Higgs physics prospects at the Muon Collider with a detailed detector simulation

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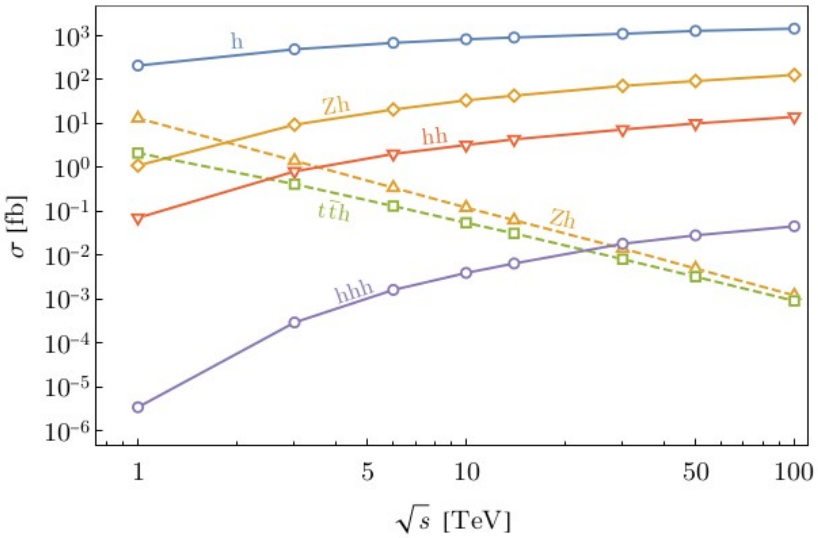
Higgs physics at a muon collider

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



	σ [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
ttH	0.42	0.14	420	1.4×10^3
HH	0.95	3.8	950	3.8×10^4
HHH	3×10^{-4}	4.2×10^{-3}	0.3	42

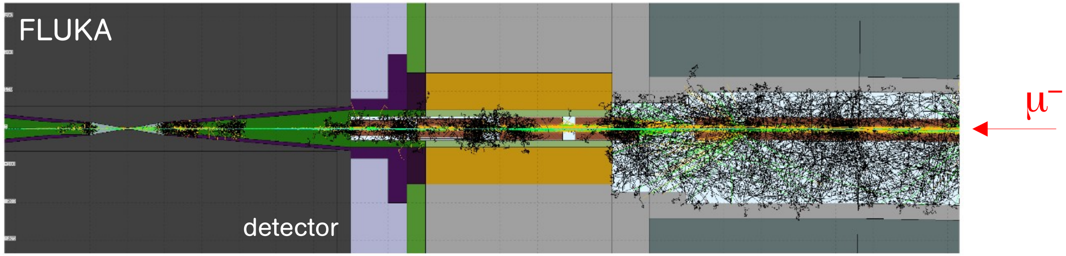
- Lepton collisions at multi-TeV center-of-mass energies provide an ideal tool for studying the properties of the Higgs boson.
- High Higgs boson production rates allow precise measurements in the Higgs sector:
  - Higgs boson couplings to fermions and bosons;
  - trilinear and quartic self-couplings of the Higgs boson (λ_3, λ_4) ➔ determination of the Higgs potential.

More about the muon collider physics program:

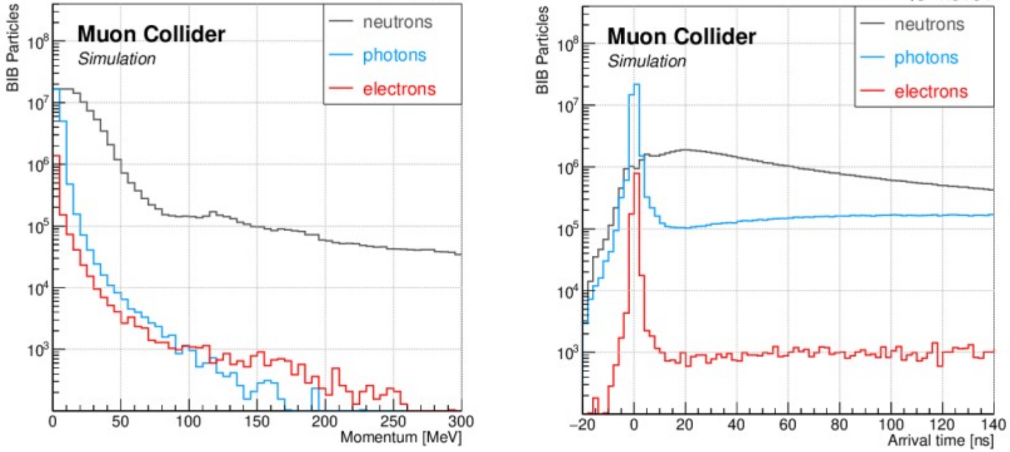
- C. Aimè, "New physics and hidden sectors at Muon Collider" in Session T10 - Searches for New Physics;
- F. Meloni, "Detecting disappearing tracks and other exotica at a Muon Collider" in Session T10 - Searches for New Physics.

The experimental environment

F. Collamati et al., 2021 JINST 15 P11009



N. Bartosik et al., arXiv:2203.07964



- D. Lucchesi, “Machine-Detector interface for multi-TeV Muon Collider” in Session T13 - Accelerators for HEP.

- Interactions of the decay products of the muons in the beams with the machine elements produce intense fluxes of background particles in the detector:
  - very high hit multiplicity in the tracking system;
  - uniform diffuse background in the calorimeters.
- Mitigation measures and specialized reconstruction algorithms are required.

Such peculiar experimental conditions make extrapolating from current experience with machine backgrounds very difficult

➔ studies with detailed detector simulation

The detector model

hadronic calorimeter

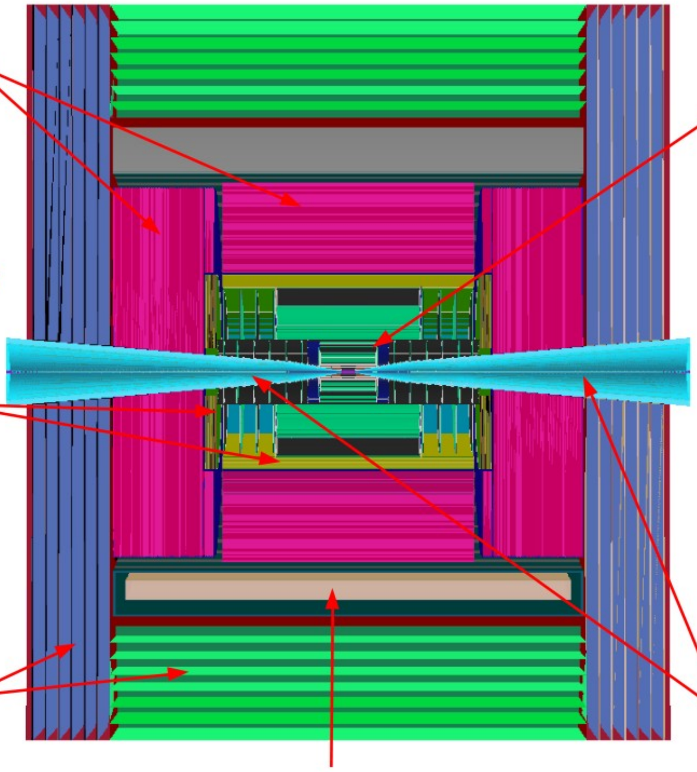
- 60 layers of 19-mm steel absorber + plastic scintillating tiles;
- 30x30 mm^2 cell size;
- 7.5 λ_I.

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.



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.

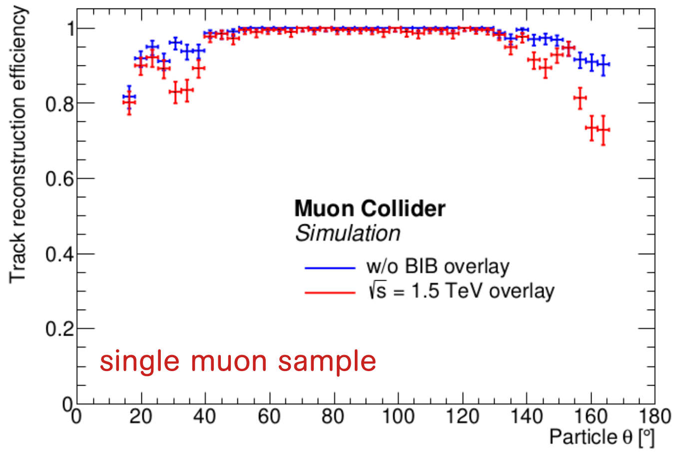
shielding nozzles

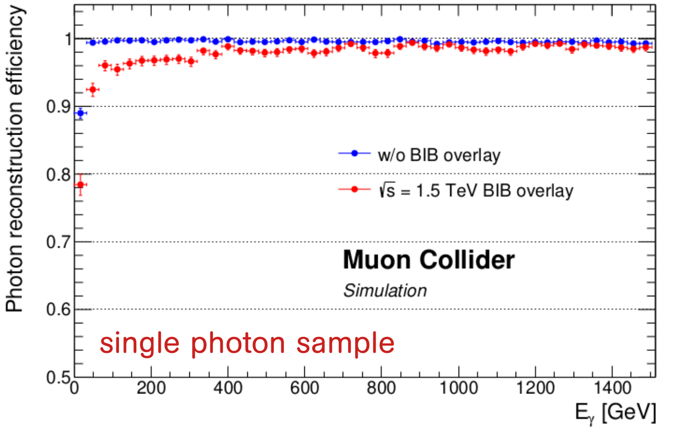
- Tungsten cones + borated polyethylene cladding.

The detector model for 3-TeV studies is based on CLIC's detector concept + the MDI and vertex detector designed by the US Muon Accelerator Program.

- L. Sestini, "R&D towards the detector for the Muon Collider" in Session T12 - Detector R&D and Data Handling.

Studies with detailed detector simulation



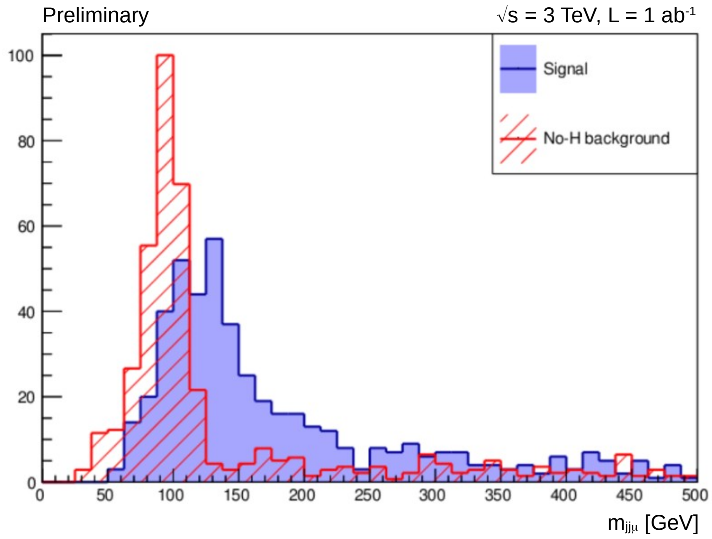


- To ensure optimal performance in the presence of machine-induced background (BIB), it is necessary to revise and fine-tune the reconstruction algorithms for all physical objects.

- The initial focus was on tracks, muons, photons, and jets
  - ➔ first physics studies carried out using a detailed detector simulation to assess the physical reach of a 3 TeV muon collider with 1 interaction point and a cumulative dataset of 1 ab^{-1} over 5 years.

- Estimated the statistical sensitivity on $\sigma_H \times BR$ for the channels:
  - $H \to WW^*, ZZ^*$ ➔ g_{HWW}, g_{HZZ};
  - $H \to b\bar{b}, \mu\mu$ ➔ g_{HWW}, g_{HZZ}, g_{Hbb}, $g_{H\mu\mu}$;
  - $H \to \gamma\gamma$ ➔ g_{HWW}, g_{HZZ}, $g_{H\gamma\gamma}$;
  - double Higgs $HH \to b\bar{b}b\bar{b}$ ➔ λ_3.

$H \to WW^*$



WHIZARD2 + PYTHIA8

Process	$\epsilon[\%]$	$\sigma\ [fb]$	N_{exp}
$\mu^+\mu^- \to H(\to WW^* \to qq\mu\nu)X$	14.1 ± 0.8	17.3	2430 ± 150
$\mu^+\mu^- \to qq\mu\nu$	0.05 ± 0.03	$5.02 \cdot 10^3$	2600 ± 1300
$\mu^+\mu^- \to qqll$	< 0.01	$1.04 \cdot 10^3$	< 100
$\mu^+\mu^- \to qq\nu\nu$	< 0.01	$1.56 \cdot 10^3$	< 100
$\mu^+\mu^- \to H \to WW^* \to qqqq$	< 0.01	108	< 10
$\mu^+\mu^- \to H \to bb$	< 0.05	313	< 150
$\mu^+\mu^- \to H \to \tau\tau$	< 0.01	34.3	< 4

- 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 muon:
    - quality cuts on jets to remove fakes from bkg;
    - jets with $p_T > 20$ GeV and $|\eta| < 2.5$;
    - muon with $p_T > 10$ GeV and $10° < \theta_\mu < 170°$;
  - cut on the score of two BDTs, trained to distinguish signal from backgrounds with and without a Higgs boson.

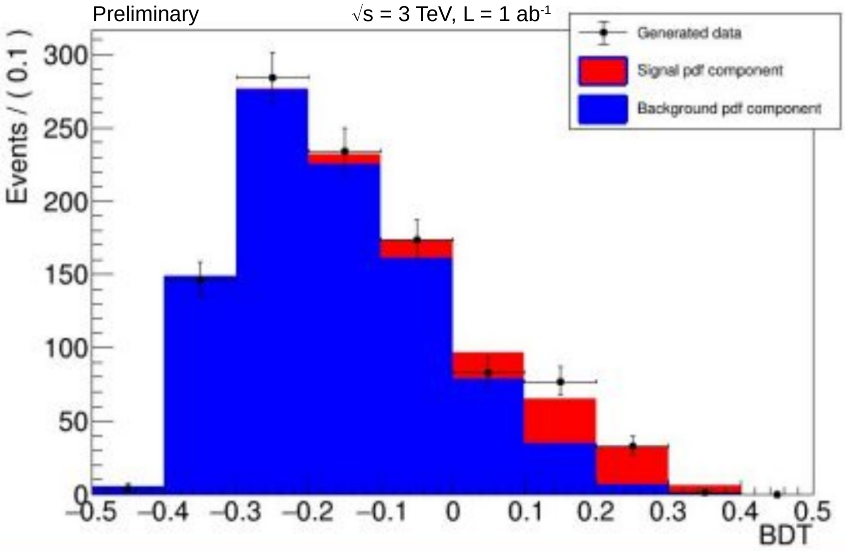
$$\frac{\Delta\, \sigma_{H\to WW}}{\sigma_{H\to WW}} \sim \frac{\sqrt{S+B}}{S} = 2.9\,\%$$

H. Abramowicz et al., Eur. Phys. J. C 77, 475 (2017)

CLIC at 3 TeV with 2 ab^{-1} ($q\bar{q}'q\bar{q}'$ + $q\bar{q}'\ell\nu_\ell$): 0.7%

$H \to ZZ^*$

- Semileptonic final state: $H \to ZZ^* \to q\bar{q}\mu^+\mu^-$.
- Event selection:
  - at least two reconstructed jets (k_t algorithm with R = 0.5) and two opposite-charge muons:
    - quality cuts on jets to remove fakes from bkg;
    - jets with p_T > 15 GeV and 30° < θ_μ < 150°;
    - muon with p_T > 10 GeV and 10° < θ_μ < 170°;
    - isolated muon: $\Delta R(j,\mu) = \sqrt{\Delta\eta^2 + \Delta\phi^2} > 0.5$;
  - cut on the score of a BDT, trained to distinguish signal from the dominant background.



$$\frac{\Delta\sigma_{H\to ZZ}}{\sigma_{H\to ZZ}} \sim \frac{\sqrt{S+B}}{S} = 17\%$$

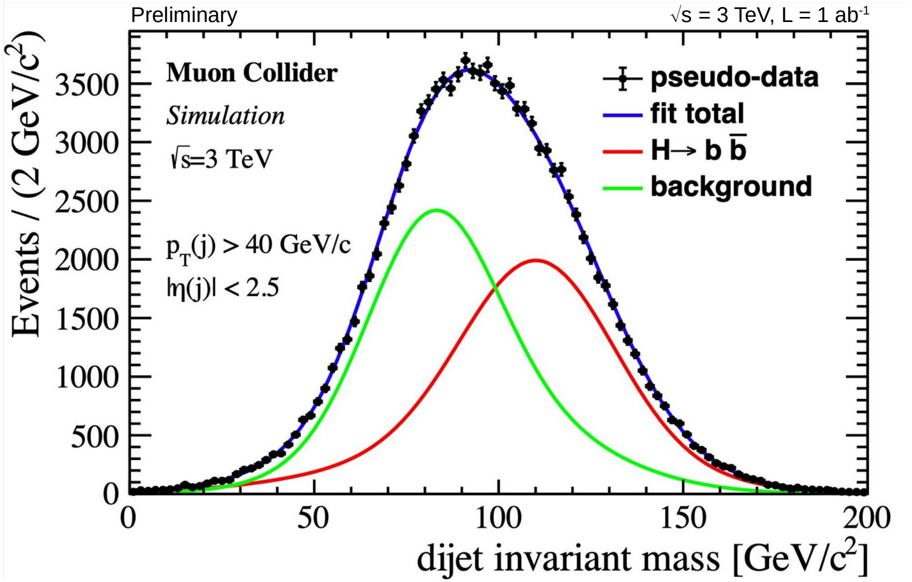
WHIZARD2 + PYTHIA8

Process	$\epsilon[\%]$	$\sigma\ [fb]$	N_{exp}
$\mu^+\mu^- \to H(\to ZZ^*)X \to qq\mu^+\mu^-X$	15.9 ± 0.6	0.345	55 ± 2
$\mu^+\mu^- \to qq\mu^+\mu^-X$	0.69 ± 0.08	5.667	39 ± 5

H. Abramowicz et al., Eur. Phys. J. C 77, 475 (2017)

CLIC at 3 TeV with 2 ab^{-1} ($q\bar{q}\ell\ell$): 3.9%

$H \to b\bar{b}$



WHIZARD2 + PYTHIA8

Process	$\epsilon[\%]$	$\sigma\ [fb]$	N_{exp}
$\mu^+\mu^- \to H(\to b\bar{b})X$	19.3 ± 0.4	308	59500 ± 1200
$\mu^+\mu^- \to q\bar{q}X, q = b, c$	11.2 ± 0.3	584	65400 ± 1800

- Event selection:
  - two reconstructed jets (k_t algorithm with R = 0.5) satisfying:
    - quality cuts to remove fake jets from bkg;
    - p_T > 40 GeV and $|\eta|$ < 2.5;
    - b-flavour tagged.
- Sensitivity estimated with a toy MC study built from signal and background's di-jet invariant mass distributions.

$$\frac{\Delta\,\sigma_{H\to b\bar{b}}}{\sigma_{H\to b\bar{b}}} \sim 0.75\,\%$$

H. Abramowicz et al., Eur. Phys. J. C 77, 475 (2017)

CLIC at 3 TeV with 2 ab^{-1}: 0.3%

$H \to \mu\mu$

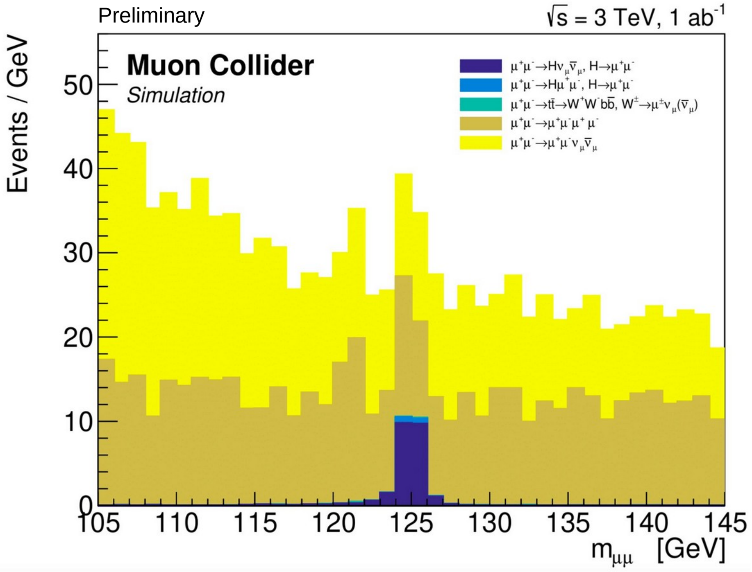
- Event selection:
  - two opposite-charge reconstructed muons:
    - $p_T > 5$ GeV and $10° < \theta_\mu < 170°$;
    - $p_{T1}+p_{T2} > 50$ GeV;
    - $p_T(\mu\mu) > 30$ GeV and $105 < m_{\mu\mu} < 145$ GeV;
  - cut on two BDTs trained to separate the signal from the two dominant backgrounds.

- Sensitivity estimated with a toy MC study built from the di-muon invariant mass distributions for signal and background.

$$\frac{\Delta\,\sigma_{H\to\mu\mu}}{\sigma_{H\to\mu\mu}} \sim 38\,\%$$

H. Abramowicz et al., Eur. Phys. J. C 77, 475 (2017)

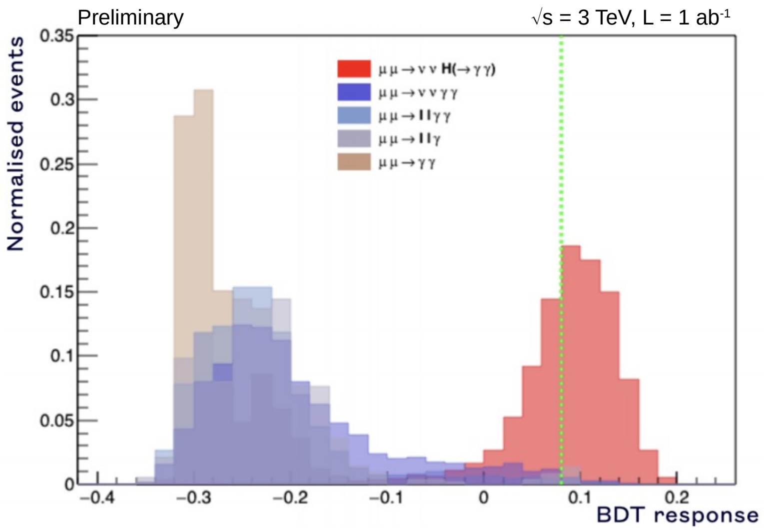
CLIC at 3 TeV with 2 ab^{-1}: 25%



MadGraph5 + PYTHIA8

Process	$\epsilon[\%]$	$\sigma\ [fb]$	N_{exp}
$\mu^+\mu^- \to H(\to \mu^+\mu^-)\nu_\mu\bar{\nu}_\mu$	22.12 ± 0.29	0.109	24.2
$\mu^+\mu^- \to H(\to \mu^+\mu^-)\mu^+\mu^-$	16.31 ± 0.26	0.010	1.6
$\mu^+\mu^- \to \mu^+\mu^-\nu\bar{\nu}_\mu$	5.74 ± 0.05	11.09	636.5
$\mu^+\mu^- \to \mu^+\mu^-\mu^+\mu^-$	0.160 ± 0.003	297.40	476.4
$\mu^+\mu^- \to t\bar{t} \to W^+W^-b\bar{b},\, W^\pm \to \mu^\pm\nu_\mu(\bar{\nu}_\mu)$	0.34 ± 0.06	0.32	1.1

$H \to \gamma\gamma$



MadGraph5 + PYTHIA8

Process	$\epsilon[\%]$	$\sigma\ [fb]$	N_{exp}
$\mu^+\mu^- \to H(\to \gamma\gamma)X$	50.89	0.91	460
$\mu^+\mu^- \to \nu_\mu\bar{\nu}_\mu\gamma\gamma$	1.10	81.98	901
$\mu^+\mu^- \to l^+l^-\gamma\gamma$	0.61	4.41	31
$\mu^+\mu^- \to l^+l^-\gamma$	0.17	159.01	302
$\mu^+\mu^- \to \gamma\gamma$	0.00	60.15	0

- Event selection:
  - at least two reconstructed photons:
    - E > 15 GeV, p_T > 10 GeV and 10° < θ_μ < 170°;
    - p_T > 40 GeV for the most energetic photon;
    - $m_{\gamma\gamma}$ > 40 GeV;
  - cut on a BDT trained to separate the signal from the mixture of backgrounds.

$$\frac{\Delta\,\sigma_{H\to\gamma\gamma}}{\sigma_{H\to\gamma\gamma}} \sim \frac{\sqrt{S+B}}{S} = 8.9\,\%$$

H. Abramowicz et al., Eur. Phys. J. C 77, 475 (2017)

CLIC at 3 TeV with 2 ab^{-1}: 10%

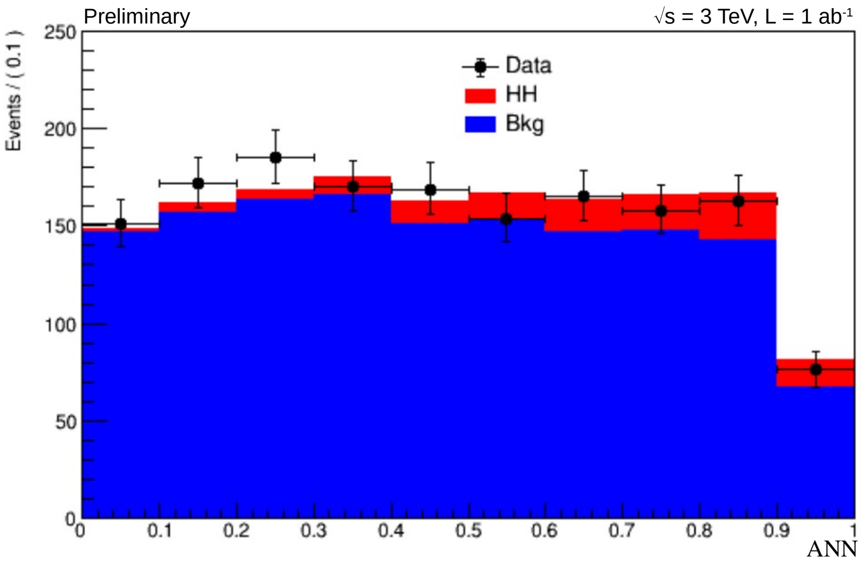
$HH \rightarrow b\bar{b}b\bar{b}$

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

$$\frac{\Delta\,\sigma_{HH\rightarrow b\bar{b}b\bar{b}}}{\sigma_{HH\rightarrow b\bar{b}b\bar{b}}} \sim 33\,\%$$

H. Abramowicz et al., Eur. Phys. J. C 77, 475 (2017)

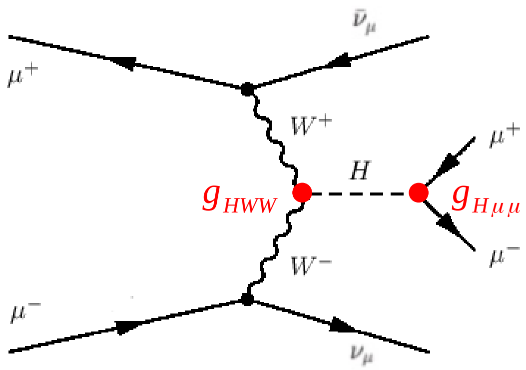
CLIC at 3 TeV with 2 ab^{-1} ($b\bar{b}b\bar{b}$ + $b\bar{b}q\bar{q}'q\bar{q}'$): 29%

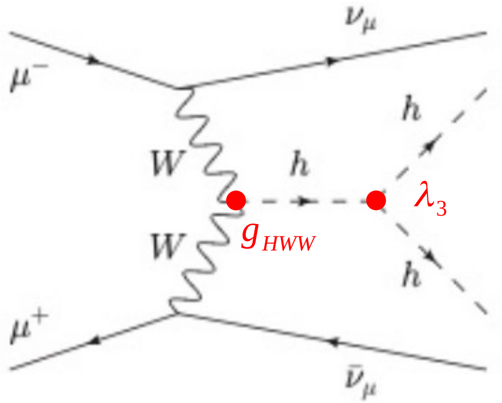


WHIZARD2 + PYTHIA8

Process	$\epsilon[\%]$	$\sigma\ [fb]$	N_{exp}
$\mu^+\mu^- \rightarrow HH\nu\bar{\nu} \rightarrow b\bar{b}b\bar{b}\nu\bar{\nu}$	27.50 ± 0.45	0.28	77
$\mu^+\mu^- \rightarrow H(\rightarrow b\bar{b})q_h\bar{q}_h\nu\bar{\nu}$	24.72 ± 0.43	2.8	698
$\mu^+\mu^- \rightarrow q_h\bar{q}_hq_h\bar{q}_h\nu\bar{\nu}$	17.70 ± 0.38	4.1	724

Towards a determination of the H couplings





- The physical observables $\sigma_H \times$ BR depend on the Higgs boson couplings to the standard model bosons and fermions (and the Higgs total width Γ_H), which can be determined with a global fit:
  - a study is currently underway to evaluate the sensitivity on Γ_H at a 3 TeV muon collider;
  - once all the most significant Higgs decay modes are available, a global fit to the cross sections can be performed to estimate the sensitivity on Higgs couplings at a 3 TeV muon collider.
- The double Higgs boson production is sensitive to the trilinear self coupling λ_3 through the tree-level process H* → HH:
  - a preliminary estimate yielded $\frac{\Delta\lambda_3}{\lambda_3} \sim 20\%$;

    L. Sestini et al., PoS (ICHEP2022) 515
  - an update is underway with an improved background modeling.

Summary

- The sensitivity to $\sigma_H \times$ BR of a 3 TeV muon collider with a dataset of 1 ab^{-1} has been studied using a detailed detector simulation for the major Higgs boson decay modes:
  - the study shows that the effects of the beam-induced background can be minimized to a degree where the reconstruction performance of physical objects is not compromised;
  - the results are promising and competitive, even though the background mitigation measures, the detector, and the reconstruction algorithms have not been fully optimized, and the analysis strategies used are relatively simple.
- There is ample room for improvement in terms of detector design, physical object reconstruction optimization, as well as more sophisticated analysis techniques and the inclusion of additional Higgs channels.