameters based on MAP studies.
- Integrated luminosity target per IP in 5 years of operation:

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

The other side of the coin

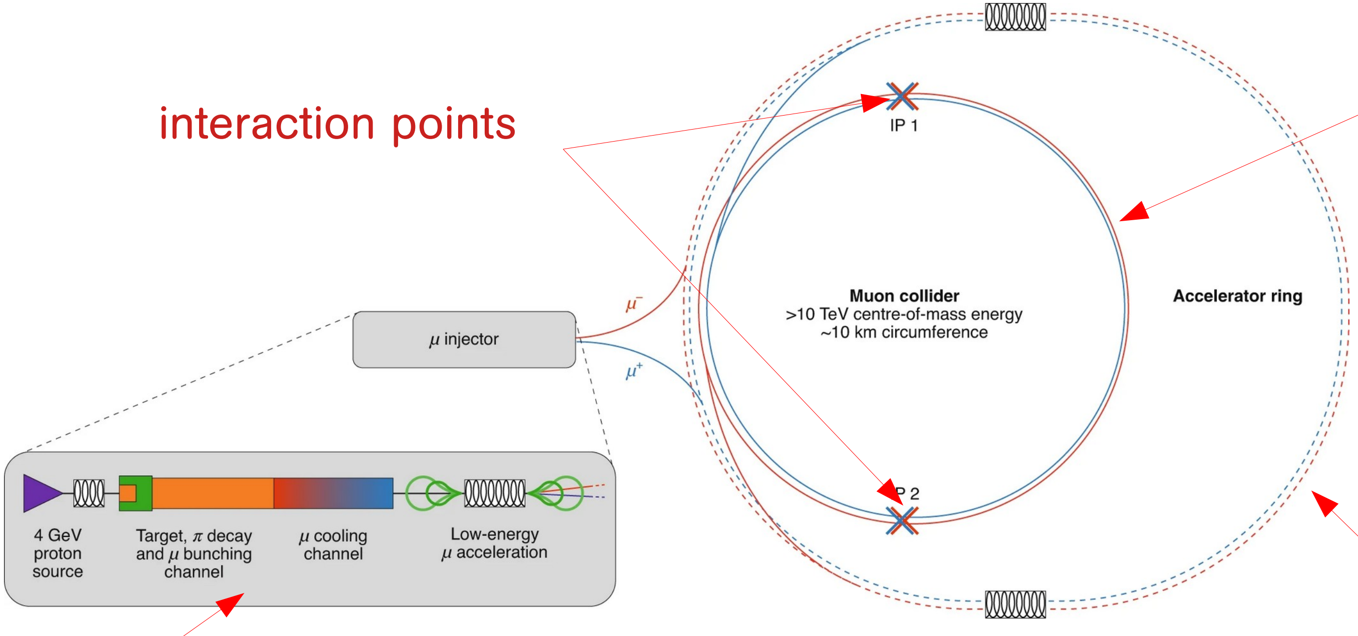


- Unfortunately, the huge physical potential of a muon collider is not coming for free
  → muons are unstable particles with $\tau_\mu = 2.2\ \mu s$ at rest.

- Fortunately, the relativistic time dilation $t_\mu = \gamma\tau_\mu$ in the laboratory system allows enough time to properly prepare, accelerate and bring to collision the μ^+ and μ^- beams (e.g. for 5-TeV muons t_μ = 105 ms in the lab).

- The electrons and positrons from beam muon decays and photons radiated by them interact with the machine elements, producing a very intense flux of background particles (e.g., at 10 TeV with 2×10^{12} μ/bunch expected on average 6.4×10^4 decays/m):
  - ► this beam-induced background has to be dealt with at all stages of the accelerator complex.

Muon collider concept



interaction points

collider ring

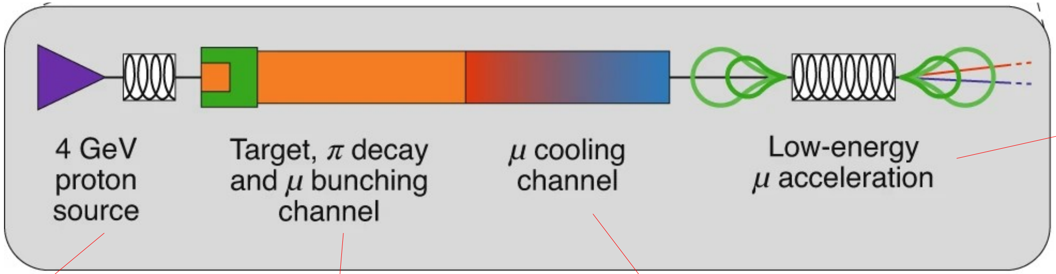
muon beam source

high-energy acceleration ring

Design fully driven by the muon lifetime.

Muon beam source

MAP's proton-driver scheme



The muon beam is pre-accelerated to ~100 GeV in a LINAC.

A proton beam with short high-intensity bunches hits a target and produces pions.

Pions are captured in a decay channel and muons from pion decays are collected and guided to a buncher.

The muon beam is cooled.

Key technical challenges:

- multi-MW proton beam with short high-charge bunches;
- high-power target;
- radiation-resistant capture superconducting magnet.

Muon beam source drives the beam quality.

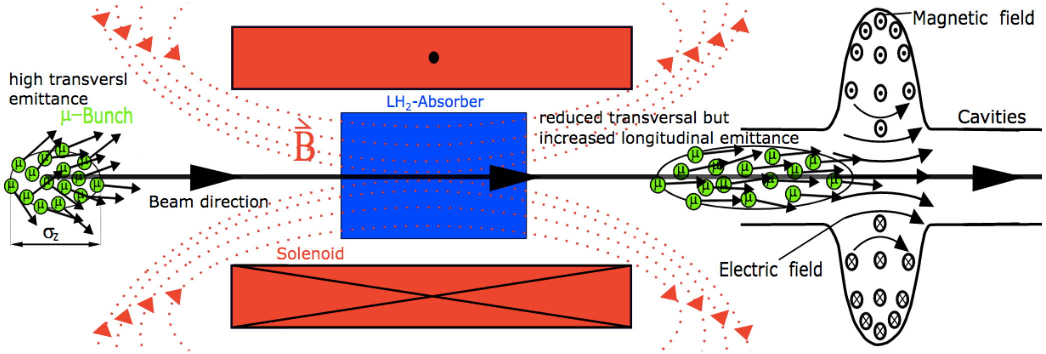
Muon cooling system

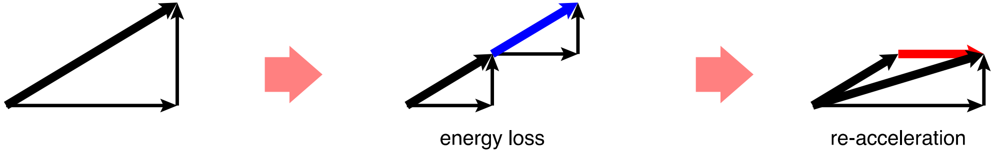
- Muons from pions decays exhibit a large 6D phase-space volume.
- In order to achieve the luminosity goal it must be reduced (“cooled”) by a factor of 10^6.
- The only cooling technique that satisfies the strict timing requirements is the ionization cooling.

Key technical challenges:

- high-gradient RFs operating in magnetic fields;
- high-field solenoids (~50 T);
- integration of all components in a dense lattice.

ionization cooling principle





Muons have large transverse momenta at production.

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

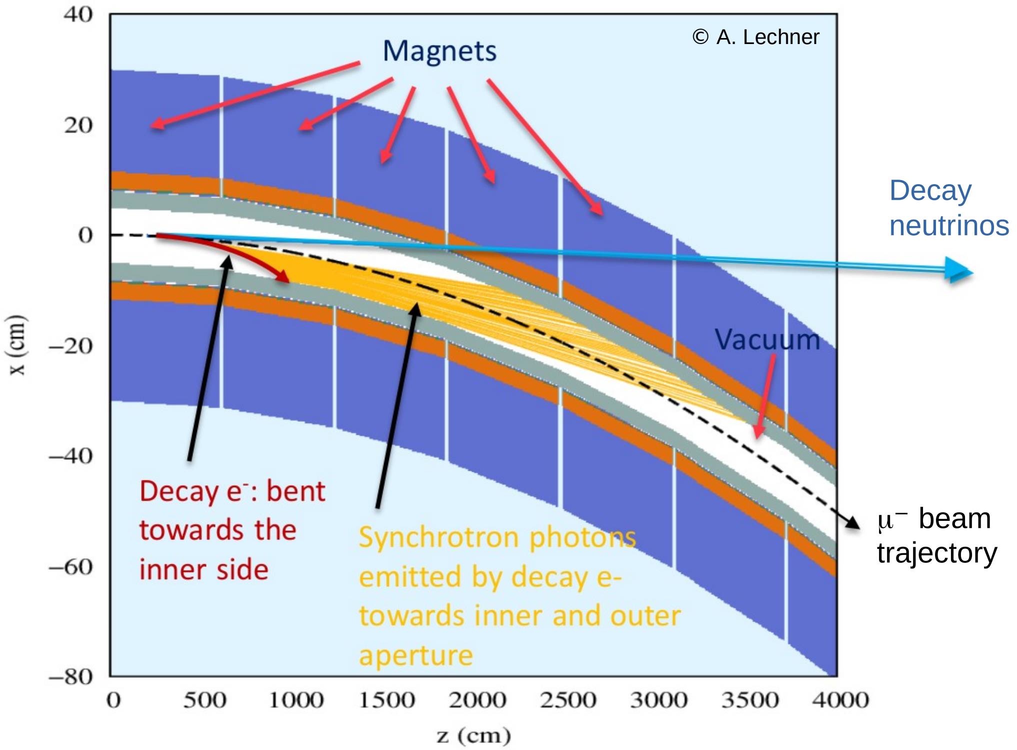
Muon acceleration in the longitudinal direction.

Acceleration and collision rings

- High-energy complex:
  - a rapid-cycling synchrotron (~30km long at 10 TeV) accelerates the $\mu^{\pm}$ beams to the collision energy;
  - collision ring (~10 km long at 10 TeV) with two interaction points (IP).
- The components of both machines must be shielded: a 5-TeV beam with 2×10^{12} μ/bunch injected at 5 Hz frequency is expected to generate a power load of ~0.5 kW/m.

Key technical challenges:

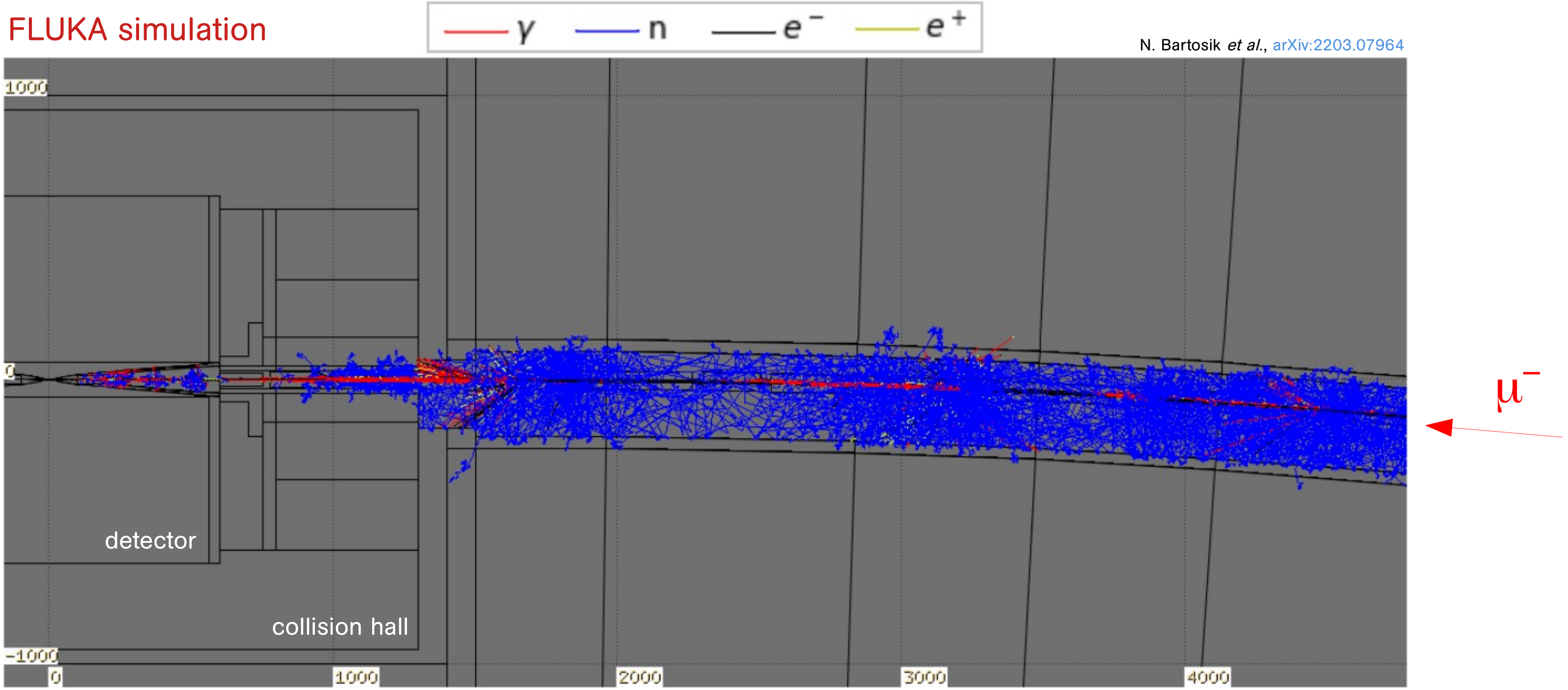
- high-field dipoles ($\gtrsim$16 T) with a 15-cm bore;
- fast-ramping magnets with cycling times of ms (possibly high-temperature superconductors);
- high-gradient radio-frequencies.



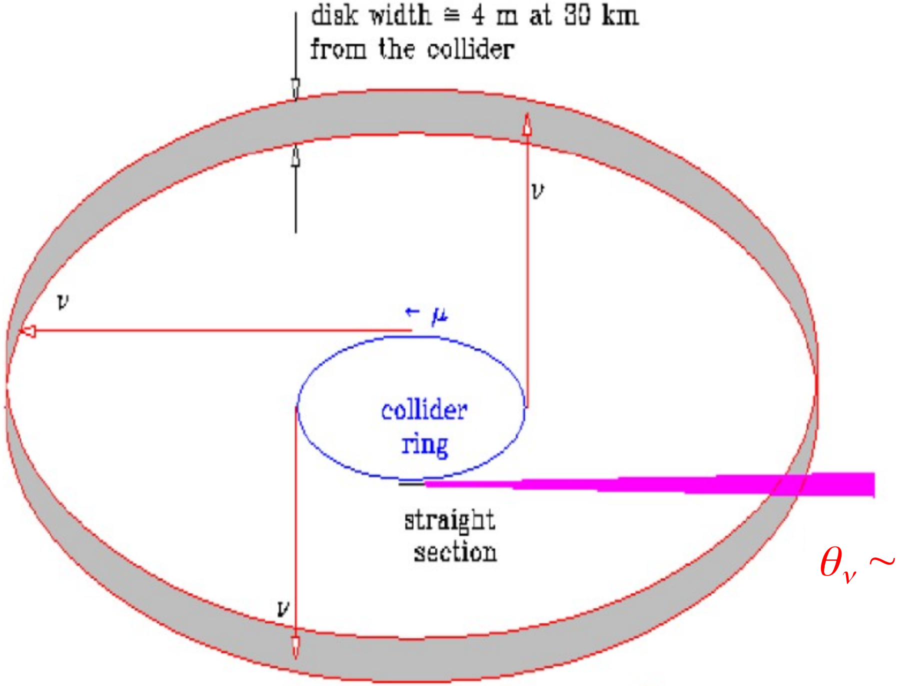
Beam-induced background in the tunnel

FLUKA simulation

N. Bartosik *et al.*, arXiv:2203.07964

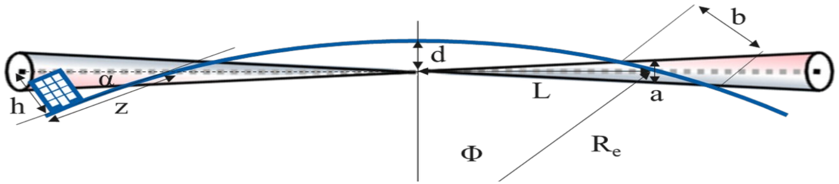


Neutrino flux

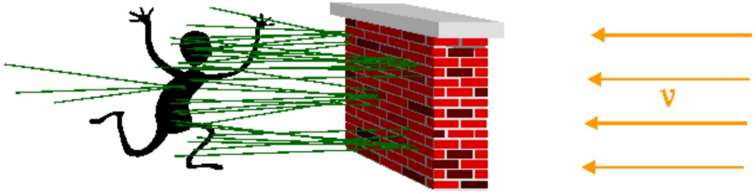


$$\theta_\nu \sim \frac{10^{-4}}{E_\mu\,[TeV]}$$

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

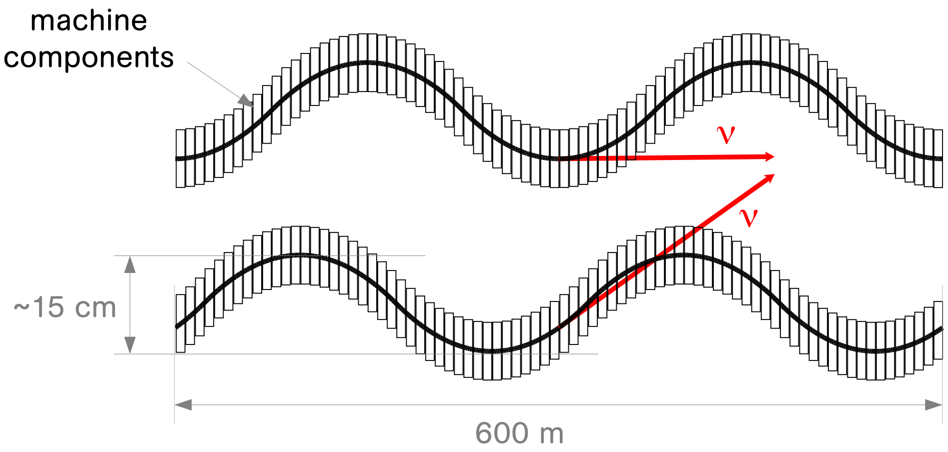


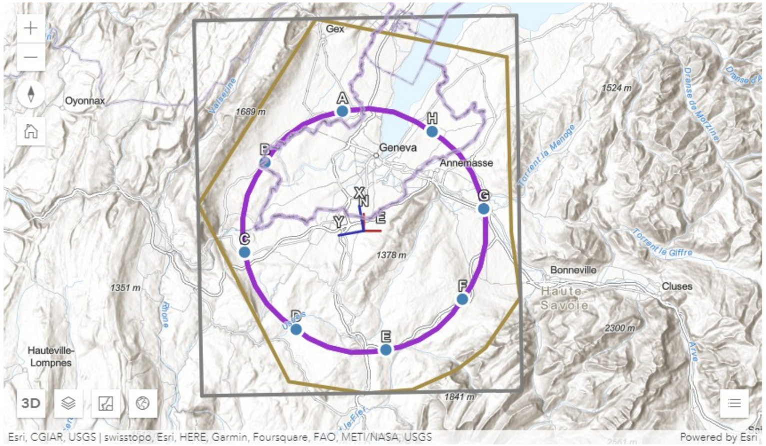
- Intense and highly collimated ν fluxes, emerging on the earth surface even very faraway from the muon collider complex, may activate in the long run the materials they cross:
  - arc sections → radiation disk;
  - straight sections → radiation hot spots.



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

Neutrino flux mitigation





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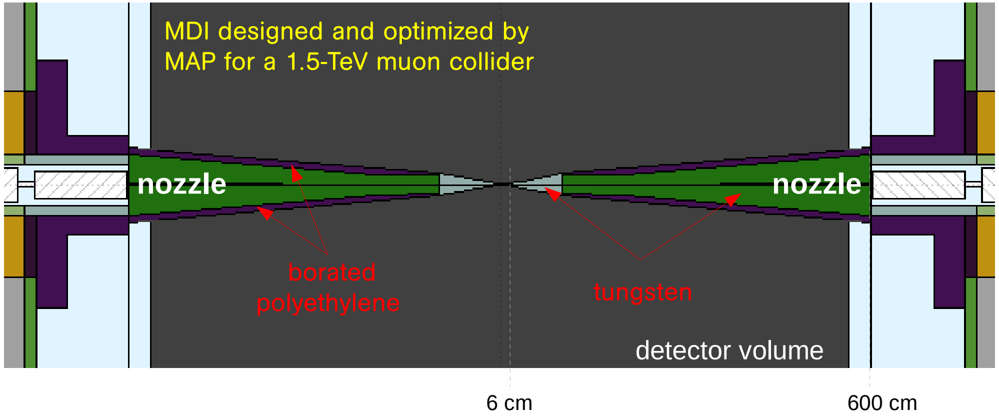
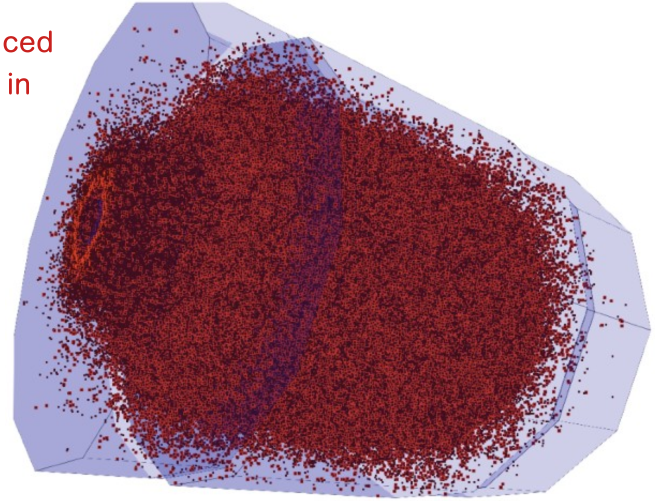
- The final goal is to keep the radiation field at a negligible level (i.e. below 10 mSv/year).
- MAP studies demonstrated that up to 3 TeV depth (~300 m at 3 TeV) and beam movements with optics adjustments might be sufficient.
- For a 10-TeV machine additional mitigation measures are necessary:
  - 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 is carrying out a geological, environmental, land and radiological analysis of the area to assess the impact of a muon collider in the LHC tunnel.

Interaction points



calorimeter hits produced by beam-induced bkg in one bunch-crossing



- The detectors have to operate under extreme background conditions: at every bunch crossing a flux of $O(10^{10})$ background particles is estimated to reach the detector.
- Background mitigation measures are necessary:
  - shielding in the machine-detector interface (MDI);
  - suitable magnet configuration in the interaction-region.

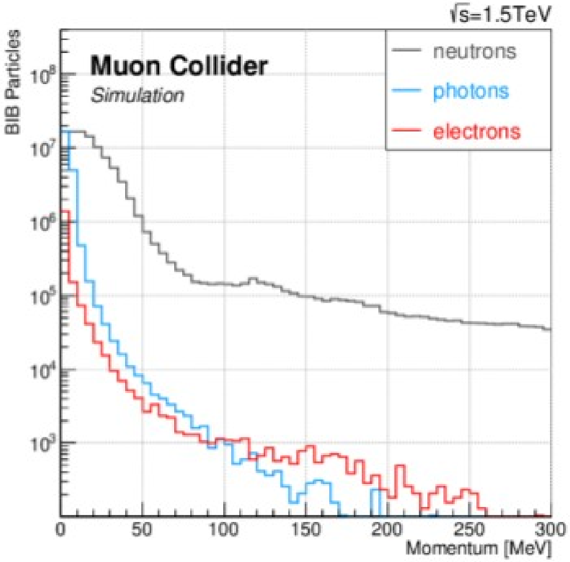
Detector key technical challenges:

- very high-granularity;
- precision timing for all hits;
- radiation-hard sensors and electronics;
- cutting-edge reconstruction algorithms.

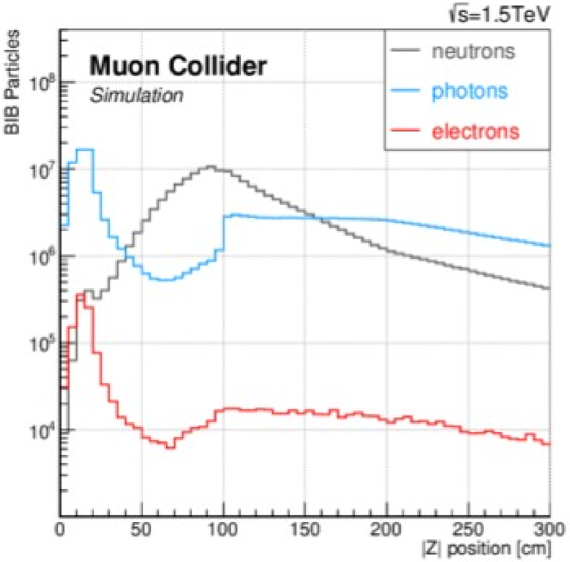
Beam-induced background in the detector

- Main BIB components entering the detector per bunch crossing:
  - photons (~10^8), neutrons (~10^8), electrons/positrons (~10^6).

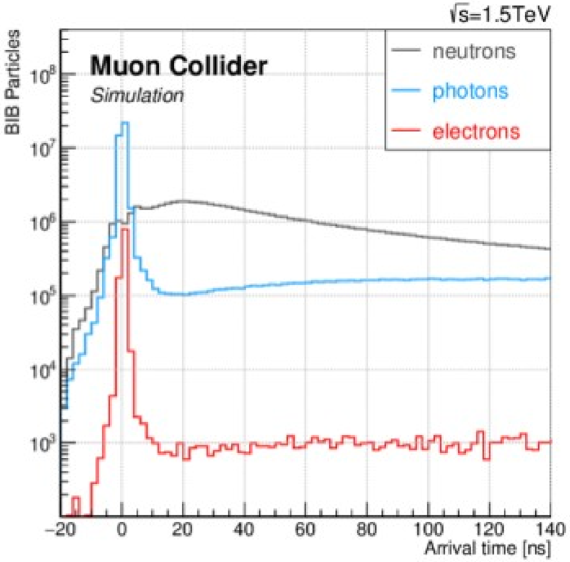
very soft momenta



displaced origin
w.r.t. the interaction region



asynchronous time of arrival
w.r.t. the bunch crossing



N. Bartosik *et al.*, arXiv:2203.07964

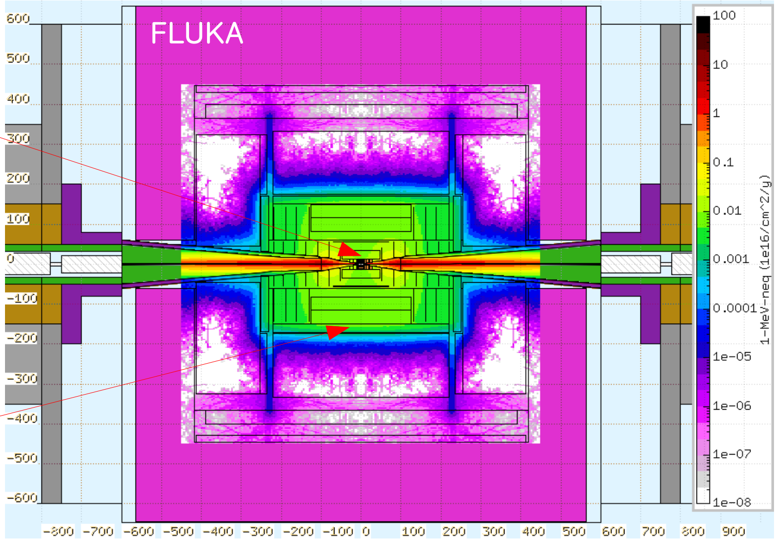
Radiation levels in the detector

- A muon collider detector must be radiation hard.
- Radiation levels in the detector will strongly depend on the collider operation mode.

Assumptions:

- collision energy: 1.5 TeV;
- collider circumference: 2.5 km;
- beam injection frequency: 5 Hz;
- days of operation per year: 200.

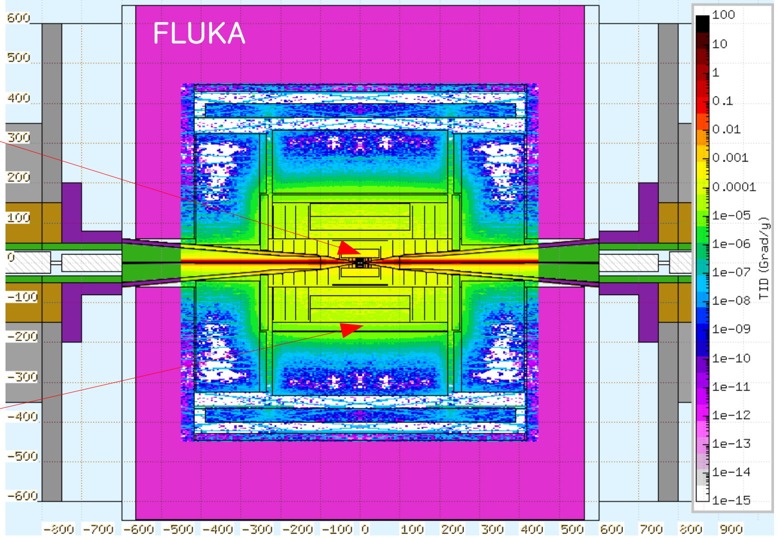
1-MeV neutron equivalent fluence per year



~10^{15} cm^{-2} y^{-1}

~10^{14} cm^{-2} y^{-1}

total ionizing dose per year



~10^4 Gy/y

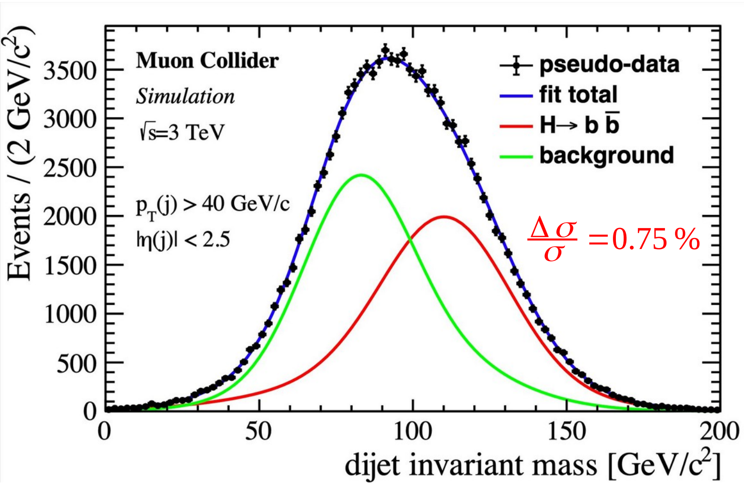
~10^3 Gy/y

S. Jindariani *et al.*, arXiv:2203.07224

Physics can be done even at a muon collider!

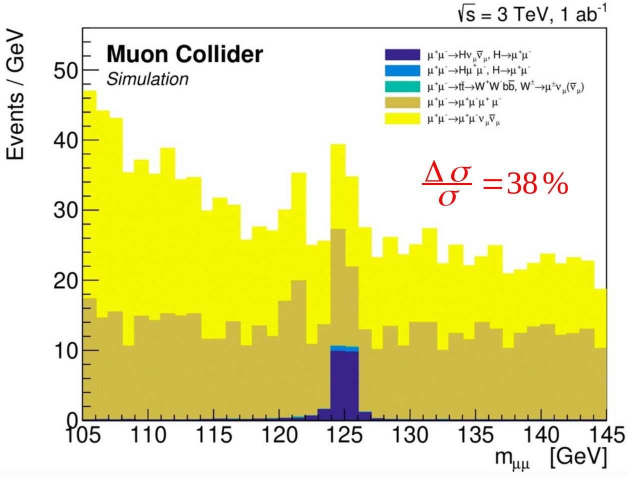
- A campaign of physics studies is ongoing with a detector detailed simulation:
  - detector, background mitigation measures and reconstruction algorithms have not been fully optimized yet.

$\mu\mu \to H\nu\nu \to b\bar{b}\nu\nu$



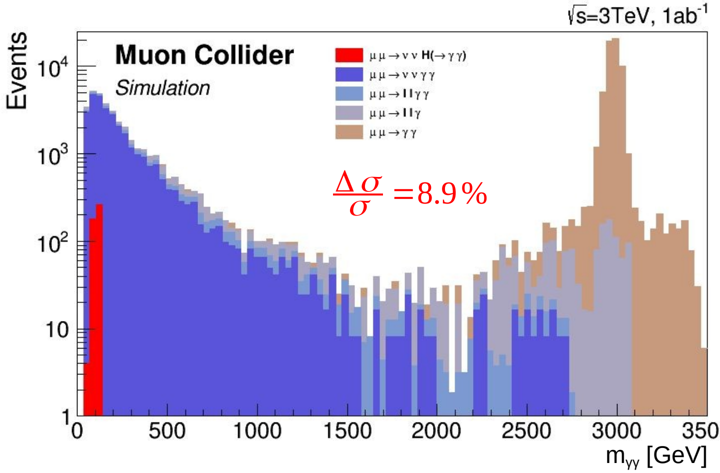
$\frac{\Delta\sigma}{\sigma} = 0.75\,\%$

$\mu\mu \to H\nu\nu \to \mu\mu\nu\nu$



$\frac{\Delta\sigma}{\sigma} = 38\,\%$

$\mu\mu \to H\nu\nu \to \gamma\gamma\nu\nu$



$\frac{\Delta\sigma}{\sigma} = 8.9\,\%$

Conclusions

- On the machine side, there are no evident insurmountable obstacles identified towards a 10+ TeV muon collider:
  - but challenging technologies and design require R&D.

- On the detector side, many ongoing detector and physics studies with a detailed detector simulation show:
  - satisfactory reconstruction performance for all physics objects, despite a non-optimal detector and still crude reconstruction algorithms and background mitigation measures;
  - extremely competitive physics results w.r.t. the other future accelerators.

Colliding muons will be very challenging, but highly rewarding in terms of both physics outcome and technical advances!

A great potential for high-energy physics!

- The muon collider potential is well summarized in a short video on YouTube:

www.youtube.com/watch?v=s_px84ukX9Q

Contacts

- International Muon Collider Collaboration secretariat:

  muon.collider.secretariat@cern.ch

- Physics Study Group:

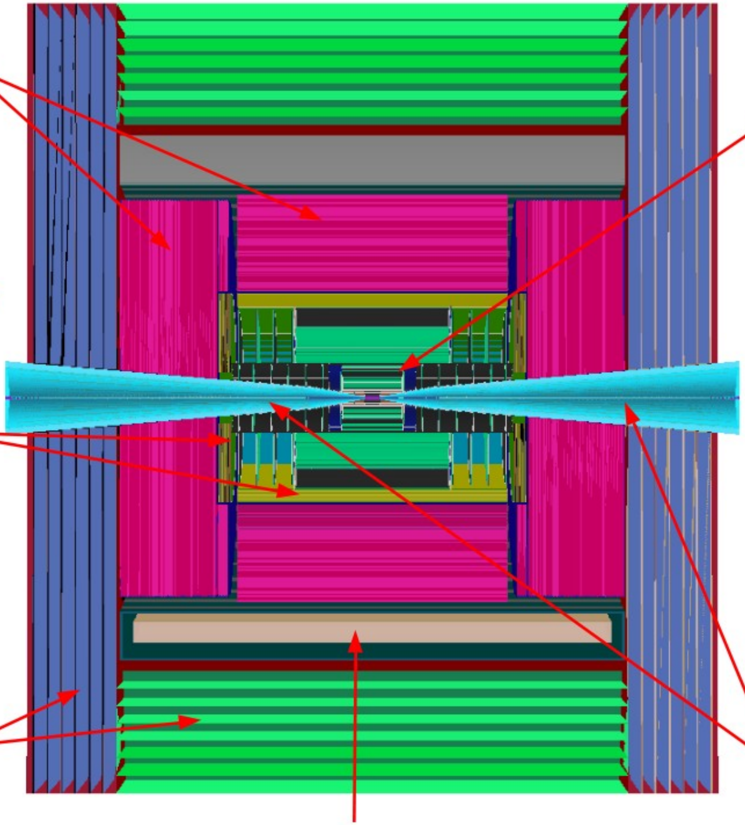
  CERN e-group *MUONCOLLIDER-DETECTOR-PHYSICS*

- Detector and Physics Studies with full simulation:

  muon_collider_studies@lists.infn.it

Backup

Detector model in the detailed simulation



hadronic calorimeter

- 60 layers of 19-mm steel absorber + plastic scintillating tiles;
- 30x30 mm^2 cell size;
- 7.5 λ_I.

electromagnetic calorimeter

- 40 layers of 1.9-mm W absorber + silicon pad sensors;
- 5x5 mm^2 cell granularity;
- 22 X_0 + 1 λ_I.

muon detectors

- 7-barrel, 6-endcap RPC layers interleaved in the magnet's iron yoke;
- 30x30 mm^2 cell size.

superconducting solenoid (3.57T)

tracking system

- Vertex Detector:
  - double-sensor layers (4 barrel cylinders and 4+4 endcap disks);
  - 25x25 μm^2 pixel Si sensors.
- Inner Tracker:
  - 3 barrel layers and 7+7 endcap disks;
  - 50 μm x 1 mm macro-pixel Si sensors.
- Outer Tracker:
  - 3 barrel layers and 4+4 endcap disks;
  - 50 μm x 10 mm micro-strip Si sensors.

shielding nozzles

- Tungsten cones + borated polyethylene cladding.