Detector performance for low- and high-momentum particles in $\sqrt{s}$ = 10 TeV muon collisions

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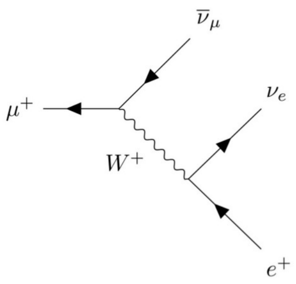
Driving factors for a muon collider detector

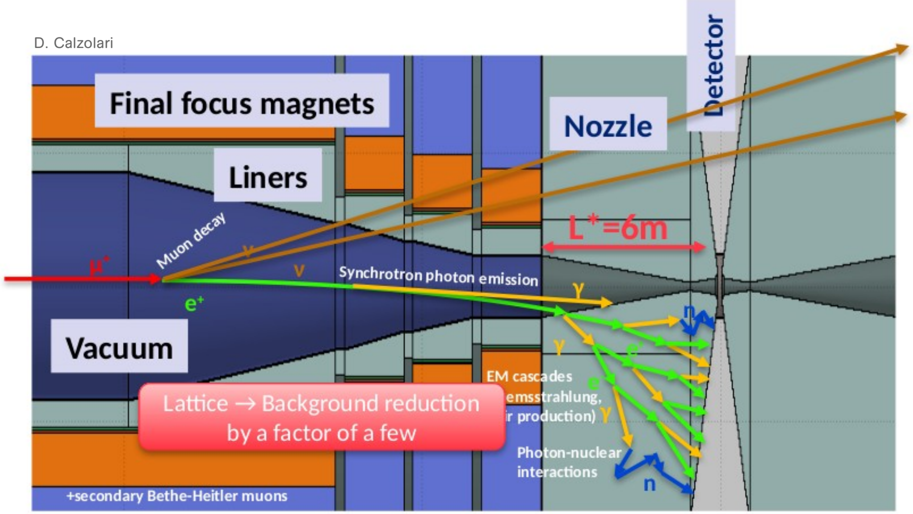
- The requirements for the detector specifications from physics are similar to those of other multi-TeV machines to reconstruct:
  - boosted low-p_T physics objects from Standard Model processes;
    - D. Zuliani, "Higgs Physics at Multi-TeV Muon Collider" on July 18 in Higgs Physics.
  - central energetic physics objects from decays of possible new massive states;
  - less conventional experimental signatures: disappearing tracks, displaced leptons, displaced photons or jets, ...
- Constraints from the machine design: final focusing quadrupoles at ± 6 m from the interaction point.
- Machine background conditions.

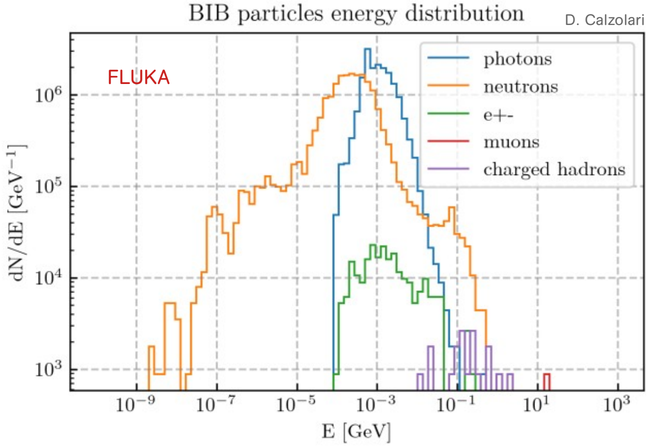
Ultimately, the detector design, the technological choices, and the development of the event reconstruction algorithms will be driven by the high levels of machine-induced background.

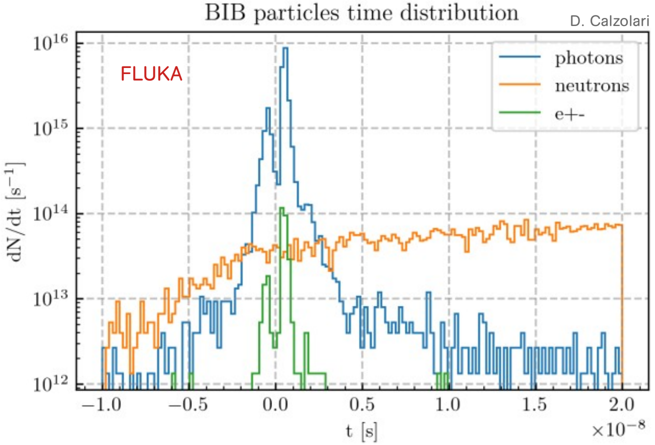
- D. Lucchesi, "Muon Collider Progress" on July 19 in Accelerators: Physics, Performance, and R&D for future facilities.

Machine background from muon decays





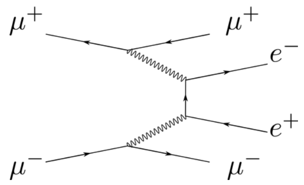


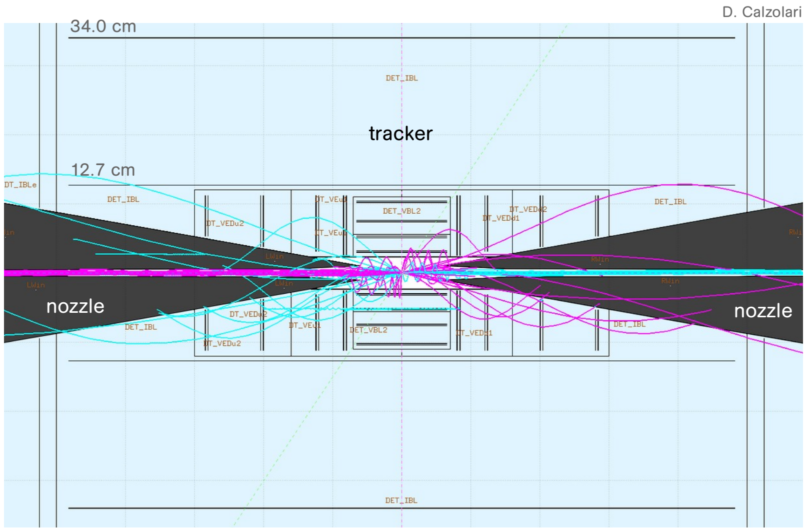


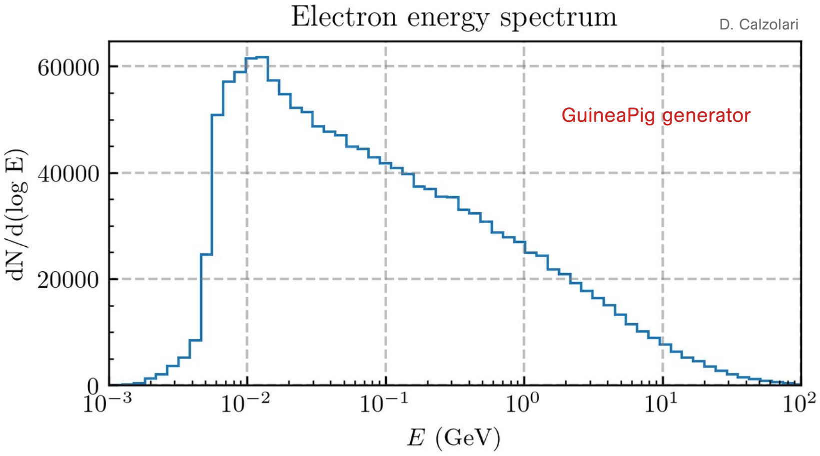
- Beam-induced background (BIB) from muon decay products interacting with the machine components and the shields inside the detector (nozzles):
  - soft particles and mostly out of time w.r.t. the bunch crossing:
  - $\sim 10^8$ photons, $\sim 10^7$ neutrons, and $\sim 10^5$ electrons/positrons enter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

D. Calzolari, "Machine-detector interface design for a 10-TeV muon collider" on July 19 in Accelerators: Physics, Performance, and R&D for future facilities.

Machine bkg from incoherent e^+e^- 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.

D. Calzolari, "Machine-detector interface design for a 10-TeV muon collider" on July 19 in Accelerators: Physics, Performance, and R&D for future facilities.

Two detector concepts for $\sqrt{s}$ = 10 TeV

- The design of the detector for a 10 TeV muon collider is based on long experience with studies at $\sqrt{s}$ = 3 TeV with a detailed detector simulation including the beam-induced background: C. Accettura et al., "Towards a muon collider", EPJC 83 (2023) 864 .

- For $\mu^+\mu^-$ collisions at 10 TeV, two detector concepts are under development (up to two interaction points are possible in the collider):
  - common features from machine and machine-detector-interface constraints:
    - conical tungsten shields inside the detector to mitigate the BIB effects;
    - final focusing magnets at 6 m form the interaction point;
  - different approaches to the global layout of subdetectors:
    - ALEPH-like*: tracking system and electromagnetic calorimeter inside the magnet bore, hadronic calorimeter outside;
    - ATLAS-like*: both calorimeters outside the superconducting solenoid.

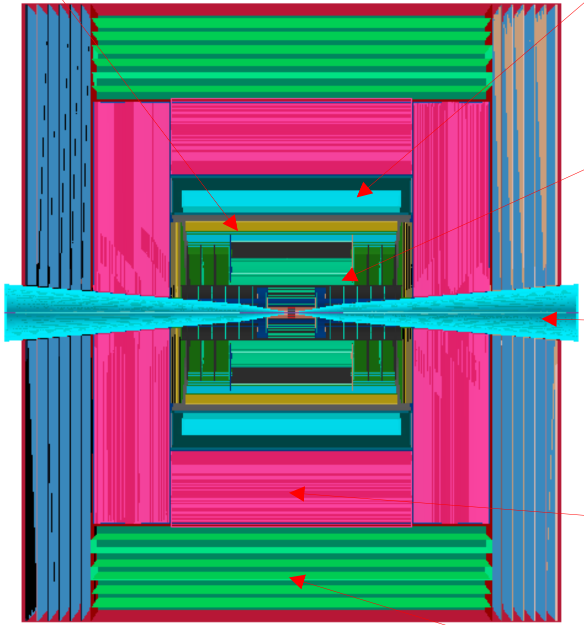
- A first version of the detectors to be frozen soon in order to meet the tight schedule for the submission of contributions to the update of the European Strategy for Particle Physics.

* Temporary detector code names defined just for this presentation.

Detector layouts

PbF$_2$-crystal electromagnetic calorimeter (inside the solenoid)

Si-W electromagnetic calorimeter (ouside the solenoid)



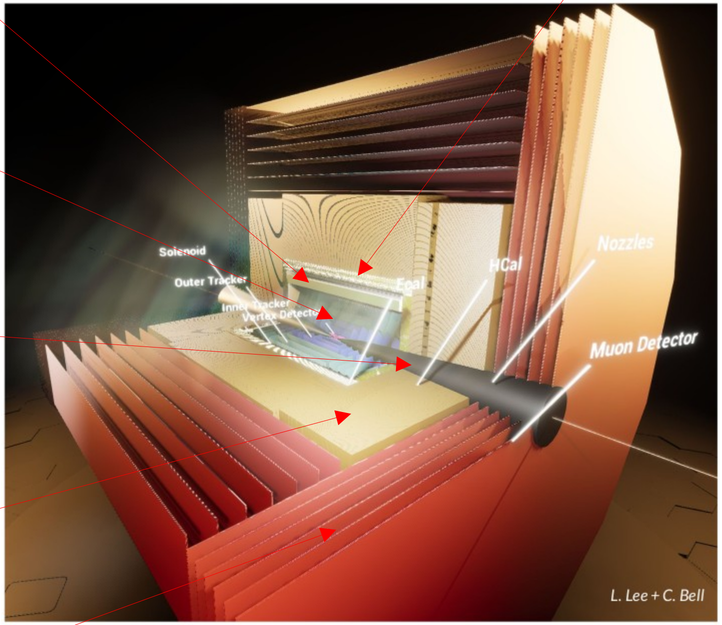
superconducting solenoid (B = 5 T)

full silicon tracking system

tungsten shielding nozzles

Fe-scintillator hadronic calorimeter (serves as B field return yoke)

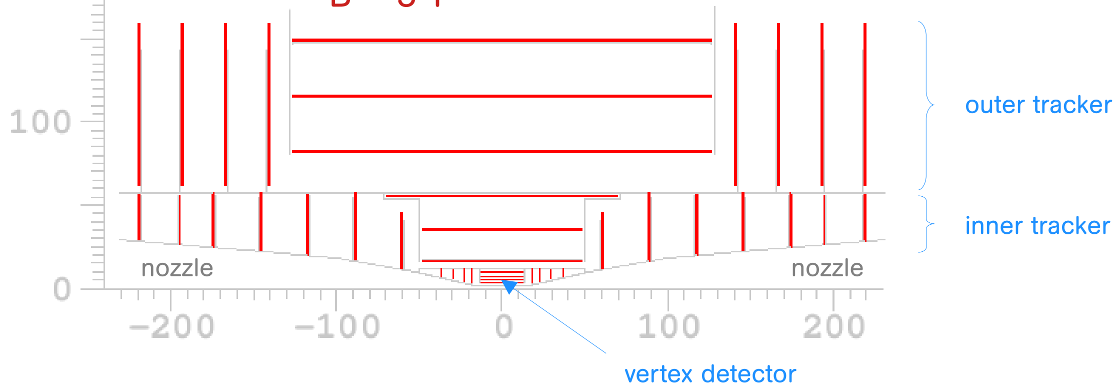
muon detectors



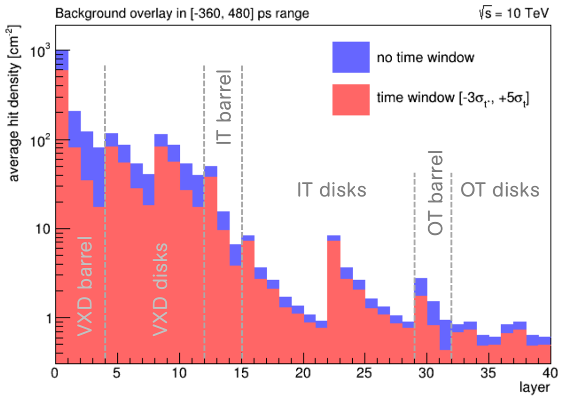
ALEPH-like detector

ATLAS-like detector

ALEPH-like: tracking system

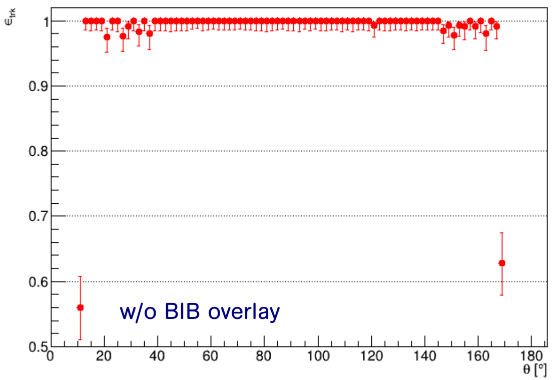


average hit density of BIB hits

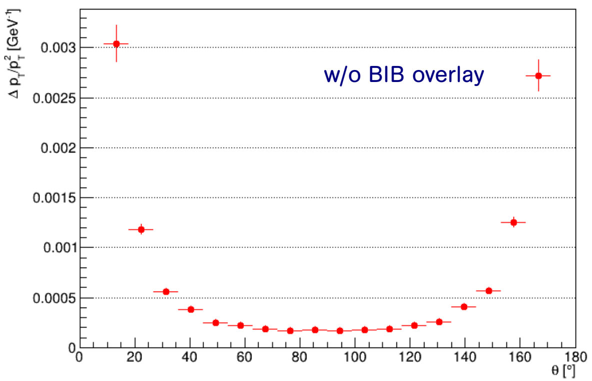


- Vertex detector (VXD):
  - 25x25 μm^2 Si pixels: 5 μm x 5 μm spatial resolution and 30 ps time resolution.
- Inner Tracker (IT) and Outer Tracker (OT):
  - 50 μm x 1 mm Si macropixels: 7 μm x 90 μm patial resolution and 60 ps time resolution.

tracking efficiency for 10 GeV muons



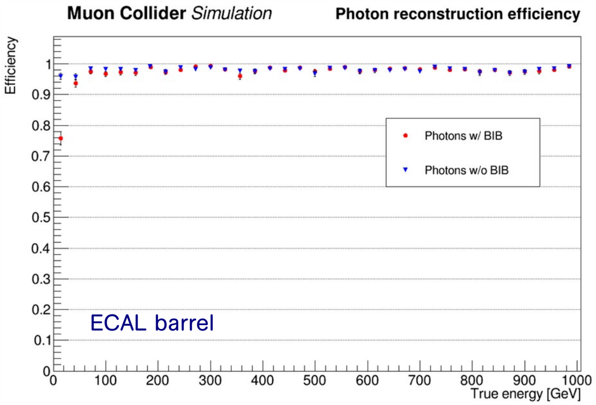
p_T resolution for 10 GeV muons

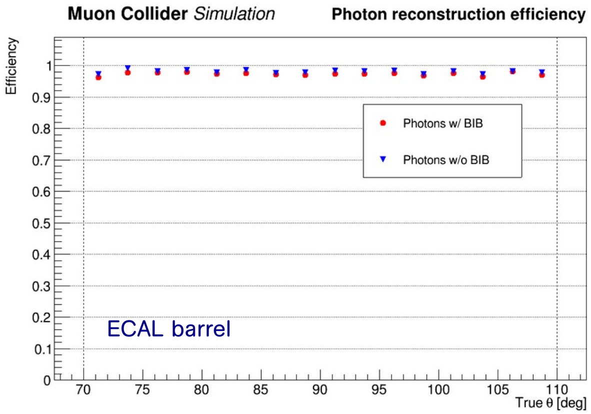


ALEPH-like: electromagnetic calorimeter

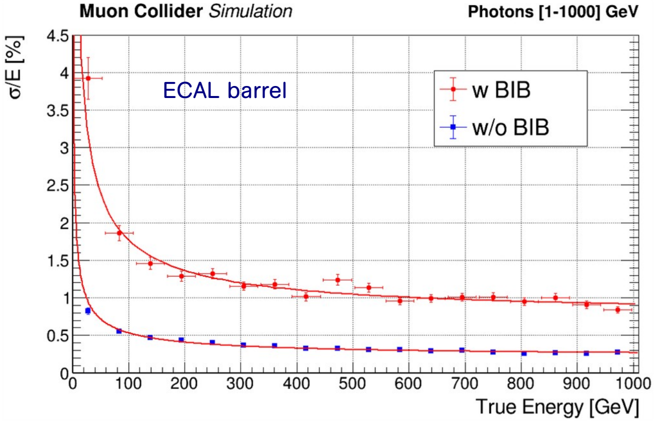
- Estimated a flux of 300 particles per cm^2 through the ECAL surface at every bunch crossing: ~96% photons with an average energy of 1.7 MeV and ~4% neutrons.
- Semi-homogeneous electromagnetic crystal calorimeter with longitudinal segmentation (CRILIN):
  - lead fluorite (PbF_2) crystals: very good timing (<100 ps), radiation hardness, affordable cost;
  - crystal layout: 5 layers of 10x10x40-mm^3 crystal matrices (22 X_0).

photon reconstruction efficiency





photon energy resolution

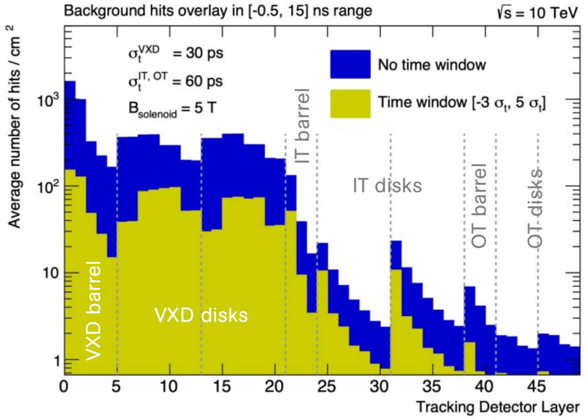


R. Gargiulo, "Crilin: a semi-homogeneous crystal calorimeter for the muon collider" on July 18 in Detectors for Future Facilities, R&D, Novel Techniques.

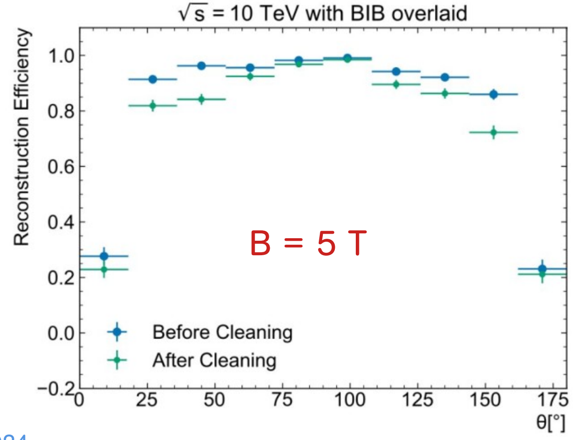
ATLAS-like: tracking system

- Vertex detector (VXD):
  - first barrel layer and endcap disks with double-layer silicon sensors;
  - 25x25 μm^2 Si pixels: 5 μm x 5 μm spatial resolution and 30 ps time resolution.
- Inner Tracker (IT):
  - 50 μm x 1 mm Si macropixels: 7 μm x 90 μm spatial resolution and 60 ps time resolution.
- Outer Tracker (OT):
  - 50 μm x 10 mm Si macrostrips: 7 μm x 90 μm patial resolution and 60 ps time resolution.

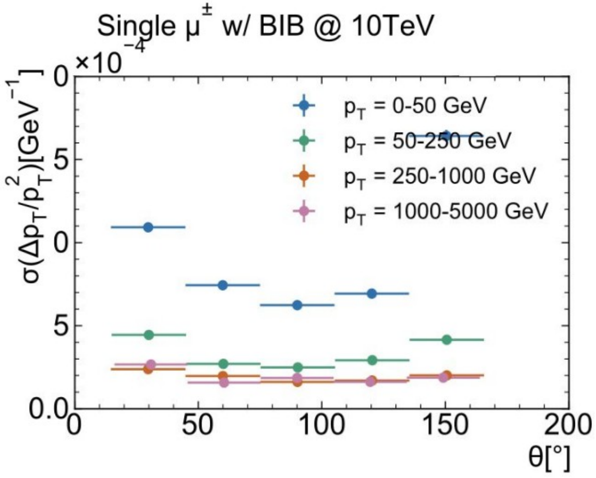
average hit density of BIB hits



track reconstruction efficiency



muon p_T resolution



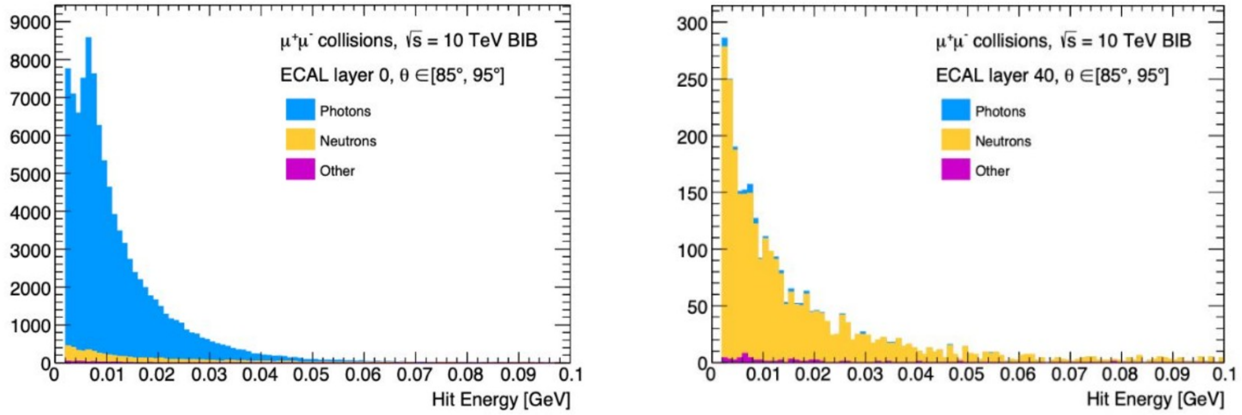
K. Kennedy et al., IMCC Detector and MDI Workshop, CERN, June 25-26, 2024

ATLAS-like: electromagnetic calorimeter

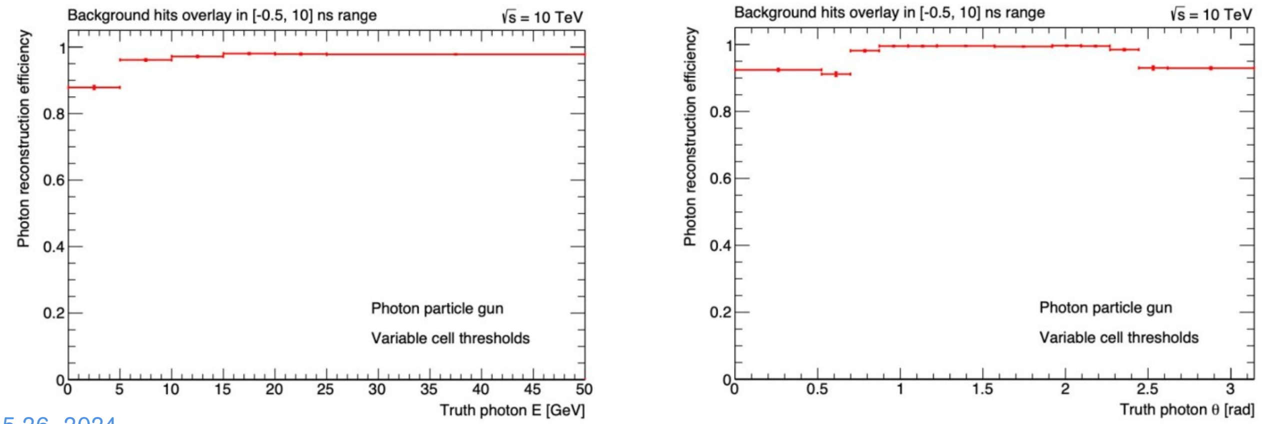
- Energy density of BIB in the electromagnetic calorimeter ~3-10 times lower due to solenoid shielding.

- Silicon-tungsten electromagnetic calorimeter:
  - 50 layers of 2.2-mm tungsten absorber and 0.5-mm thick silicon pads (28 X_0);
  - 5.1 x 5.1 mm^2 cell granularity.

ECAL hit energy distributions in 1st and 40th layer



photon reconstruction efficiency



K. Kennedy et al., IMCC Detector and MDI Workshop, CERN, June 25-26, 2024

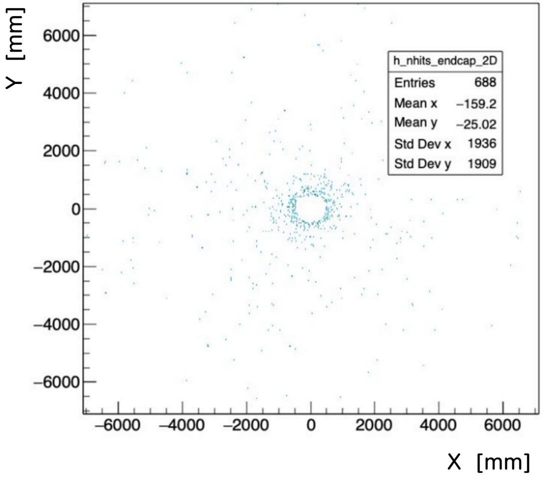
Hadronic calorimeter and muon system

- Milder machine background effects are expected in the hadronic calorimeter and muon detectors, except in the endcap regions closer to the beamline.

- Hadronic calorimeter:
  - both detector designs adopt an HCAL with iron absorber and scintillator pads;
  - both plan to use the Fe absorber as a return yoke for the magnetic field flux → need to define the necessary amount of iron and an adequate support structure to sustain the stress forces.

L. Longo, "MPGD-based Hadronic calorimeter for a future experiment at Muon Collider" on July 20 in Detectors for Future Facilities, R&D, Novel Techniques.

BIB hits in muon detector's endcap



- Muon detectors:
  - no technological choice made yet: information of muon detectors not integrated with tracking (no magnetic field in the muon detectors and not very effective with very high-momentum muons);
  - reconstruction and identification of very high-momentum muons will likely rely on global algorithms that exploit information from all the subdetectors.

C. Aimè, "Designing the muon system for a 10 TeV muon collider" on July 19 in Detectors for Future Facilities, R&D, Novel Techniques.

Summary and outlook

- Two detector concepts for a 10 TeV muon collider are under development and well advanced.

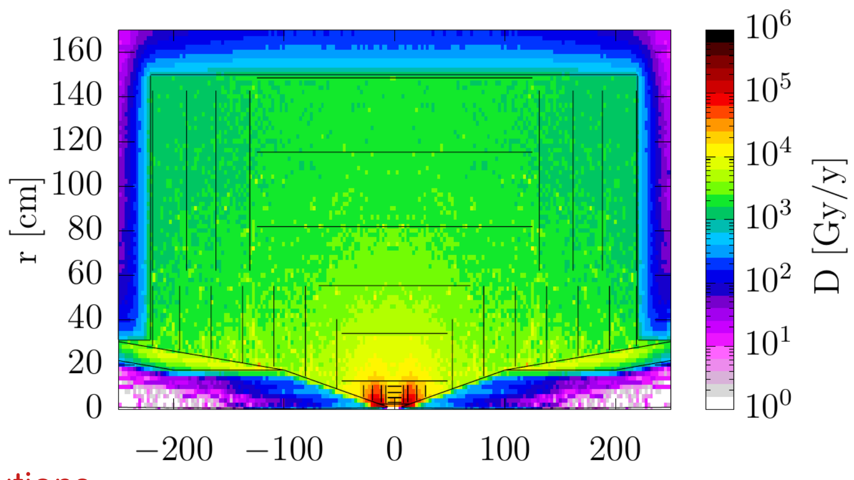
- Preliminary versions of the two detectors, and the machine-detector interface, will soon be finalized to be used in the input studies for the update of the European Strategy for Particle Physics:
  - the ultimate detector performance will be assessed on a set of benchmark physics processes, featuring low- and high-p_T physics objects, with a detailed detector simulation that includes the machine backgrounds from muon decay and incoherent e^+e^- pair production.

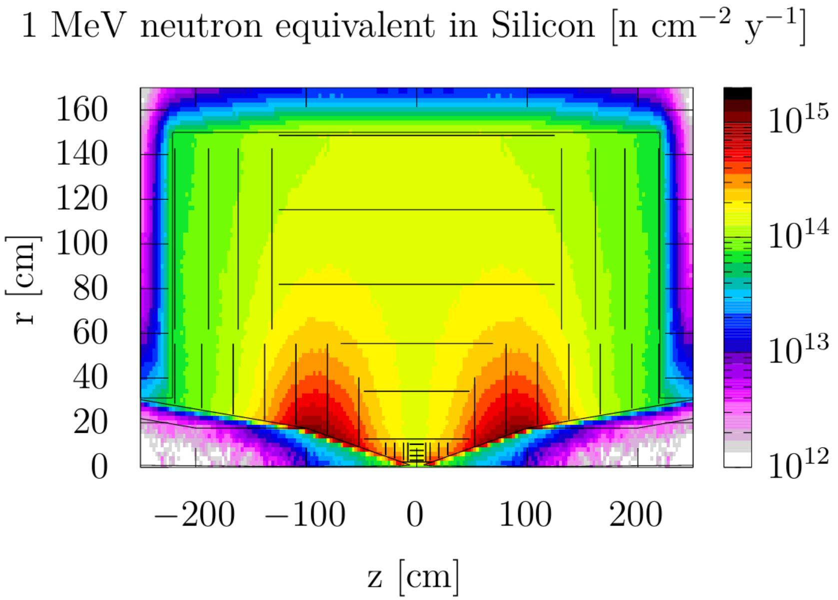
- The status of the IMCC's ongoing studies for a 10 TeV muon collider can be found in:

  C. Accettura et al., "Interim Report for the International Muon Collider Collaboration (IMCC)", arXiv:2407.12450

Backup

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}