One Year Progress: Detector Overview

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IMCC and MuCol Annual Meeting
DESY, May12-16, 2025

Co-funded by the European Union

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, ...
- 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.

arXiv:2504.21417

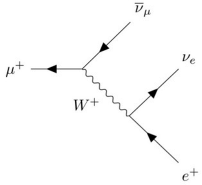
Requirement	**Baseline**	**Aspirational**
Angular acceptance $\eta = -\log(\tan(\theta/2))$	$\lvert\eta\rvert < 2.5$	$\lvert\eta\rvert < 4$
Minimum tracking distance [cm]	~ 3	< 3
Forward muons ($\eta > 5$)	tag	$\sigma_p/p \sim 10\%$
Track σ_{p_T}/p_T^2 [GeV^{-1}]	4×10^{-5}	1×10^{-5}
Photon energy resolution	$0.2/\sqrt{E}$	$0.1/\sqrt{E}$
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

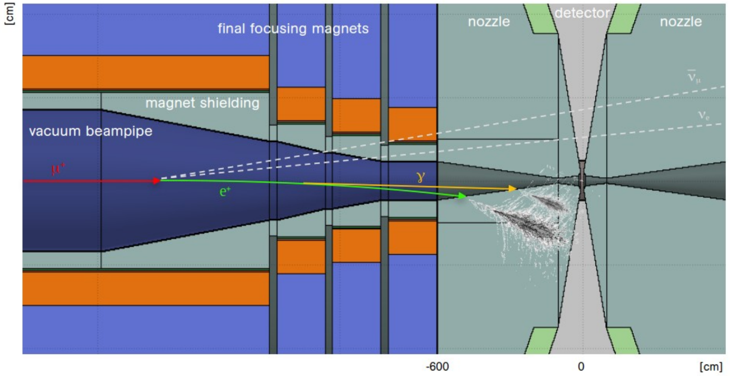
Ultimately, the detector design, the technological choices, and the development of the event reconstruction algorithms will be driven by the high levels of machine-induced background.

Dominant machine-induced backgrounds

background from muon decay (BIB)

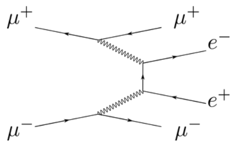
($\sim 10^8$ γ, $\sim 10^7$ n, and $\sim 10^5$ $e^{\pm}$ in the time window [-1, 15] ns)

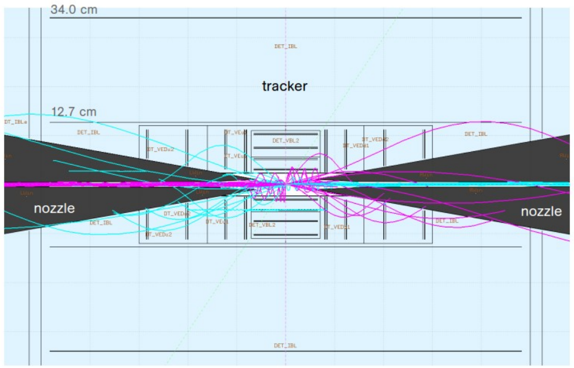




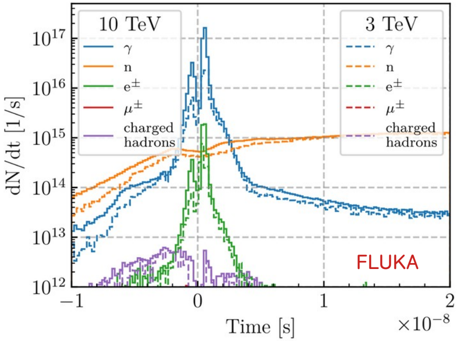
background from incoherent e⁺e⁻ pair production

($\sim 10^6$ γ, $\sim 10^5$ n, and $\sim 10^5$ $e^{\pm}$)

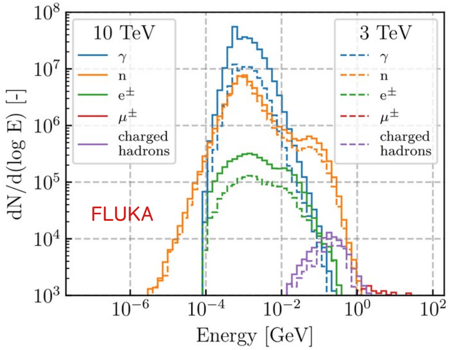




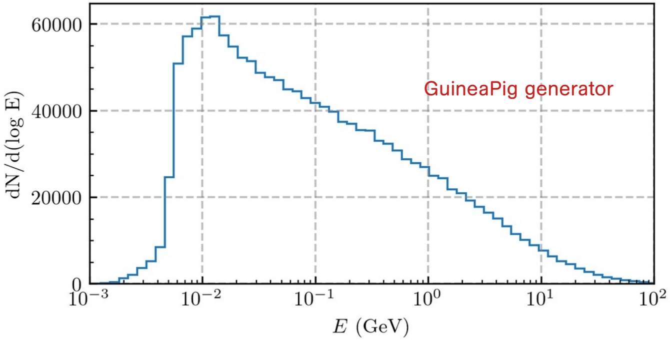
arrival time of BIB particles at the detector



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



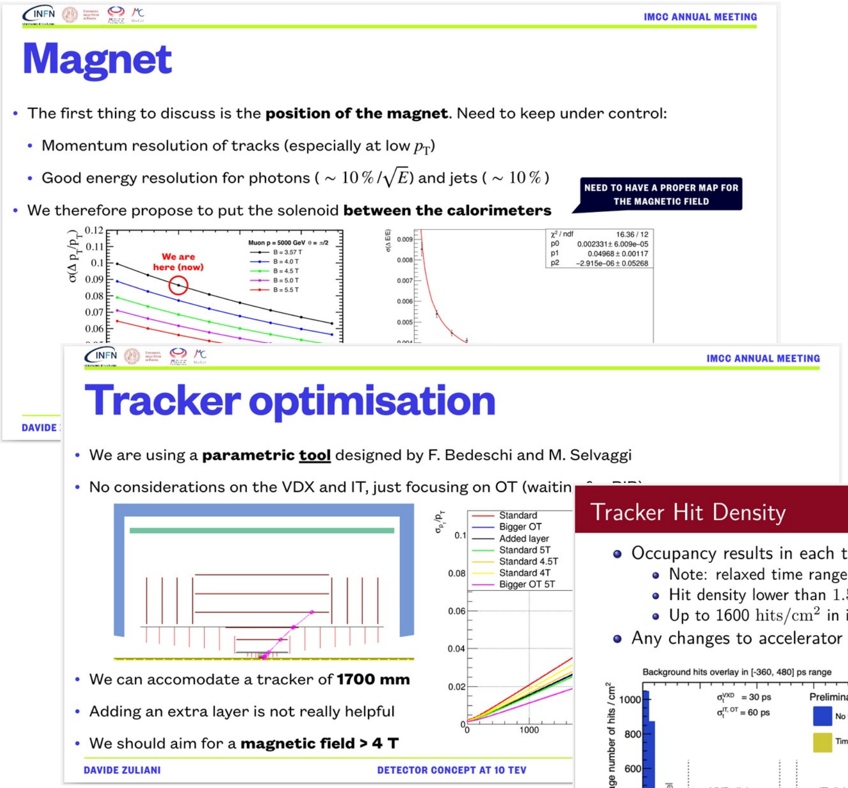
e± energy

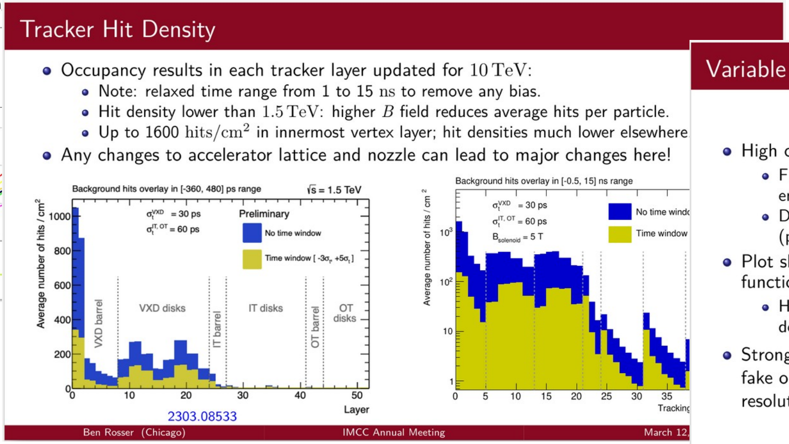


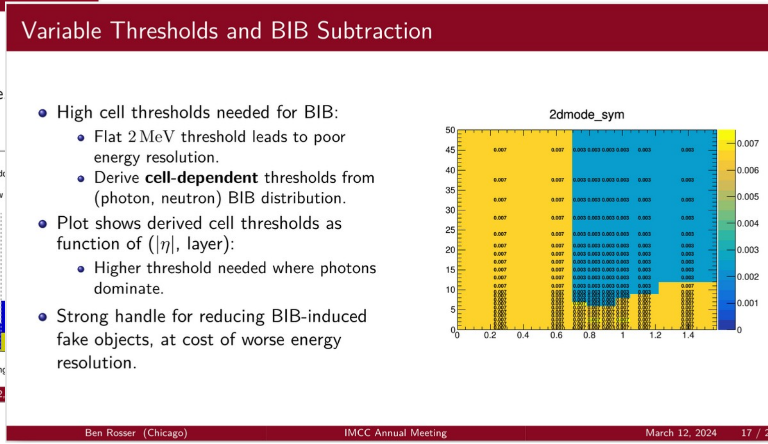
- New noozle design and interaction-region lattice optimized for 10 TeV (D. Calzolari in Thursday session on Physics and Detector).

Where we were a year ago

- Building on our experience with full simulation studies at $\sqrt{s}$ = 3 TeV, we were in the early stages of developing the design of two as yet unnamed detector concepts for 10 TeV collisions:
  - finalizing the layout, dimensions, and position of the subdetectors;
  - determining the optimal magnetic field intensity;
  - performing initial preliminary studies on the detector background occupancy and basic physics object reconstruction.







Where we are now

- After a year of intensive work, primarily targeted to the ESPP update deadline, we have now new 10-TeV machine-background samples, generated with the 10-TeV nozzles and interaction-region lattice, and two “working” multipurpose detector concepts designed for $\mu^+\mu^-$ collisions at 10 TeV:
  - MAIA (Muon Accelerator Instrumented Apparatus):

    C. Bell et al., “MAIA: A new detector concept for a 10 TeV muon collider”, arxiv:2502.00181.
  - MUSIC (MUon System for Interesting Collisions):

    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 $H \to b\bar{b}$, $H \to WW^*$, and $HH \to b\bar{b}b\bar{b}$ 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.
- The MAIA and MUSIC concepts are fully integrated into the MuonColliderSoft framework and have been used in full-simulation studies, including the two dominat machine-induced backgrounds, on the reconstruction performance of key physics objects, and on the current reach for measurements of benchmark Higgs boson channels.
- More details in presentations by K. Kennedy and L. Sestini in the Wednesday session on Physics and Detector and in the IMCC report submitted to the ESPP update:

  C. Accettura et al., “The Muon Collider”, arXiv:2504.21417.

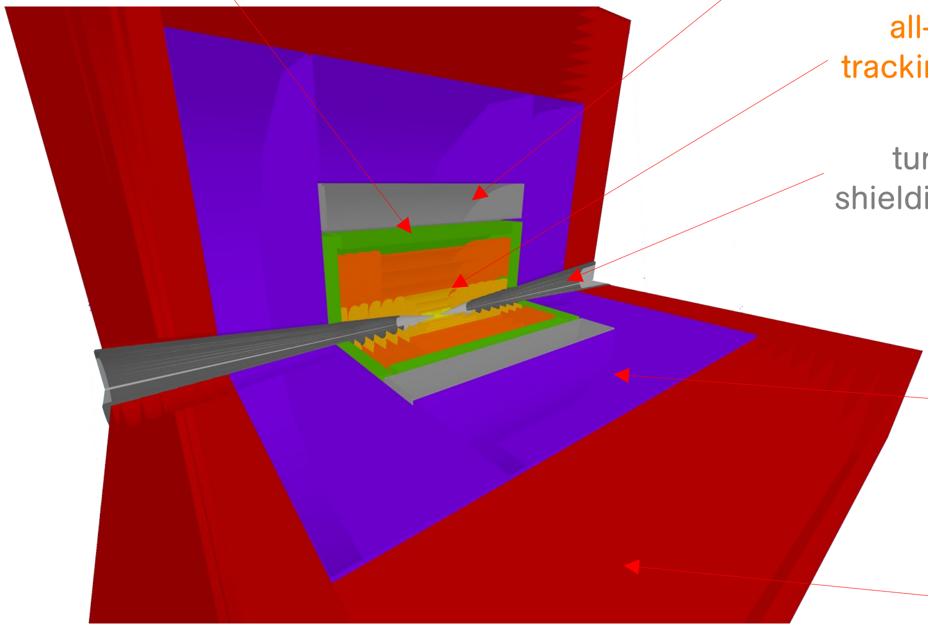
The MUSIC and MAIA detector concepts

PbF_2-crystal electromagnetic calorimeter (inside the solenoid)

superconducting solenoid (B = 5 T)

Si-W electromagnetic calorimeter (outside the solenoid)

D. Zuliani

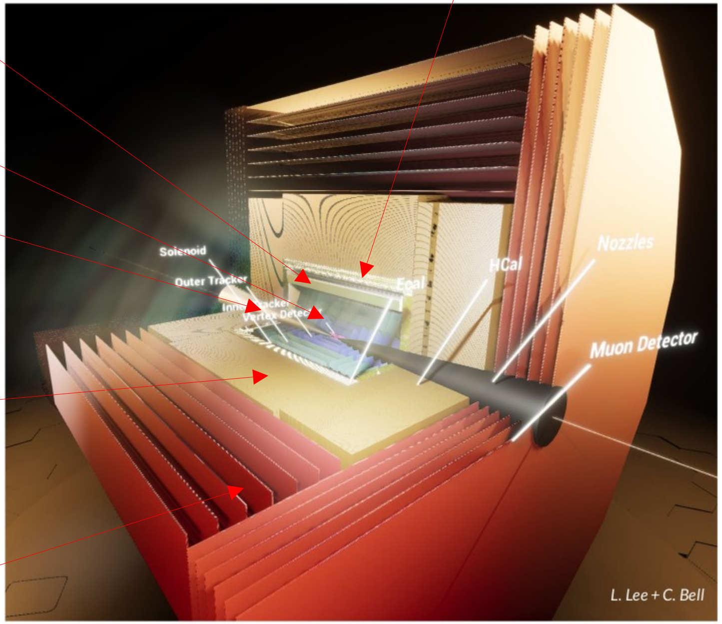


all-silicon tracking system

tungsten shielding nozzles

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

muon detectors

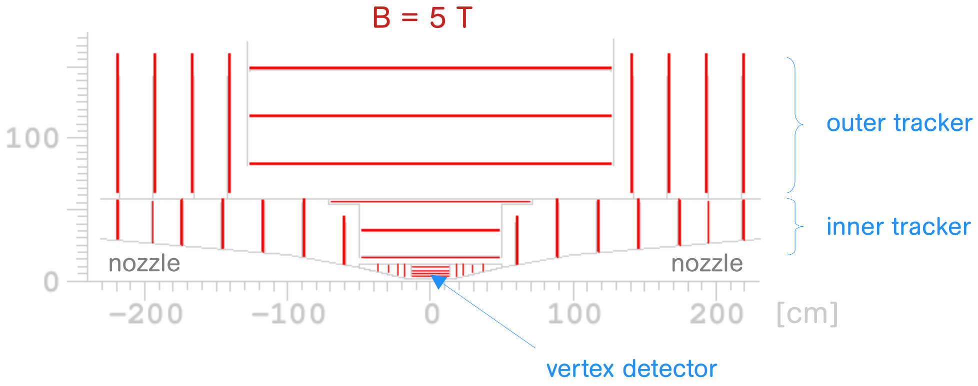


MUSIC

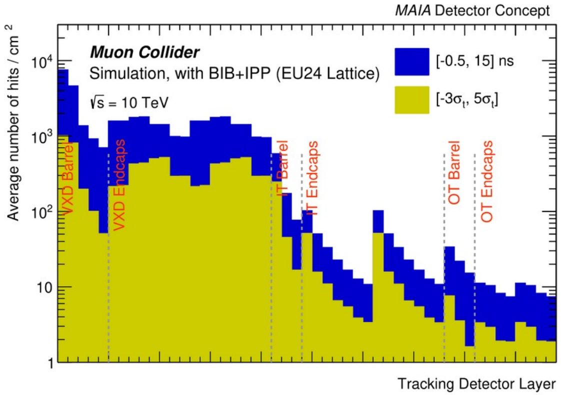
MAIA

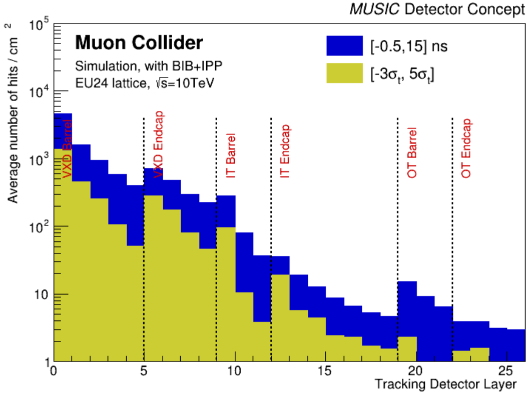
Tracking system

- The tracking system is the subdetector closest to the beamline and is most affected by the machine-induced backgrounds.
- Background impact on the tracking system:
  huge number of noise hits that produce many hit combinations during the pattern-recognition phase of the tracking process.
- Both MAIA and MUSIC use all-silicon technology with high granularity and advanced timing capabilities:
  - similar inner and outer tracker geometries, different vertex detectors.
- Main background mitigation measures:
  - strong magnetic field;
  - tight timing requirements on the hit time;
  - track finding algorithm based on Combinatorial Kalman Filter (more from P. Andreetto in Thursday Physics and Detector session).



average density of machine-induced background per layer

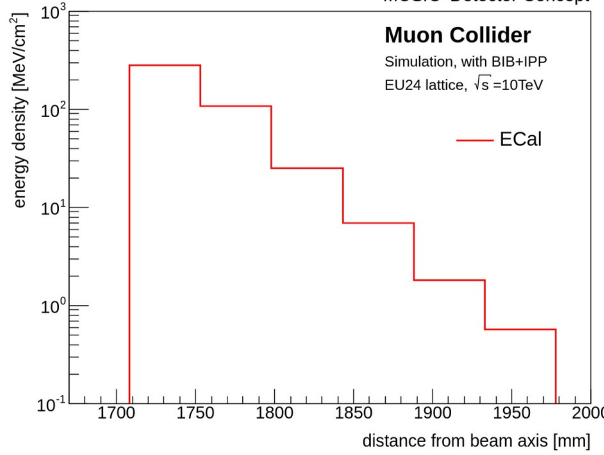


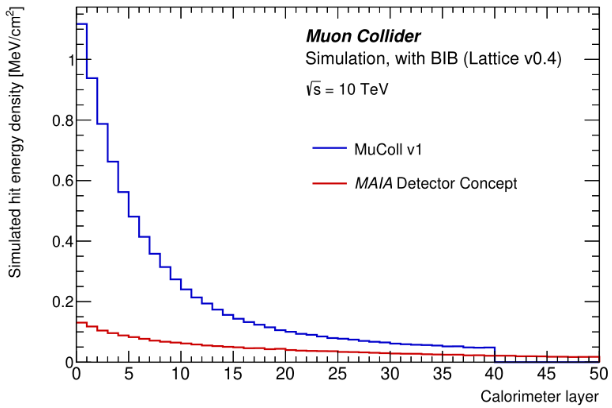


Electromagnetic calorimeter

- At every bunch crossing, expected an almost uniform flux of ~300/cm^2 background soft particles (~96% photons and ~4% neutrons) at R = 1500 cm.
- MUSIC:
  - semi-homogeneous crystal calorimeter with longitudinal segmentation (CRILIN): 6 layers of 10x10x40-mm^3 PbF_2 crystals (26.5 X_0).
- MAIA:
  - Si-W calorimeter: 50 layers of 2.2-mm tungsten absorber and 0.5-mm thick 5.1x5.1-mm^2 silicon pads (28 X_0).
- Background mitigation:
  - hit time information;
  - tuning of reconstruction algorithms: optimization of the ECAL cell energy thresholds for different detector regions and layers;
  - subtraction of the background average energy contribution in ECAL cells;
  - screen from magnet material (MAIA barrel).

average background energy in the ECAL barrel

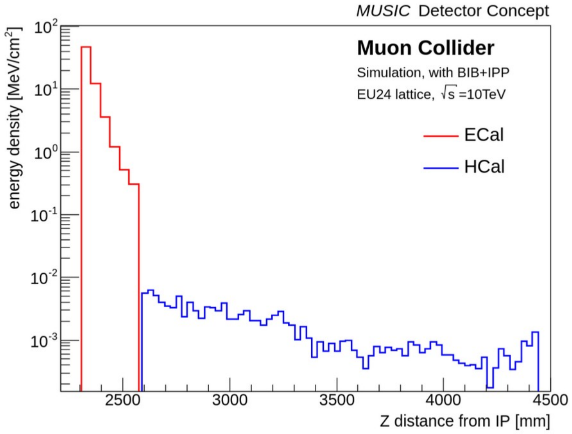




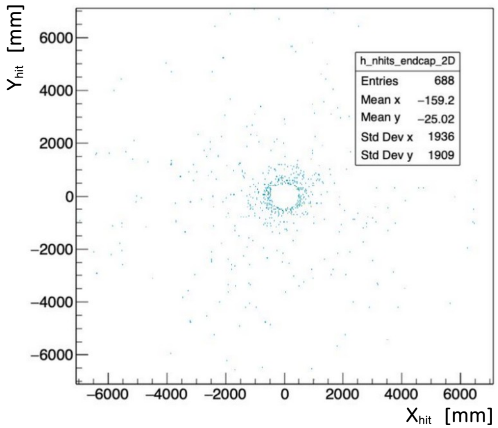
Hadronic calorimeter and muon system

- 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 iron-scintillator sampling calorimeters: 20-mm thick Fe absorber interleaved with 30x30-mm^2 3-mm thick scintillator pads ($\lambda_I \sim 7$);
  - 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.
- Muon system:
  - no final design or technology defined yet; for the time being, MAIA and MUSIC use the muon detectors employed in the 3 TeV detector model: 7-barrel and 6-endcap RPC layers of 30x30-mm^2 cells.

average background energy in the ECAL and HCAL endcaps



BIB hits in muon detector's endcap

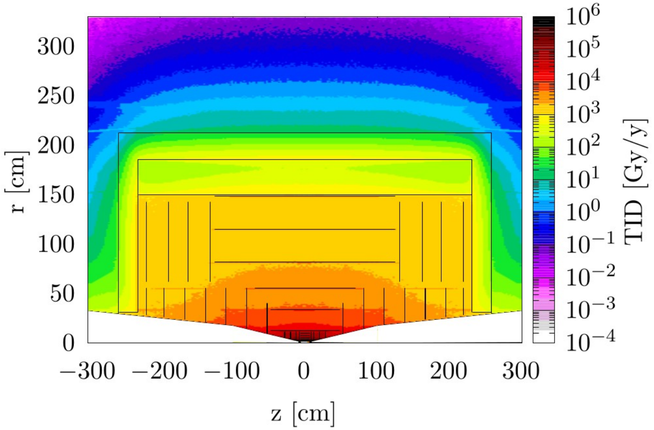


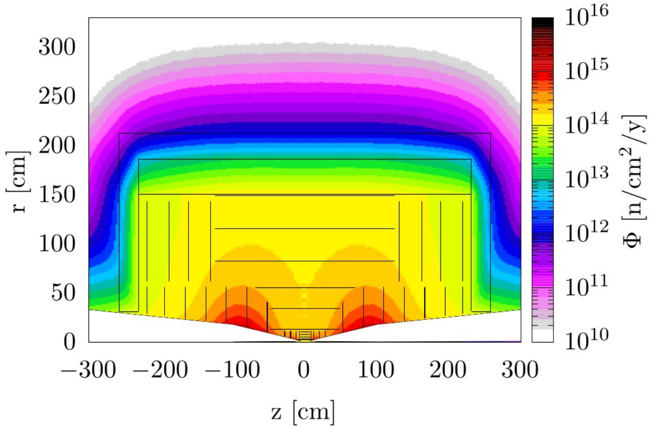
Radiation environment at $\sqrt{s}$ = 10 TeV

yearly total ionizing dose

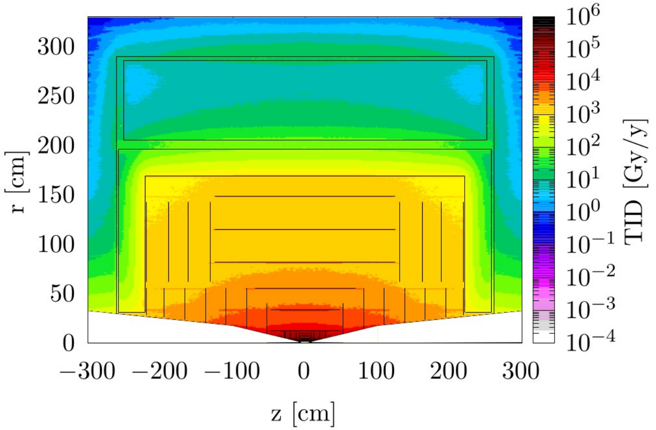
yearly 1 MeV n equivalent fluence in Si

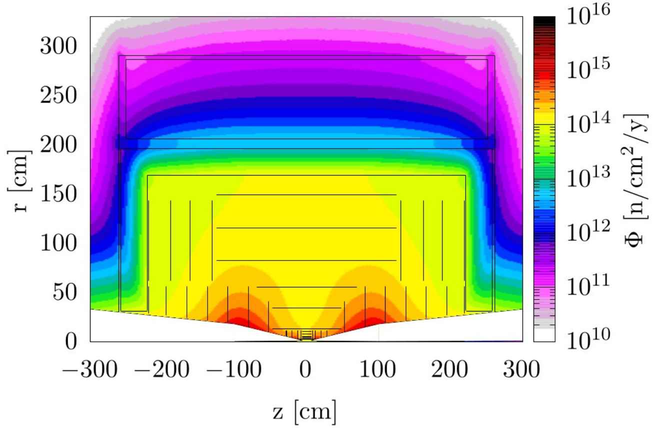
MAIA





MUSIC





only contributions from muon-decay background

		HL-LHC	MuC
max TID [kGy]	@ VXD	~1000	2000
	@ ECAL	~1	~0.6/~1.4
max fluence [n/cm^2]	@ VXD	~10^{15}	~10^{14}
	@ ECAL	~10^{13}	~$10^{13\text{-}14}$

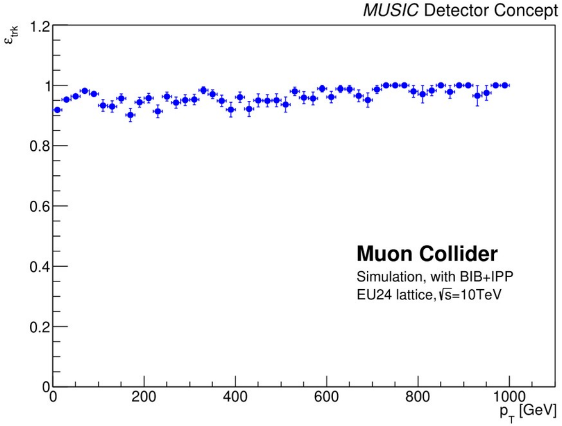
Assumptions:
- collision energy: 10 TeV;
- collider circumference: 10 km;
- beam injection frequency: 5 Hz;
- days of operation per year: 139.

MAIA and MUSIC performance

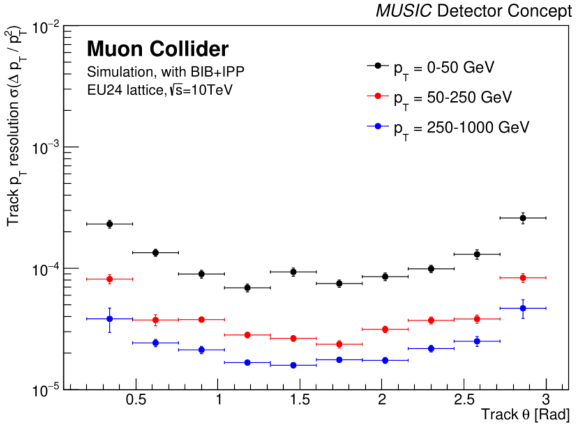
- We have characterized and evaluated the performance of the MAIA and MUSIC detectors with full simulation studies, including the machine-induced backgrounds from muon decays and incoherent e^+e^- pair production, in terms of:
  - reconstruction efficiencies and parameter resolutions for key physics objects (tracks, photons, neutrons, electrons, muons) in single particle samples;
  - reconstruction efficiencies and momentum resolutions of jets, and jet flavor identification performance in $b\bar{b}$, $c\bar{c}$, and light-quark pair samples;
  - full-fledged physics analyses to estimate our current sensitivity on the Higgs boson production cross sections for the channels $H \to b\bar{b}$, $H \to WW^*$, and $HH \to b\bar{b}b\bar{b}$, as well as on the Higgs boson trilinear self-coupling.
- Some representative examples in the following slides.

Track reconstruction

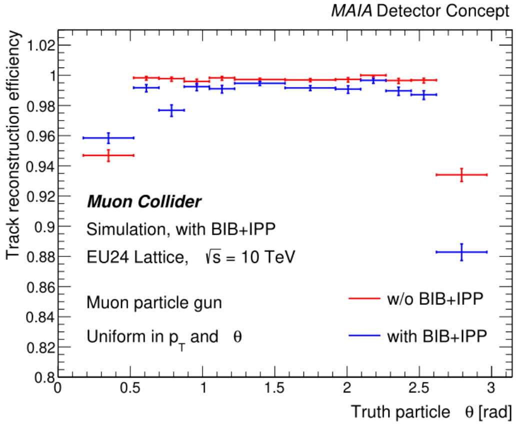
track reconstruction efficiency vs true muon p_T



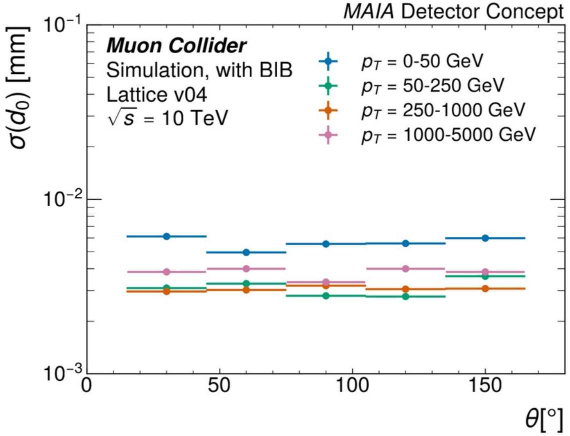
transverse momentum resolution vs true muon θ



track reconstruction efficiency vs true muon θ



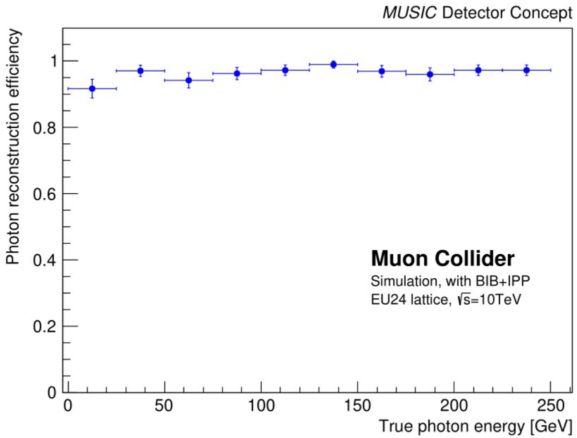
transverse impact parameter resolution vs true muon θ



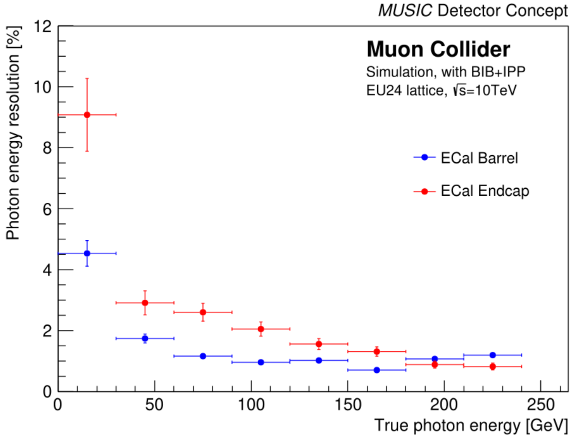
single muon samples

Photon reconstruction

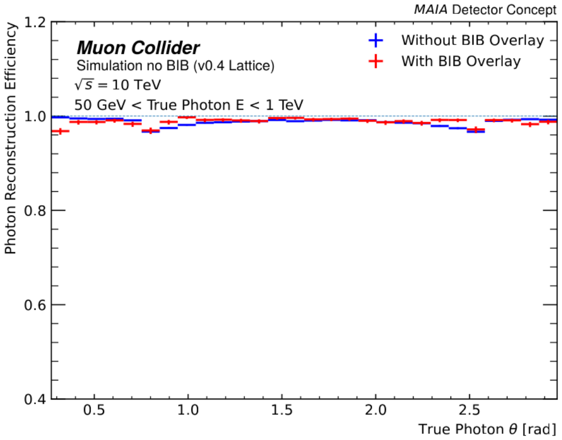
photon reconstruction efficiency vs true energy



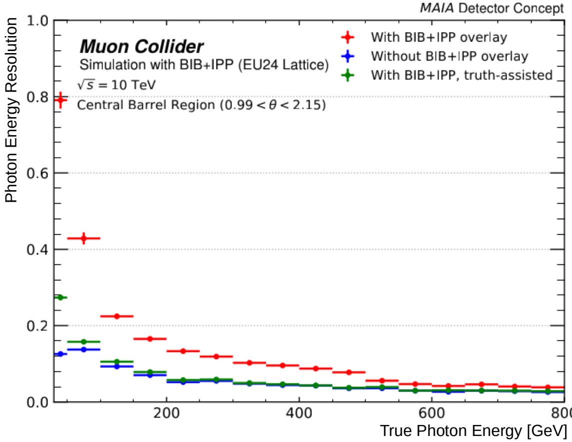
photon energy resolution vs true photon energy



photon reconstruction efficiency vs true photon θ



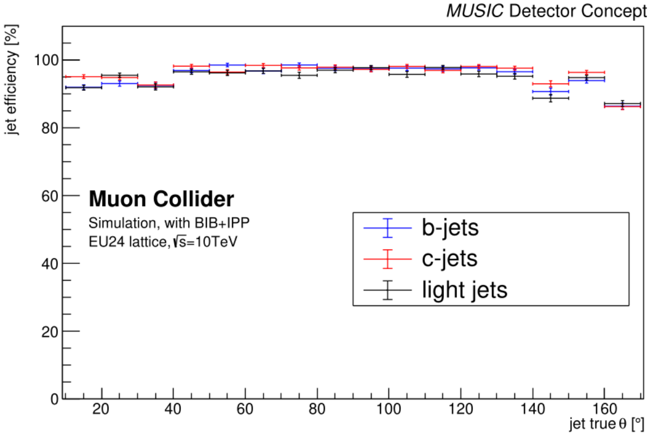
photon energy resolution vs true photon energy



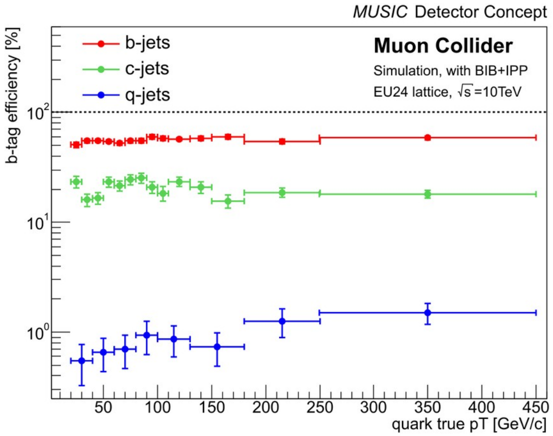
single photon samples

Jet reconstruction and flavor tagging

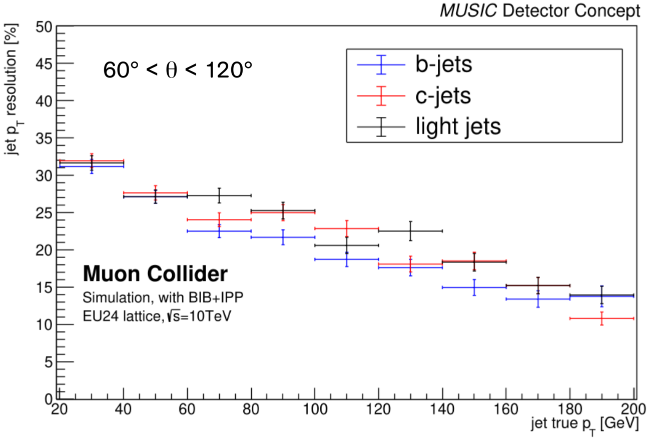
jet reconstruction efficiency vs true jet θ



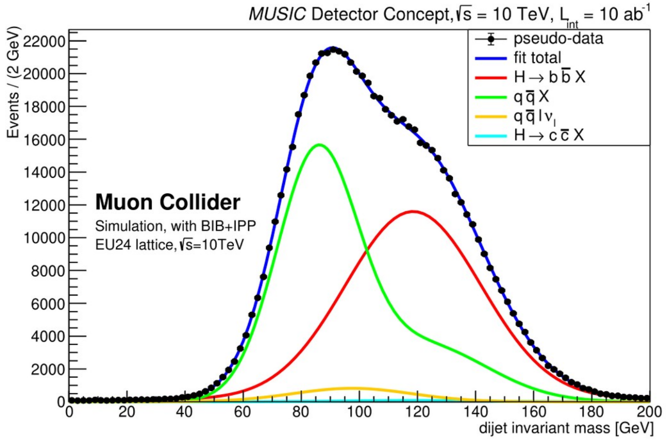
b tagging efficiency vs true quark p_T



jet p_T resolution vs true jet p_T



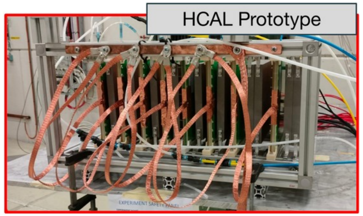
dijet invatiant mass in the channel $\mu^+\mu^- \rightarrow H\nu_\mu\bar{\nu}_\mu \rightarrow b\bar{b}\nu_\mu\bar{\nu}_\mu$



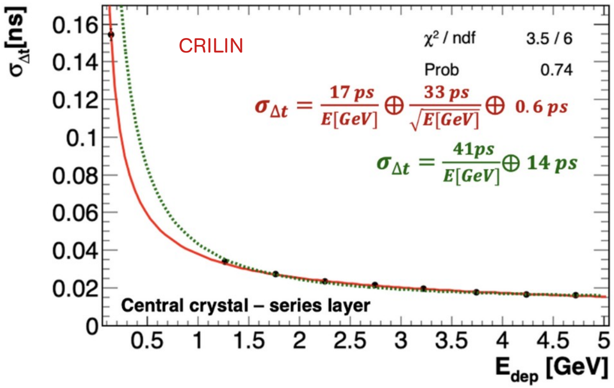
dijet samples

Ongoing R&D projects

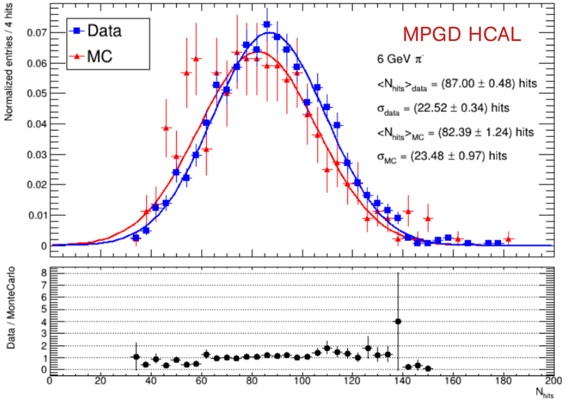
- In parallel with the full-simulation studies, dedicated R&D efforts are underway:
  - CRILIN (CRystal calorimeter with Longitudinal InformatioN): a semi-homogeneous electromagnetic calorimeter consisting of multiple layers of 10x10x40-mm^3 PbF_2 crystal matrices;
  - MPGD-HCAL: a sampling hadronic calorimeter with iron absorber and Micro-Pattern Gaseous Detectors as the active layer;
  - GEM and PICOSEC detectors for the muon system.
- 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.
- More details in presentations by L. Longo and L. Palombini in the Thursday session on Physics and Detector.



measured time resolution vs deposited energy



total number of hits measured and simulated



Summary

- It's been a year of more intensive work than we had expected a year ago, due to the early deadline for the 2026 ESPP update. Despite the short timeframe, we accomplished a great deal.

- We have machine-induced background samples at 10 TeV, generated with a nozzles design and interaction region lattice optimized for $\sqrt{s}$ = 10 TeV.

- We developed two detector concepts, MAIA and MUSIC, specifically designed for 10 TeV $\mu^+\mu^-$ collisions.

- The two new detector concepts are fully integrated into the MuonColliderSoft framework and have been extensively used for full-simulation studies, including the dominant machine-induced backgrounds from muon decays and incoherent e^+e^- pair production.

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