Physics results with full sim and comparison with fast sim

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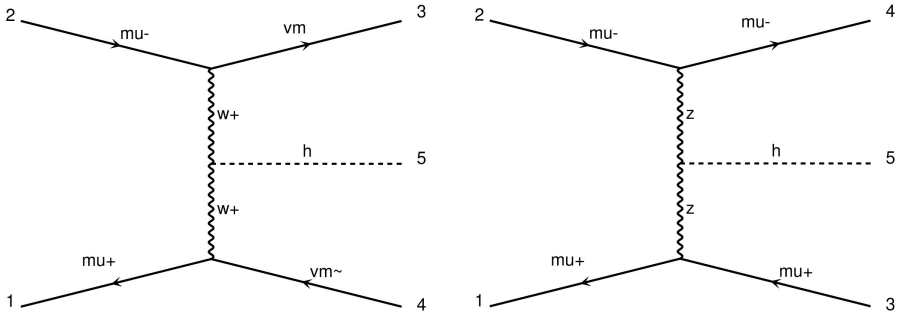
Outlook

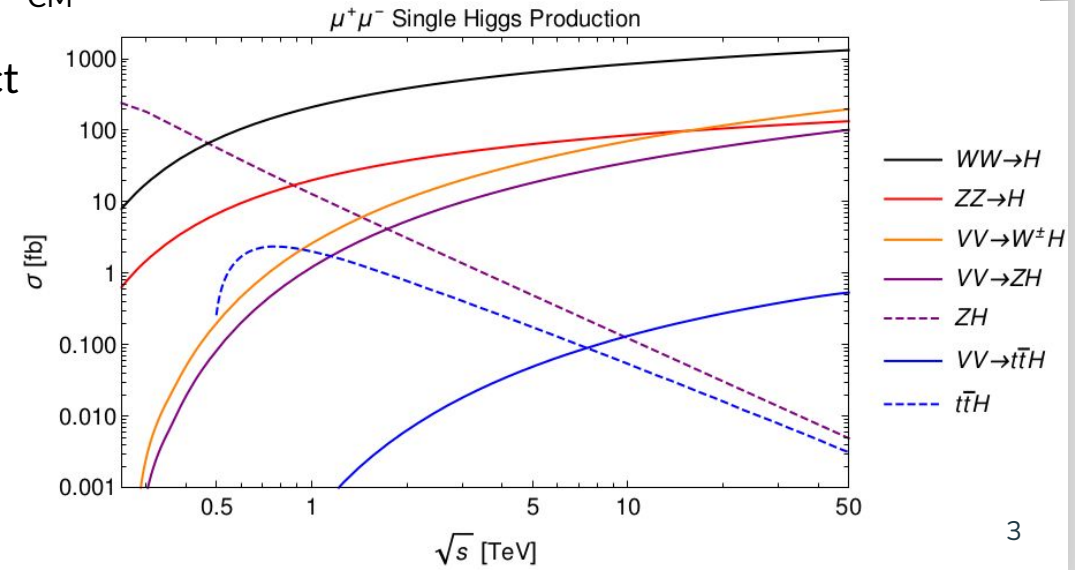
- **1 ab^{-1} @ 3 TeV Muon Collider** considered in this presentation
- Higgs physics results with full simulation compared with studies based on Delphes fast sim
- Full simulation studies include Beam Induced Background (BIB), unless otherwise specified
  - One BIB event superimposed on each physics event
  - BIB simulated for 1.5 TeV Muon Collider
  - Conservative approach: BIB is expected to be more forward at higher E_{CM}
  - 3 TeV BIB preliminary studies show that it's not worse than the 1.5 TeV one

Higgs production

Dominant Higgs production modes:

- WBF: μμ->vvH, ~500 fb
- ZBF: μμ->μμH, ~50 fb
- Both increases logarithmically with E_{CM}
- With ZBF, final state muons are forward, therefore difficult to detect
- In both full and fast sim studies both diagrams are considered





Full Simulation

3 TeV Muon Collider detector used for full sim studies

hadronic calorimeter

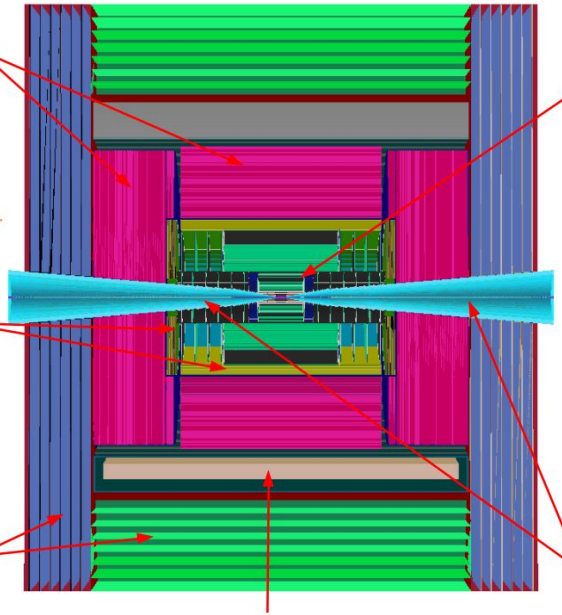
- 60 layers of 19-mm steel absorber + plastic scintillating tiles;
- 30x30 mm^2 cell size;
- 7.5 λ_I.

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.

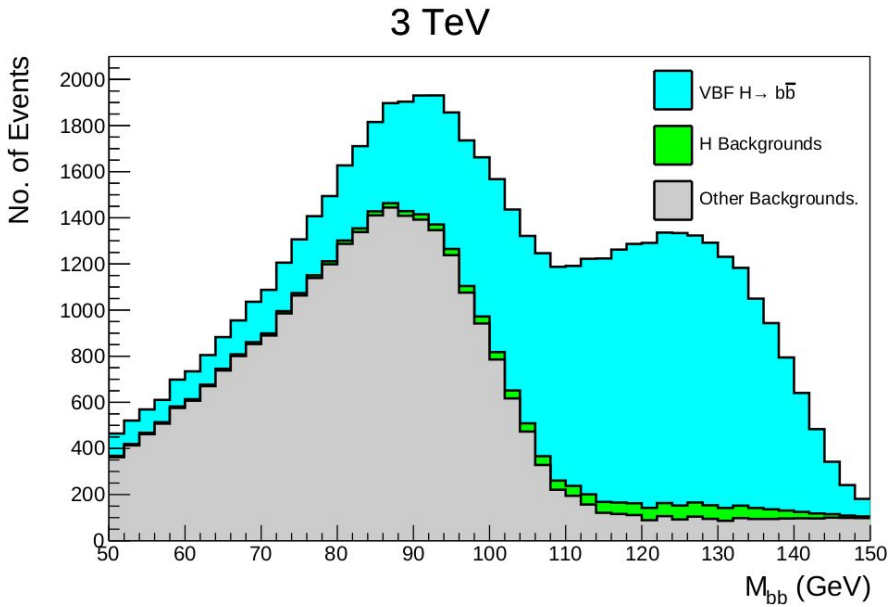
Fast Simulation

- Events generated with MG5+Pythia8, Delphes to model detector performance
  https://indico.cern.ch/event/957299/contributions/4023467/attachments/2106044/3541874/delphes_card_mucol_mdi%20.pdf
- Jet p_T resolution 2% for $|\eta| < 0.76$ and 5% for $|\eta| > 0.76$
- Cut-off at $|\eta| = 2.5$ to simulate presence of nozzles
- b-tagging: 50% efficiency, flat in p_T and η
  - c-mistag: 0.07%-3%
  - light mistag: 0.02%-0.7%
- Muon efficiency close to 100%
- Photon efficiency ~90%
- Cut based analysis, resolution estimated from event counts as $\frac{\Delta\sigma}{\sigma} = \frac{\sqrt{S+B}}{S}$
- See: *High precision Higgs from high energy muon colliders*, JHEP **08** (2022), 185

H->bb fast sim

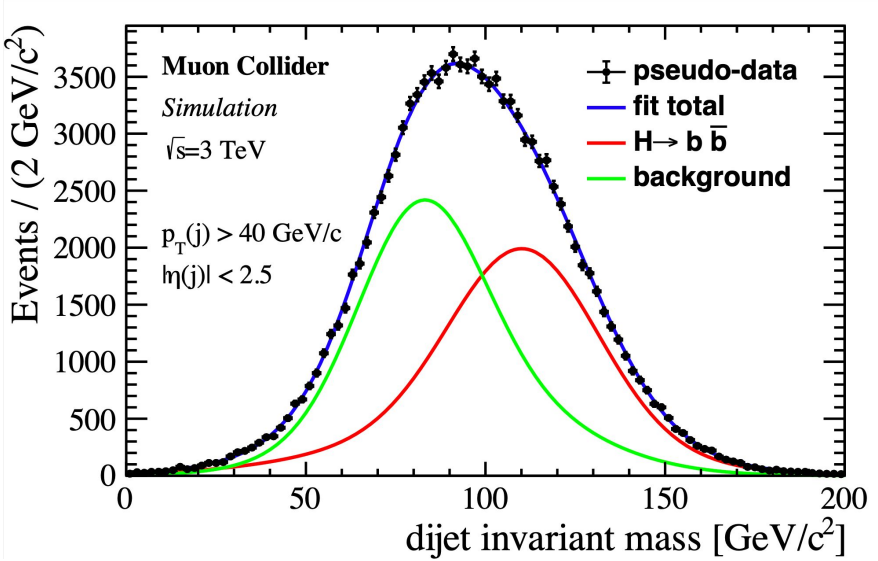
- Part of the 2-body hadronic Higgs decay study
- Events with two b-tagged jets with $p_T > 40$ GeV and invariant mass $100\ \text{GeV} < m_H < 150\ \text{GeV}$
- Main background from VBF Z->jj

$$\frac{\Delta\sigma}{\sigma} = \frac{\sqrt{S+B}}{S} \longrightarrow 0.76\%$$



H->bb full sim

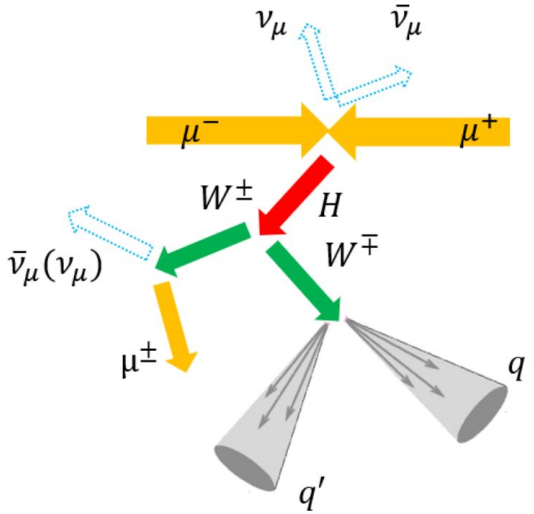
- Signal μμ->(H->bb)X and background μμ->qqX (q=b,c) generated with Whizard+Pythia8. X is a pair of neutrinos or muons
- Required 2 jets with a secondary vertex each
- S= 59 500, B=65 400 in 1 ab^{-1}
- Signal yield from template fit to pseudo-experiments using invariant mass
- Statistical relative uncertainty on σ x BR = 0.75%



H->WW* fast sim

- Semileptonic decay: full Higgs reconstruction not possible
- Events with 2 R=0.5 jets + 1 isolated lepton, all with p_T > 20 GeV
  - **Note**: electron and muon decays used together
- Dominant backgrounds:
  - On-shell diboson production
  - $\mu^+\mu^-$ -> vv vl jj
  - $\mu^+\mu^-$ -> ll vl jj
- 5 GeV < m_{jj} < 90 GeV, 20 GeV < m_{jjl} < 110 GeV
- 40 GeV < E_{jj} < 700 GeV, 85 GeV < E_{jjl} < 800 GeV

$$\frac{\Delta\sigma}{\sigma} = \frac{\sqrt{S+B}}{S} \longrightarrow \textbf{1.7\%}$$



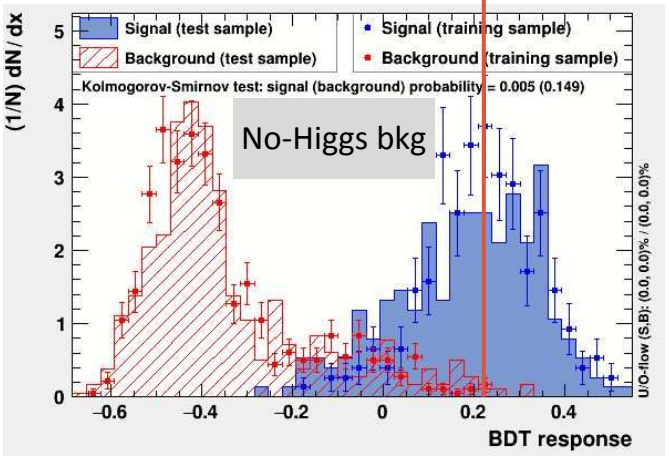
H->WW* full sim

- 1 Muon + 2 jets final state (no electron)
- Signal and backgrounds (with and without Higgs) simulated with Whizard+Pythia8
- Cuts on two BDTs to select signal vs backgrounds
- S=2 430, B=2 600 in 1 ab^{-1}

Event	Expected Events
$\mu^+\mu^- \to H\nu\bar{\nu} \to WW^*\nu\bar{\nu} \to qq\mu\nu\nu\bar{\nu}$	2430 ± 150
$\mu^+\mu^- \to\to qq\mu\nu$	2600 ± 1300
$\mu^+\mu^- \to\to qqll$	< 100 $C.L. = 68\%$
$\mu^+\mu^- \to\to qq\nu\nu$	< 100 $C.L. = 68\%$
$\mu^+\mu^- \to H \to WW^* \to qqqq$	< 10 $C.L. = 68\%$
$\mu^+\mu^- \to H \to bb$	< 150 $C.L. = 68\%$
$\mu^+\mu^- \to H \to \tau\tau$	< 4 $C.L. = 68\%$

$$\frac{\Delta\sigma}{\sigma} = \frac{\sqrt{S+B}}{S} \longrightarrow 2.9\%$$

0.22



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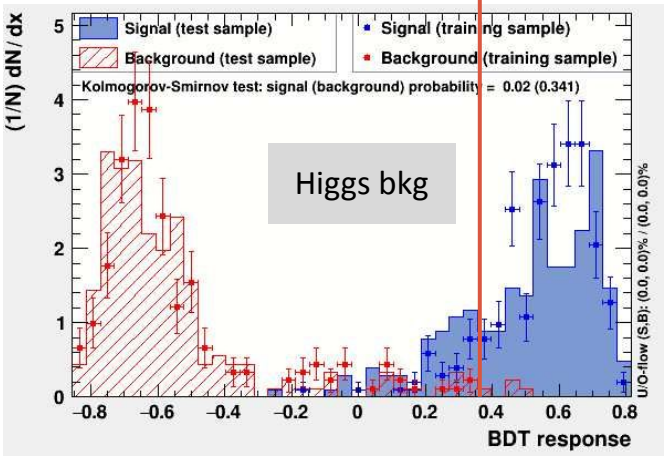


H->ZZ* fast sim

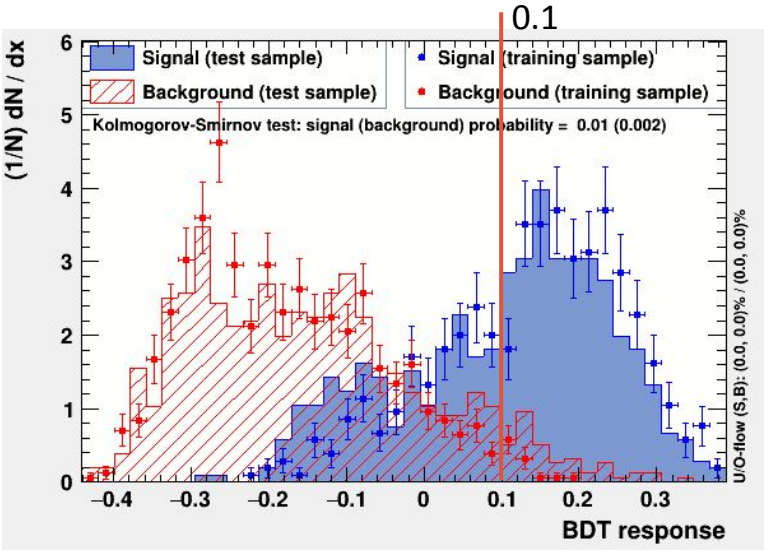
- Events with 2 leptons and 2 R=0.5 jets, all with p_T > 20 GeV
  - **Note**: electron and muon decays used together
- The pair of either leptons or jets with invariant mass closer to m_Z is assigned to the on-shell Z
- Main backgrounds:
  - $\mu^+\mu^-$ -> vv ll jj
  - $\mu^+\mu^-$ -> vl ll jj
- 20 GeV < m_Z < 100 GeV for on-shell Z
- 5 GeV < m_{Z^*} < 60 GeV for off-shell Z
- 100 GeV < m_H < 130 GeV if lepton pair reconstruct the on-shell Z, 80 GeV < m_H < 135 GeV otherwise

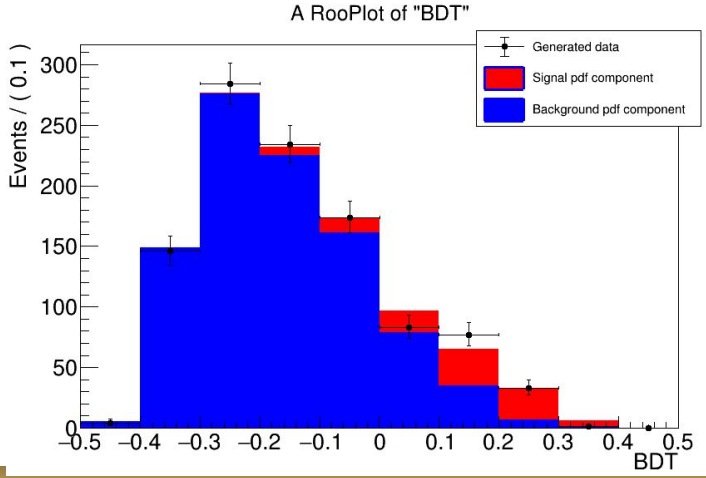
	$4j$	$2j2\ell$	4ℓ
$\mu^+\mu^- \to \nu_\mu\bar{\nu}_\mu H;\ H \to ZZ^* \to X$	124	103	5
$\mu^+\mu^- \to \mu^+\mu^- H;\ H \to ZZ^* \to X$	3	9	0
Backgrounds	6700	50	0

$$\frac{\Delta\sigma}{\sigma} = \frac{\sqrt{S+B}}{S} \longrightarrow 11\%$$

H->ZZ* full sim

- 2 muons + 2 jets final state
- Signal generated with MG5+Pythia8
- Inclusive $\mu^+\mu^-$ -> vv $\mu^+\mu^-$ jj background (excluding signal) generated with Whizard+Pythia8
- BDT used to select signal vs background
- Resolution obtained with cut-based approach and with fit of BDTs, giving the same result





$$\frac{\Delta\sigma}{\sigma} = \frac{\sqrt{S+B}}{S} \longrightarrow 17\%$$

H->$\mu^+\mu^-$ fast sim

- Events with two muons with opposite charge and p_T > 20 GeV
- Two main backgrounds: $\mu^+\mu^-$->$\mu^+\mu^-\nu\nu$ and $\mu^+\mu^-$->$\mu^+\mu^-\mu^+\mu^-$
- 124 < m_H < 126 GeV

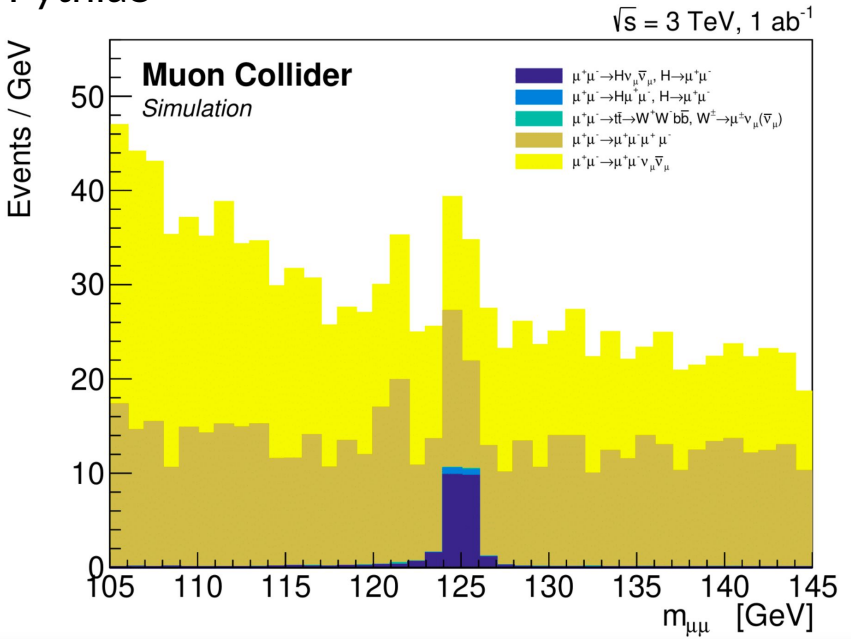
	σ (fb)	ϵ (%)	N
$\mu^+\mu^- \to \nu_\mu\bar{\nu}_\mu H;\ H \to \mu^+\mu^-$	0.11	52	57
$\mu^+\mu^- \to \mu^+\mu^- H;\ H \to \mu^+\mu^-$	0.011	43	5
$\mu^+\mu^- \to \nu_\mu\bar{\nu}_\mu\mu^+\mu^-$	67.2	0.30	198
$\mu^+\mu^- \to \mu^+\mu^-\mu^+\mu^-$	211	0.16	345

$$\frac{\Delta\sigma}{\sigma} = \frac{\sqrt{S+B}}{S} \longrightarrow 40\%$$

H->$\mu^+\mu^-$ full sim

- Signal and backgrounds generated with MG5+Pythia8
- BIB not used (low impact in muon chambers)
- Selection cuts on two BDTs trained to discriminate signal from the backgrounds
- Uncertainty on signal yield obtained from unbinned maximum likelihood fit to dimuon invariant mass

Process $105 < m_{\mu\mu} < 145$ GeV	Expected events with 1 ab^{-1}
[l]$\mu^+\mu^- \to H\nu_\mu\bar{\nu}_\mu$, $H \to \mu^+\mu^-$	24.2
[l]$\mu^+\mu^- \to H\mu^+\mu^-$, $H \to \mu^+\mu^-$	1.6
$\mu^+\mu^- \to \mu^+\mu^-\nu\bar{\nu}_\mu$	636.5
$\mu^+\mu^- \to \mu^+\mu^-\mu^+\mu^-$	476.4
[tl]$\mu^+\mu^- \to t\bar{t} \to W^+W^-b\bar{b}$, $W^\pm \to \mu^\pm\nu_\mu(\bar{\nu}_\mu)$	1.1

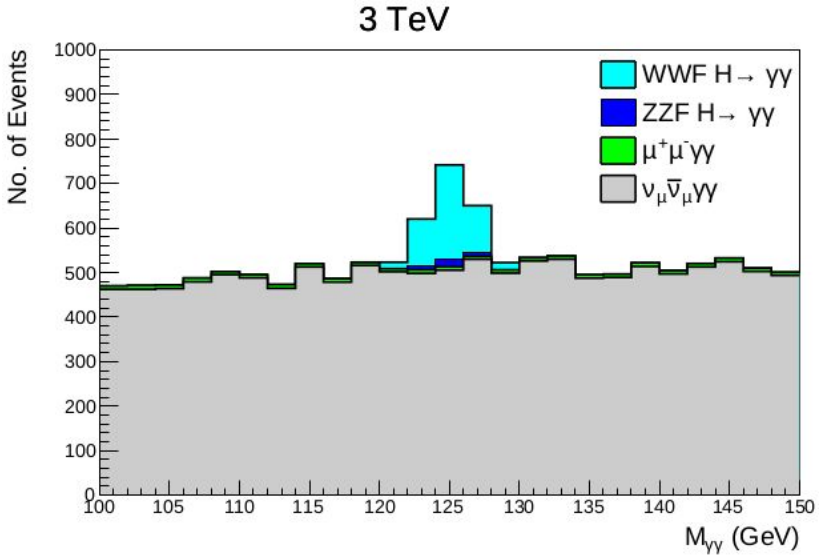


Relative uncertainty on **σ = 38%**

H->γγ fast sim

- Events with at least two isolated photons, no jets and no leptons
- Selected two photons with largest p_T, requiring p_T > 40 GeV
- 122 < m_H < 128 GeV

	σ (fb)	ϵ (%)	N
$\mu^+\mu^- \to \nu_\mu\bar{\nu}_\mu H;\ H \to \gamma\gamma$	1.14	37	419
$\mu^+\mu^- \to \mu^+\mu^- H;\ H \to \gamma\gamma$	0.12	29	34
$\mu^+\mu^- \to \nu_\mu\bar{\nu}_\mu\gamma\gamma$	198	0.16	311
$\mu^+\mu^- \to \mu^+\mu^-\gamma\gamma$	297	0.001	3



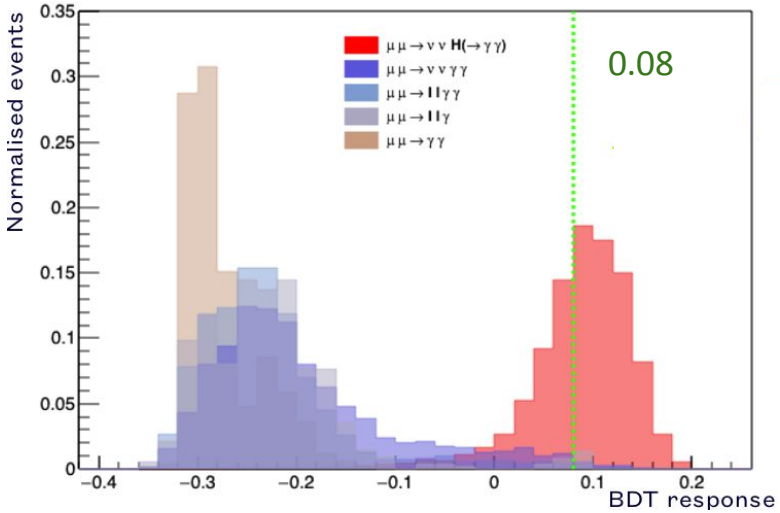
$$\frac{\Delta\sigma}{\sigma} = \frac{\sqrt{S+B}}{S} \longrightarrow \mathbf{6.1\%}$$

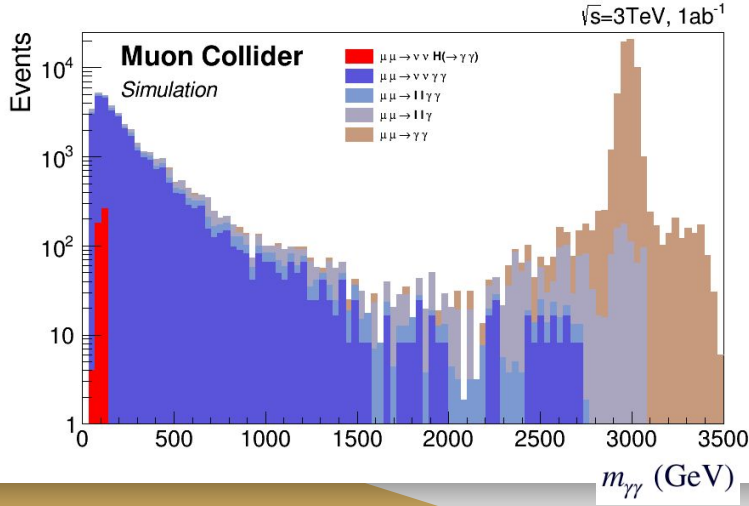
H->γγ full sim

- Signal and backgrounds generated with MG5+Pythia8
- Preliminary result: **No BIB at the moment** and some minor bkg still missing
- Used a BDT to perform signal vs. background separation
- Cut on BDT output to maximize S/√(S+B)

Process	σ (fb)	Events
$\mu\mu \to H\nu\nu, H \to \gamma\gamma$	0.9025 ± 0.0026	707
$\mu\mu \to \nu\nu\gamma\gamma$	81.98 ± 0.27	30168
$\mu\mu \to ll\gamma\gamma$	4.419 ± 0.016	2678
$\mu\mu \to ll\gamma$	159.0 ± 0.6	4738
$\mu\mu \to \gamma\gamma$	60.15 ± 0.03	59933

$$\frac{\Delta\sigma}{\sigma} = \frac{\sqrt{S+B}}{S} \longrightarrow 8.9\%$$





Trilinear coupling

- HH->4b, EFT approach, no background considered
- Acceptance cuts:

$$p_T(b) > 30 \text{ GeV}, \quad 10^\circ < \theta_b < 170^\circ, \quad \Delta R_{bb} > 0.4$$

- The four most energetic jets in the event are paired to minimize

$$(m_{j_1 j_2} - m_H)^2 + (m_{j_3 j_4} - m_H)^2$$

- Other requirements:

$$|m_{jj} - m_H| < 15 \text{ GeV}$$

$$M_{\text{recoil}} = \sqrt{(p_{\mu^+} + p_{\mu^-} - p_{H_1} - p_{H_2})^2} > 200 \text{ GeV}$$

- λ_3 obtained from likelihood fit in bins of m_{HH}

$$m_{HH} = [0, 350, 450, 550, 650, 750, 950, 1350, 5000] \text{ GeV}$$

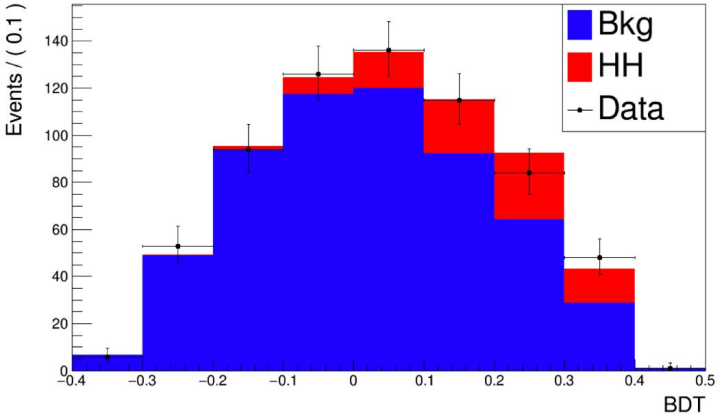
95% CL confidence interval

$\sqrt{s}$ (TeV)	3
benchmark lumi (ab^{-1})	1
$(\Delta\lambda_3)_{\text{in}}$	25%

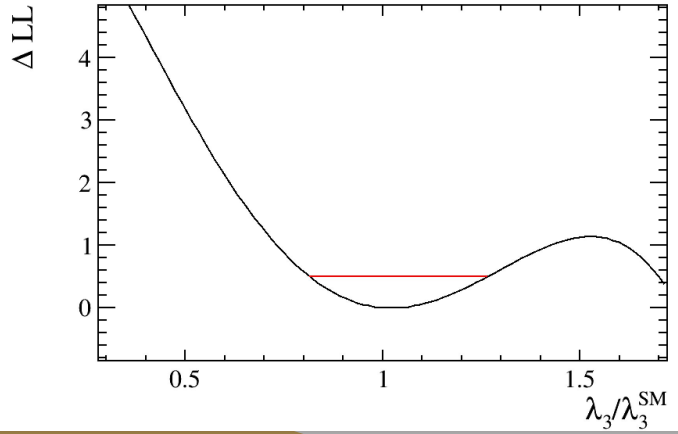
Electroweak couplings of the Higgs boson at a multi-TeV muon collider, Phys.Rev.D 103 (2021) 1, 013002

HH->bb bb and trilinear coupling

- Signal and backgrounds (H+bb and 4b) generated with Whizard+Pythia8
- Events with 4 jets, at least 2 must contain a secondary vertex
  - S = 50, B = 432 in 1 ab^{-1}
- BDT trained for sig-vs-bkg discrimination, fit on BDT output to find resolution
  - Δσ/σ of **30%** is found



- Two MLPs are used: HH vs 4b and trilinear vs HH
- Simulated events with different λ_3 hypothesis, resolution on λ_3 obtained from a likelihood scan
  - Stat. uncertainty of ~**20% @ 68% CL** is found
  - CLIC: [-8%, 11%] @ 68% CL with 2.5 ab^{-1} @ 1.4 TeV + 5 ab^{-1} @ 3 TeV



Higgs couplings from full sim

- The measurement of Higgs width Γ_H is the key that allows to determine Higgs couplings from previous measurements of σ x BR

$$\sigma(\mu^+\mu^- \to H\nu_\mu\bar{\nu}_\mu) \times BR(H \to xx) \propto g^2_{HWW} g^2_{Hxx}/\Gamma_H$$

- A study for Γ_H with full simulation is ongoing
- Previous measurements combined to extract couplings assuming $\Gamma_H = \Gamma_H^{SM}$
- Results compared with CLIC [**Eur. Phys. J. C 77, 475 (2017)**]
  - CLIC fitted also Γ_H
  - CLIC used multiple energy stages and larger integrated luminosity
  - CLIC: 25 years program
  - Muon Collider: 5 years 3 TeV stage

	Muon Collider 1 ab^{-1} @ 3 TeV	CLIC 0.5 ab^{-1} @ 350 GeV + 1.5 ab^{-1} @ 1.4 TeV + 2 ab^{-1} @ 3 TeV
Γ_H	SM	3.5%
g_{HZZ}	8.2%	0.8%
g_{HWW}	0.9%	0.9%
g_{Hbb}	0.8%	0.9%
$g_{H\mu\mu}$	19%	7.8%
$g_{H\gamma\gamma}$	4.5%	3.2%

Higgs couplings from fast sim

- Similar fit to couplings, but from results of fast simulation
- kappa-0 framework: Higgs width excluded from fit of couplings

$$\mu_i = \frac{\sigma_i \cdot \mathrm{BR}_f}{\sigma_i^{\mathrm{SM}} \cdot \mathrm{BR}_f^{\mathrm{SM}}} = \frac{\kappa_i^2 \kappa_f^2}{\kappa_H^2}, \qquad \kappa_H = \sum_f \frac{\kappa_f^2 \Gamma_f^{SM}}{\Gamma_H^{SM}}$$

- Currently a fast sim study of Γ_H with only a high energy (multi-TeV) muon collider has not been done yet

Fast sim

κ_W	0.55
κ_Z	5.1
κ_γ	3.2
κ_b	0.97
κ_μ	20

Full sim

g_{HZZ}	8.2%
g_{HWW}	0.9%
g_{Hbb}	0.8%
$g_{H\mu\mu}$	19%
$g_{H\gamma\gamma}$	4.5%

Results overview

	Full sim		Fast sim	
Cross sections resolution →	H->WW	2.9%	H->WW	1.7%
	H->ZZ	17%	H->ZZ	11%
	H->bb	0.75%	H->bb	0.76%
	H->μμ	38%	H->μμ	40%
	H->γγ	8.9%	H->γγ	6.1%
	HH->4b	30%		
Couplings resolution →	g_{HWW}	0.9%	g_{HWW}	0.55%
	g_{HZZ}	8.2%	g_{HZZ}	5.1%
	g_{Hbb}	0.8%	g_{Hbb}	0.97%
	$g_{Hμμ}$	19%	$g_{Hμμ}$	20%
	$g_{Hγγ}$	4.5%	$g_{Hγγ}$	3.2%
	λ_3	20%	λ_3 (95% CL)	25%

Next steps

- Indirect measurement of Higgs width from measurement of off-shell H->ZZ and H->WW
- The use of the off-shell signal alone allows to disentangle the degeneracy between couplings and width
- Approach:
  - Simulate background + off-shell Higgs in the high invariant mass region with different hypothesis of g_{HZZ} and g_{HWW}
  - Determine resolution on off-shell couplings, in both channels, from a **likelihood scan**
  - Resolution on Higgs width can be obtained later from Δg_{HZZ} and Δg_{HWW}

Summary

- Analyzed results for 5 Higgs decay channels, comparing full sim and fast sim
- Similar results in the two cases
  - Better resolution in H->ZZ and H->WW with fast sim, also because both electronic and muonic decay channels were used (unlike full sim)
- Determined resolutions on Higgs couplings, assuming for the moment $\Gamma_H = \Gamma_H^{SM}$
- Presented also measurements of HH->4b and trilinear coupling
- Need for a measurement of Γ_H with off-shell Higgs decays to vector bosons
- Only some Higgs decay channels studied up to now->add further channels (e.g. H->ττ)

Fast sim performance