Higgs Physics at a 10 TeV Muon Collider with the MUSIC detector

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I.Raghib On behalf of the International Muon Collider Collaboration

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Motivation and Challenges

MOTIVATION

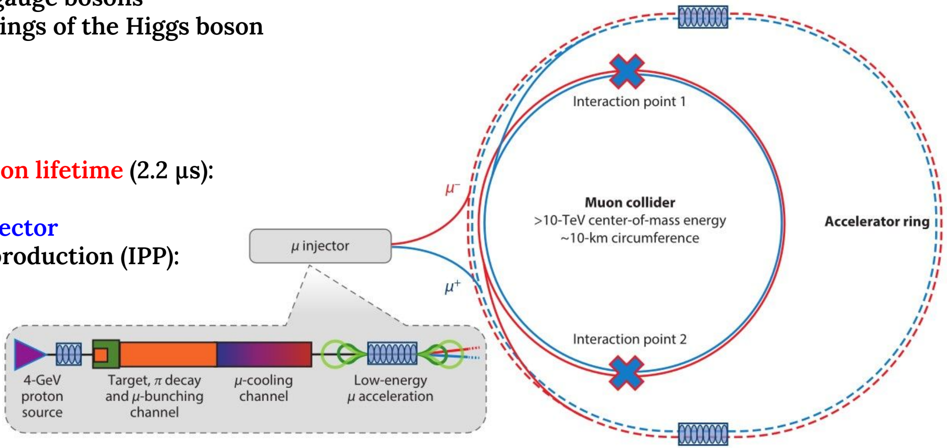
- Muon collider is the most efficient and effective way of achieving leptonic collisions at multi-TeV center-of-mass energies in a relatively compact circular machine
  - No parton structure like in the LHC giving more precise measurements
  - Low synchrotron radiation due to large muon mass

- Multi-TeV $\mu^+\mu^-$ collisions will allow high-precision tests of the Standard Model in a previously unexplored energy regime and enabling both direct and indirect extensive searches for new physics

- Higgs production rates of Higgs bosons allow precise measurements in the Higgs sector
  - Higgs production from Vector Boson Fusion
  - Higgs boson couplings to fermions and gauge bosons
  - Trilinear and possibly quartic self-couplings of the Higgs boson

DETECTOR CHALLENGES

- Dominant machine-induced background due to short muon lifetime (2.2 μs):
  - Background from muon decay (BIB):
    tungsten shields (nozzles) inside the detector
  - Background from incoherent e+e- pair production (IPP):
    strong detector solenoidal field



Detector concept for simulation studies: MUSIC

hadronic calorimeter

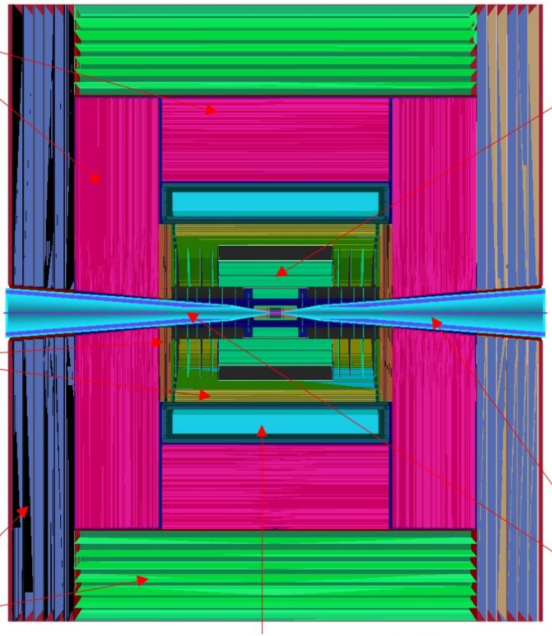
- sampling calorimeter with 70 layers of 2-cm iron absorber + 3 x 3 cm^2 plastic scintillating tiles
- timing with σ_t = 100 ps
- 7 nuclear interaction lengths
- serves as magnetic field return yoke

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



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

- MUon System for Interesting Collisions (MUSIC) detector is used in these studies
- Optimized to mitigate the machine induced background effects

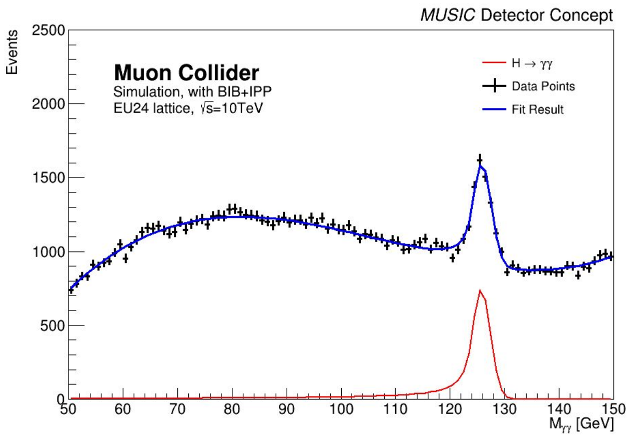
Talk by L.Sestini

https://arxiv.org/abs/2511.23273

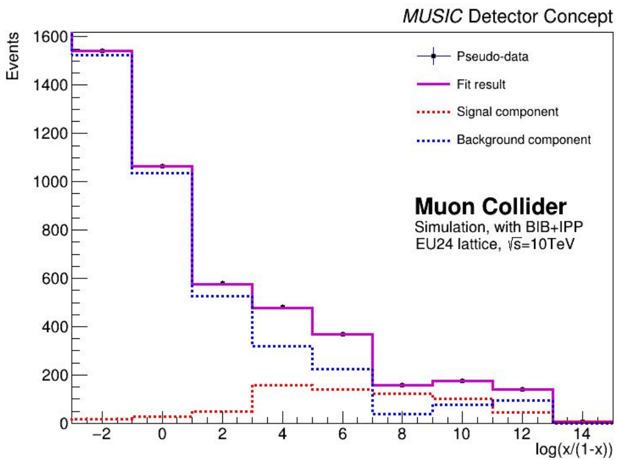
- Methodology:
  - Signal and physics-background samples generated with MADGRAPH/WHIZARD + PYTHIA for parton hadronization
  - Detector response simulated with Geant4: Machine induced Background overlaid to the physical processes event by event
  - Reconstruction algorithm for physics objects revised to account for the machine-induced backgrounds
- Reconstruction Algorithm:
  - Dedicated digitizer with optimized time and energy thresholds for each sub-detectors and optimized sub-region, only hits above threshold are kept
  - PandoraPFA algorithm to reconstruct particles from tracks and calorimeter clusters
- Experimental scenario: $L = 10\ ab^{-1}$ expected to be collected from one experiment ($L = 20\ ab^{-1}$ from two experiments) in five years
- Goal: Determination of the statistical sensitivity on Higgs cross-sections: $\sigma(H \rightarrow XX) = N_H/\varepsilon_H\ L$

$H \rightarrow \gamma\gamma$, $H \rightarrow ZZ^*$

- $H \rightarrow \gamma\gamma$
- Event Selection:
  - Two photons
  - p_T > 20 GeV and 10° < θ < 170°
  - 50 < $M^{\gamma\gamma}$ < 150 GeV



- $H \rightarrow ZZ^* \rightarrow \mu^+\mu^- jj$
- Event Selection:
  - Two reconstructed jets and two muons
  - Jets with p_T > 10 GeV and 10° < θ < 170°
  - Muons with p_T > 20 GeV and 10° < θ < 170°
- Multi Layer Perceptron trained to separate signal from backgrounds



Other Process Analysis

- $H \to \mu^+\mu^-$
  - Two opposite charged muons
  - $p_T > 10$ GeV and $10° < \theta < 170°$
- $H \to WW^*$
  - Two reconstructed jets and one isolated muon/electron
  - Jets with $p_T > 20$ GeV and $10° < \theta < 170°$
  - Muons/electrons with $p_T > 10$ GeV and $10° < \theta < 170°$
  - Two BDTs trained to distinguish the signal from the backgrounds
- $H \to b\bar{b}$
  - Two reconstructed jets
  - $p_T > 40$ GeV and $10° < \theta < 170°$
  - b-flavor tagged

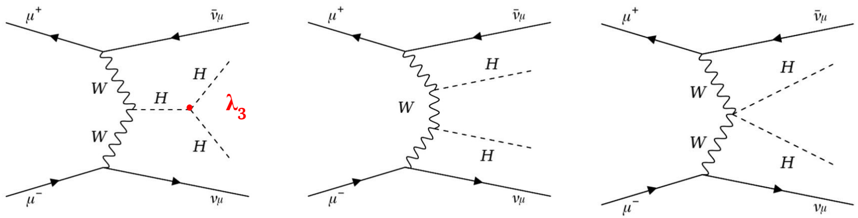
Process $H \to XX$	Sensitivity (%)* $\Delta\sigma (H \to XX)/\sigma (H \to XX)$
$H \to \gamma\gamma$	1.089
$H \to ZZ^*$	4.245
$H \to \mu^+\mu^-$	6.859
$H \to WW^*$	0.346
$H \to b\bar{b}$	0.177

- We have verified that these results are compatible with the sensitivity expected from phenomenological studies
- We have demonstrated with the detailed simulation of the detector that we are able to achieve the expected precision despite the presence of machine induced background

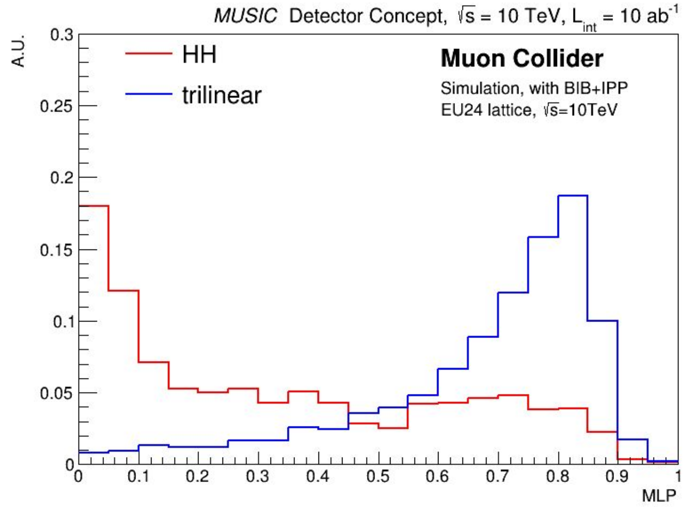
*Sensitivity from two experiments, obtained by dividing the sensitivity from one experiment by $\sqrt{2}$

Trilinear Higgs self-coupling

- HH→bb̄bb̄
- Event Selection:
  - Four reconstructed jets
  - p_T > 20 GeV and 10° < θ < 170°
  - b-flavor tagged
- Sensitivity on the HH cross section from two experiments:
  - $\Delta\sigma$ (H→bb̄bb̄)/σ (H→bb̄bb̄) = 4.243%

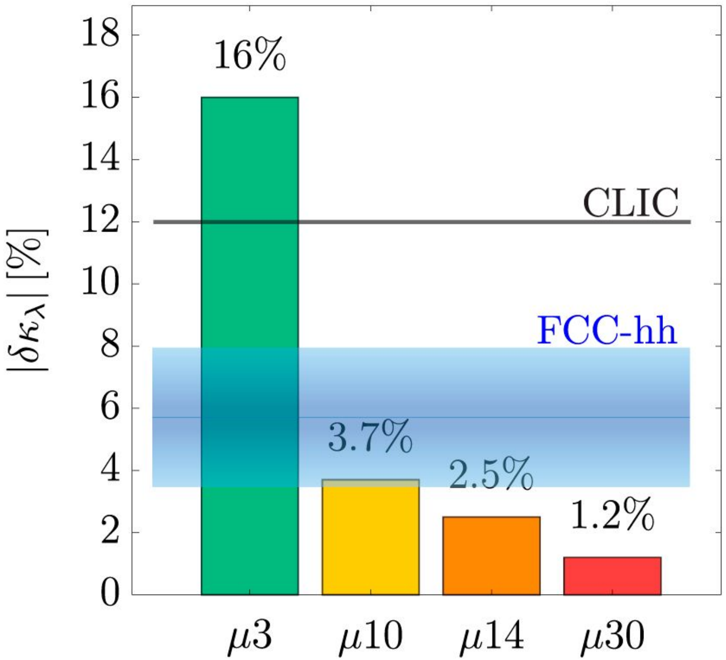


- The double-Higgs production is sensitive to the trilinear Higgs self-coupling λ_3
- A machine learning algorithm that exploits the HH kinematics is used to separate the trilinear contribution from the full HH production
- λ_3 is extracted from a maximum-likelihood template fit to the distribution of the machine learning outputs:
  - $0.94 < \lambda_3/\lambda_3^{SM} < 1.08$ @ 68% C.L. from one experiment with an average uncertainty of 7%, and 4.95% from two experiments



Summary

- A 10 TeV muon collider is expected to yield abundant samples of single and double Higgs bosons, enabling studies of Higgs properties with unprecedented precision
- We have demonstrated with the detailed simulation of the detector that we are able to achieve the expected precision on Higgs cross section measurements despite the presence of machine induced background
- The Higgs trilinear self coupling can be measured with a precision of 4.95%, qualifying the Muon Collider as one of the best machines for it's measurement



Expected trilinear coupling sensitivity from phenomenological study

https://arxiv.org/abs/2203.08033

THANK YOU

Backup: Simulation studies for Higgs Physics at √s = 3 TeV

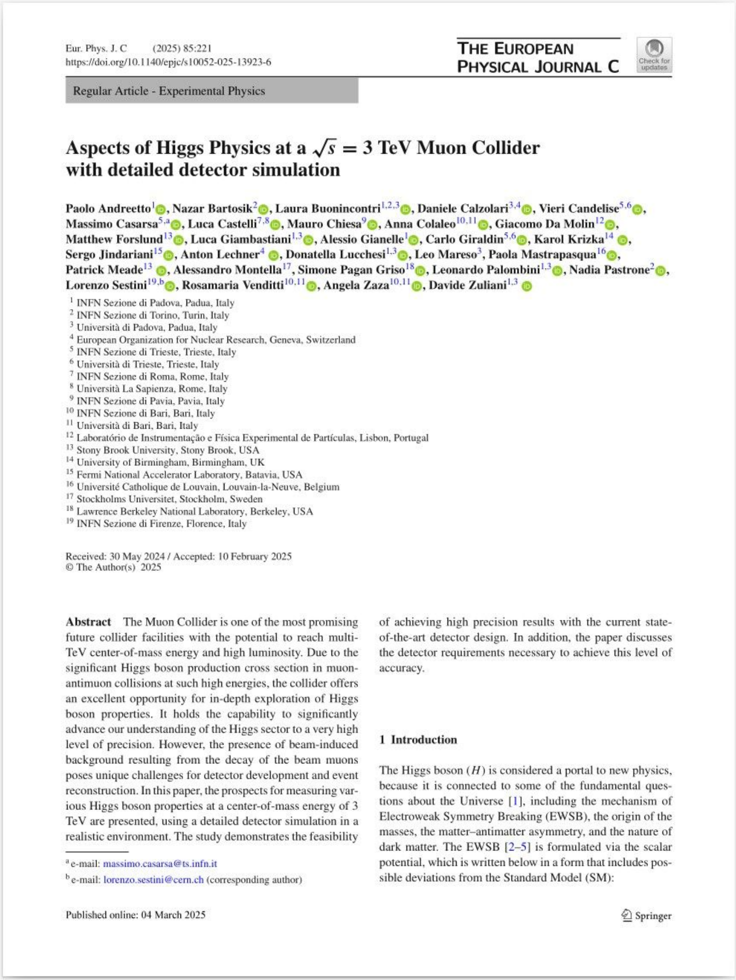
- An initial campaign of Higgs studies at √s = 3 TeV with a detailed detector simulation was carried out for Snowmass 2021
    - Assuming 1 ab-1, collected by one experiment in 5 years
    - Background from muon decays included
- Confirmed results from parametric simulation with an ideal detector:
-

Process H→XX	Sensitivity (%) $\Delta\sigma$ (H→XX)/σ (H→XX)	Parametric simulation (%)
H→$\gamma\gamma$	7.5	6.1
H→ZZ*	17	11*
H→μ+μ-	39	40
H→WW*	2.9	1.7*
H→b$\bar{b}$	0.78	0.76

- λ_3/λ_3^{SM} | [0.81, 1.44] @ 68% C.L.** | [0.73, 1.35] U [1,85, 1.94] @ 68% C.L.**

*includes also the electron channel
**uses only the HH→bbbb

https://link.springer.com/article/10.1007/JHEP08(2022)185
https://arxiv.org/abs/2203.07261



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Regular Article - Experimental Physics

Aspects of Higgs Physics at a $\sqrt{s} = 3$ TeV Muon Collider with detailed detector simulation

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Abstract The Muon Collider is one of the most promising future collider facilities with the potential to reach multi-TeV center-of-mass energy and high luminosity. Due to the significant Higgs boson production cross section in muon-antimuon collisions at such high energies, the collider offers an excellent opportunity for in-depth exploration of Higgs boson properties. It holds the capability to significantly advance our understanding of the Higgs sector to a very high level of precision. However, the presence of beam-induced background resulting from the decay of the beam muons poses unique challenges for detector development and event reconstruction. In this paper, the prospects for measuring various Higgs boson properties at a center-of-mass energy of 3 TeV are presented, using a detailed detector simulation in a realistic environment. The study demonstrates the feasibility of achieving high precision results with the current state-of-the-art detector design. In addition, the paper discusses the detector requirements necessary to achieve this level of accuracy.

1 Introduction

The Higgs boson (H) is considered a portal to new physics, because it is connected to some of the fundamental questions about the Universe [1], including the mechanism of Electroweak Symmetry Breaking (EWSB), the origin of the masses, the matter–antimatter asymmetry, and the nature of dark matter. The EWSB [2–5] is formulated via the scalar potential, which is written below in a form that includes possible deviations from the Standard Model (SM):

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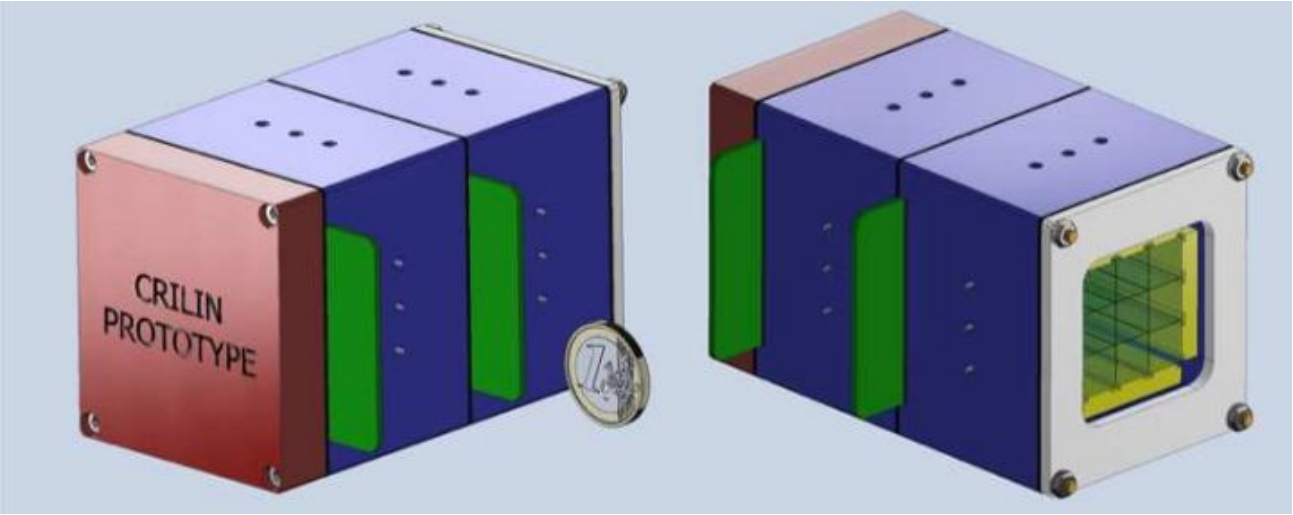
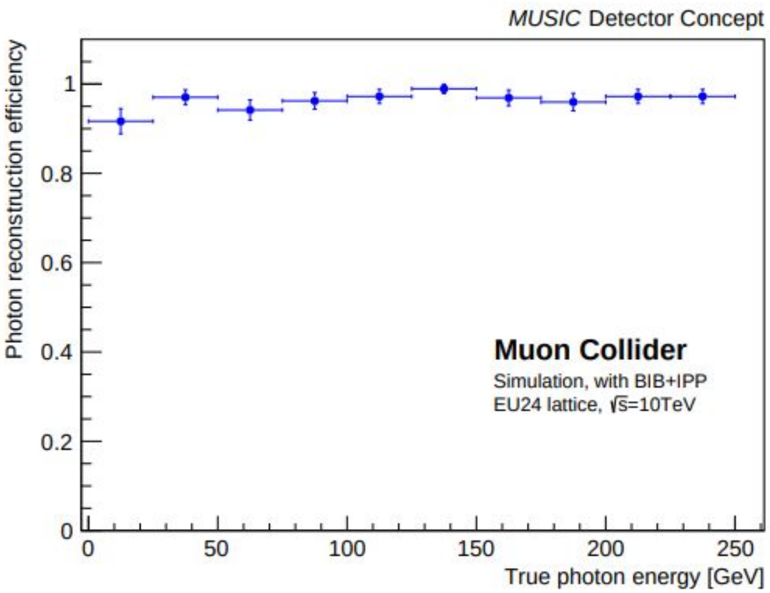
Backup: CRILIN calorimeter

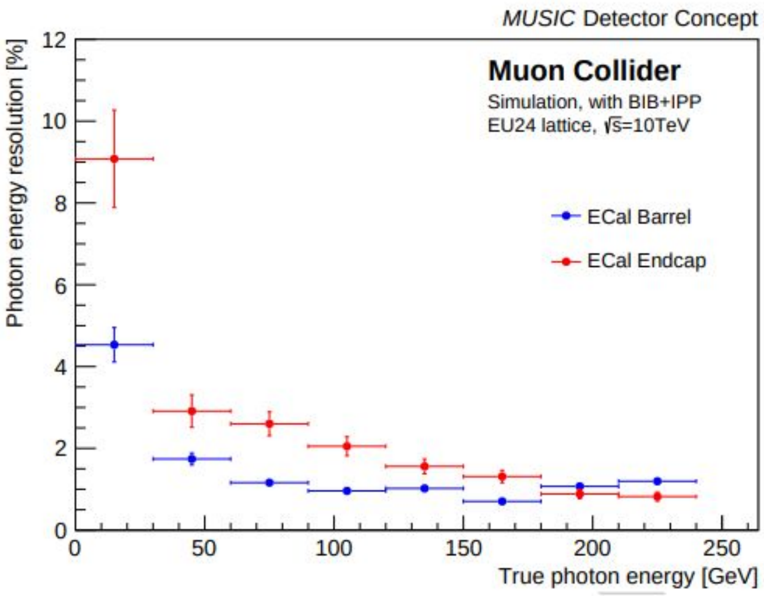


https://doi.org/10.48550/arXiv.2206.05838

- CRystal calorImeter with Longitudinal INformation (CRILIN)
- Precision electromagnetic calorimeter
- It consists of 1 × 1 × 4-cm3 lead-fluorite crystals
- Arranged in six layers for a total of 26.5 radiation lengths

Backup: Photon reconstruction performance

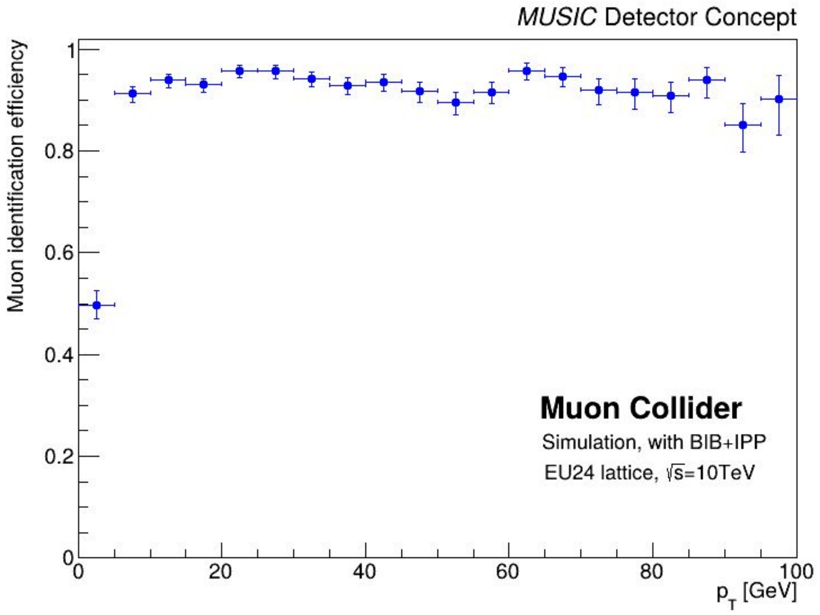


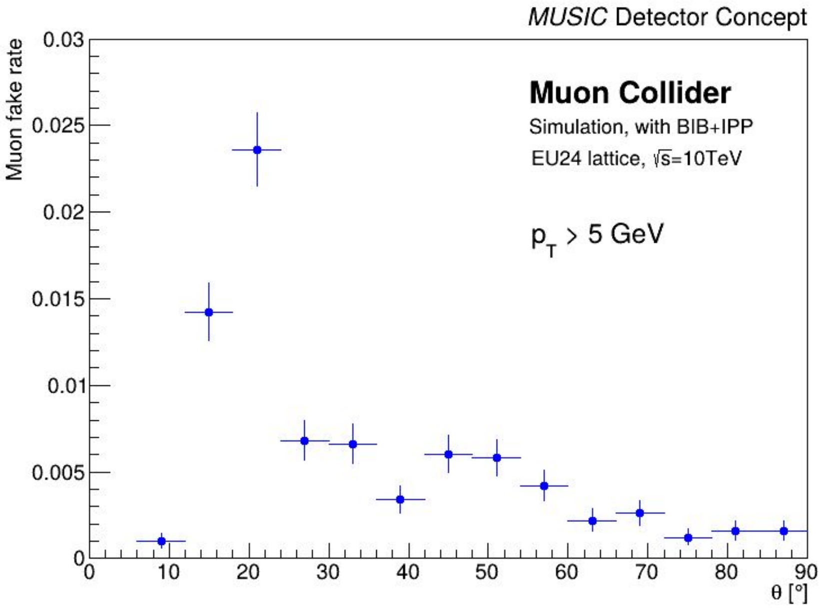


Plots from https://thesis.unipd.it/retrieve/85415af8-64c3-4b21-a607-e3327da707b9/Palombini_Leonardo.pdf

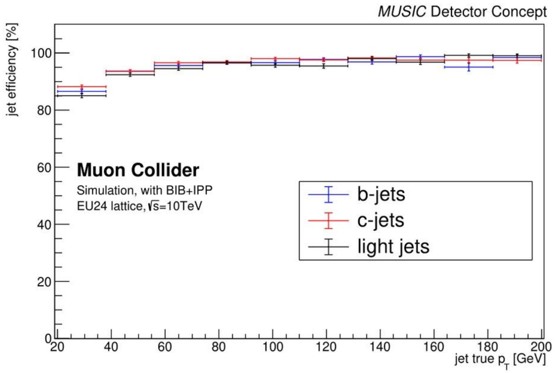
- The photon reconstruction efficiency is close to 1
- The energy resolution $\Delta E/E \simeq 10\%/\sqrt{E}$ in the barrel and $\Delta E/E \simeq 17\%/\sqrt{E}$ in the endcaps

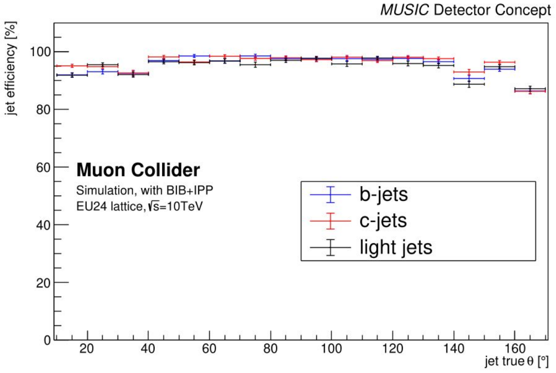
Backup: Muon reconstruction performance

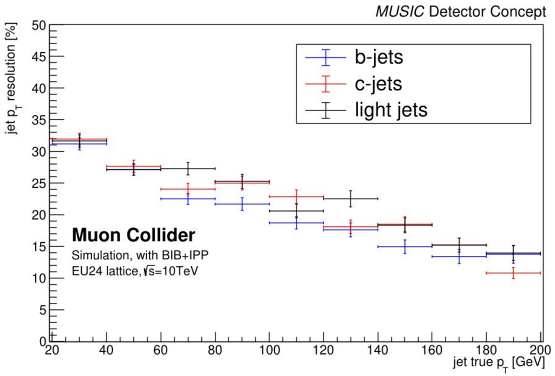


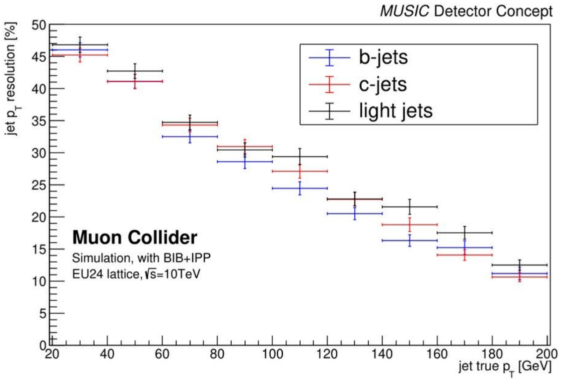


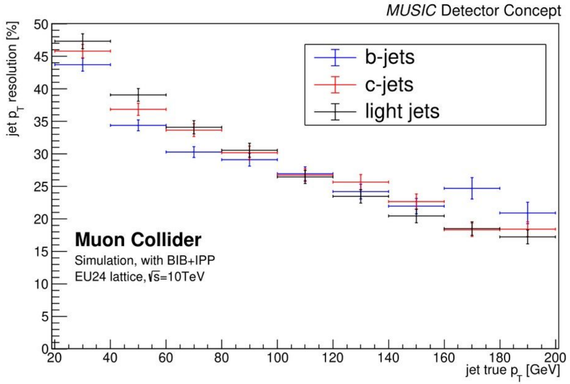
Backup: Jet reconstruction performance



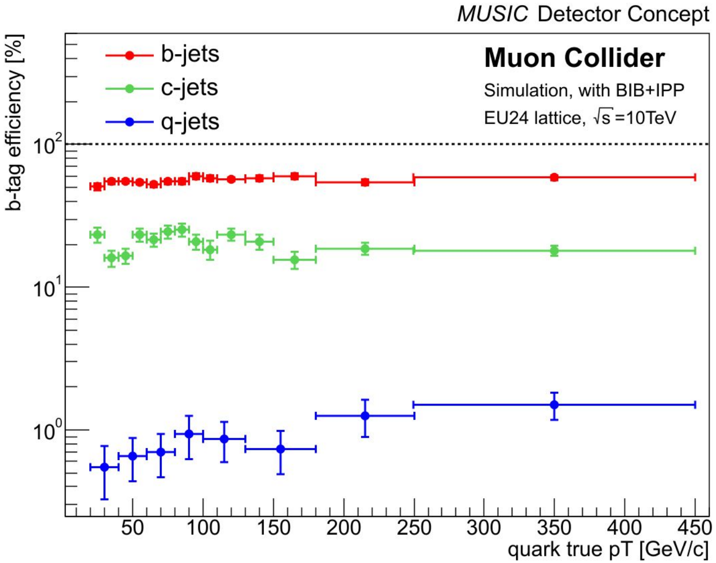


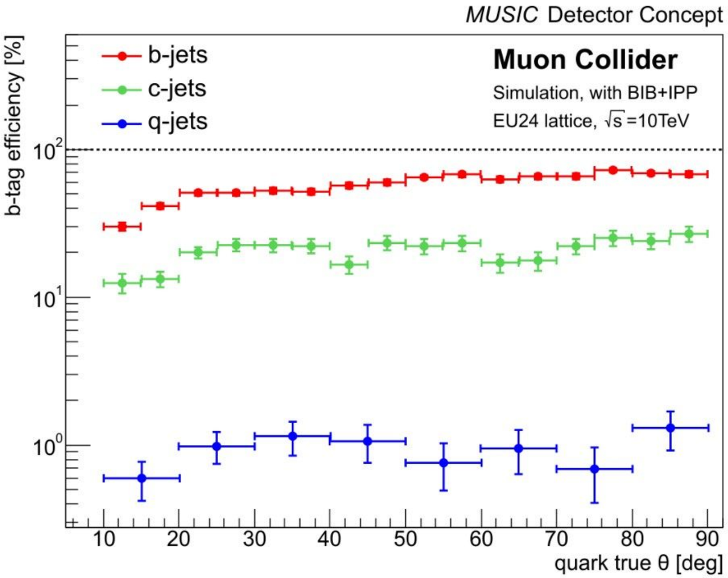






Backup: Jet flavor identification





Backup: