MUSIC: a detector concept for 10 TeV $\mu^+\mu^-$ collisions

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on behalf of the International Muon Collider Collaboration

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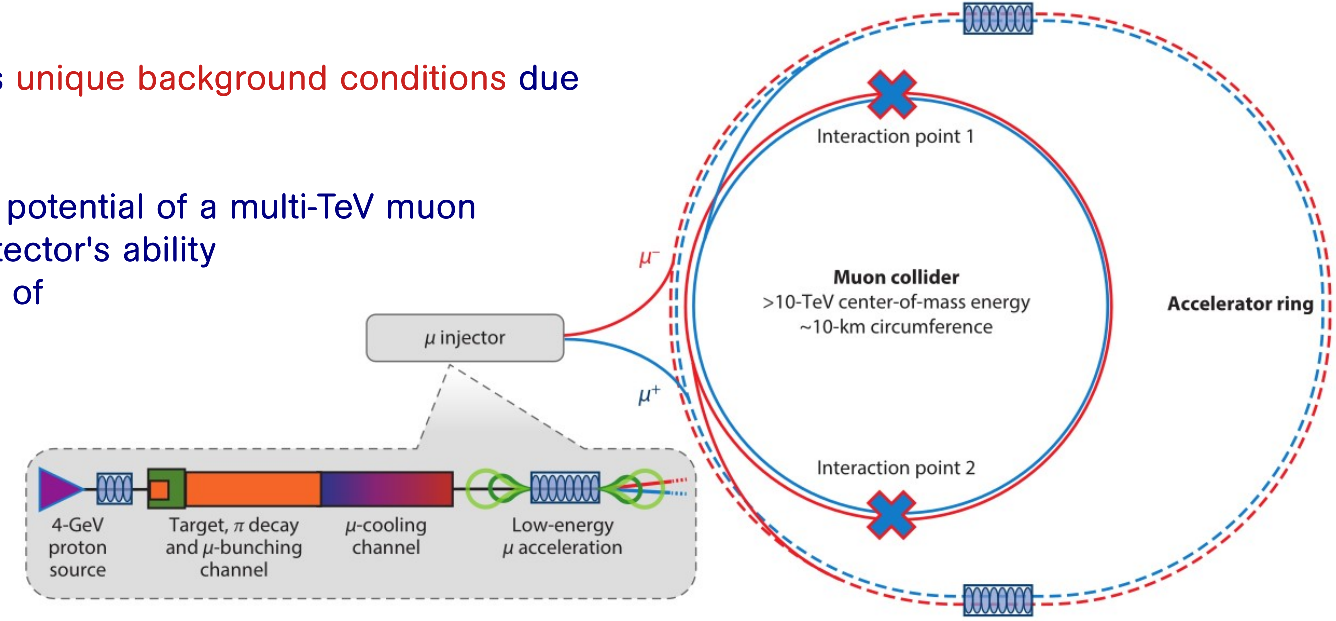
Why a muon collider?

- A muon collider represents the most efficient and effective way to get leptonic collisions at multi-TeV center-of-mass energies in a relatively compact circular machine.
- Multi-TeV $\mu^+\mu^-$ collisions will open the door to an extraordinary physics program, providing high-precision tests of the Standard Model in a previously unexplored energy regime, probing the structure of the Higgs sector and the shape of the Higgs potential, and enabling both direct and indirect searches for new physics.
- However, a muon collider presents unique background conditions due to the unstable nature of muons.
- The full exploitation of the physics potential of a multi-TeV muon collider will ultimately lie in the detector's ability to cope with unprecedented levels of machine-induced backgrounds.



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;
  - central energetic physics objects from decays of possible new massive states;
  - less conventional experimental signatures: disappearing tracks, displaced leptons, displaced photons or jets, ...

C. Accettura et al., arXiv:2504.21417

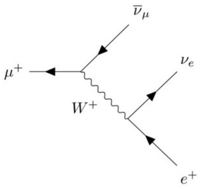
Requirement	Baseline	Aspirational
Angular acceptance $\eta = -\log(\tan(\theta/2))$	$\lvert\eta\rvert < 2.5$	$\lvert\eta\rvert < 4$
Minimum tracking distance [cm]	~ 3	< 3
Forward muons ($\eta > 5$)	tag	$\sigma_p/p \sim 10\%$
Track σ_{p_T}/p_T^2 [GeV^{-1}]	4×10^{-5}	1×10^{-5}
Photon energy resolution	$0.2/\sqrt{E}$	$0.1/\sqrt{E}$
Neutral hadron energy resolution	$0.4/\sqrt{E}$	$0.2/\sqrt{E}$
Timing resolution (tracker) [ps]	$\sim 30 - 60$	$\sim 10 - 30$
Timing resolution (calorimeters) [ps]	100	10
Timing resolution (muon system) [ps]	~ 50 for $\lvert\eta\rvert > 2.5$	< 50 for $\lvert\eta\rvert > 2.5$
Flavour tagging	b vs c	b vs c, s-tagging
Boosted hadronic resonance identification	h vs W/Z	W vs Z

- Constraints from the machine and machine-detector interface design: final focusing quadrupoles at ± 6 m from the interaction point.

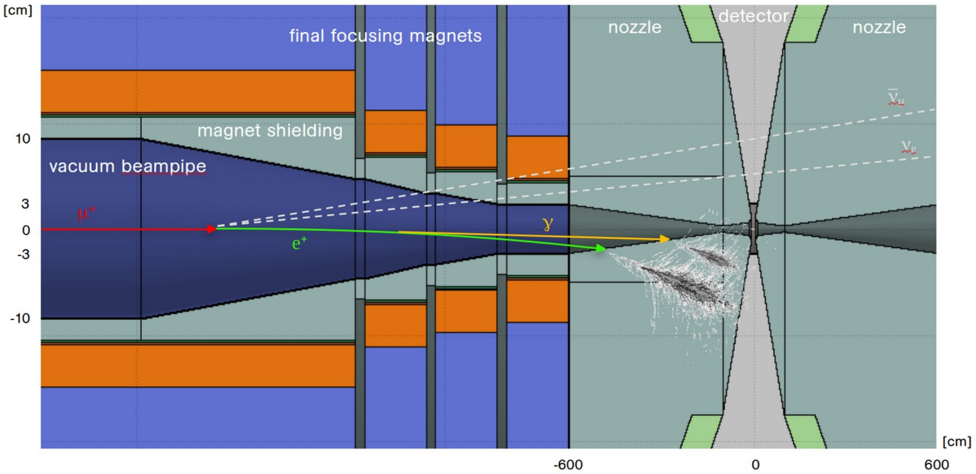
- Machine background conditions and necessary mitigation measures.

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.

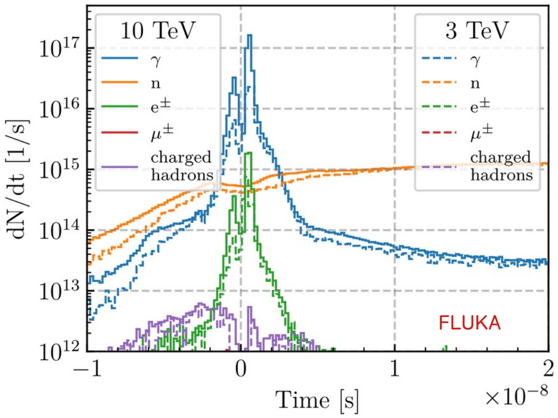
Background from muon decays



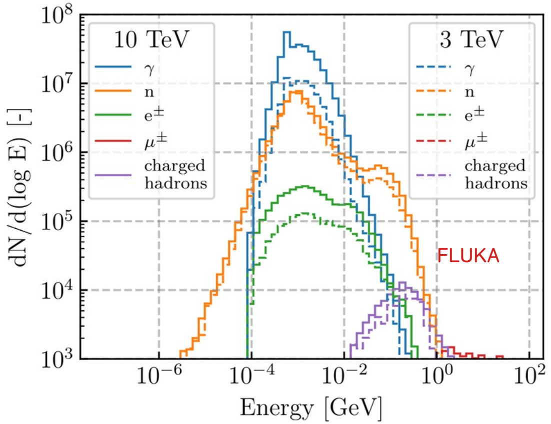
nozzle design and interaction-region lattice optimized for 10 TeV



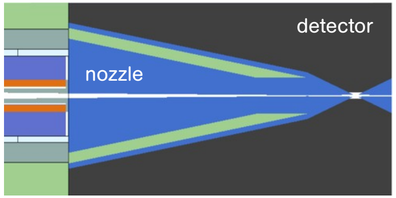
arrival time of BIB particles at the detector



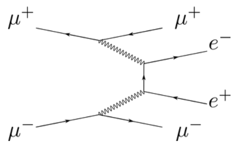
energy of the BIB particles within [-1, 15] ns

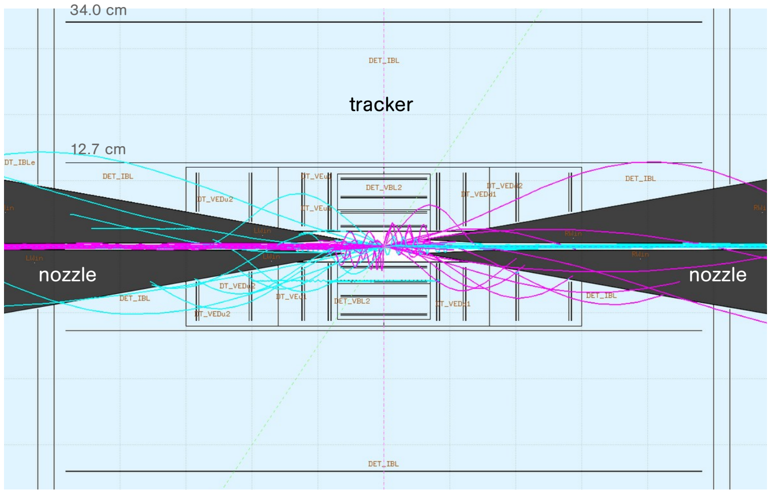


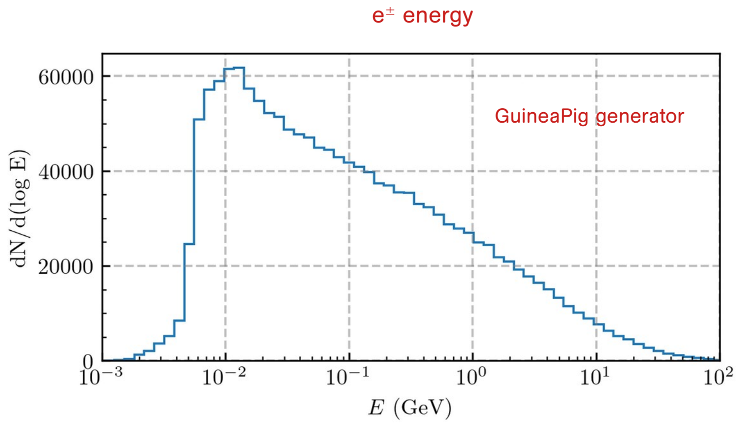
- To shield the detector from the high-energy primary products of muon decays, conical tungsten nozzles are placed along the beamline.
- Nonetheless, a portion of the resulting particle showers leaks into the detector, generating the beam-induced background (BIB):
  - soft particles and mostly out of time w.r.t. the bunch crossing;
  - the dominant source of background in the detector.



Bkg from incoherent e^+e^- pair production







- Background from incoherent e^+e^- pairs produced at bunch crossing (IPP):
  - relatively high-energy $e^{\pm}$, which enter the detector at the interaction point in time with the bunch crossing;
  - 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.

particles entering the detector at each bunch crossing

10 TeV	BIB	IPP
Photons	9.9E+07	4.0E+06
Neutron	1.1E+08	1.3E+05
e+/e-	1.2E+06	2.1E+05

MUSIC detector concept

MUSIC = MUon System for Interesting Collisions

hadronic calorimeter

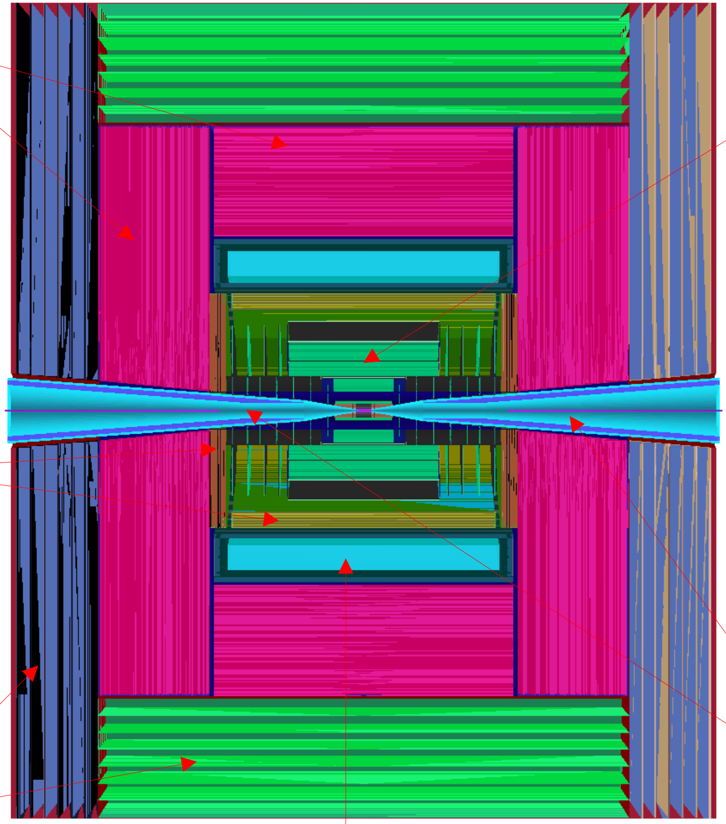
- sampling calorimeter with 70 layers of 2-cm iron absorber + 3 x 3 cm^2 plastic scintillating tiles
- timing with σ_t = 100 ps
- 7 nuclear interaction lengths
- serves as magnetic field return yoke

electromagnetic calorimeter (CRILIN)

- semi-homogeneous PbF_2 crystal calorimeter with longitudinal segmentation
- 6 layers of 1 x 1 x 4 cm^3 crystals
- timing with σ_t = 100 ps
- 26.5 X_0

muon detectors

- 7-barrel, 6-endcap RPC layers
- 3 x 3 cm^2 cell size
- timing with σ_t = 100 ps



superconducting solenoid (5T)

tracking system

- Vertex Detector
  - 5 barrel layers at R = 2.9 - 10.1 cm and 4 + 4 endcap disks at |z| = 18.0 - 36.6 cm
  - 25 x 25 μm^2 pixel Si sensors
  - timing with σ_t = 30 ps
- Inner Tracker
  - 3 barrel layers at R = 16.1 - 55.4 cm and 7 + 7 endcap disks at |z| = 60.7 - 219.0 cm
  - 50 μm x 1 mm macropixel Si sensors
  - timing with σ_t = 60 ps
- Outer Tracker
  - 3 barrel layers at 81.9 - 148.6 cm and 4 + 4 endcap disks at |z| = 141.0 - 219.0 cm
  - 50 μm x 1 mm macropixel Si sensors
  - timing with σ_t = 60 ps

shielding nozzles

- tungsten cones + borated polyethylene cladding

MUSIC detector performance

- The performance of the MUSIC detector has been evaluated using a GEANT4-based full simulation:
  - impact of machine-induced backgrounds on detector response using background-only samples (BIB + IPP);
  - reconstruction efficiencies and parameter resolutions for key physics objects (tracks, muons, photons, electrons, jets) using single particle and dijet samples, with BIB and IPP overlaid on an event-by-event basis.

    ➔ some representative examples in the following slides

- Detector performance was further assessed through full-fledged physics analyses aimed at estimating the sensitivity (given the current detector configuration and reconstruction algorithms) on the Higgs boson production cross sections for the channels $H \rightarrow b\bar{b}$, $H \rightarrow WW^*$, and $HH \rightarrow b\bar{b}b\bar{b}$, as well as on the Higgs boson trilinear self-coupling, using full simulation with BIB and IPP overlaid on both signal and physics background events.

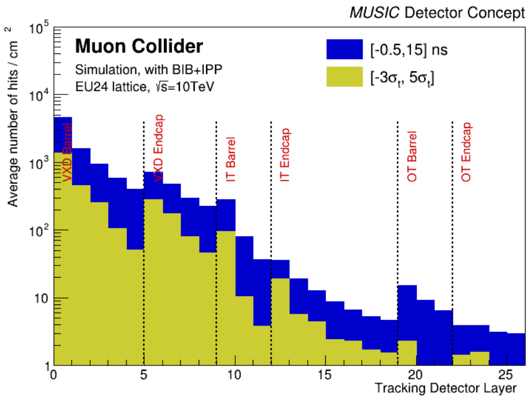
    ➔ further details in "Higgs physics at a 10 TeV Muon Collider" on July 11 in T08 – Higgs Physics

- P. Andreetto et al., "Performance study of the MUSIC detector in $\sqrt{s}$ = 10 TeV muon collisions",Contribution #32 to the 2026 ESPP Update
- P. Andreetto et al., "Sensitivity study on $H \rightarrow b\bar{b}$, $H \rightarrow WW^*$, and $HH \rightarrow b\bar{b}b\bar{b}$ cross sections and trilinear Higgs self-coupling with the MUSIC detector in $\sqrt{s}$ = 10 TeV muon collision", Contribution #184 to the 2026 ESPP Update

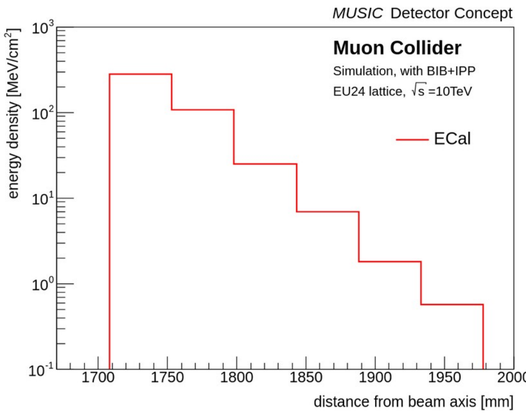
Machine-induced bkg impact on the detector

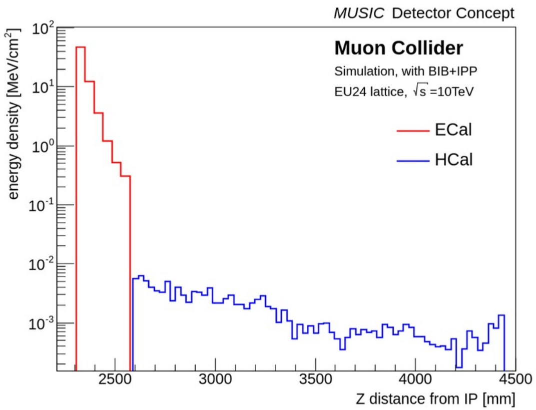
- The tracking system and ECAL are the most affected by the machine-induced backgrounds.

average density of background hits per layer in the tracking system



average energy from background in the ECAL layers



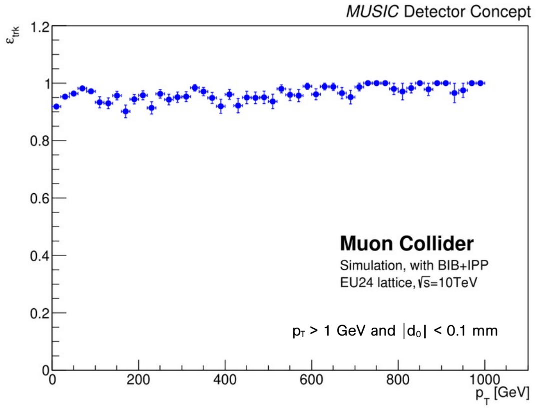


- Huge number of spurious hits from background.
- Mitigation measures:
  - high granularity;
  - hit timing requirements;
  - strong magnetic field;
  - optimized track finding algorithm.

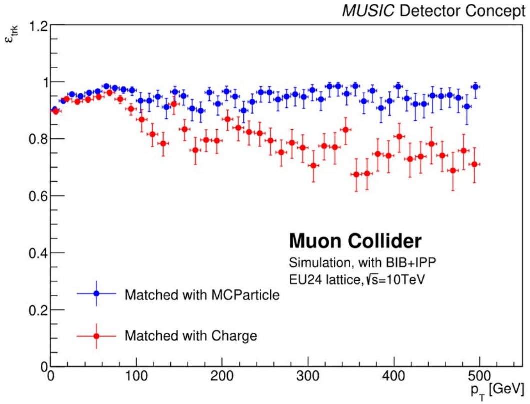
- Diffuse uniform background mostly from soft photons.
- Mitigation measures:
  - high granularity and longitudinal segmentation;
  - hit timing requirements;
  - optimized hit reconstruction algorithm in different ECAL regions and layers.

Tracks and muons

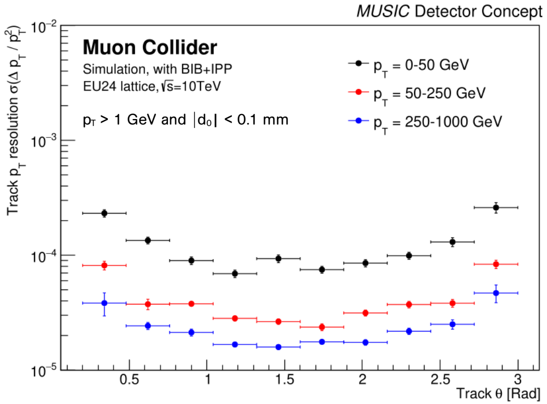
track reconstruction efficiency vs true muon p_T



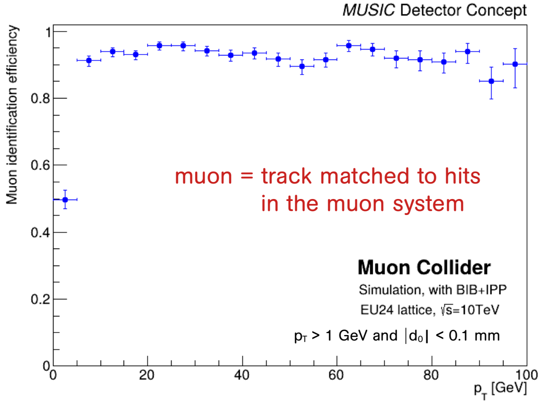
correct charge assignment vs true muon p_T



transverse momentum resolution vs true muon θ



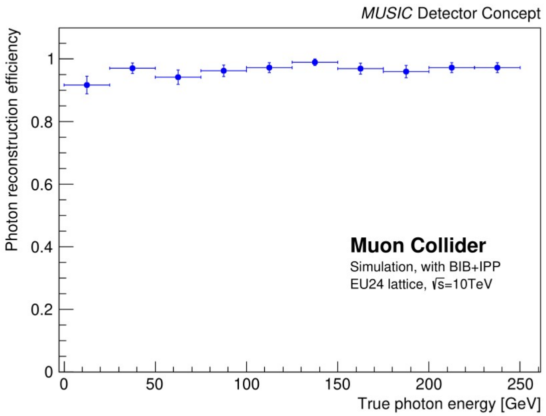
muon identification efficiency vs true muon p_T



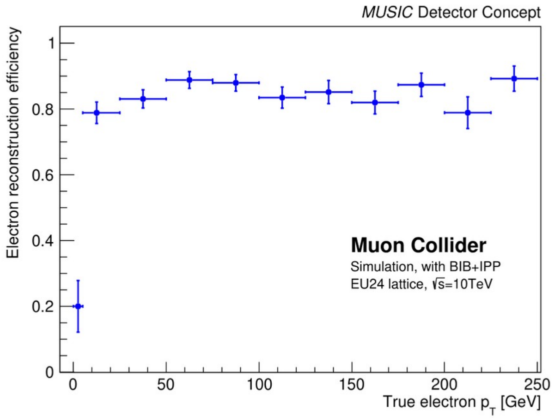
single muon samples

Photons and electrons

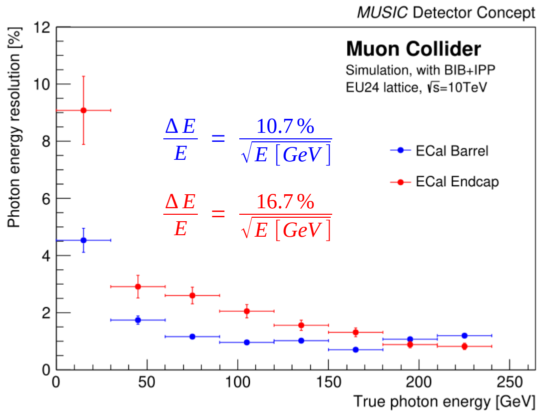
photon reconstruction efficiency vs true energy



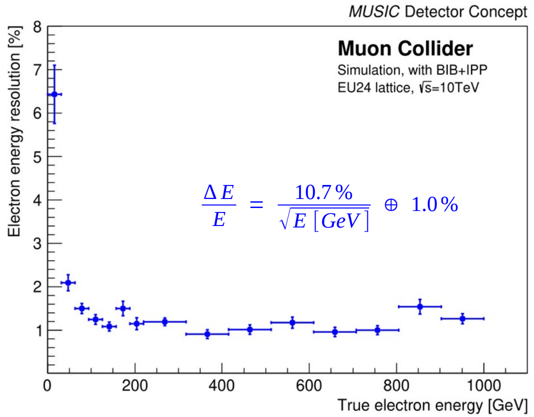
electron reconstruction efficiency vs true p_T



photon energy resolution vs true energy



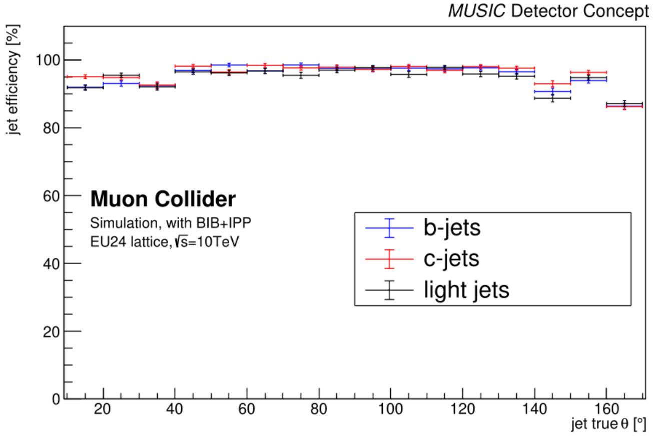
electron energy resolution vs true energy



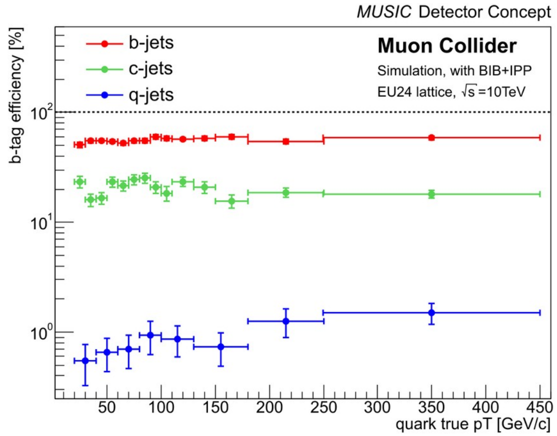
single photon and electron samples

Jets

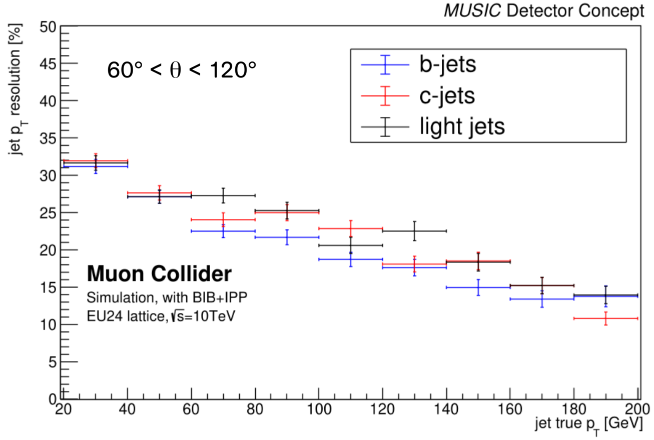
jet reconstruction efficiency vs true jet θ



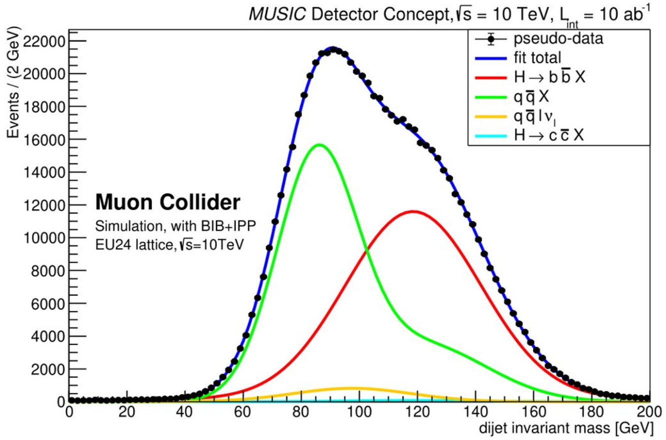
b tagging efficiency vs true quark p_T



jet p_T resolution vs true jet p_T



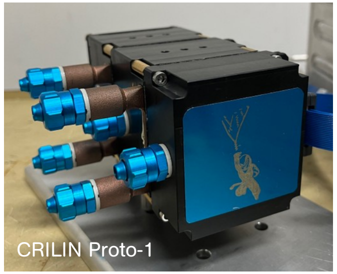
dijet invatiant mass in the channel $\mu^+\mu^- \to H\nu_\mu\bar{\nu}_\mu \to b\bar{b}\nu_\mu\bar{\nu}_\mu$

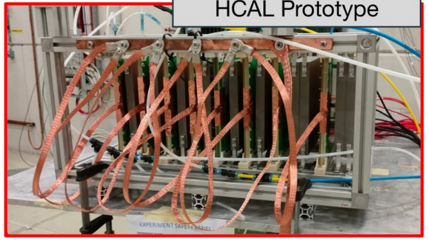


dijet samples

Ongoing R&D efforts

- In parallel with the full-simulation studies, dedicated R&D efforts are underway to identify the most suitable technologies for the muon collider environment:
  - CRILIN (CRystal calorimeter with Longitudinal InformatioN): a semi-homogeneous electromagnetic calorimeter consisting of multiple layers of PbF_2 crystal matrices;
    - ➔ E. Di Meco, "Crilin: a highly granular semi-homogeneous crystal calorimeter with excellent timing for future colliders" on July 10 in T11-Detectors
  - MPGD-HCAL: a sampling hadronic calorimeter with iron absorber and Micro-Pattern Gaseous Detectors (MPGD) as the active layer;
    - ➔ R. Venditti, "MPGD-HCAL for future collider experiments: status and perspectives" on July 10 in T11-Detectors
  - R&D on GEM and PICOSEC detectors for the muon system: C. Aimè et al., "Designing the muon system for a 10 TeV muon collider", PoS ICHEP2024 (2025) 1109.
- All three R&D projects are at the prototype stage:
  - several testbeam campaigns in the past years to evaluate and characterize different detector configurations, assess the detector performance, and validate the simulations.


CRILIN Proto-1

HCAL Prototype



PICOSEC

Summary

- A new detector concept, MUSIC (MUon System for Interesting Collisions), has been developed, specifically designed for 10 TeV $\mu^+\mu^-$ collisions.

- The MUSIC detector concept is fully integrated into the software framework of the International Muon Collider Collaboration and has been extensively used for detector studies and full-fledged Higgs boson analyses, based on full simulation that includes the dominant machine-induced backgrounds from muon decays and incoherent e^+e^- pair production.

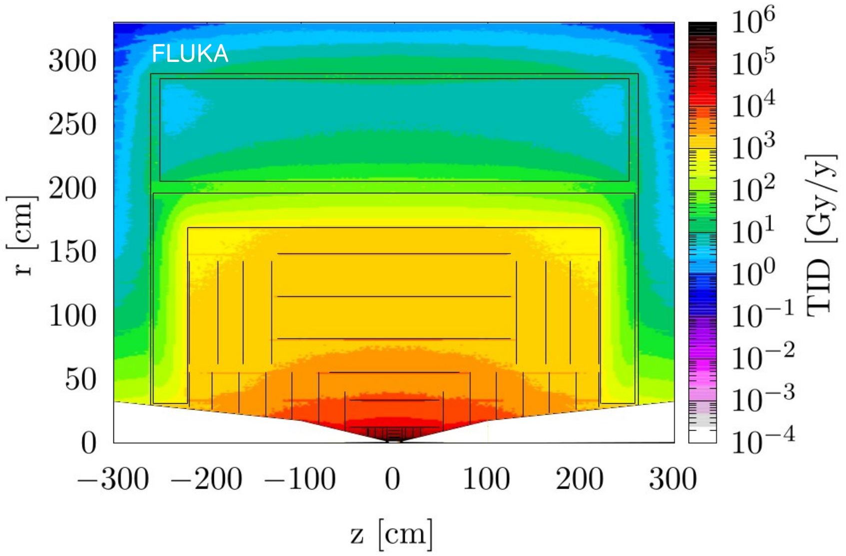
- The results demonstrate promising reconstruction performance for key physics objects and competitive sensitivity for measurements in the Higgs sector, even under challenging background conditions, highlighting the detector's strong potential for high-energy muon collider experiments.

- In parallel with the full simulation studies, R&D efforts (CRILIN, MPGD-HCAL, PICOSEC) are underway to identify the most suitable technologies to meet the muon collider requirements.

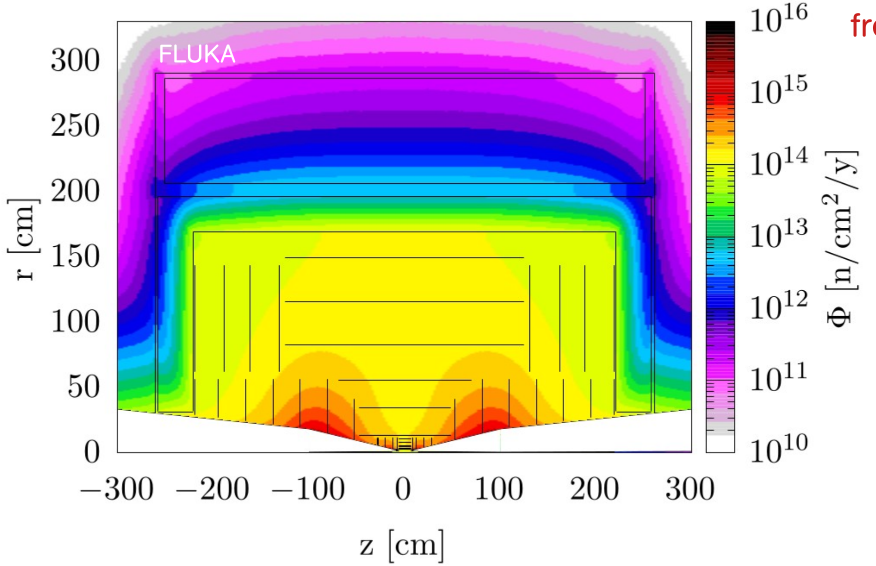
Backup

Radiation environment at √s = 10 TeV

total ionizing dose per year



1-MeV neutron-equivalent fluence in Si per year



only contributions from muon-decay background

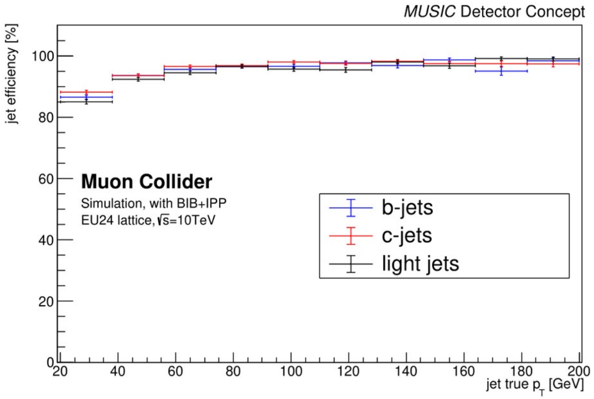
C. Accettura et al., arXiv:2504.21417

Component	Dose [kGy]	1 MeV neutron-equivalent fluence (Si) [10^{14} n/cm^2]
Vertex (barrel)	1000	2.3
Vertex (endcaps)	2000	8
Inner trackers (barrel)	70	4
Inner trackers (endcaps)	30	10
ECAL	1.4	1

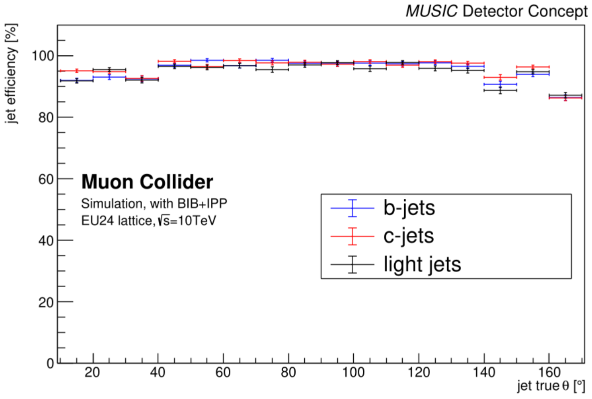
Assumptions:
- collision energy: 10 TeV;
- collider circumference: 10 km;
- muons per bunch: 1.8 x 10^{12};
- beam injection frequency: 5 Hz;
- days of operation per year: 139.

Jet reconstruction performance

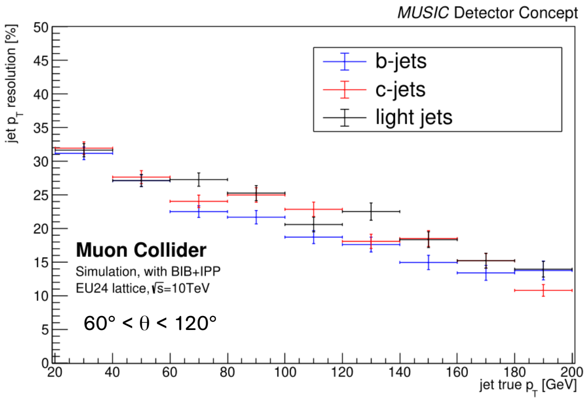
jet reconstruction efficiency vs true jet p_T

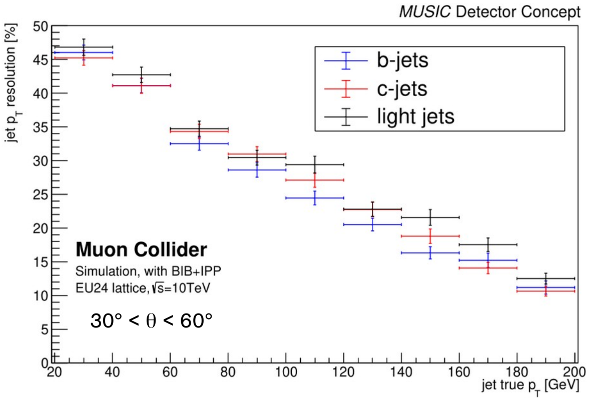


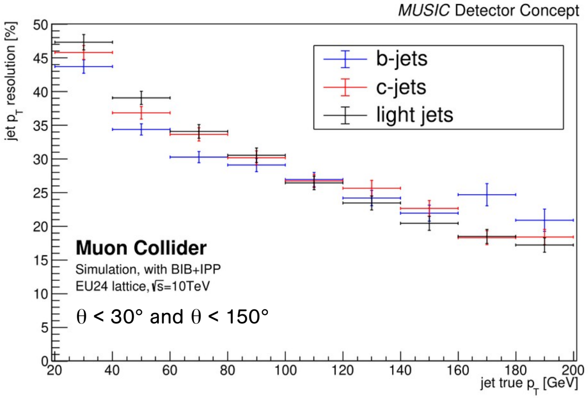
jet reconstruction efficiency vs true jet θ



jet p_T resolution vs true jet p_T

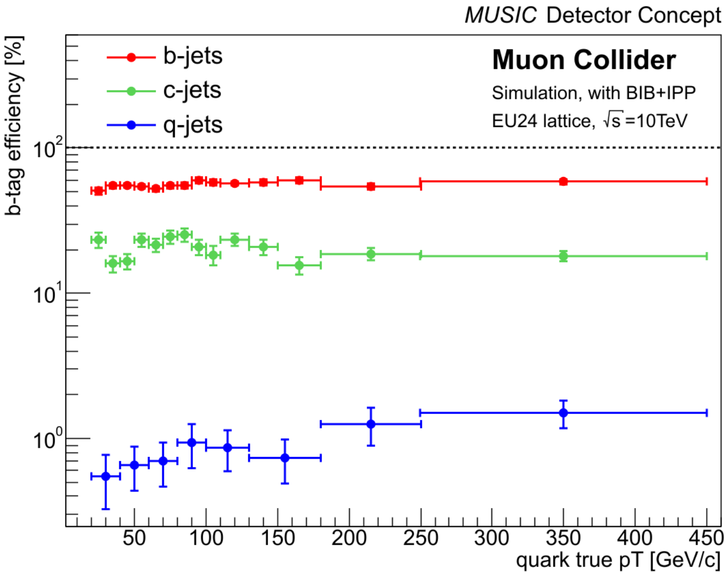




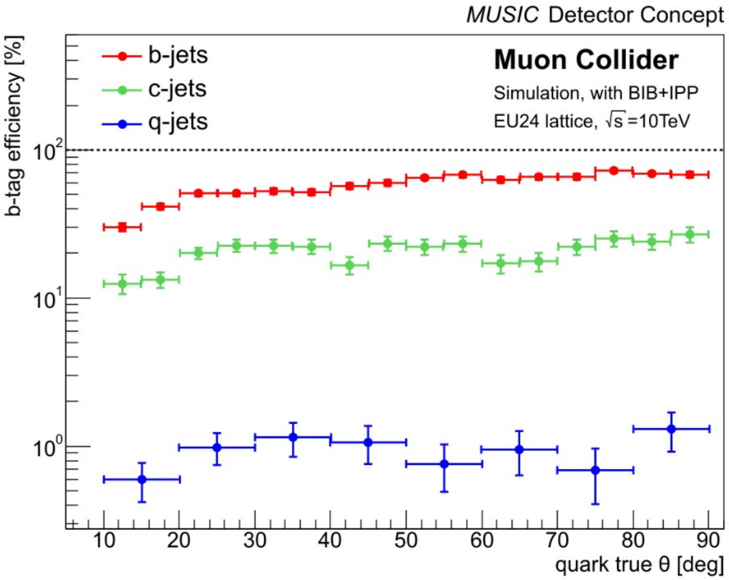


Jet flavor identification

b tagging efficiency vs true quark p_T



b tagging efficiency vs true quark θ

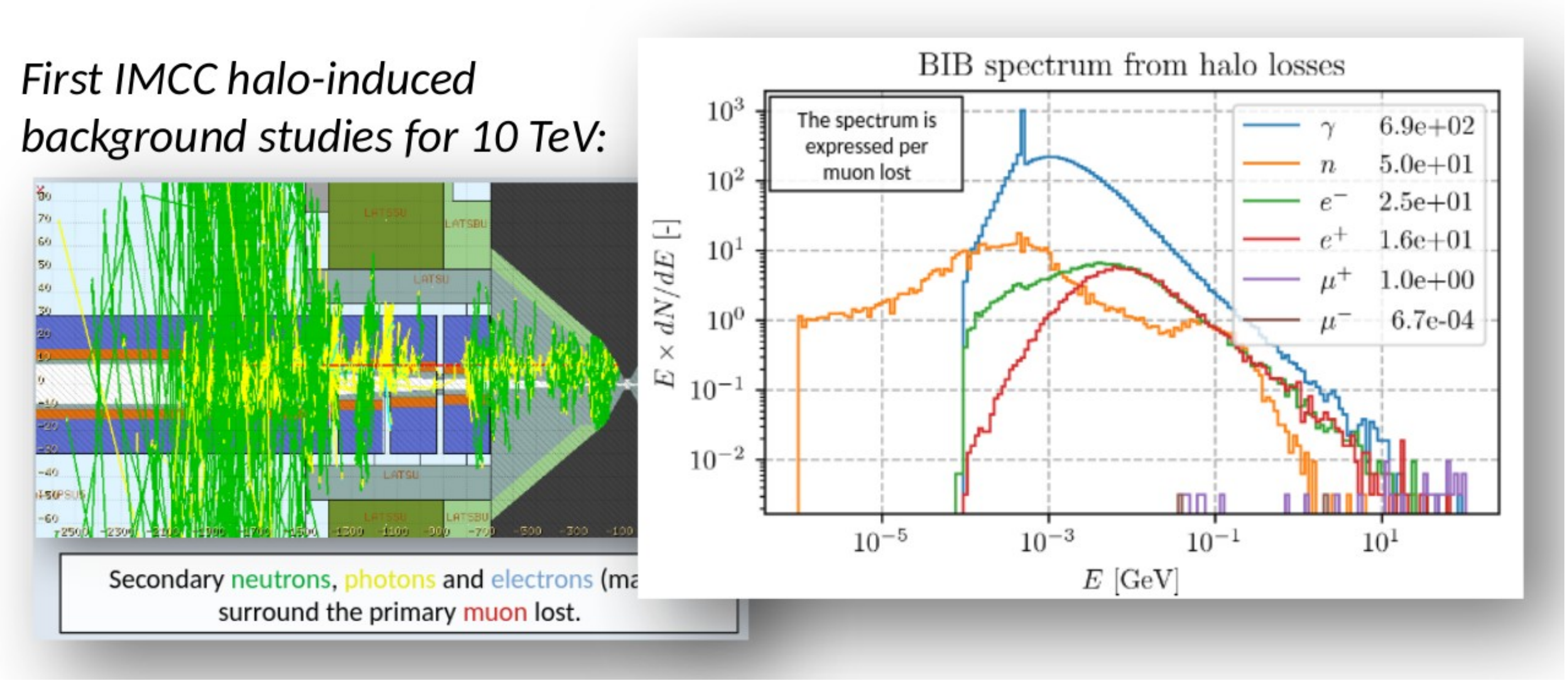


Machine-induced backgrounds

	Description	Relevance as background
Muon decay	**Decay of stored muons around the collider ring**	**Dominating source**
Synchrotron radiation by stored muons	Synchrotron radiation emission by the beams in magnets near the IP (including IR quads → large transverse beam tails)	**Small**
Muon beam losses on the aperture	Halo losses on the machine aperture, can have multiple sources, e.g.: • Beam instabilities • Machine imperfections (e.g. magnet misalignment) • Elastic (Bhabha) μμ scattering • Beam-gas scattering (Coulomb scattering or Bremsstrahlung emission) • Beamstrahlung (deflection of muon in field of opposite bunch)	**Can be significant** (although some of the listed source terms are expected to yield a small contribution like elastic μμ scattering, beam-gas, Beamstrahlung)
Coherent e^-e^+ pair production	Pair creation by real* or virtual photons of the field of the counter-rotating bunch	**Expected to be small** (but should nevertheless be quantified)
Incoherent e^-e^+ pair production	Pair creation through the collision of two real* or virtual photons emitted by muons of counter-rotating bunches	**Significant**

D. Calzolari, "Machine-detector interface design for a 10-TeV muon collider", ICHEP2024

Muon halo losses in the detector



D. Calzolari, "Machine-detector interface design for a 10-TeV muon collider", ICHEP2024