Higgs physics at a 10 TeV Muon Collider

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on behalf of the International Muon Collider Collaboration

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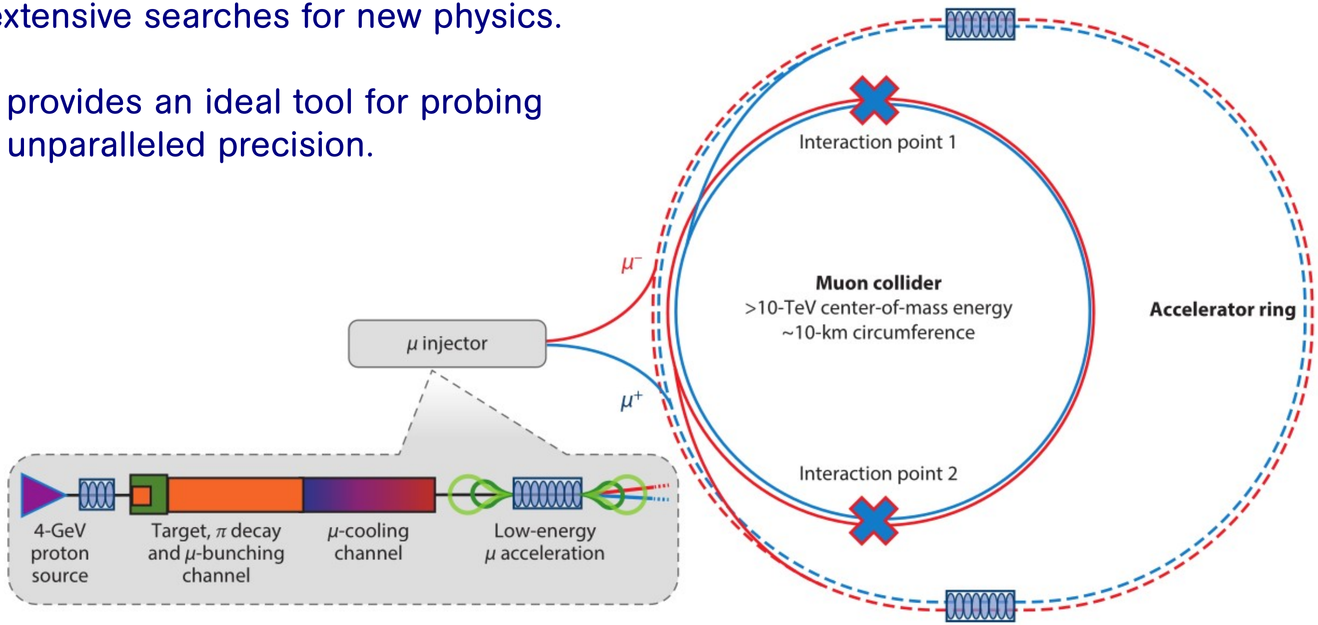
Motivation for a muon collider

- A 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.
- Multi-TeV $\mu^+\mu^-$ collisions will open the door to a broad and novel physics program, allowing high-precision tests of the Standard Model in a previously unexplored energy regime and enabling both direct and indirect extensive searches for new physics.
- In particular, a multi-TeV muon collider provides an ideal tool for probing the properties of the Higgs boson with unparalleled precision.

a muon collider combines
precision physics and
high energy reach

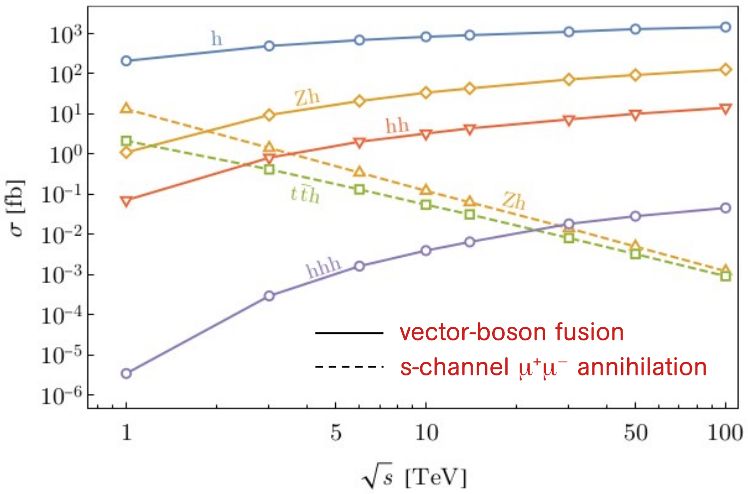


➔ R. Taylor, "Muon Colliders and their future R&D" on July 7 in T13 – Accelerators for HEP

Higgs physics at a muon collider

Higgs boson production cross sections in $\mu^+\mu^-$ collisions

H.A. Ali et al., 2022 Rep. Prog. Phys. 85 084201

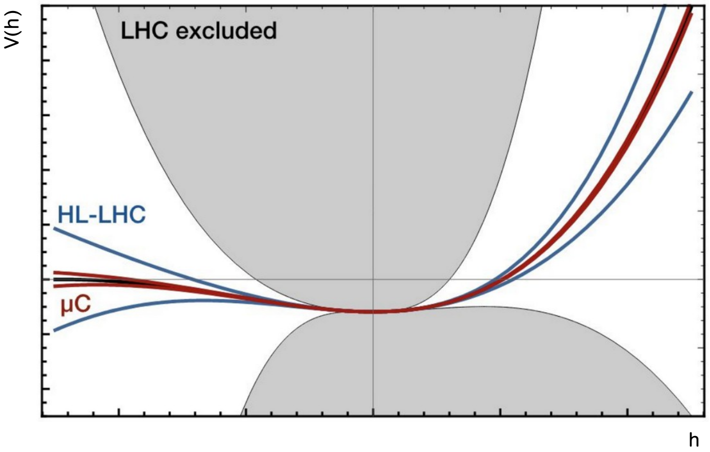


	cross section [fb]		expected events	
	3 TeV	10 TeV	1 ab^{-1} at 3 TeV	10 ab^{-1} at 10 TeV
H	550	930	5.5×10^5	9.3×10^6
ZH	11	35	1.1×10^4	3.5×10^5
$t\bar{t}H$	0.42	0.14	420	1.4×10^3
HH	0.95	3.8	950	3.8×10^4
HHH	3.0×10^{-4}	4.2×10^{-3}	0.30	42

- High production rates of Higgs bosons allow precise measurements in the Higgs sector:
  - Higgs boson couplings to fermions and bosons;
  - trilinear and possibly quartic self-couplings of the Higgs boson (λ_3, λ_4) ➔ determination of the Higgs potential shape

$$V(h) = \frac{1}{2} m_h^2 h^2 + \lambda_3 v h^3 + \frac{1}{4} \lambda_4 h^4$$

credits to R. Petrossian-Byrne

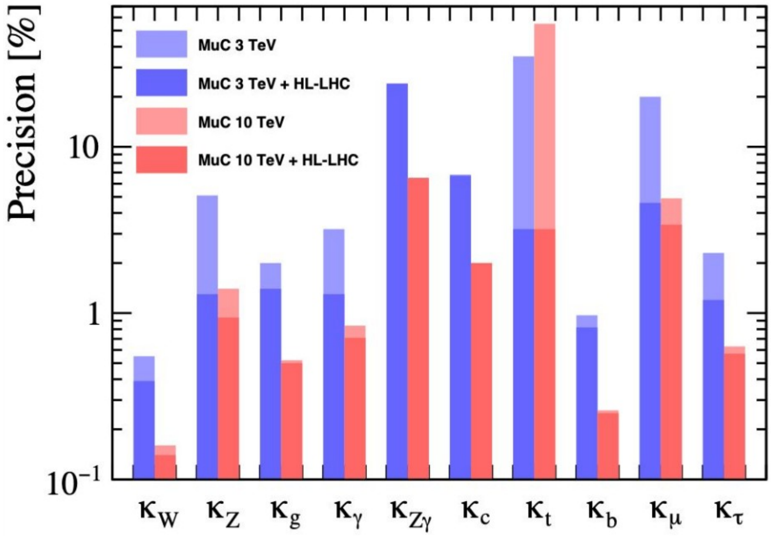


Higgs studies with parametric simulation

- The potential of a muon collider in probing the Higgs sector has been demonstrated through various phenomenological and parametric-simulation studies, with varying levels of sophistication.

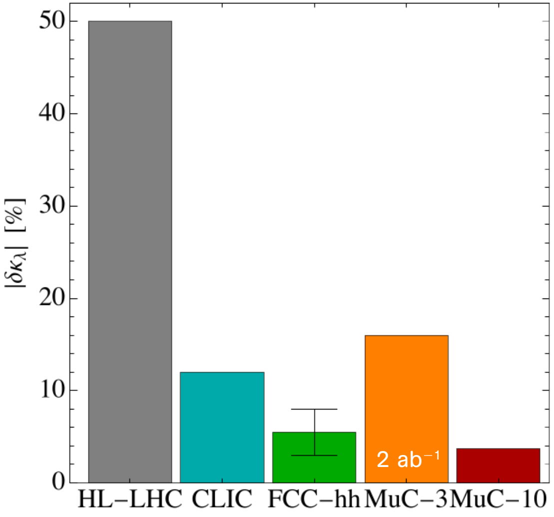
estimated precision on Higgs couplings

plotted values from M. Forslund and P. Meade, JHEP 08 (2022) 185



estimated precision on trilinear Higgs self-coupling

C. Accettura et al., arXiv:2504.21417



experimental scenarios

$\sqrt{s}$ = 3 TeV
- ➔ $L_{int} = 1\ ab^{-1}$
- ➔ 1 experiment

$\sqrt{s}$ = 10 TeV
- ➔ $L_{int} = 10\ ab^{-1}$
- ➔ 1 experiment

quartic Higgs self-coupling

M. Chiesa et al., JHEP 09 (2020) 098

$$-0.37 < \delta\kappa_4 < 0.54 \quad @\ 68\%\ CL$$

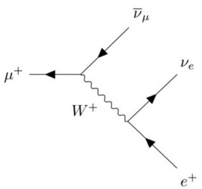
- at $\sqrt{s}$ = 10 TeV with $L_{int} = 20\ ab^{-1}$, assuming $\lambda_3 = \lambda_3^{SM}$

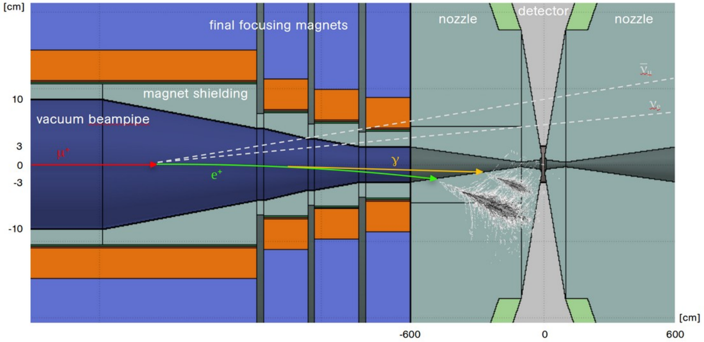
- The results above include the physics backgrounds and use a parametric simulation for the detector response. However, the machine-induced backgrounds are not taken into account.

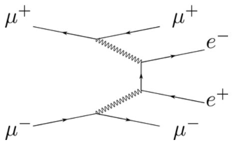
Challenging experimental conditions

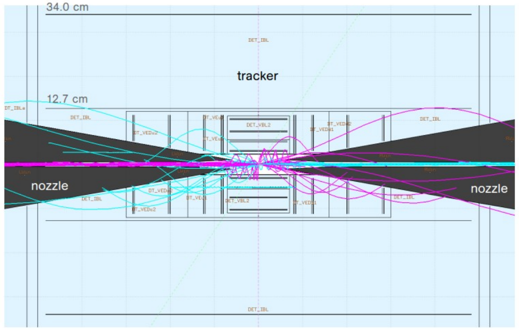
C. Accettura et al., arXiv:2504.21417

- Sources of the dominant machine-induced background in the detector:
  - background from muon decay (BIB)
  - mitigation: tungsten shields (nozzles) inside the detector
  - bkg from incoherent e^+e^- pair production (IPP)
  - mitigation: strong detector solenoidal field

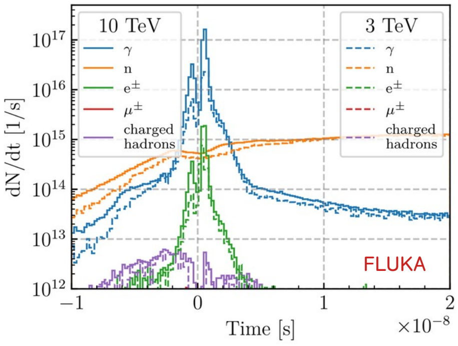




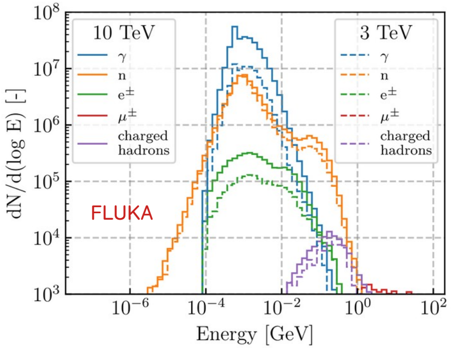




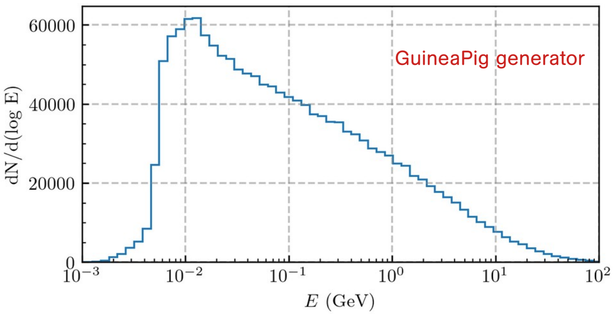
arrival time of BIB particles at the detector



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



electron and positron energy



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

Full-simulation studies at $\sqrt{s}$ = 3 TeV

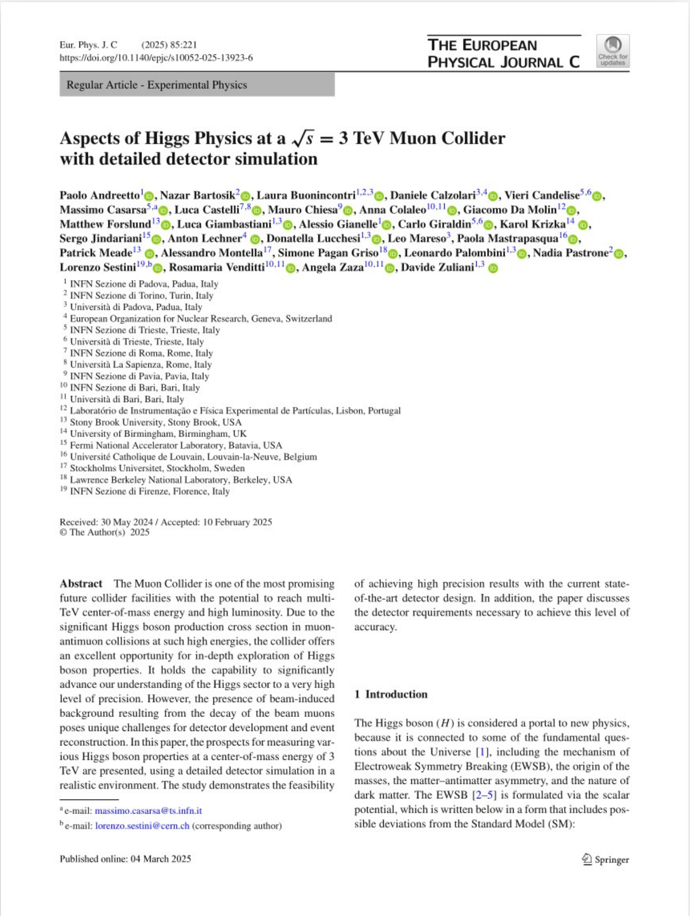
P. Andreetto et al., Eur. Phys. J. C 85 (2025) 85

- An initial campaign of Higgs studies at $\sqrt{s}$ = 3 TeV with a detailed detector simulation was carried out for Snowmass 2021:
  - assuming 1 ab^{-1}, collected by 1 experiment in 5 years;
  - background from muon decays included.
- Confirmed results from parametric simulation with an ideal detector.

$\sqrt{s}$ = 3 TeV, 1 ab^{-1}, 1 exp.	full simulation with beam-induced bkg	parametric simulation
$\sigma(H \to b\bar{b})$	0.78%	0.76%
$\sigma(H \to WW^* \to q\bar{q}'\mu\nu_\mu)$	2.9%	1.7% *
$\sigma(H \to ZZ^* \to q\bar{q}\mu^+\mu^-)$	17%	11% *
$\sigma(H \to \mu^+\mu^-)$	39%	40%
$\sigma(H \to \gamma\gamma)$	7.5%	6.1%
$\sigma(HH \to b\bar{b}b\bar{b})$	33%	-
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 $HH \to b\bar{b}b\bar{b}$ channel

cross sections from M. Forslund and P. Meade, JHEP 08 (2022) 185
trilinear self-coupling from J. de Blas et al., arXiv:2203.07261


Eur. Phys. J. C (2025) 85:221
https://doi.org/10.1140/epjc/s10052-025-13923-6

The European Physical Journal C

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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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New full-simulation studies at $\sqrt{s}$ = 10 TeV

- New set of full-simulation studies at $\sqrt{s}$ = 10 TeV, targeted to the 2026 update of the European Strategy for Particle Physics:
  - the machine lattice at the interaction region, the nozzles, and the detector specifically designed for 10 TeV $\mu^+\mu^-$ 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 collisions", Contribution #184 to the 2026 ESPP Update
- Experimental scenario: 10 ab^{-1}, expected to be collected by 1 experiment in 5 years.
- Methodology:
  - signal and physics-background samples generated with WHIZARD + PYTHIA for parton hadronization;
  - detector response simulated with GEANT4: BIB + IPP overlaid to the physical processes event by event;
  - reconstruction algorithms for physics objects revised to account for the machine-induced backgrounds, but still not fully optimized.
- Estimated the statistical sensitivity on:
  - $\sigma(H \to XX) = \dfrac{N_H}{\varepsilon_H\, L_{\text{int}}}$ for $H \to b\bar{b}$, $H \to WW^*$, and $HH \to b\bar{b}b\bar{b}$;
  - trilinear Higgs self-coupling λ_3.

The detector model: MUSIC

MUon System for Interesting Collisions

hadronic calorimeter

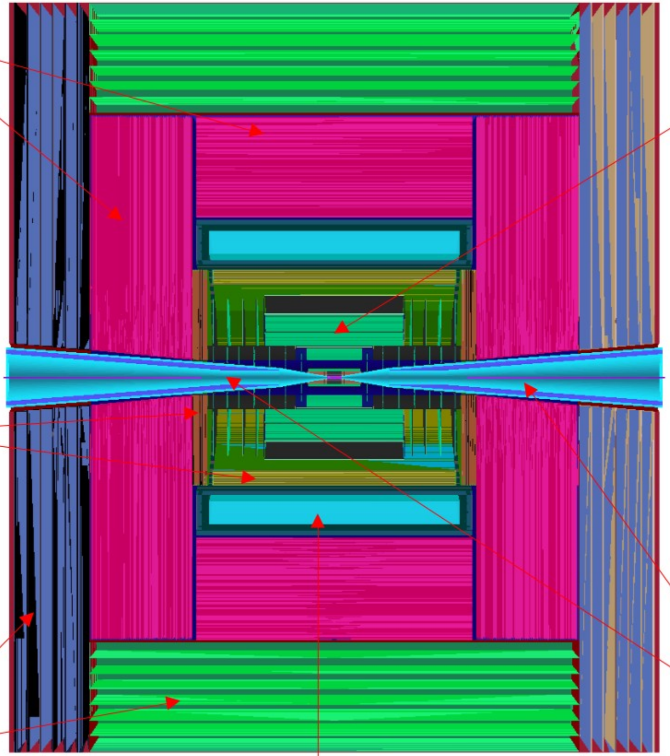
- sampling calorimeter with 70 layers of 2-cm iron absorber + 3 x 3 cm^2 plastic scintillating tiles
- timing with σ_t = 100 ps
- 7 nuclear interaction lengths
- serves as magnetic field return yoke

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

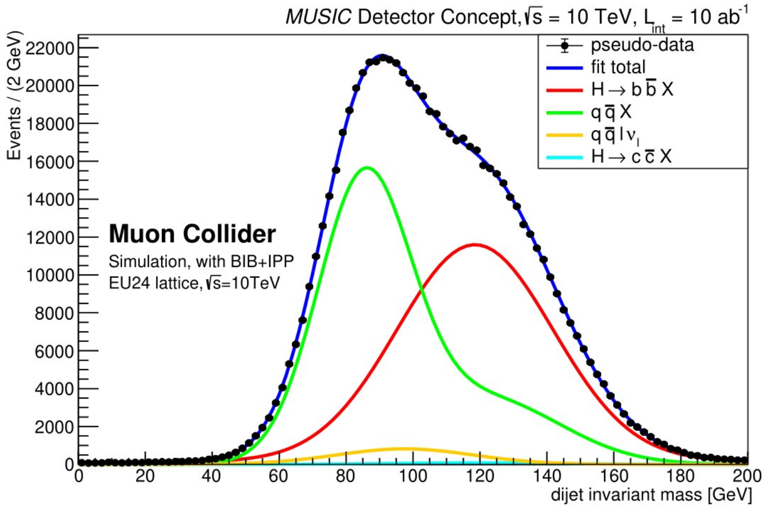
shielding nozzles

- tungsten cones + borated polyethylene cladding

➔ details in "MUSIC: a detector concept for 10 TeV $\mu^+\mu^-$ collisions" on July 8 in T11 – Detectors

$H \to b\bar{b}$

10 ab^{-1}, 1 experiment



Process	σ [fb]	ϵ_{presel} [%]	ϵ_{tag} [%]	N_{exp}
$\mu^+\mu^- \to H(\to b\bar{b})X$	490	22.2	32.4	351518
$\mu^+\mu^- \to H(\to c\bar{c})X$	24.3	22.2	4.49	2422
$\mu^+\mu^- \to q\bar{q}\nu_\ell\bar{\nu}_\ell$	2674	25.6	5.00	341598
$\mu^+\mu^- \to q\bar{q}\ell\ell$	4339	1.86	1.31	10533
$\mu^+\mu^- \to q\bar{q}\ell\nu_\ell$	9763	21.46	0.10	20974

- $H \to b\bar{b}$ event selection:
  - at least two reconstructed jets (k_t algorithm with R = 0.5) satisfying:
    - quality cuts to remove fake jets from machine bkg;
    - p_T > 40 GeV and 10° < θ < 170°;
    - b-flavor tagged.
- Statistical sensitivity estimated with a toy MC study built from signal and background's di-jet invariant mass distributions:

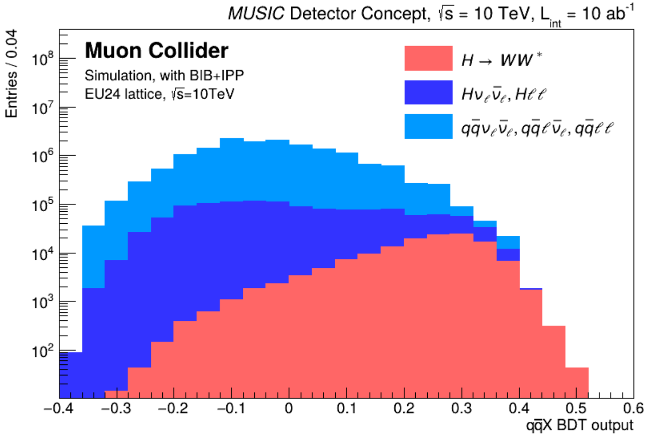
$$\frac{\Delta\sigma(H \to b\bar{b})}{\sigma(H \to b\bar{b})} = 0.28\,\%$$

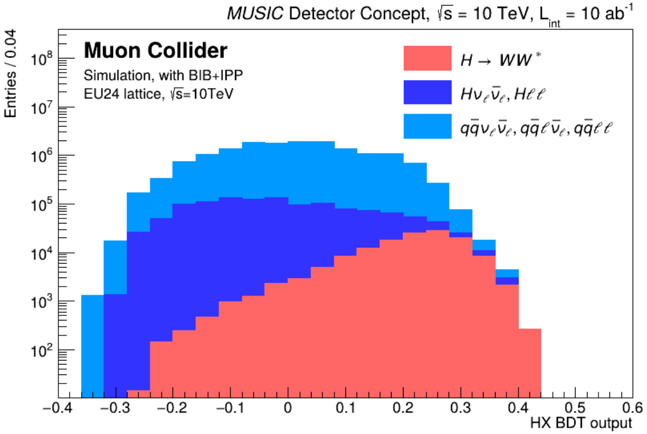
$H \to WW^* \to q\bar{q}'\mu\nu_\mu$

10 ab^{-1}, 1 experiment

- Semileptonic final state: $H \to WW^* \to q\bar{q}'\mu\nu_\mu$.
- Event selection:
  - at least two reconstructed jets (k_t algorithm with R = 0.5) and one isolated muon:
    - quality cuts on jets to remove fakes from machine bkg;
    - jets with p_T > 20 GeV and 10° < θ < 170°;
    - muon with p_T > 10 GeV and 10° < θ < 170°.
- Two BDTs trained to distinguish the signal from the bkgs $q\bar{q}X$ and HX.

Process	σ [fb]	ϵ_{presel} [%]	N_{exp}
$\mu^+\mu^- \to H(\to WW^* \to q\bar{q}\mu\nu_\mu)X$	26.3	47.3	137493
$\mu^+\mu^- \to H\nu_\ell\bar{\nu}_\ell$	820	12.2	1000906
$\mu^+\mu^- \to H\ell\ell$	84.8	12.5	106226
$\mu^+\mu^- \to q\bar{q}\ell\nu_\ell$	9763	11.4	11110294
$\mu^+\mu^- \to q\bar{q}\nu_\ell\bar{\nu}_\ell$	2674	10.2	2731663
$\mu^+\mu^- \to q\bar{q}\ell\ell$	4339	1.8	772342





- Sensitivity estimated from a toy MC study that uses the 2D distributions BDT(HX) vs BDT($q\bar{q}$X):

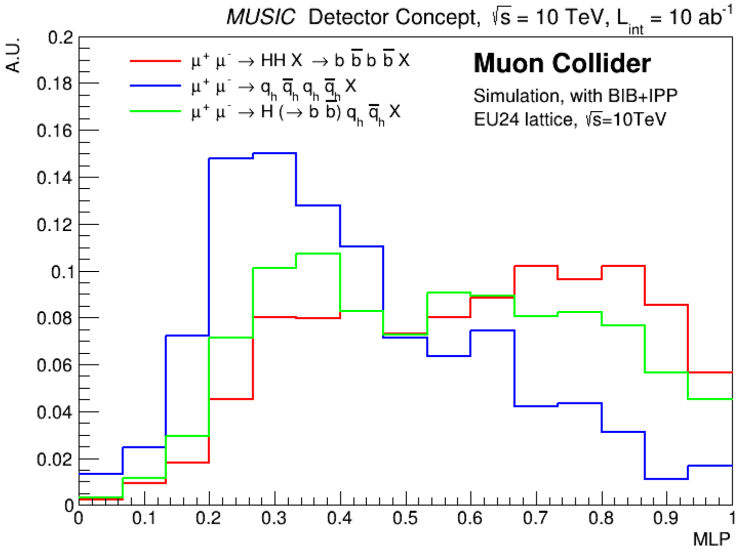
$$\frac{\Delta\sigma(H \to WW)}{\sigma(H \to WW)} = 0.58\,\%$$

$HH \to b\bar{b}b\bar{b}$

10 ab^{-1}, 1 experiment

- Only all-hadronic final state: $HH \to b\bar{b}b\bar{b}$.
- Event selection:
  - at least four reconstructed jets (k_t algorithm with R = 0.5):
    - p_T > 20 GeV and 10° < θ < 170°;
    - H candidates built pairing jets that minimize $\sqrt{(m_{ij}-m_H)^2+(m_{kl}-m_H)^2}$;
    - b-tagging is required for at least one jet per pair.
- MLP trained to separate signal from backgrounds.
- Sensitivity estimated with a toy MC study built from signal and bkg distributions of the MLP output:

$$\frac{\Delta\sigma(HH\to b\bar{b}b\bar{b})}{\sigma(HH\to b\bar{b}b\bar{b})} = 6\%$$

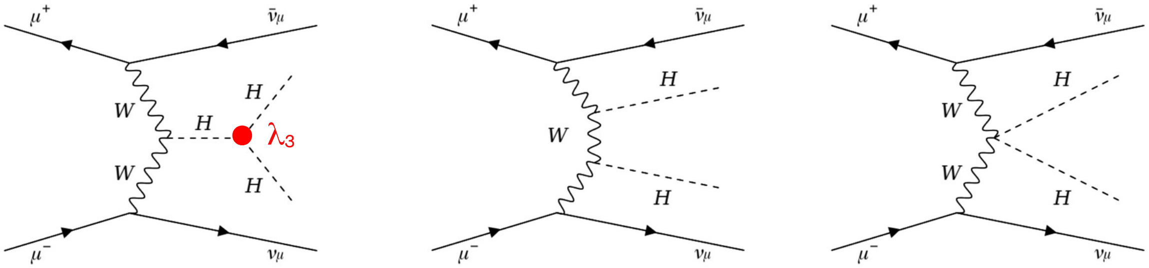


Process	σ [fb]	ϵ[%]	N_{exp}
$\mu^+\mu^- \to HHX \to b\bar{b}b\bar{b}X$	1.14	18.47	2100
$\mu^+\mu^- \to H(\to b\bar{b})q_h\bar{q}_hX$	7.27	15.56	11307
$\mu^+\mu^- \to q_h\bar{q}_hq_h\bar{q}_hX$	10.89	8.99	9787

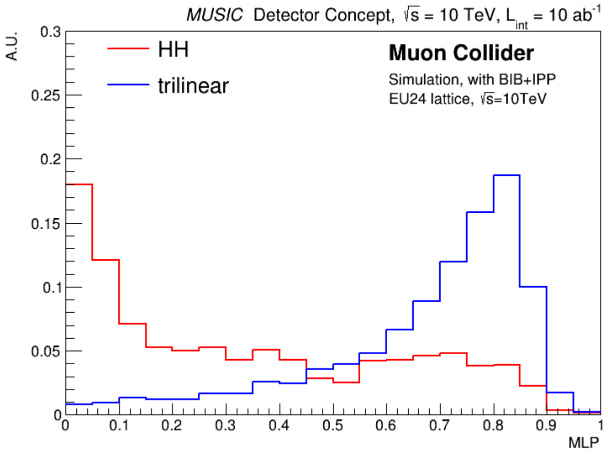
Trilinear Higgs self-coupling

10 ab^{-1}, 1 experiment

- The double-Higgs production cross section is sensitive to the trilinear Higgs self-coupling λ_3:



- Only all-hadronic final state $HH \to b\bar{b}b\bar{b}$:
  - same selection as used in the cross section analysis;
  - two MLPs trained to distinguish HH signal from physics backgrounds and the production via H* → HH from the other modes.



- λ_3 is extracted from a maximum-likelihood template fit to the 2D distribution of the two MLP outputs:

$$0.94 < \frac{\lambda_3}{\lambda_3^{SM}} < 1.08 \quad @\ 68\%\ C.L.$$

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.

- The presented full-simulation studies, which assume 10 ab^{-1} collected by 1 experiment in 5 years and take into account the dominant machine-induced backgrounds, demonstrate that:

  - the production cross sections for $H \to b\bar{b}$ and $H \to WW^*$ can be measured with permille-level precision, and the trilinear Higgs self-coupling at the percent level using only the $HH \to b\bar{b}b\bar{b}$ channel, even with detector and reconstruction algorithms not yet fully optimized;

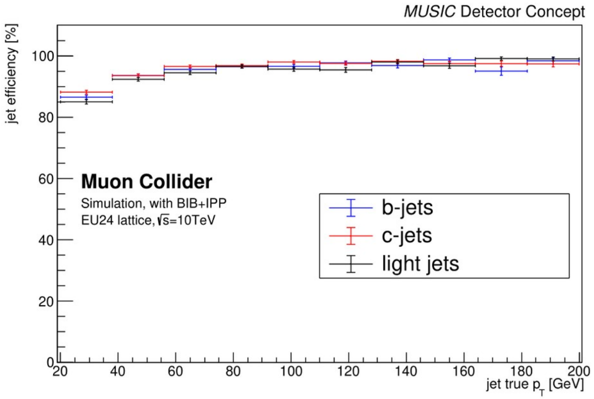
  - the machine-induced background effects can be effectively mitigated and the precision levels projected in parametric analyses are attainable.

- Work is in progress to extend cross-section studies to all major Higgs boson channels and final states, with the goal of enabling a global fit to assess sensitivity to the Higgs boson couplings.

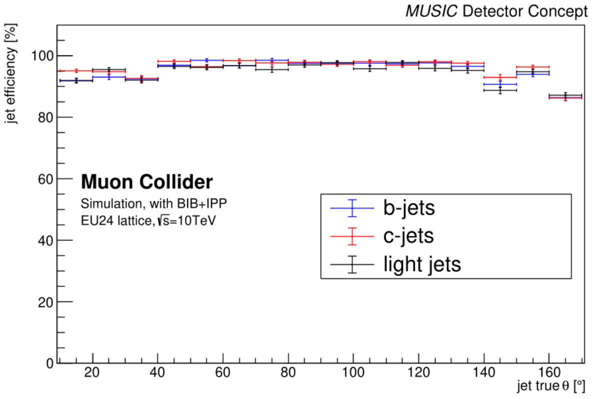
Backup

Jet reconstruction performance

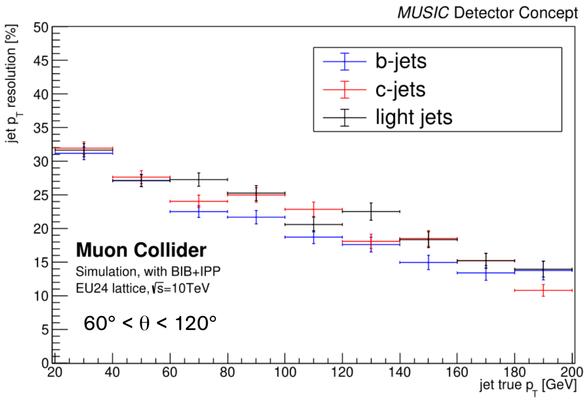
jet reconstruction efficiency vs true jet p_T

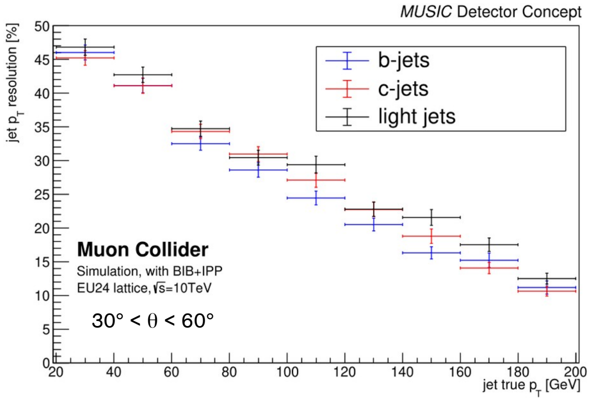


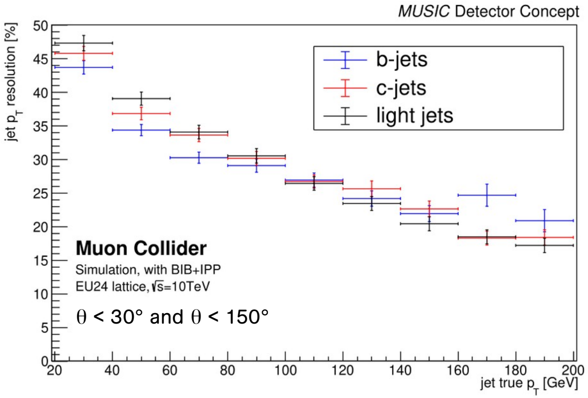
jet reconstruction efficiency vs true jet θ



jet p_T resolution vs true jet p_T

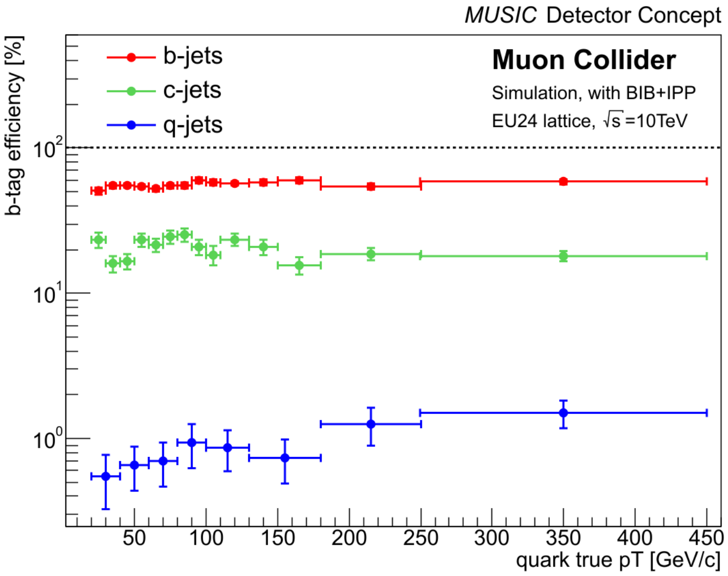




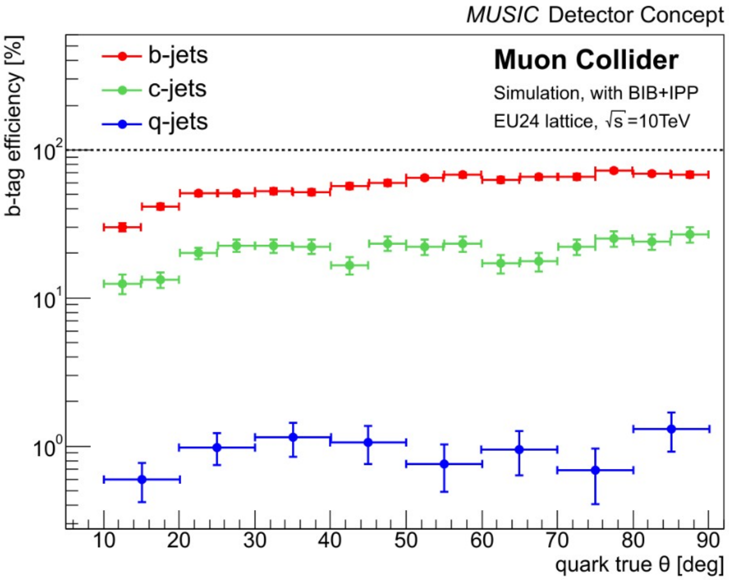


Jet flavor identification

b tagging efficiency vs true quark p_T

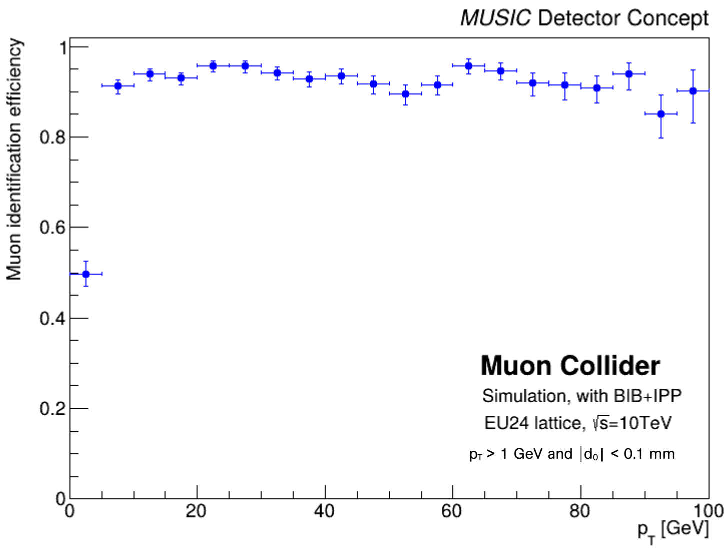


b tagging efficiency vs true quark θ

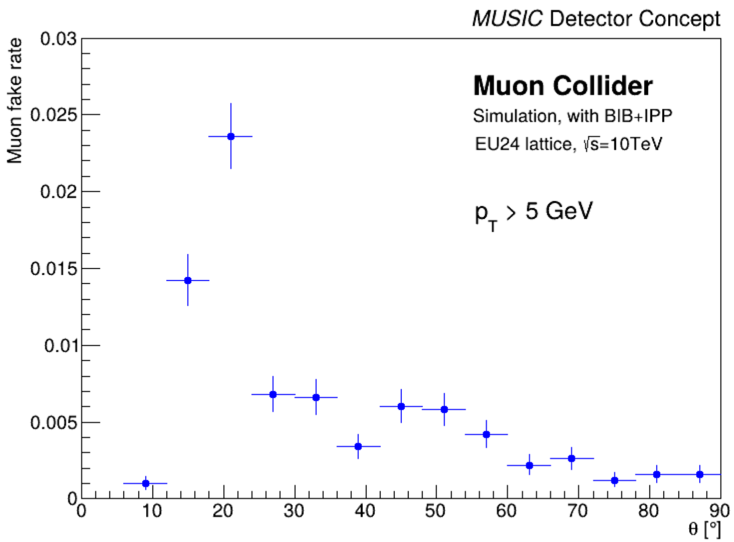


Muon reconstruction performance

muon identification efficiency vs true muon p_T



muon fake rate vs true muon θ



Comparison with parametric simulation

$\sqrt{s}$ = 10 TeV, 10 ab^{-1}, 1 exp.	full simulation with BIB and IPP bkgs	parametric simulation
$\sigma(H \to b\bar{b})$	0.28%	0.21%
$\sigma(H \to WW^* \to q\bar{q}'\mu\nu_\mu)$	0.58%	0.45% *
$\sigma(HH \to b\bar{b}b\bar{b})$	6.0%	-
λ_3/λ_3^{SM}	[0.94, 1.08] @ 68% C.L.**	[0.965, 1.037] @ 68% C.L.**

* includes also the electron channel
** uses only the $HH \to b\bar{b}b\bar{b}$ channel

cross sections from M. Forslund and P. Meade, JHEP 08 (2022) 185
trilinear self-coupling from J. de Blas et al., arXiv:2203.07261