Challenges and concepts for a multi-TeV Muon Collider experiment

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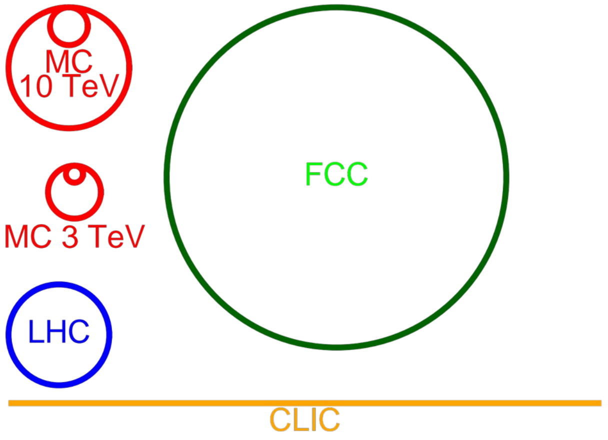
Motivation for a muon collider

- A muon collider can provide leptonic collisions at multi-TeV center-of-mass energies in a 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.

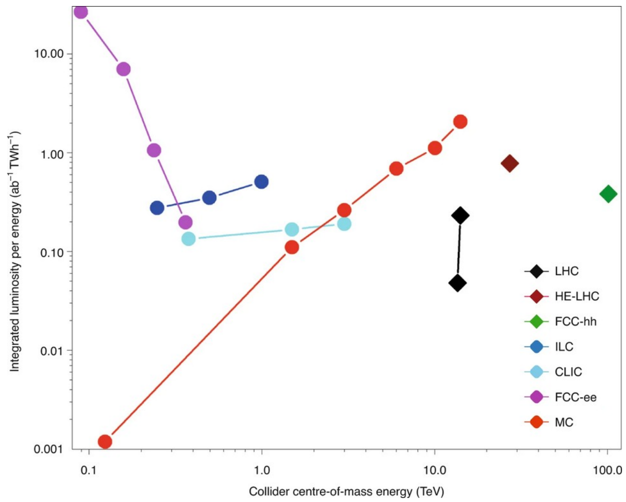
footprints for different high-energy facilities



- 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.

Muon collider tentative parameters

- The International Muon Collider Collaboration is focusing on developing two muon collider concepts:
  - a 10 TeV collider with an integrated luminosity target of 10 ab^{-1}/IP in 5 years of operation;
  - a possible intermediate stage at 3 TeV with an integrated luminosity target of 1 ab^{-1}/IP in 5 years of operation.
- Initial parameters are based on studies by the US Muon Accelerator Program (MAP).

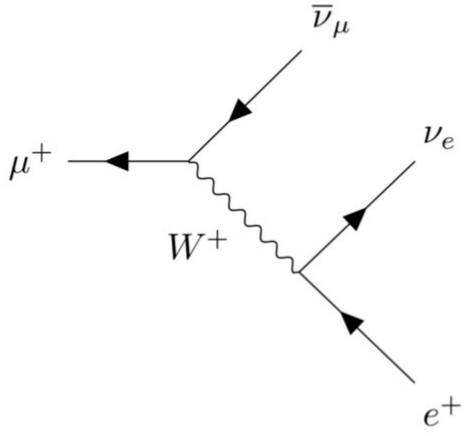
Parameter	Unit	3 TeV	10 TeV
L	10^{34} $cm^{-2}s^{-1}$	2	20
N	10^{12}	2.2	1.8
f_r	Hz	5	5
P_{beam}	MW	5.3	14
C	km	4.5	10
<B>	T	7	10.5
ε_L	MeV m	7.5	7.5
σ_E / E	%	0.1	0.1
σ_z	mm	5	1.5
β^*	mm	5	1.5
ε	µm	25	25
$\sigma_{x,y}$	µm	3	0.9

Experiment at a multi-TeV muon collider

- An experiment at a multi-TeV muon collider has many features in common with the experiments at the other multi-TeV machines (possible synergic R&Ds), but also has unique characteristics due to the unstable nature of muons.

- The design of the detector at a muon collider is mainly driven by:
  - the physics program;
  - the background conditions;
  - constraints from the machine.

- Will outline the findings from the initial studies using a detailed detector simulation at $\sqrt{s}$ = 3 TeV, which will be a basis for the design of a detector for 10 TeV collisions and provide guidance for the required R&Ds.

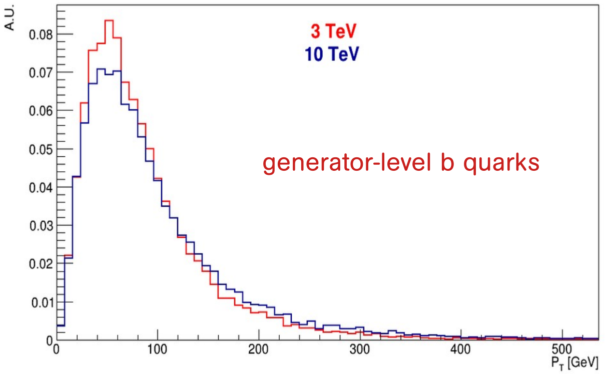


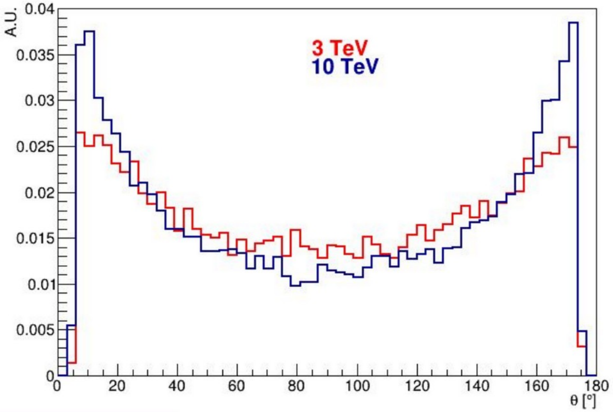
In the laboratory reference frame:

- at 10 TeV, t_μ = 104 ms
  ➔ expected 6.4×10^4 decays/m per bunch in the machine;
- at 3 TeV, t_μ = 31 ms
  ➔ expected 2.1×10^5 decays/m per bunch in the machine.

Requirements form the physics program

$\mu\mu \rightarrow H\nu\bar{\nu} \rightarrow b\bar{b}\nu\bar{\nu}$ at $\sqrt{s}$ = 3 and 10 TeV

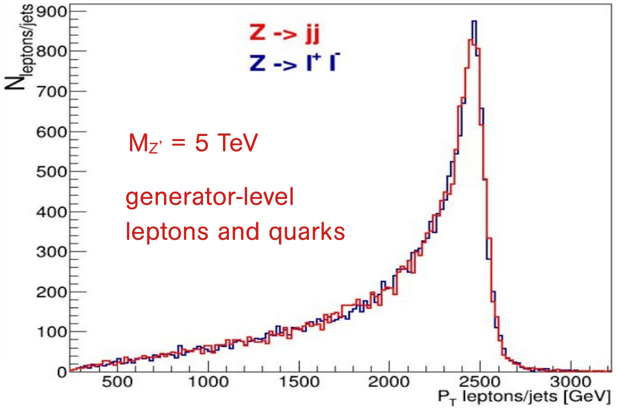


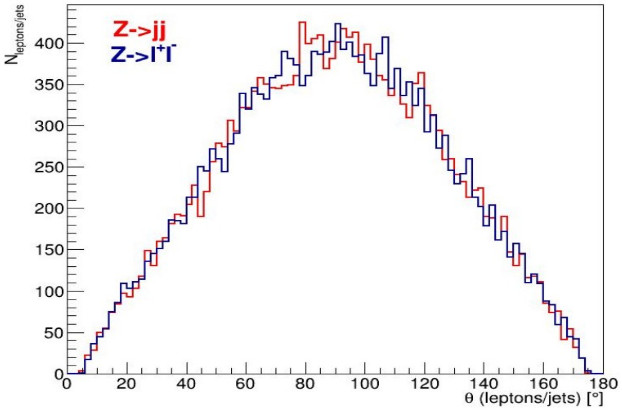


- The muon collider will pursue a broad physics program:
  - high-precision measurements of Standard Model processes with:
    - relatively light SM particles;
    - forward-boosted physical objects;
  - search for new physics with:
    - new, possibly heavy, states;
    - very energetic and mostly central physical objects.

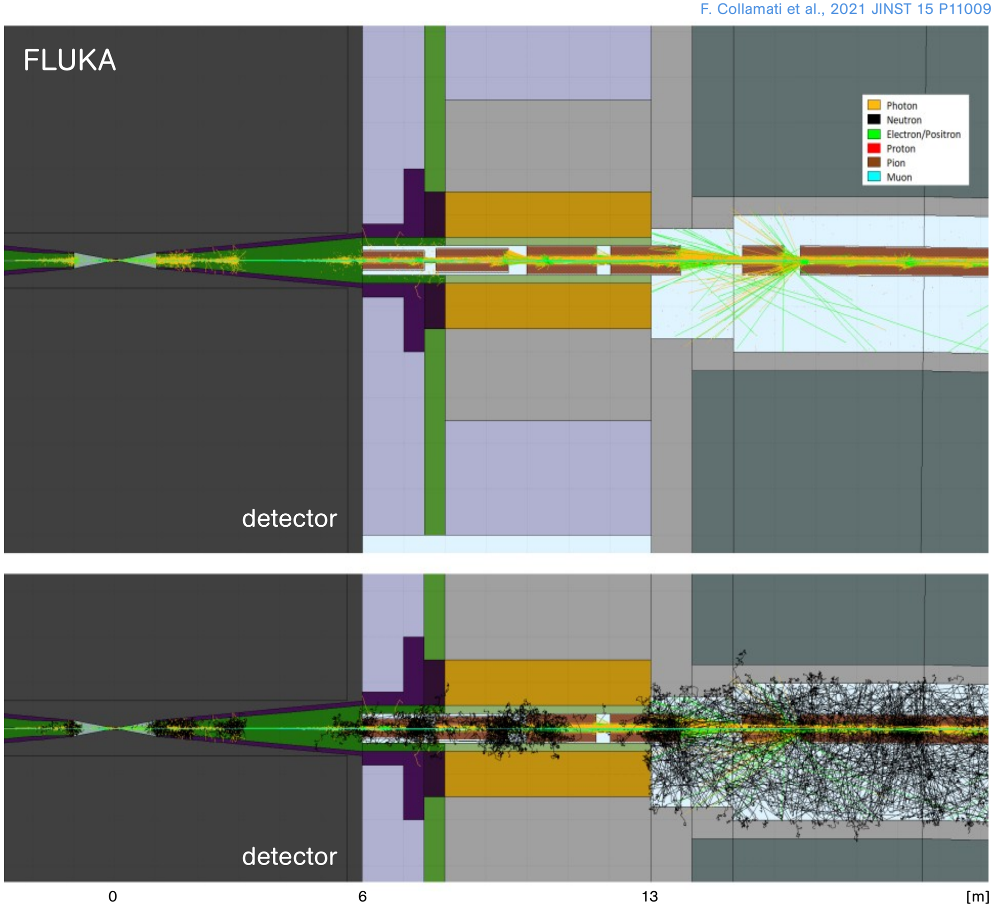
Physics objects must be reconstructed with high efficiency and high resolution across a wide energy spectrum.

$\mu\mu \rightarrow Z'X \rightarrow q\bar{q}/\ell\ell\ X$ at $\sqrt{s}$ = 10 TeV

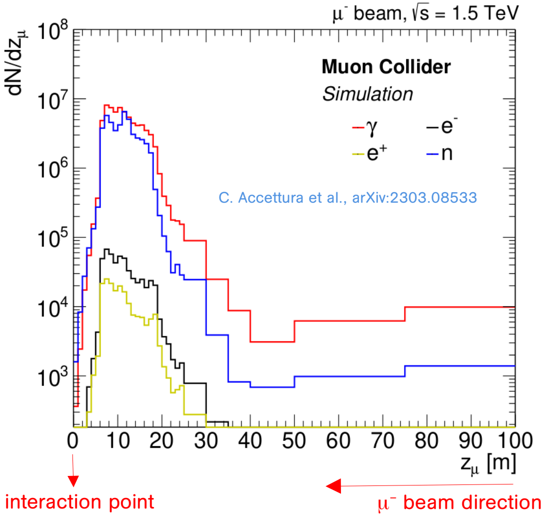




Background conditions



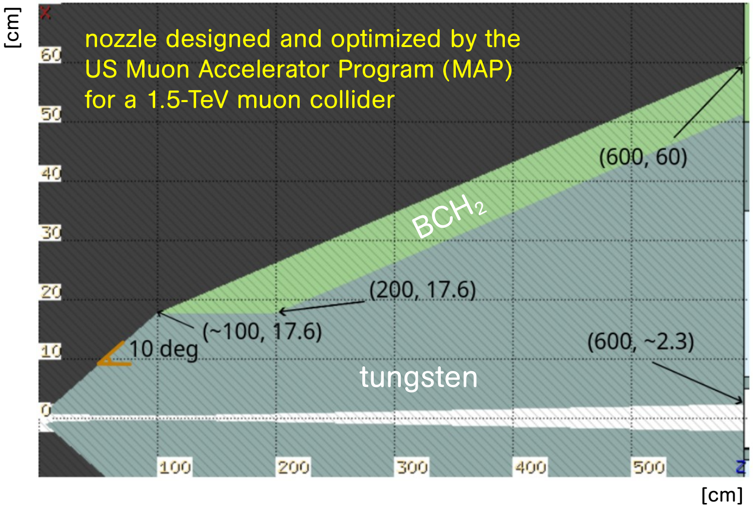
- The primary source of machine background arises from the interaction of the decay products of the muons in the beams with the machine components (beam-induced background, BIB):
  - at each bunch crossing, high levels of photons, neutrons, and electrons/positrons enter the detector.



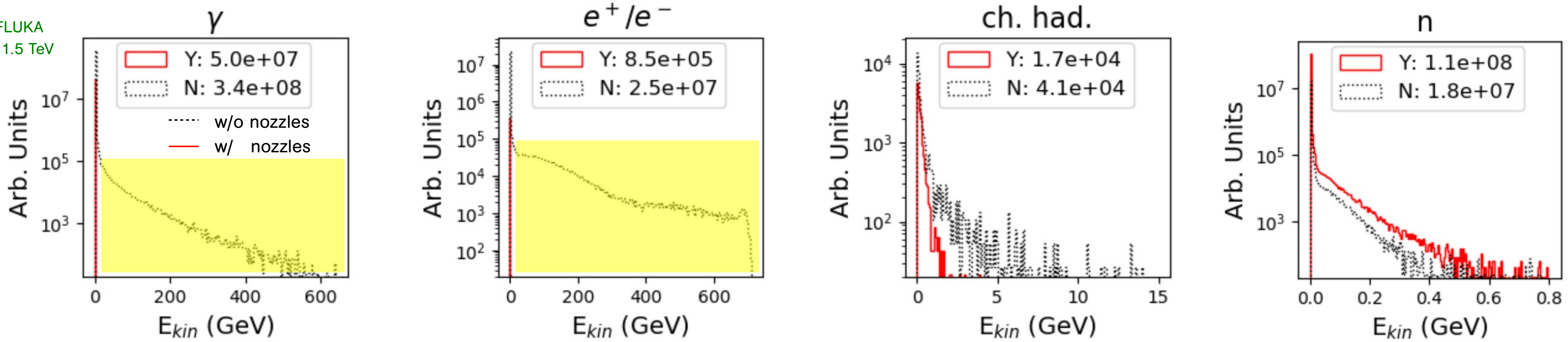
decay position of muons contributing to the background in the detector

MDI: the first line of defense

- The machine-detector interface (MDI) includes two conical tungsten shields (“nozzles”) coated with borated polyethylene:
  - combined with an appropriate configuration of the interaction-region magnets, reduce significantly the background particle flux into the detector;
  - absorb the high-energy tails of the background electromagnetic component;
  - but affect the detector angular acceptance (cone opening angle = 10°).

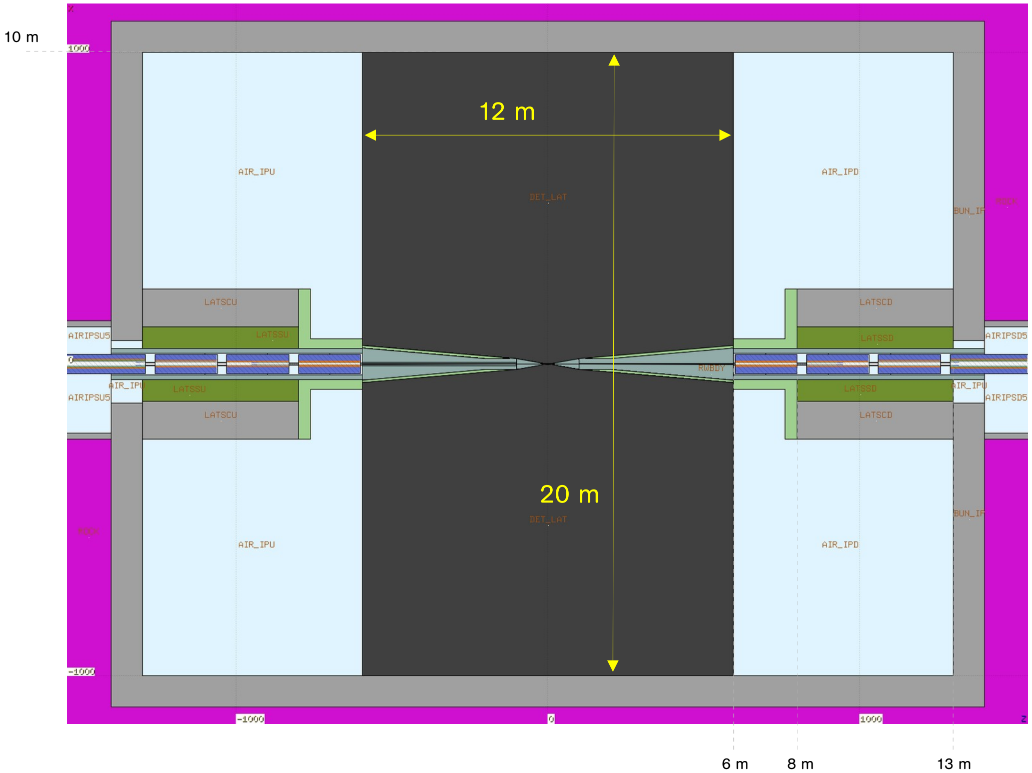


FLUKA @ 1.5 TeV



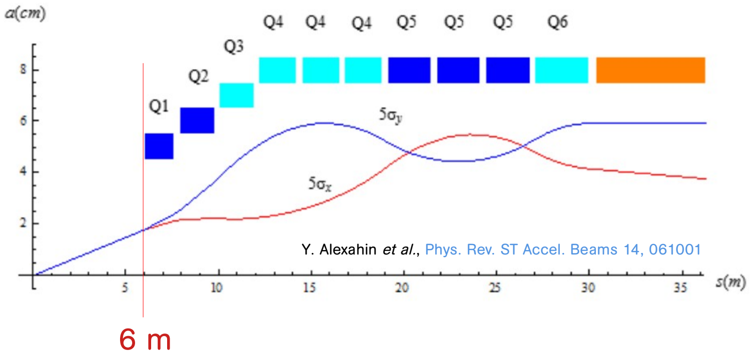
F. Collamati et al., 2021 JINST 15 P11009

Spatial constraints from the machine



- The longitudinal size of the detector will most likely be determined by the position of the machine's final focusing magnets, which are currently located at ±6 m from the interaction point.

preliminary interaction-region configuration for a 3 TeV collider



Y. Alexahin *et al.*, Phys. Rev. ST Accel. Beams 14, 061001

Detector concept for $\sqrt{s}$ = 3 TeV

hadronic calorimeter

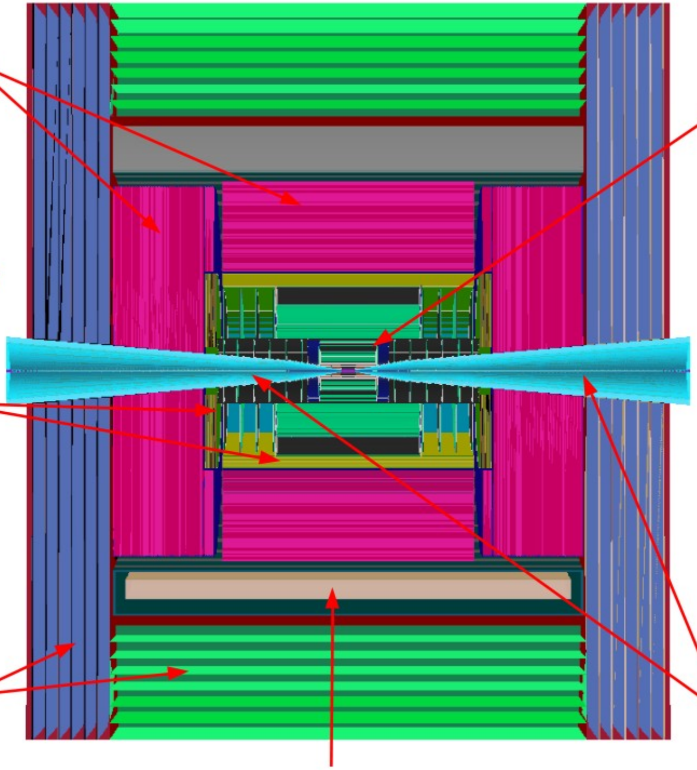
- 60 layers of 19-mm steel absorber + plastic scintillating tiles;
- 30x30 mm^2 cell size;
- 7.5 λ_I.

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.

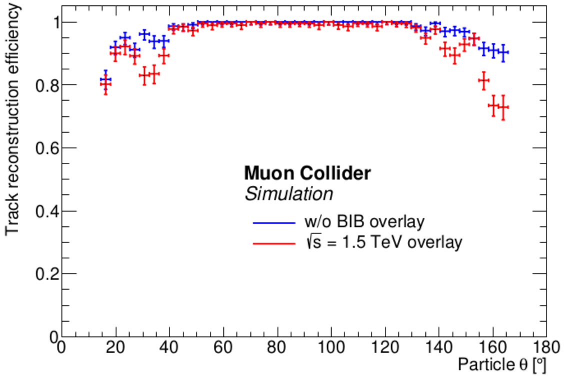
shielding nozzles

- Tungsten cones + borated polyethylene cladding.

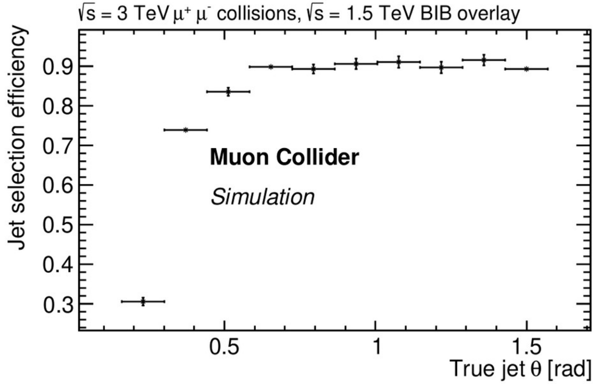
The detector model for 3-TeV studies is based on CLIC's detector concept + the MDI and vertex detector designed by the US Muon Accelerator Program.

Examples of 3-TeV detector performance

muon track reconstruction efficiency vs θ

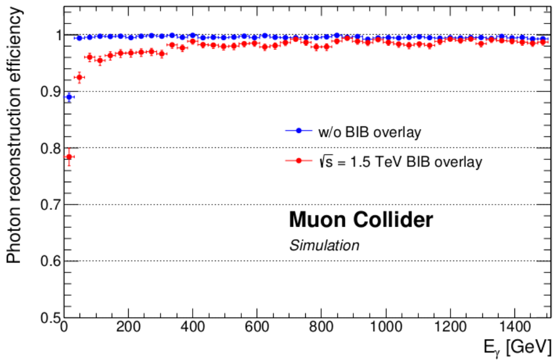


jet reconstruction efficiency vs θ

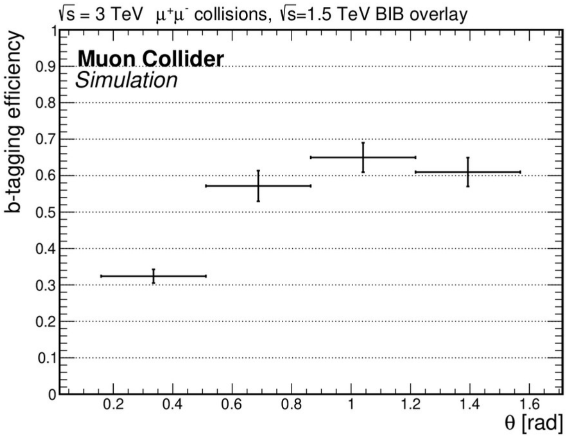


- State-of-the-art reconstruction algorithms will be essential to take full advantage of the most advanced detector technologies.
- Nevertheless, the current performance of the 3 TeV detector is already satisfactory despite crude background mitigation measures and non-optimised reconstruction algorithms.

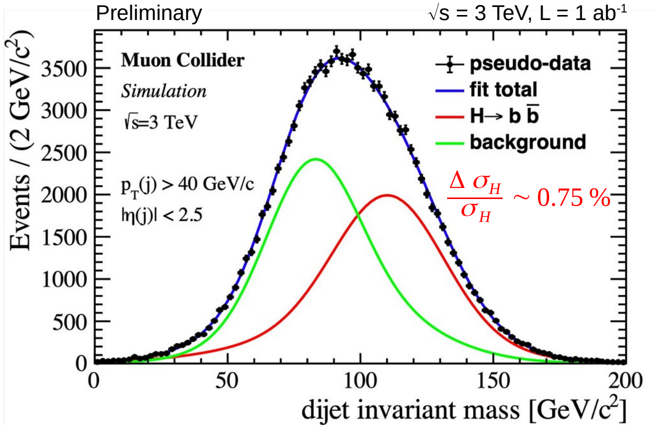
photon reconstruction efficiency vs E_γ



b-tagging efficiency vs θ



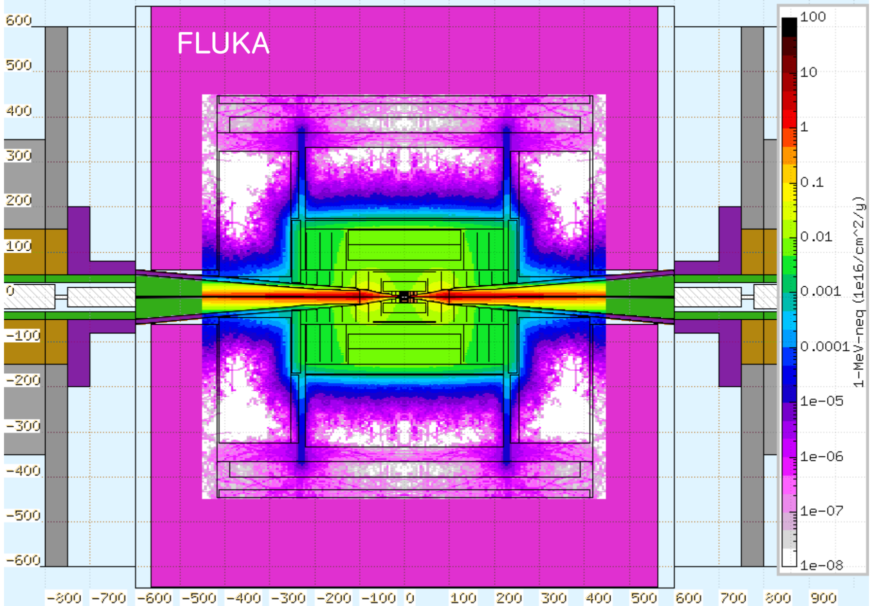
$\mu\mu \to H\nu\bar{\nu} \to b\bar{b}\nu\bar{\nu}$



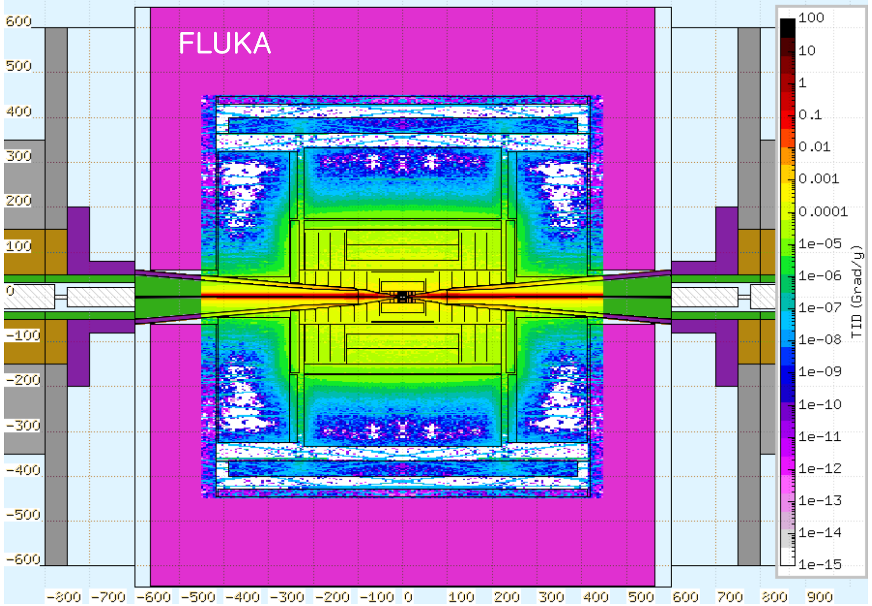
Radiation environment

C. Accettura et al., arXiv:2303.08533

1-MeV neutron equivalent fluence per year



total ionizing dose per year



Assumptions:

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

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

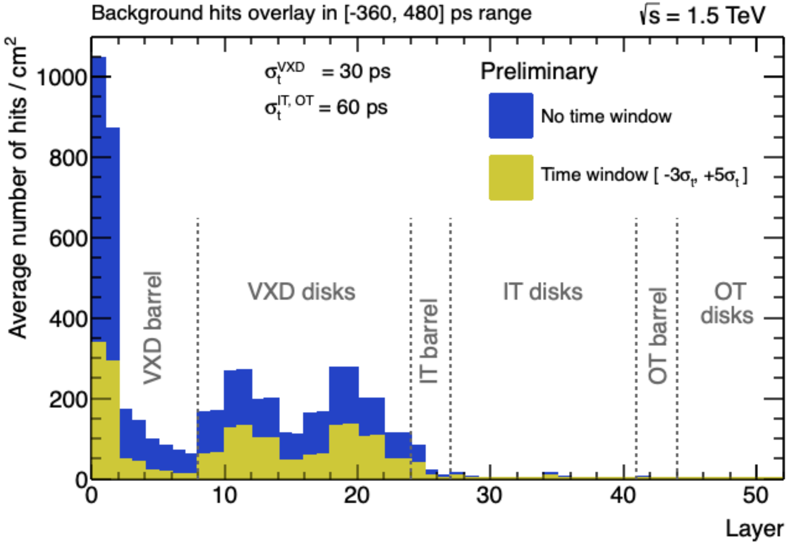
Radiation hardness requirements are similar to what expected at HL-LHC.

Tracking system

- 3-TeV baseline tracking system: full-Si detector.
- The BIB produces a huge amount of spurious hits: the track finding is very challenging.
- Key features to deal with the BIB:
  - high granularity and precise timing;
  - directional information or sensor crossing angle;
  - characteristics of the detector response (pulse shape and pixel cluster size).
- More details and ongoing R&D in:

  N. Bartosik, "Tracking-detector design for a multi-TeV Muon Collider" in Session F2: Future Energy Frontier Detectors .

density of BIB hits per layer



Detector Reference	Hit Density [mm^{-2}] MCD	ATLAS ITk	ALICE ITS3
Pixel Layer 0	3.68	0.643	0.85
Pixel Layer 1	0.51	0.022	0.51

C. Accettura et al., arXiv:2303.08533

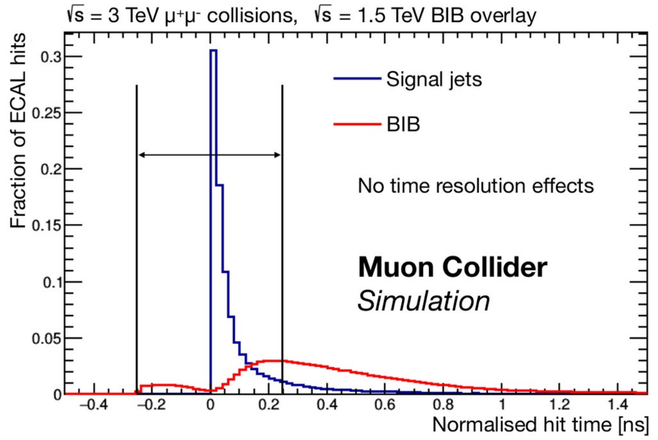
Higher hit occupancies than at HL-LHC detectors are expected, but the crossing rate at the muon collider is ∼100 kHz vs 40 MHz at LHC.

Electromagnetic calorimeter

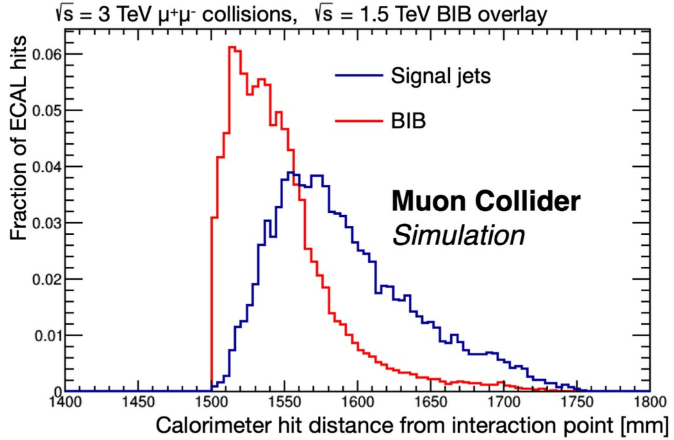
- 3-TeV baseline ECAL: W-Si calorimeter.
- Estimated a flux of 300 particles per cm^2 through the ECAL surface at every bunch crossing:
  - 96% photons and 4% neutrons;
  - average photon energy: 1.7 MeV.
- Key calorimeter features to mitigate the BIB effects:
  - timing ($\sigma_t \sim$ 100 ps);
  - high granularity;
  - fine longitudinal segmentation.
- An ongoing R&D for an alternative ECAL:

  I. Sarra, "R&D status for an innovative crystal calorimeter for the future Muon Collider" in Session G2: Future Energy Frontier Detectors .

time of ECAL barrel hits



shower profile of signal jets vs bkg

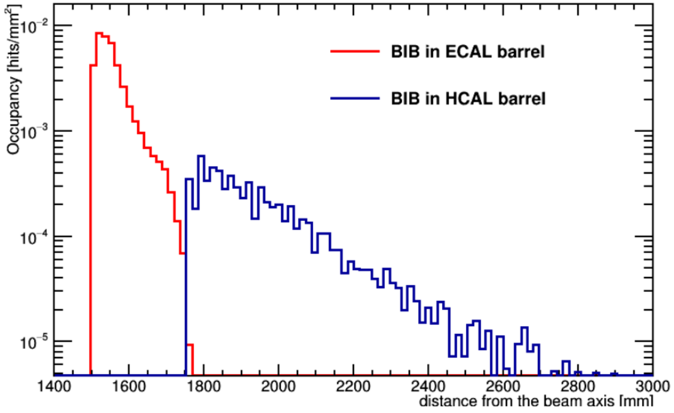


Hadronic calorimeter

- 3-TeV baseline HCAL: steel-plastic scintillator calorimeter.
- Expected a ~10 times lower hit occupancy due to the BIB (photons and neutrons) than in the ECAL

  ➔ less stringent requirements on the detector specs.

density of BIB hits vs calorimeter barrel depth

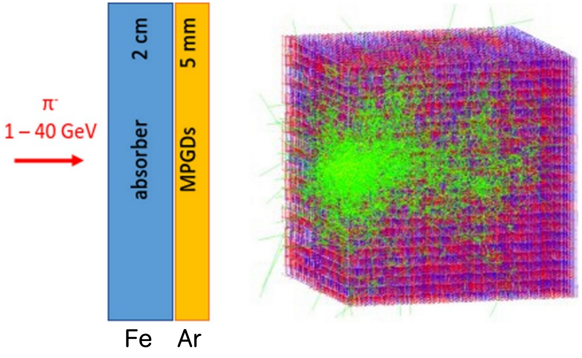


C. Aruta et al., NIM A 1047 (2023) 167731

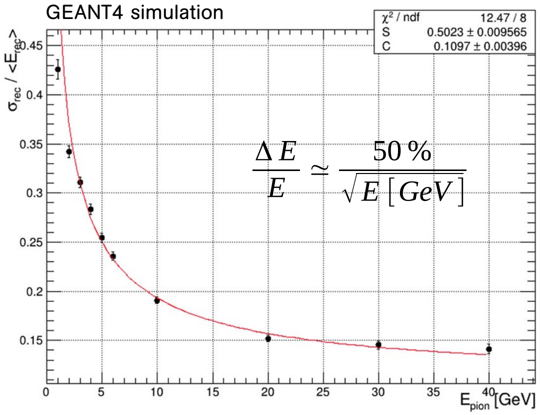
R&D for a HCAL based on Micro-Pattern Gaseous Detectors

A HCAL based on MPGDs is under study:

- good energy and spatial resolution, time resolution of a few ns;
- high rate capability (MHz/cm^2);
- can operate with eco-friendly gas mixtures;
- radiation hard.



pion energy resolution vs E_π



$$\frac{\Delta E}{E} \simeq \frac{50\,\%}{\sqrt{E\,[GeV]}}$$

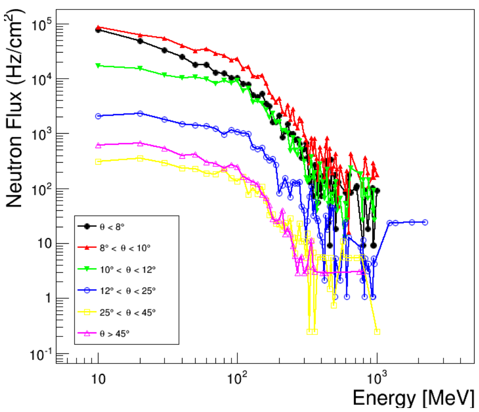
Design studied with standalone GEANT4 simulations. The simulation results are being validated with prototypes at dedicated test beams.

Muon system

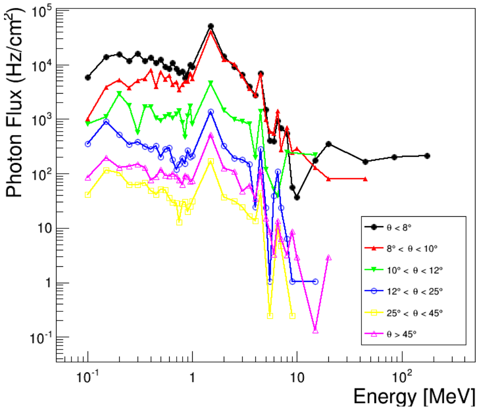
- 3-TeV baseline muon detectors: glass RPCs.
- In the muon system, significant BIB effects (mostly from photons and neutrons) only in the endcap regions close to the beamline

  ➔ at the limit of RPC's rate capability.
- Requirements: good spatial resolution ($\sim$100 μm) and possibly sub-ns time resolution.

neutron flux vs E_n and θ



photon flux vs E_γ and θ

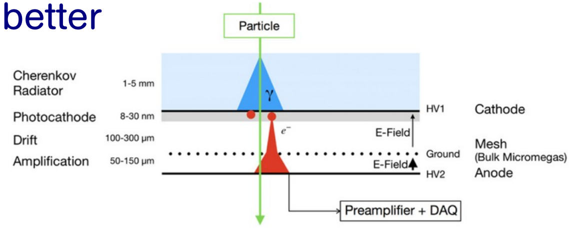


C. Aimè et al., NIM A 1046 (2023) 167800

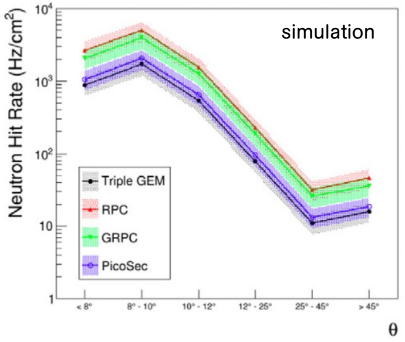
R&D for a PicoSec Micromegas detector

Currently being studied as an alternative to RPCs:

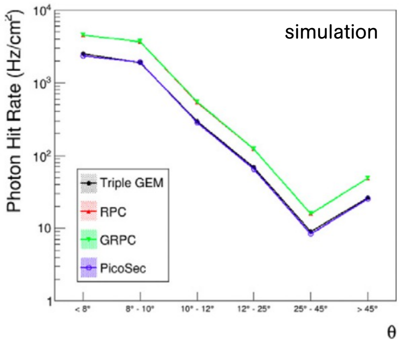
- time resolution better than 25 ps;
- very high rate capability.



neutron rate vs θ



photon rate vs θ



Test beams for the detector characterization are underway.

Detector challenges at 10-TeV collisions

- Global layout and design will depend on the choice of the magnetic system: à la ATLAS or à la CMS.

Tracking system

- see N. Bartosik's talk.

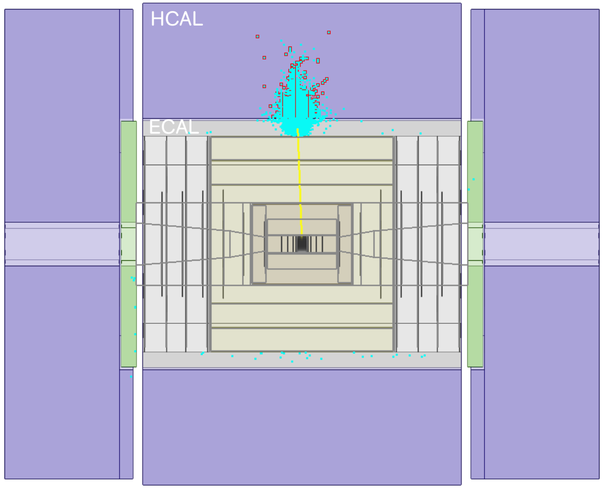
Muon detectors

- Required reconstruction of muons from a few GeV up to a few TeV.
- A precise measurement of the momentum, and the charge, of very high-p_T muons will be challenging.
- A novel global approach will be needed which possibly combines information from the tracker, the calorimeters, and the muon detectors.

Calorimeters

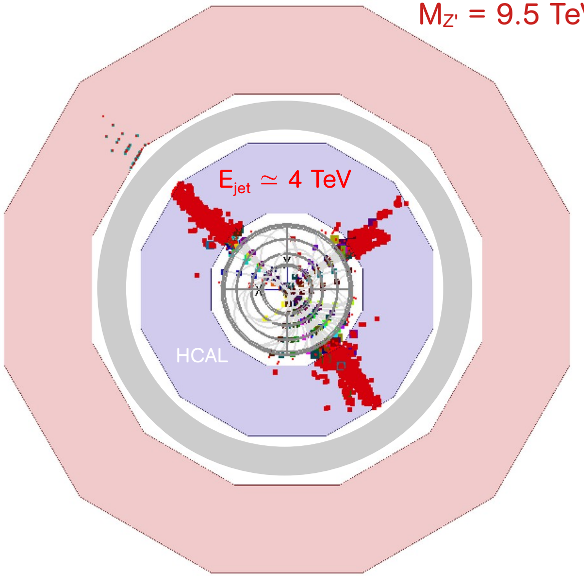
- Need for deep calorimeters to contain the showers produced by very energetic particles, but also capable of reconstructing softer objects with energies below 100 GeV and identify or resolve boosted overlapping objects.

central 5 TeV photon



$\mu\mu \to Z' \to q\bar{q}$ at $\sqrt{s}$ = 10 TeV

$M_{Z'}$ = 9.5 TeV



Summary

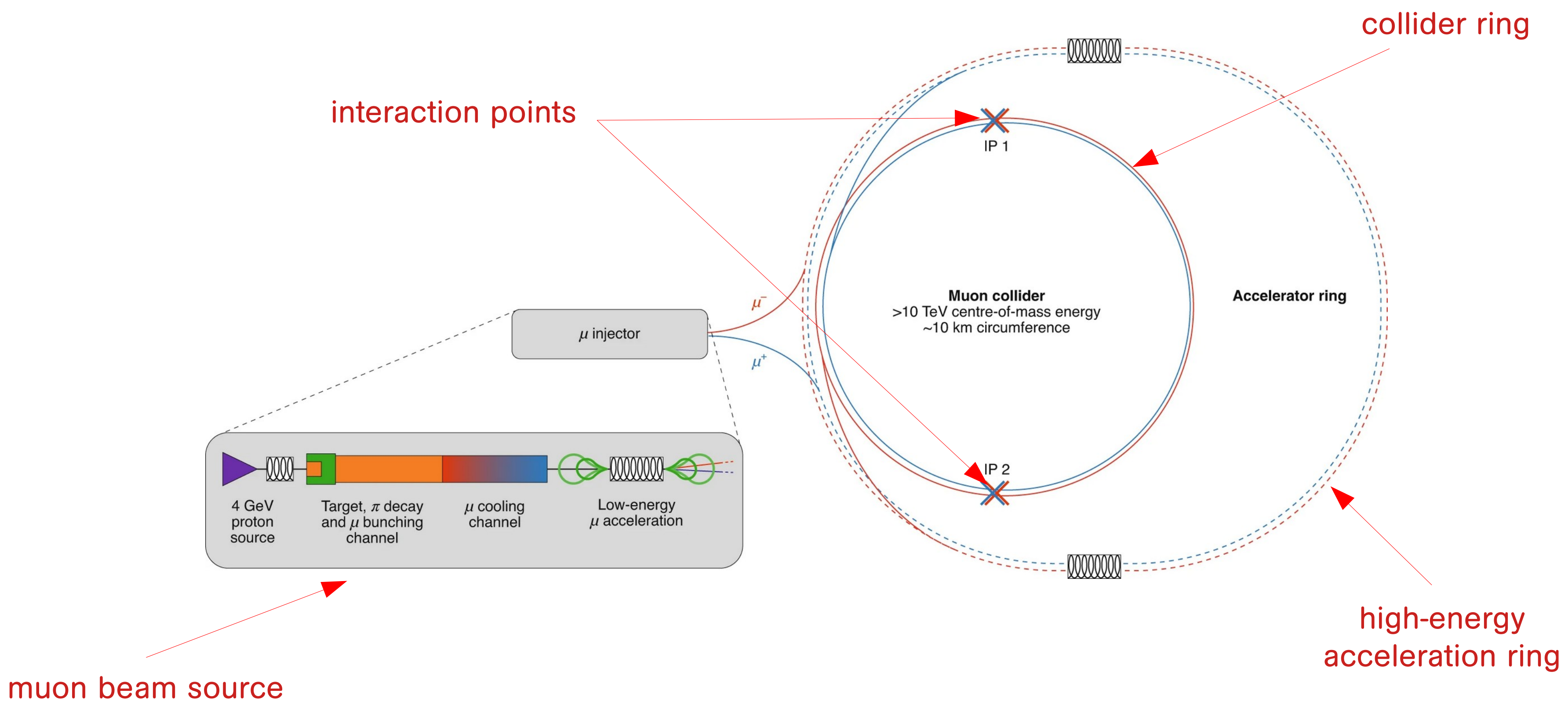
- A multi-TeV muon collider represents a unique machine, which can give access to an unexplored energy regime of leptonic collisions and enable an extraordinary and novel physics program.

- At a future muon collider, detectors are expected to operate under severe background conditions, that will represent one of the main drivers of the detector design, the technological choices and the event reconstruction algorithms:
  - first studies with a detector detailed simulation at a 3 TeV collider prove already a satisfactory reconstruction performance for the most relevant high-p_T physical objects, despite a nonoptimal detector and very crude reconstruction algorithms;
  - the design of a detector for collisions at 10 TeV is underway.

- Ongoing hardware R&D and improved software algorithms, mostly in synergy with ongoing HL-LHC and other future collider projects, are foreseen to significantly enhance the detector performance.

Backup

Conceptual layout of a muon collider



Design fully driven by the muon lifetime.