Detector design for a multi-TeV muon collider

Massimo Casarsa

INFN-Trieste, Italy

on behalf of the Muon Collider Physics and Detector Group

15th Pisa Meeting on Advanced Detectors
La Biodola, Isola d'Elba, Italy – May 22-28, 2022

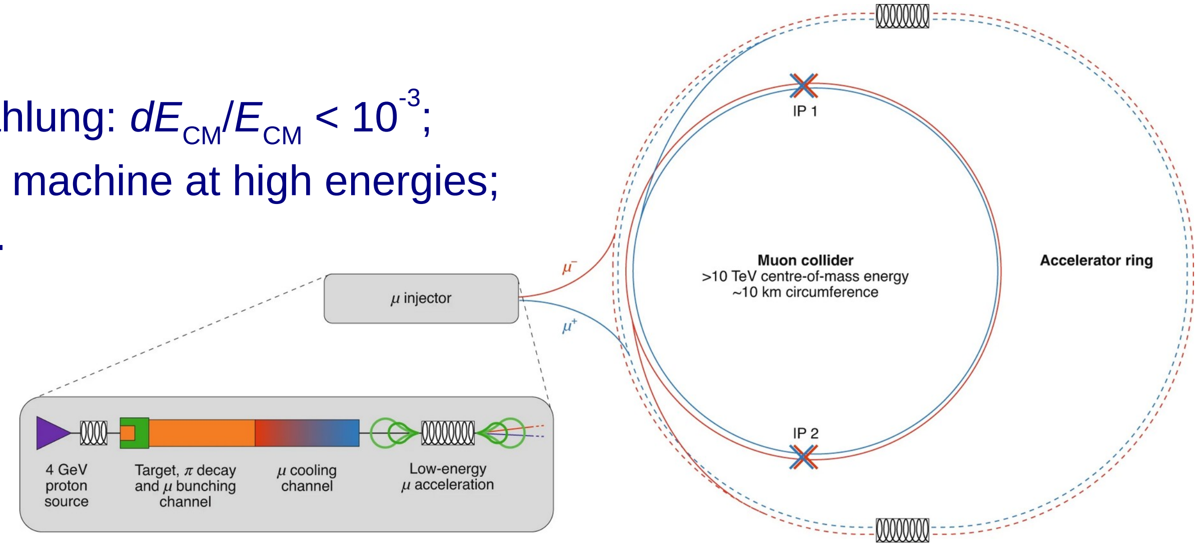
Outline

- Brief introduction to the advantages and challenges of colliding muons:
  - the beam-induced background.
- Impact of the beam-induced background on different detector sub-systems and overview of the background mitigation measures under study.
- Preliminary assessment of the current reconstruction performance in the presence of the beam-induced background with a detector detailed simulation.
- Ongoing R&Ds and conclusions.

Why to collide muons?

- Muons are impervious to synchrotron radiation ($m_\mu/m_e \sim 200$):
  - can be accelerated to a multi-TeV energy range in compact circular machines.
- Muons are fundamental point-like particles:
  - well defined initial state and cleaner final states;
  - all collision energy available in the hard-scattering process.
- Moreover:
  - no significant beam-strahlung: $dE_{CM}/E_{CM} < 10^{-3}$;
  - the most power-efficient machine at high energies;
  - relatively small footprint.

The physics potential of leptonic collisions at several TeV is overwhelming.

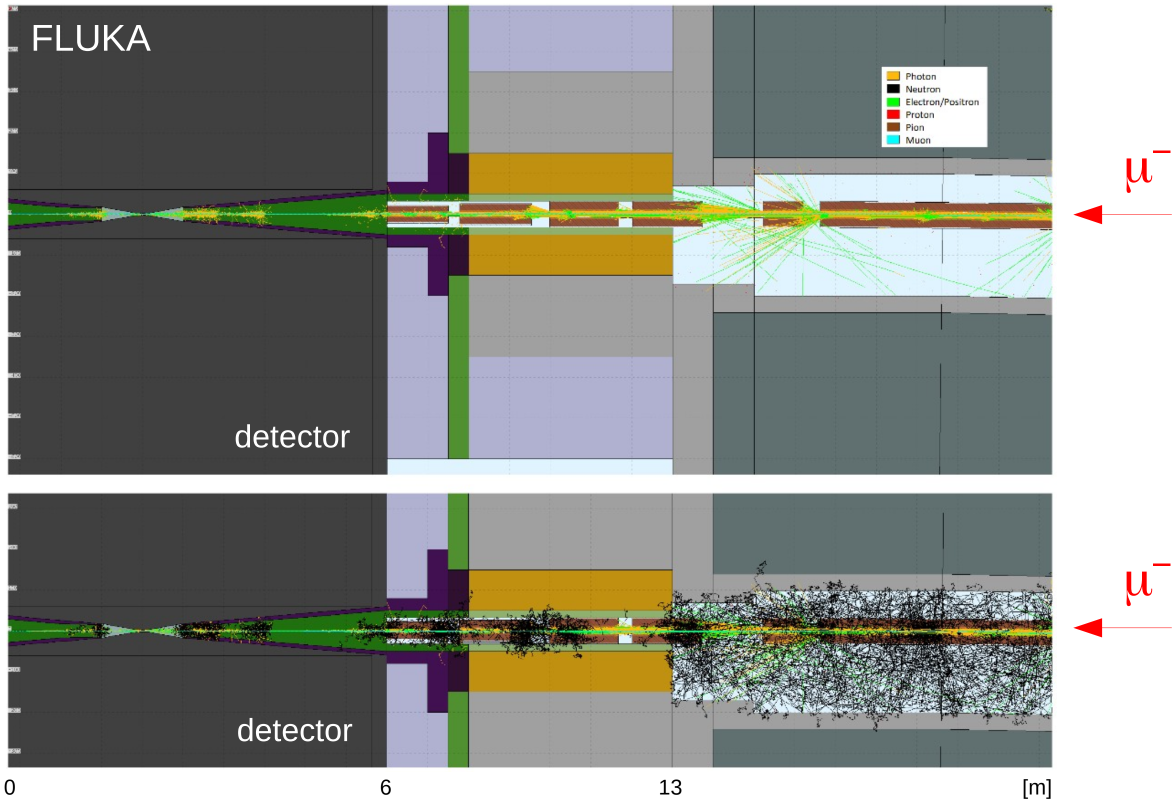


An unprecedented technical challenge

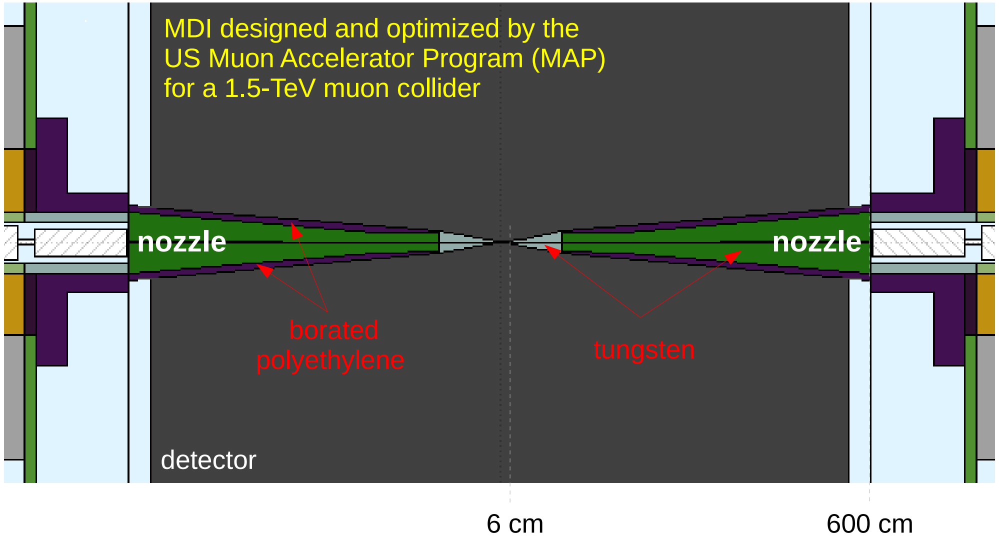
- The unstable nature of muons (τ_μ = 2.2 μs) poses unprecedented technical challenges to every stage of the accelerator complex.
- The decay products of the circulating muons interact with the machine elements generating an intense flux of background particles (expected 4×10^5 decays/m at 1.5 TeV with 2×10^{12} μ/beam).
- O(10^{10}) background particles are estimated to reach the detector at every bunch crossing: beam-induced background (BIB).

Coping with the BIB will represent the main driver of the detector design and the development of the event reconstruction algorithms.

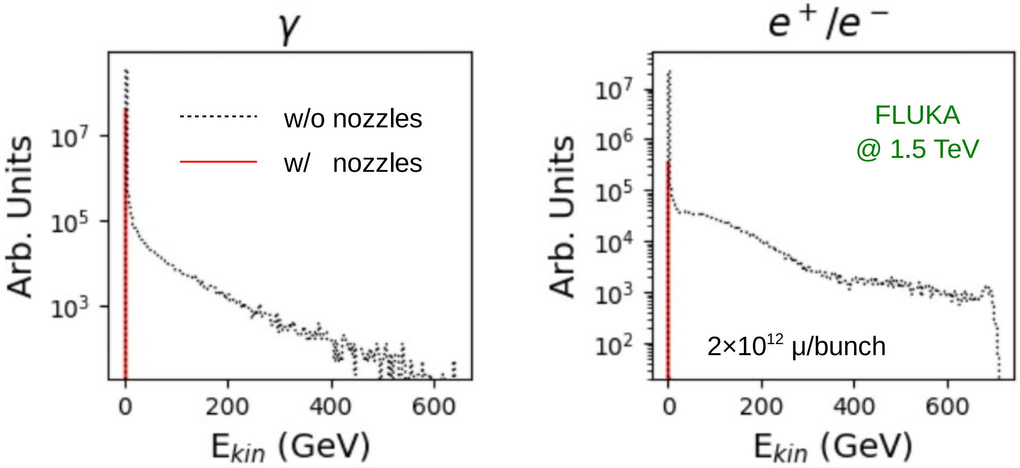
F. Collamati *et al.*, 2021 JINST 15 P11009



MDI: the first line of defense



F. Collamati *et al.*, 2021 JINST 15 P11009

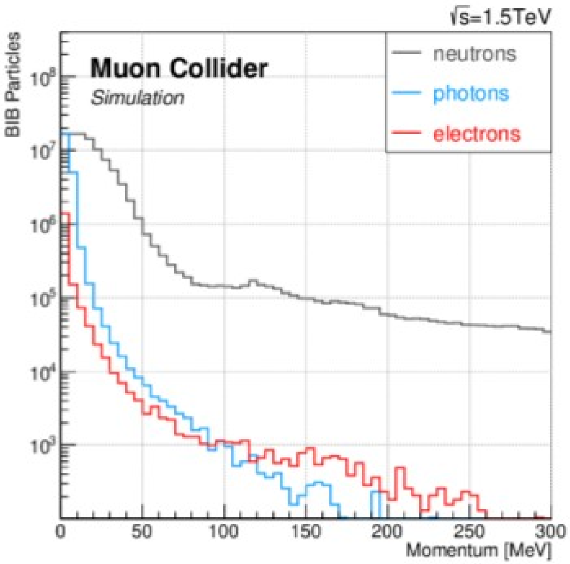


- The machine-detector interface (MDI) features two conical tungsten shieldings ("nozzles") cladded with borated polyethylene, which:
  - reduce the background particle flux into the detector by 2-3 orders of magnitude (together with a suitable configuration of the interaction-region magnets);
  - filter out the high-energy tails of the electromagnetic BIB component;
  - but affects the detector angular acceptance (cone opening angle = 10°).

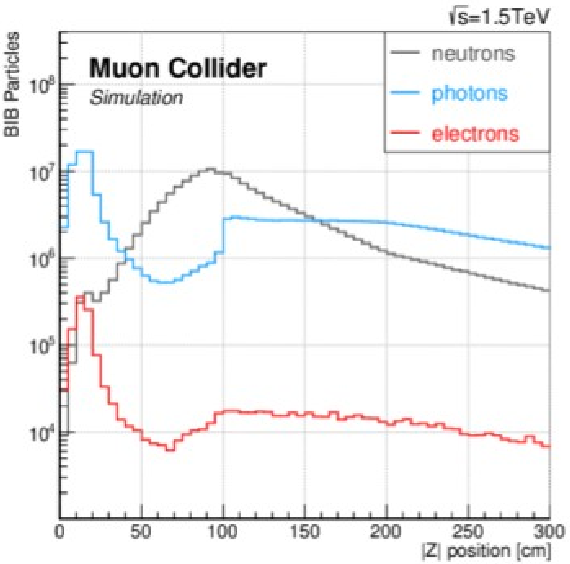
Beam-induced background in the detector

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

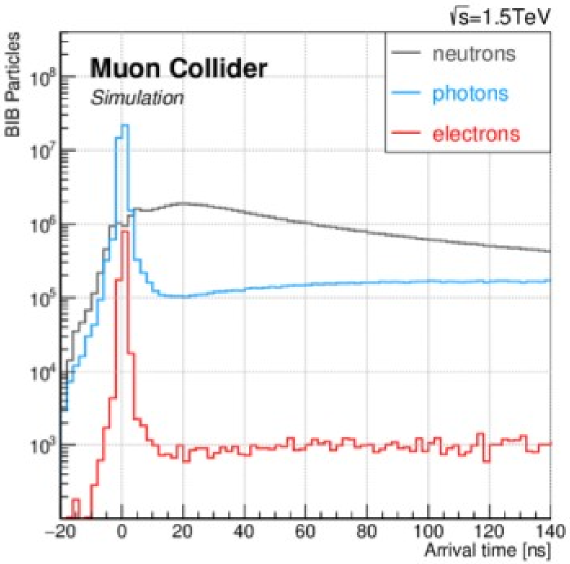
very soft momenta



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

Detector model in the detailed simulation

hadronic calorimeter

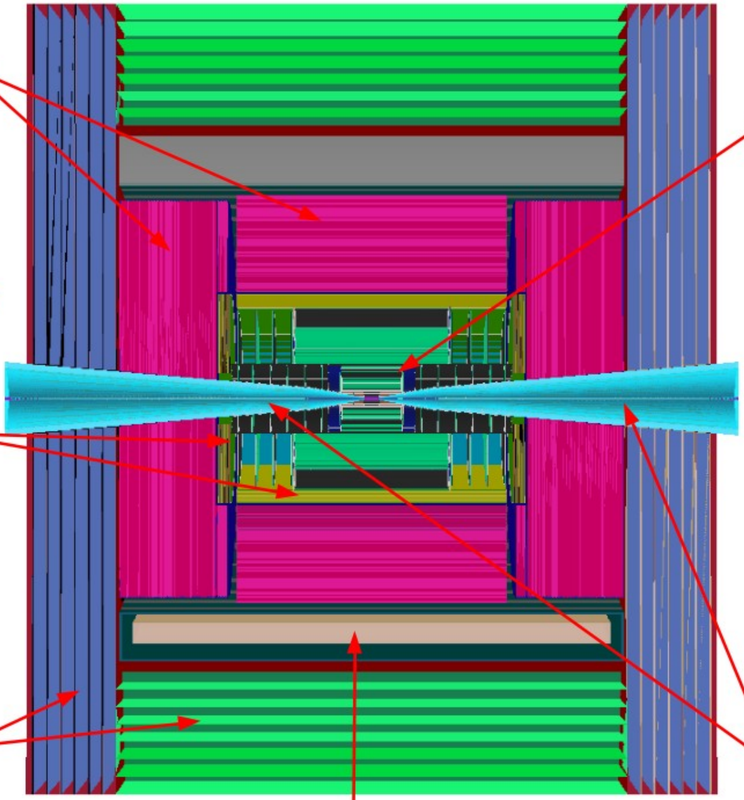
- 60 layers of 19-mm steel absorber + plastic scintillating tiles;
- 30x30 mm^2 cell size;
- 7.5 λ_I.

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.

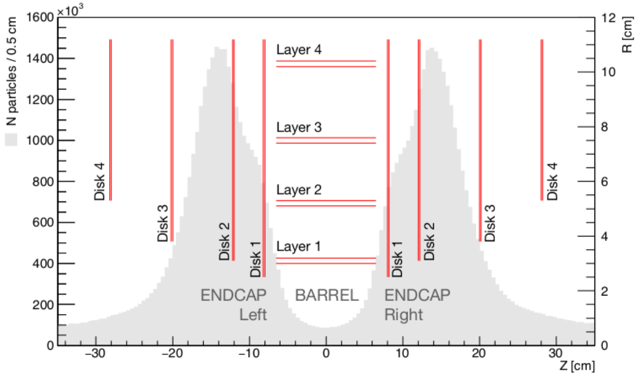
shielding nozzles

- Tungsten cones + borated polyethylene cladding.

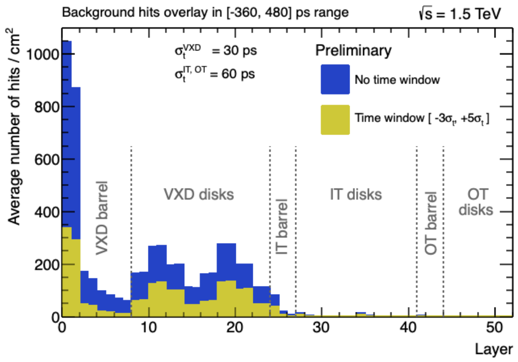
Tracking system

- The closest detector to the beamline and the most affected by the BIB: huge amount of spurious hits produced that makes detector operation and track finding very challenging.
- Several BIB mitigation measures under study, mainly involving dedicated detector designs and on-detector hit filtering, plus state-of-the-art reconstruction algorithms.

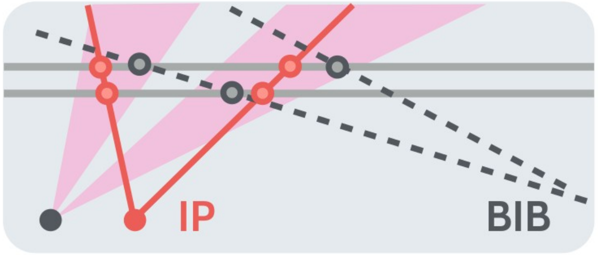
detector design to avoid BIB hot spots



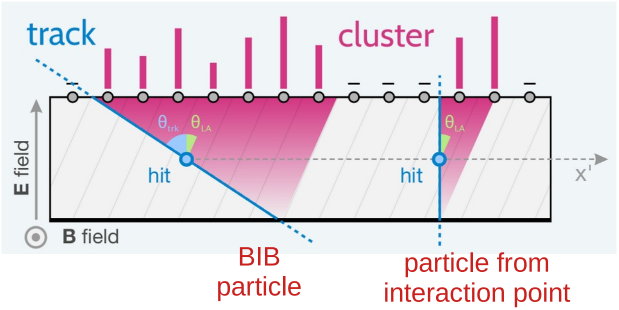
high granularity and high precision timing



interaction-region pointing and sensor crossing angle

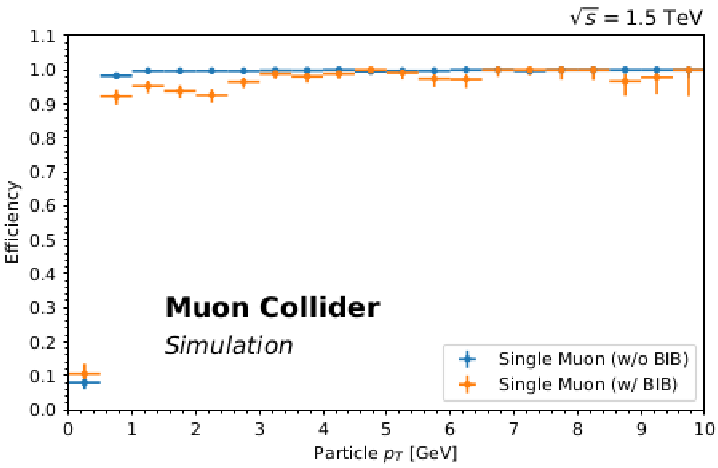


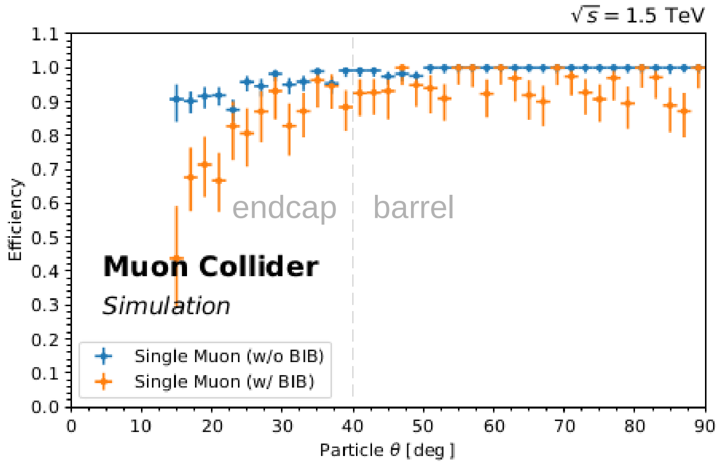
characteristics of the detector response to BIB

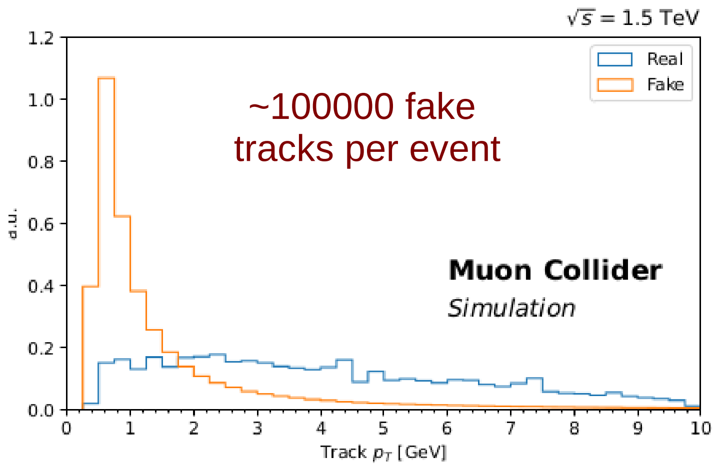


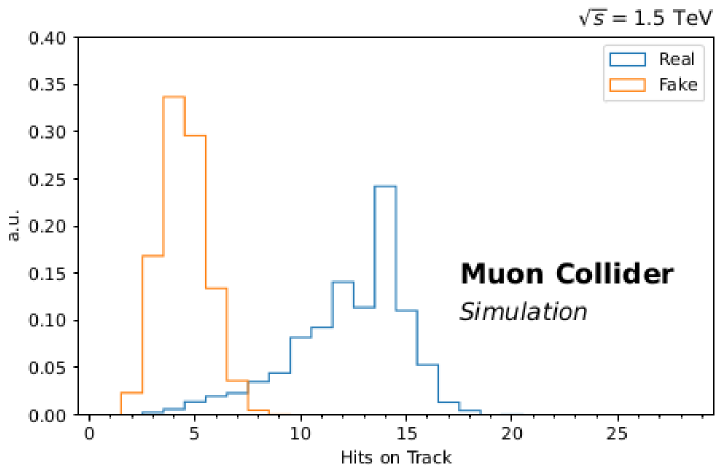
Track reconstruction performance

Track reconstruction performance already satisfactory despite a not-optimized detector and crude background mitigation measures.



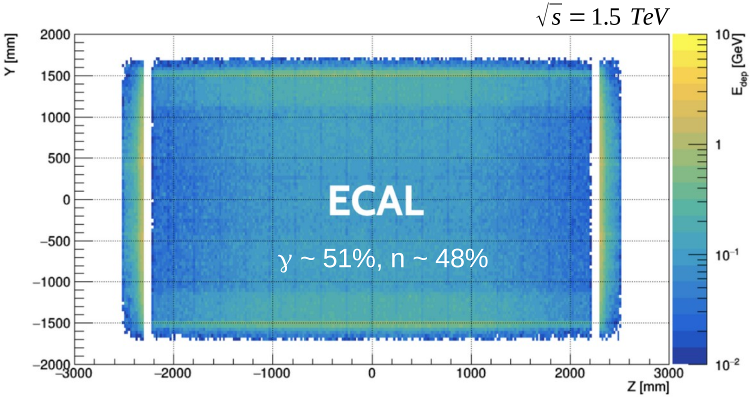


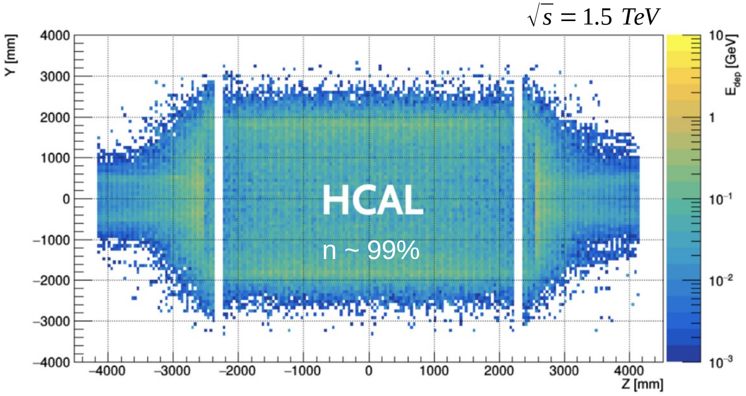


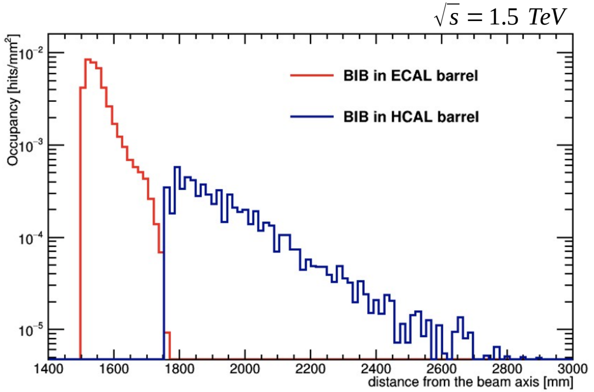


N. Bartosik *et al.*, arXiv:2203.07964

Electromagnetic and hadronic calorimeters

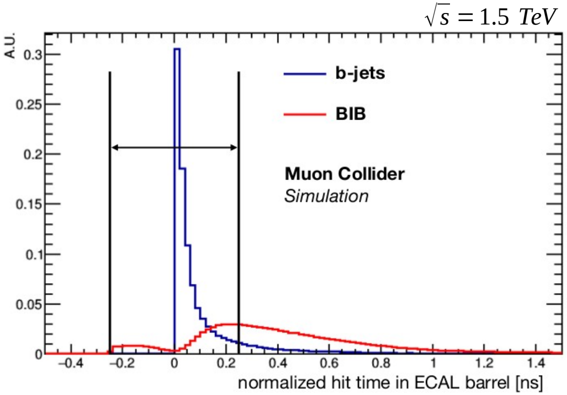




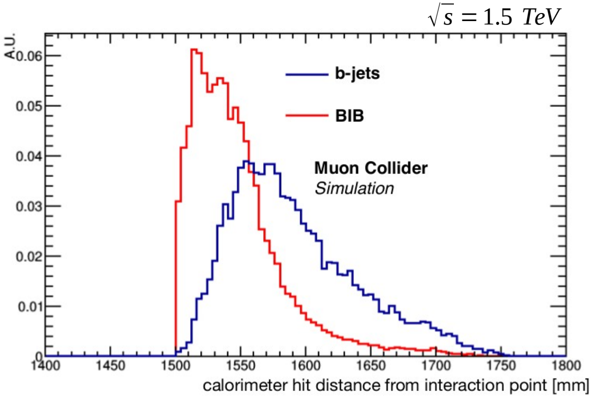


- Energy deposited by BIB in the calorimeters ~uniformly distributed.
- Timing, very high granularity, fine longitudinal segmentation and state-of-the-art Particle Flow algorithms needed to cope with BIB.

high granularity and high precision timing

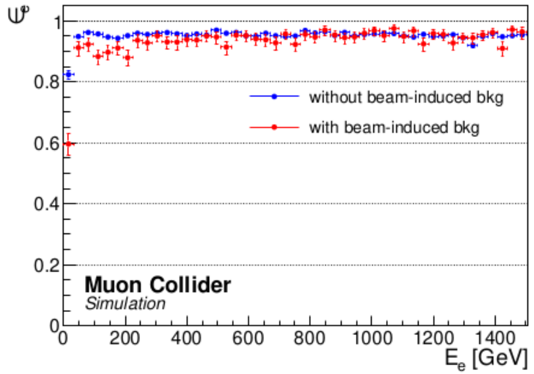


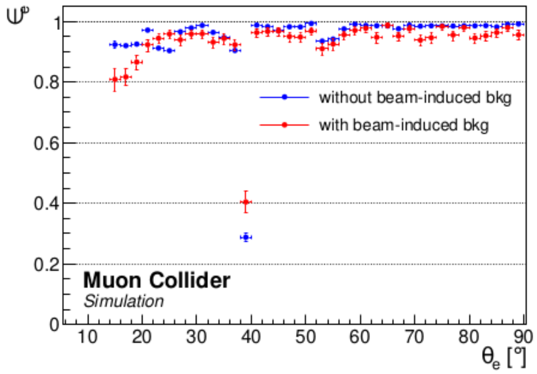
fine longitudinal segmentation



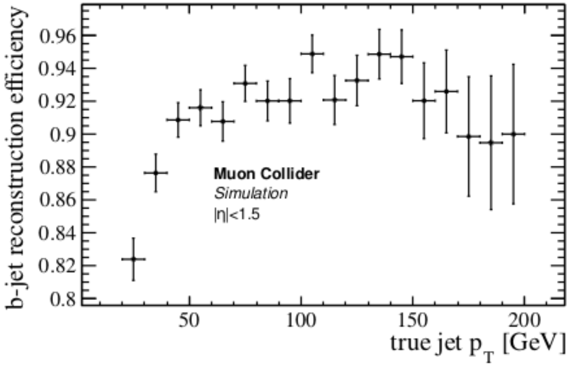
Examples of physical objects reconstruction

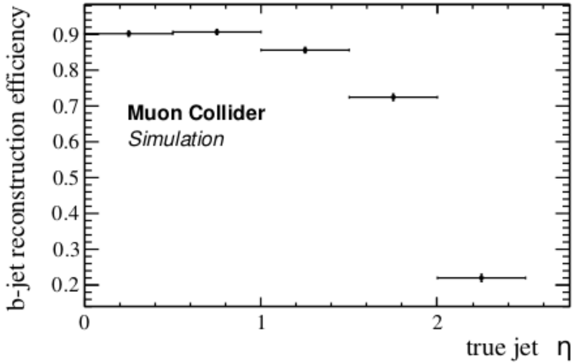
electrons



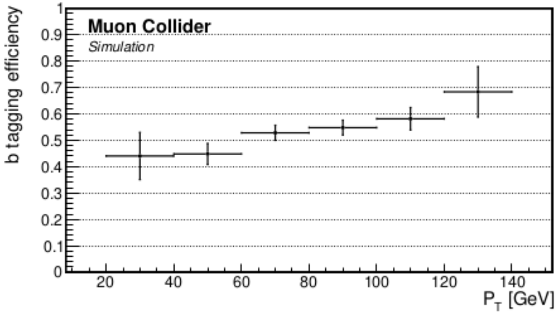


jets

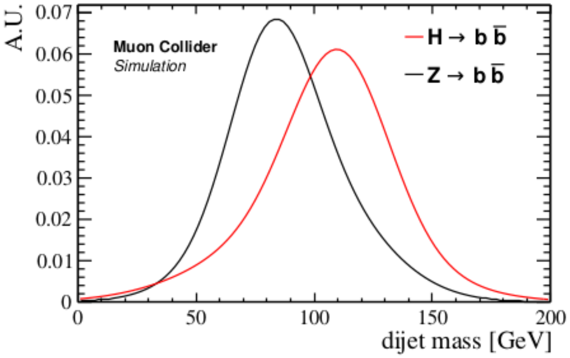




b-jet tagging



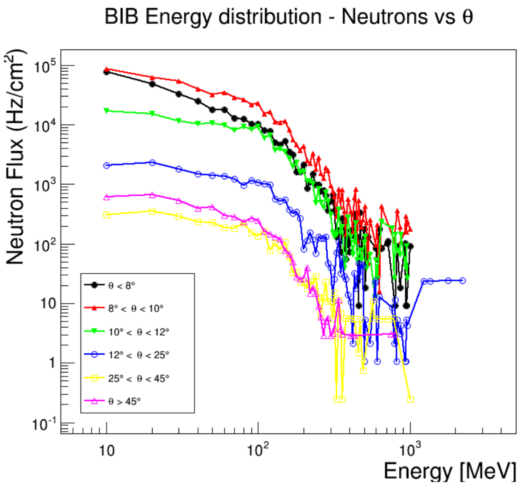
di-jet mass resolution

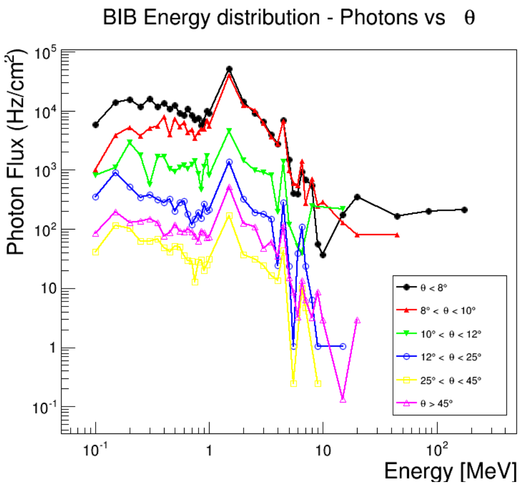


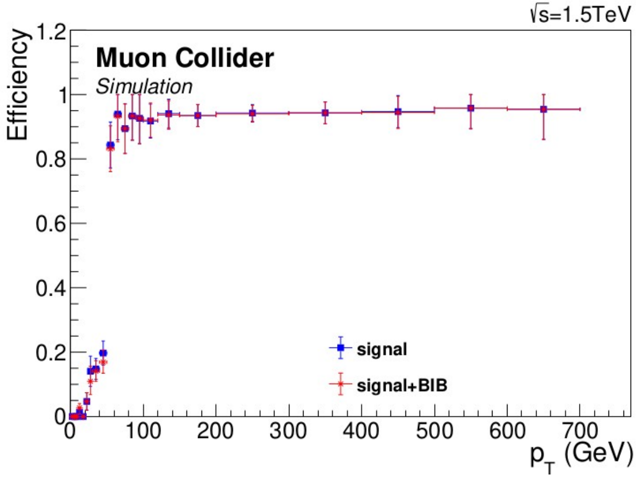
N. Bartosik *et al.*, arXiv:2203.07964

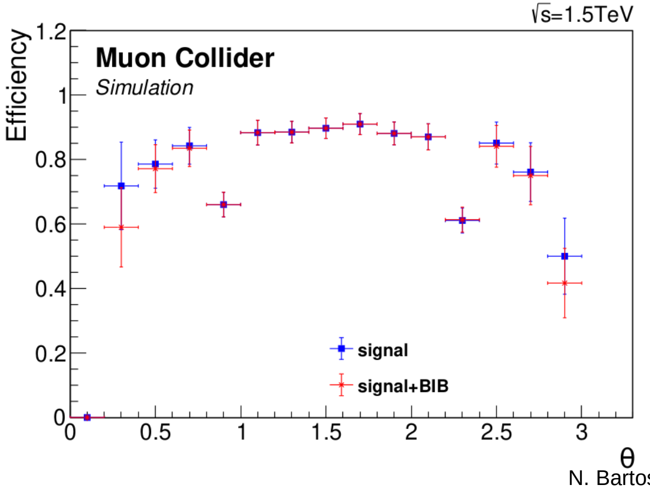
Muon detector

- In the outermost region of the detector, less severe BIB levels.
- The biggest effects in the endcap regions close to the beamline.
- Neutrons and photons main background components.









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

Radiation levels in the detector

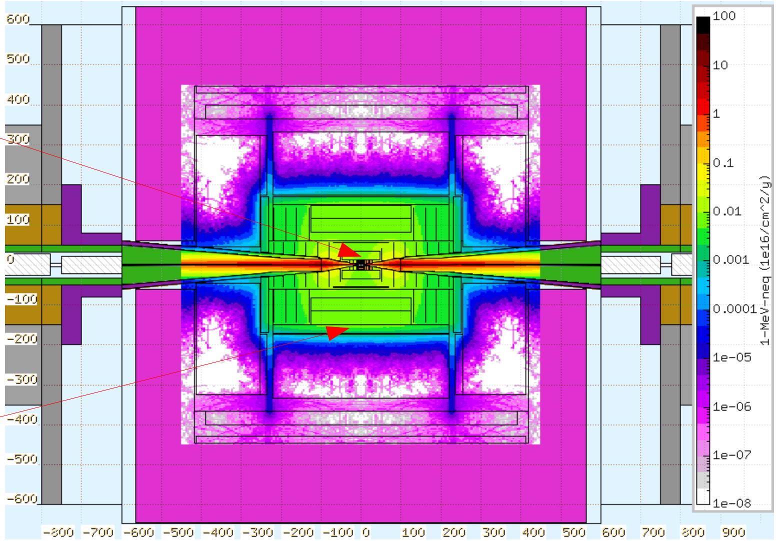
- A muon collider detector must be radiation hard.
- Radiation levels in the detector will strongly depend on the collider operation mode.

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

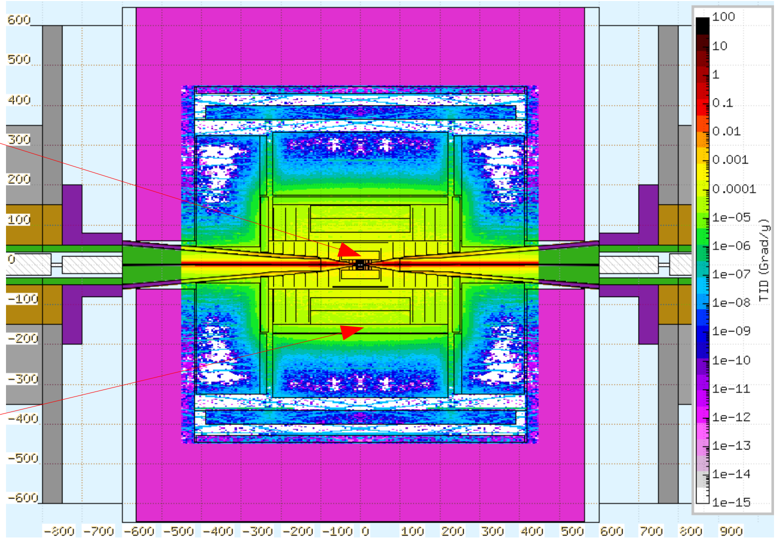
~10^{14}-10^{15} cm^{-2} y^{-1}



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

total ionizing dose per year

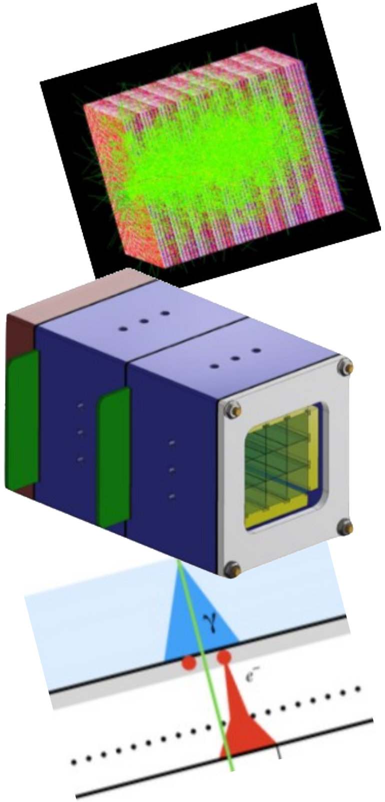
~10^4 Gy/y



~10^3 Gy/y

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

Ongoing hardware R&Ds



- The preliminary results with the detailed simulation are fostering an increasing number of dedicated hardware R&Ds aiming to explore alternative technology solutions to meet the muon collider requirements.
- In this conference:
  - A. Stamerra: “Design and simulation of a MPGD-based hadronic calorimeter for a Muon Collider” in the Calorimetry Session on Wed. 25;
  - D. Paesani: “CRILIN: a semi-homogeneous Crystal Calorimeter for a future Muon Collider” in the Calorimetry – Poster Session on Wed. 25;
  - C. Aimè: “Muon detector for a Muon Collider” in the Gas Detector – Poster Session on Fri. 27.

Conclusions

- 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 physical program.
- At a future muon collider, detectors are expected to operate under severe background conditions, that will represent the main driver of the detector design, the technological choices and the event reconstruction algorithms.
- Nonetheless, preliminary studies with a detector detailed simulation prove already a satisfactory reconstruction performance for the most relevant high-p_T physical objects, despite a nonoptimal detector and very crude reconstruction algorithms.
- Future hardware R&Ds and improved software algorithms, mostly in synergy with ongoing HL-LHC and other future collider efforts, are foreseen to significantly enhance the detector performance.

Snowmass 2021 White Papers

- C. Aimè *et al.*, "Muon Collider Physics Summary", arXiv:2203.07256;
- J. De Blas *et al.*, "The physics case of a 3 TeV muon collider stage", arXiv:2203.07261;
- D. Stratakis *et al.*, "A Muon Collider Facility for Physics Discovery", arXiv:2203.08033;
- N. Bartosik *et al.*, "Simulated Detector Performance at the Muon Collider", arXiv:2203.07964;
- S. Jindariani *et al.*, "Promising Technologies and R&D Directions for the Future Muon Collider Detectors", arXiv:2203.07224.

Snowmass 2021