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Higgs boson couplings measurement at a Multi-TeV Muon Collider

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Higgs boson couplings: from present to future

- One of the goals of future colliders: precise measurement of Higgs couplings with SM particles

$$\mathcal{L} = -g_{Hf\bar{f}}\; f\bar{f}H + \frac{g_{3H}}{6}H^3 + \frac{g_{4H}}{24}H^4 + \delta_V V_\mu V^\mu \left(g_{HVV}H + \frac{g_{HHVV}}{2}H^2\right)$$

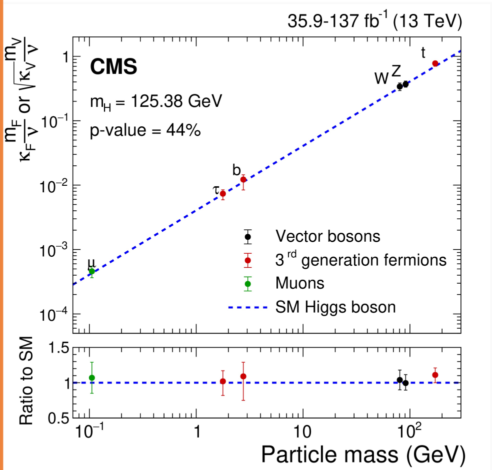
$$g_{Hf\bar{f}} = \frac{\mathrm{m_f}}{v}\ , \mathrm{g_{HVV}} = \frac{2\mathrm{m_V^2}}{v}\ , \mathrm{g_{HHVV}} = \frac{2\mathrm{m_V^2}}{v^2}\ , \mathrm{g_{3H}} = \frac{3\mathrm{m_H^2}}{v}\ , g_{4H} = \frac{3m_H^2}{v^2}$$

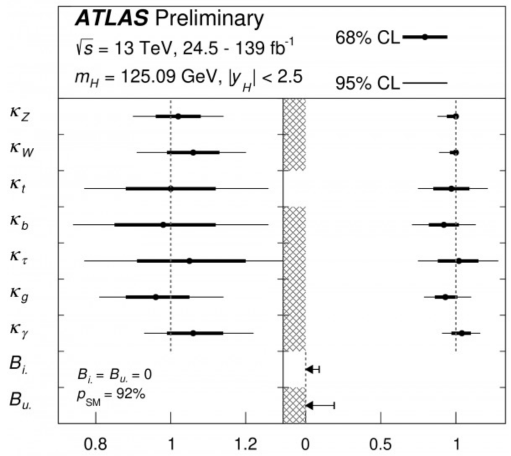
→push the knowledge of the couplings below the 1% precision

→ access un-explored couplings

→ use the Higgs boson as a tool to probe beyond standard model scenarios!

The present





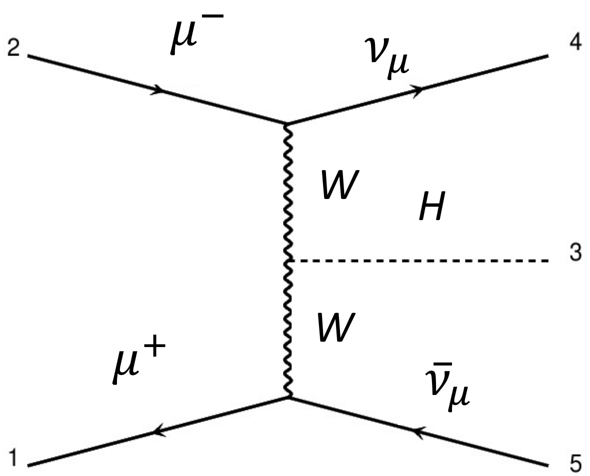
The future

kappa-0	HL-LHC	LHeC	HE-LHC		ILC			CLIC			CEPC	FCC-ee		FCC-ee/eh/hh
			S2	S2′	250	500	1000	380	15000	3000		240	365	
κ_W [%]	1.7	0.75	1.4	0.98	1.8	0.29	0.24	0.86	0.16	0.11	1.3	1.3	0.43	0.14
κ_Z [%]	1.5	1.2	1.3	0.9	0.29	0.23	0.22	0.5	0.26	0.23	0.14	0.20	0.17	0.12
κ_g [%]	2.3	3.6	1.9	1.2	2.3	0.97	0.66	2.5	1.3	0.9	1.5	1.7	1.0	0.49
κ_γ [%]	1.9	7.6	1.6	1.2	6.7	3.4	1.9	98⋆	5.0	2.2	3.7	4.7	3.9	0.29
$\kappa_{Z\gamma}$ [%]	10.	–	5.7	3.8	99⋆	86⋆	85⋆	120⋆	15	6.9	8.2	81⋆	75⋆	0.69
κ_c [%]	–	4.1	–	–	2.5	1.3	0.9	4.3	1.8	1.4	2.2	1.8	1.3	0.95
κ_t [%]	3.3	–	2.8	1.7	–	6.9	1.6	–	–	2.7	–	–	–	1.0
κ_b [%]	3.6	2.1	3.2	2.3	1.8	0.58	0.48	1.9	0.46	0.37	1.2	1.3	0.67	0.43
κ_μ [%]	4.6	–	2.5	1.7	15	9.4	6.2	320⋆	13	5.8	8.9	10	8.9	0.41
κ_τ [%]	1.9	3.3	1.5	1.1	1.9	0.70	0.57	3.0	1.3	0.88	1.3	1.4	0.73	0.44

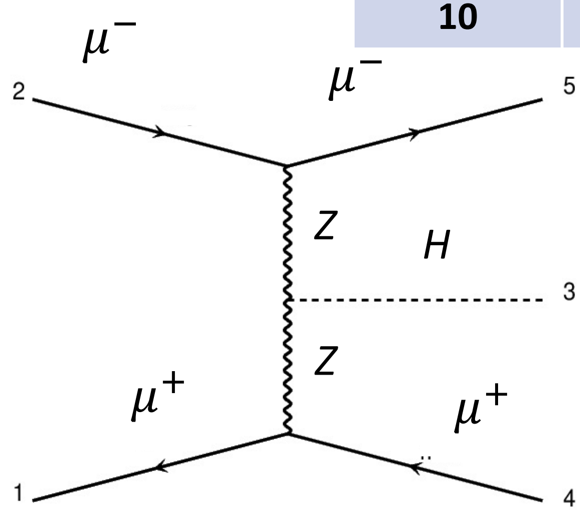
Higgs Physics at a Muon Collider

$\sqrt{s}$ [TeV]	$\mathcal{L}$ (4 year)[ab^{-1}]
1.5	0.5
3.0	1.3
10	8.0

- Dominant Higgs boson production mechanism: vector boson fusion
- Main contribution from WW fusion.



$\sigma = 2.1 \cdot 10^2\ fb\ (\sqrt{s}\ = 1\text{TeV})$
$\sigma = 5 \cdot 10^2\ fb\ (\sqrt{s}\ = 3\text{TeV})$



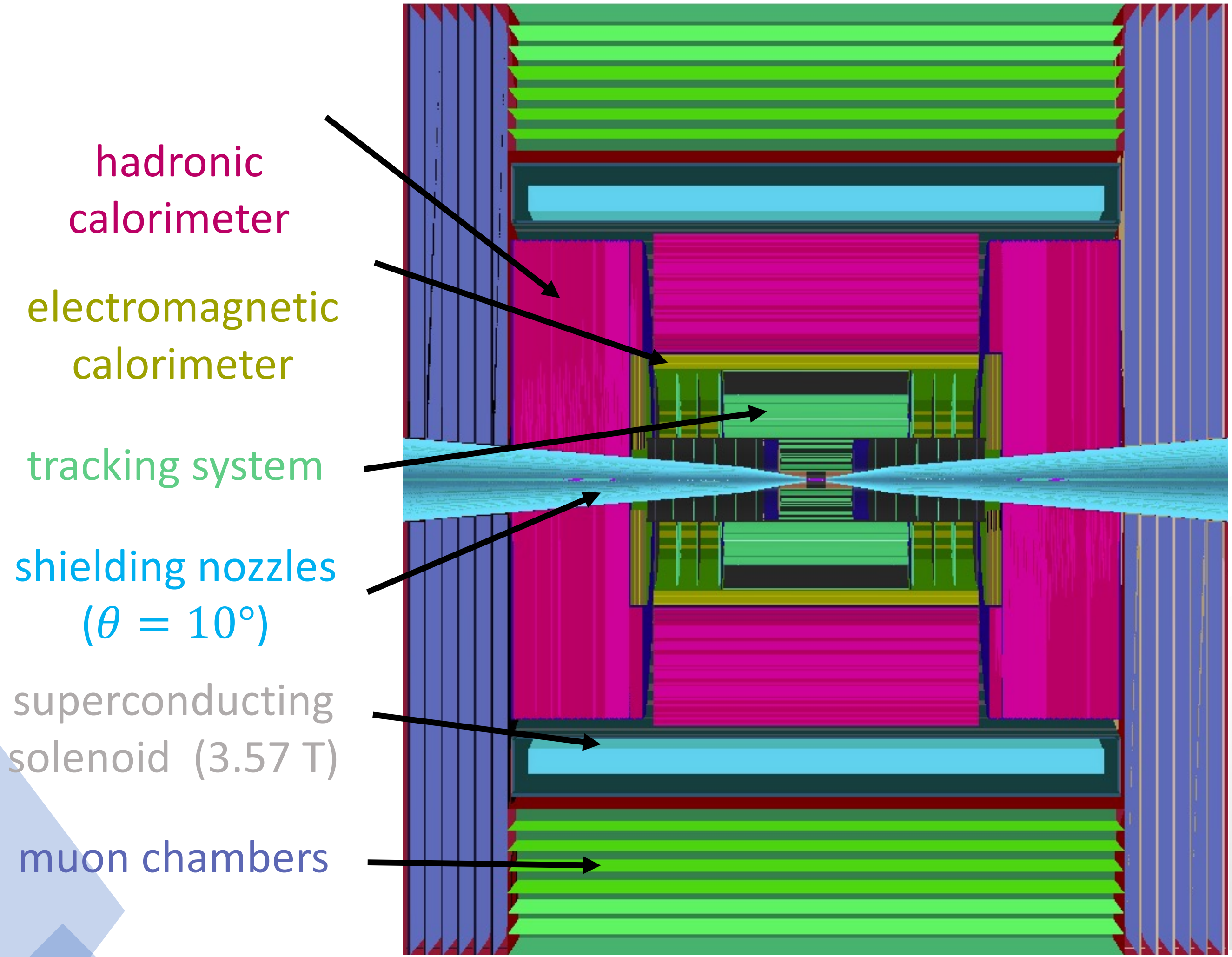
$\sigma = 1.5 \cdot 10^1\ fb\ (\sqrt{s}\ = 1\text{TeV})$
$\sigma = 3.8 \cdot 10^1\ fb\ (\sqrt{s}\ = 3\text{TeV})$

O(1M) Higgs produced in the low energy (<10 TeV scenario)

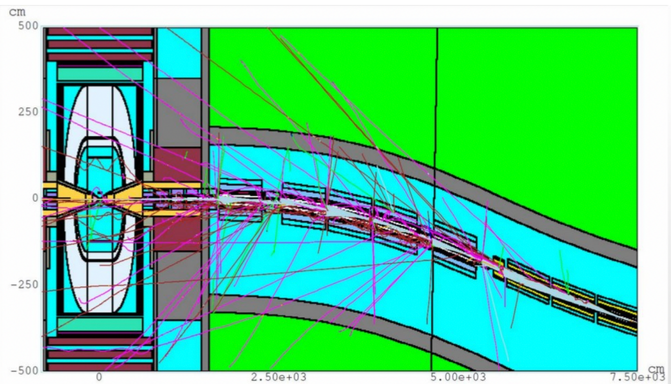
Clean events as in e+e- colliders with high collision energy as in hadron colliders
The muon collider is the dream machine for Higgs physics measurements

In this work: first estimation on Higgs couplings to Z bosons and c-quark

The Muon Collider experiment and challenges

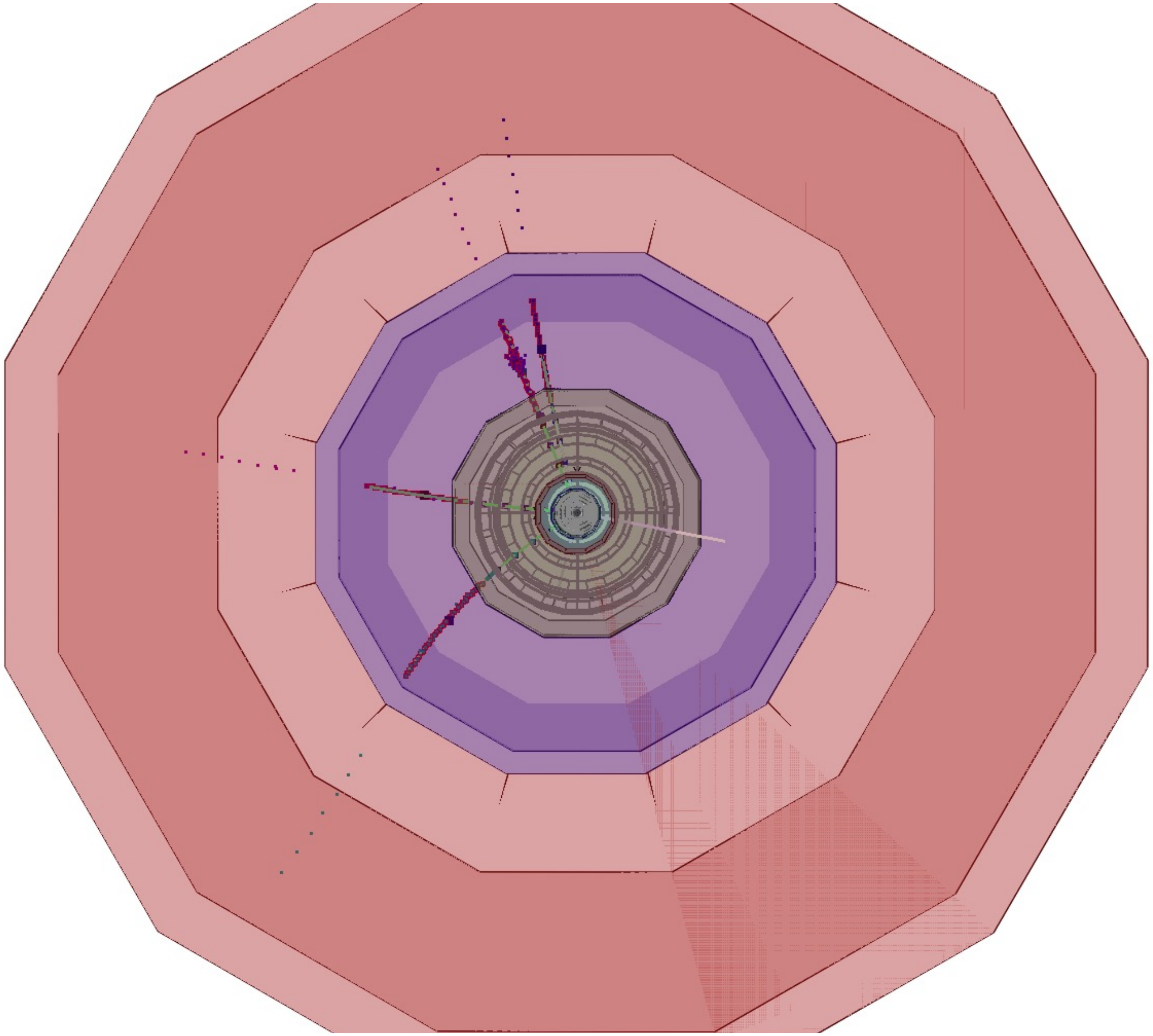


Main challenges:
- **Muon production**
- **Beam-Induced Background (BIB)**: Decays of circulating beam muons into electrons, positrons and neutrinos→interactions with the machine → production of secondary particles



See N. Bartosik talk: Muon Collider: prospects, challenges and the latest progress

$H \rightarrow ZZ^* \rightarrow 4\mu$ at a multi-TeV muon collider experiment



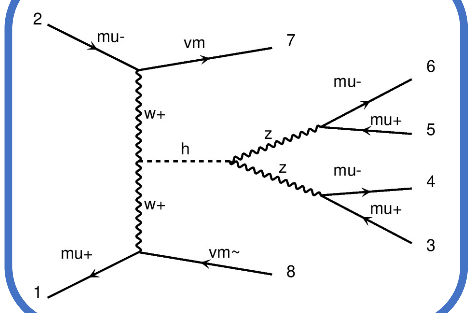
Signal and background

$H \rightarrow ZZ^* \rightarrow 4\mu$ is a standard candle in the Higgs sector:

- large signal/background ratio
- small yields [$BR(H \rightarrow ZZ) = 2.62 \cdot 10^{-2}$, $BR(Z \rightarrow \mu^+\mu^-) = 3.37 \cdot 10^{-2}$]
- favored to measure the Higgs boson coupling to Z bosons at a muon collider.
- MC samples fully simulated with the latest geometry of the Muon Collider

➢ SIGNAL PROCESS:

$\mu^+\mu^- \rightarrow H\nu_\mu\bar{\nu}_\mu$
$\quad \hookrightarrow ZZ^* \rightarrow 4\mu$



SIGNAL $H \rightarrow ZZ^* \rightarrow 4\mu$

$\sqrt{s}$ (TeV)	L (fb^{-1})	σ (fb)	Expected events
1.5	500	$9.14 \cdot 10^{-3}$	4.57
3.0	1300	$1.47 \cdot 10^{-2}$	19.16

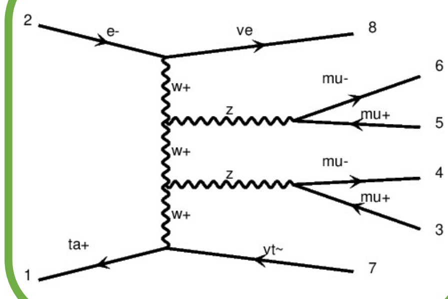
➢ SM IRREDUCIBLE BACKGROUND:

$\mu^+\mu^- \rightarrow 4\mu\ \nu_\mu\bar{\nu}_\mu$

~ 5000 Feynman diagrams

Selections applied at the generator level:

$p_T > 5\ GeV$; $|\eta| < 2.5$; $10 < m_{\mu^+\mu^-} < 150\ GeV$.



4μ-SM BACKGROUND

$\sqrt{s}$ (TeV)	L (fb^{-1})	σ (fb)	Expected events
1.5	500	$9.18 \cdot 10^{-3}$	4.59
3.0	1300	$1.79 \cdot 10^{-2}$	23.21

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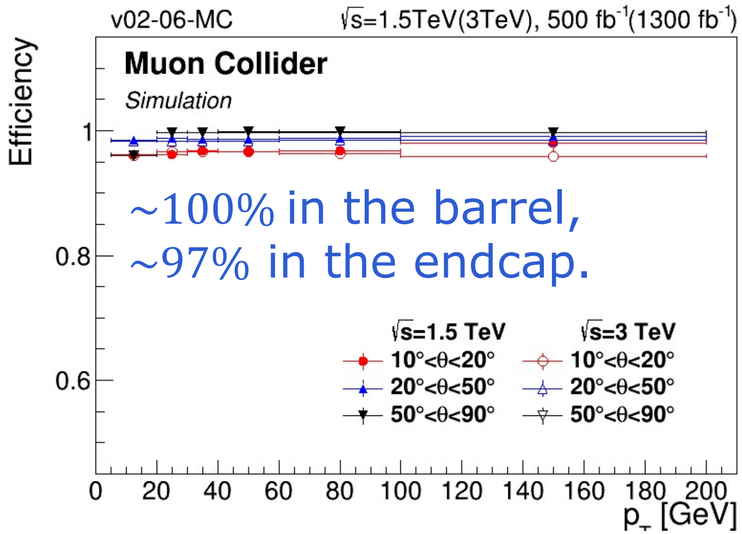
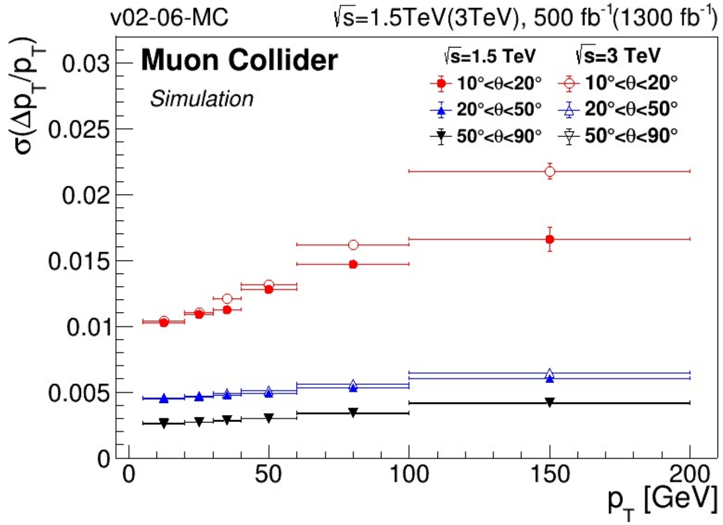
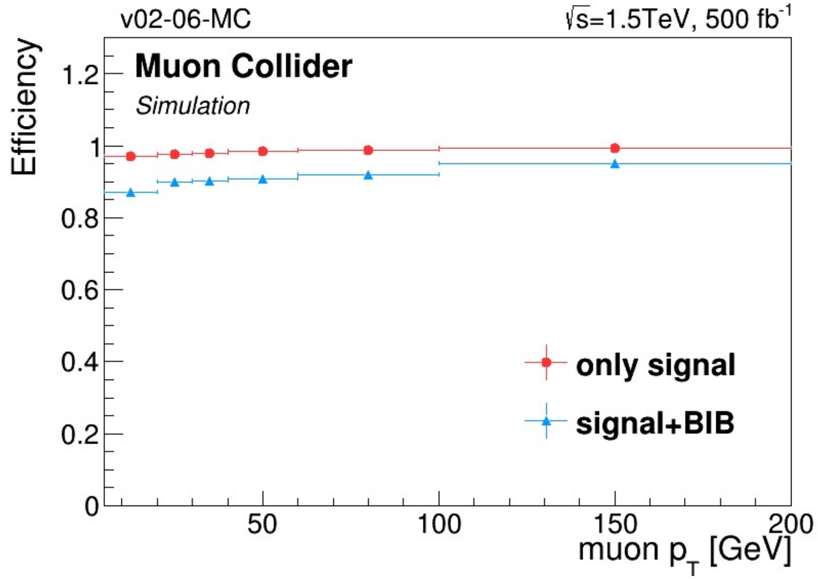
Muon reconstruction performance

- Track reconstruction based on conformal tracking
- Muons are reconstructed with a particle flow approach combining tracker tracks with hits in calorimeters and muon system





Estimation of the impact of the BIB: cone-filter for tracker hits to reduce the processing time.



- ➢ Tracking efficiency slightly reduced when including BIB **O(10%)**→ mitigation strategy under development
- ➢ Results used for parametric evaluation of the BIB impact on the final results

$H \to ZZ^* \to 4\mu$ topological selection

Good quality final state muons:

- $p_T > 5\ GeV;\ |\eta| < 2.5;$
- $D_0 < 2mm;\ Z_0 < 10mm;$

Z candidates:

OS muon pairs $12 < m_{\mu\mu} < 120\ GeV.$

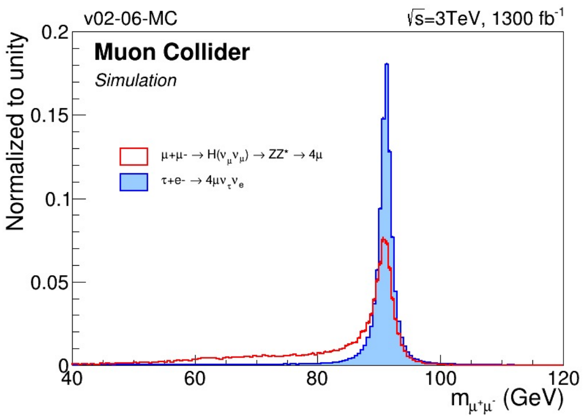
ZZ candidates: non-overlapping Zs

- Z_1: Z candidate with mass closest to the nominal value
- Z_2: other Z candidate

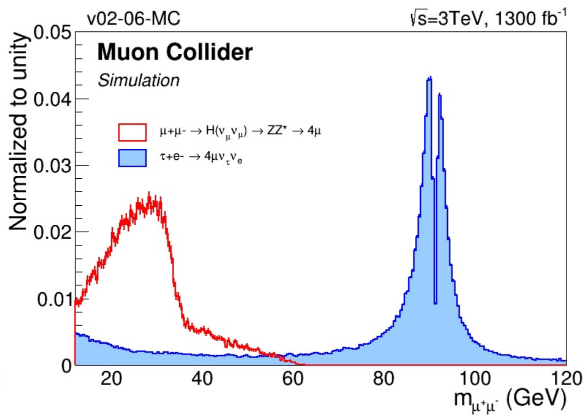
Selection of ZZ candidates:

- $\Delta R(\mu_i, \mu_j) > 0.02$
- $p_{T,\mu_i} > 20$ GeV
- $p_{T,\mu_j} > 10$ GeV
- Z_1 mass > 40 GeV
- $m_{4\mu} > 70$ GeV
- Arbitration based on Z1 mass

Z_1 reconstructed mass



Z_2 reconstructed mass



$\sqrt{s} = 1.5$ TeV

Signal		Background	
Events	Efficiency (%)	Events	Efficiency (%)
2.97±0.02	65.13±.21	3.93±0.01	85.77±0.01

$\sqrt{s} = 3$ TeV

Signal		Background	
Events	Efficiency (%)	Events	Efficiency (%)
10.77±0.06	56.19 ± 0.22	18.6 ±0.1	80.04 ±0.09

$H \to ZZ^* \to 4\mu$ Preliminary results

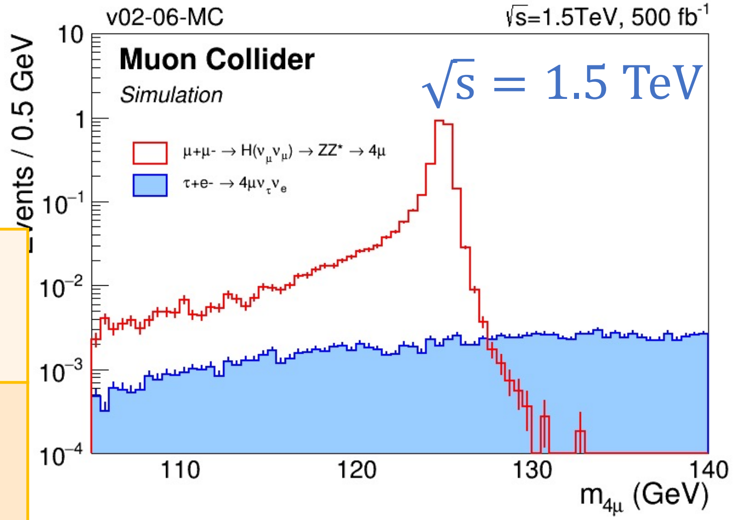
$$\sigma(\mu^+\mu^- \to H\nu\nu \to ZZ\nu\nu) = \sigma(\nu\nu H) \cdot BR(H \to XX) = \frac{g^2_{HWW} g^2_{HXX}}{\Gamma_H}$$

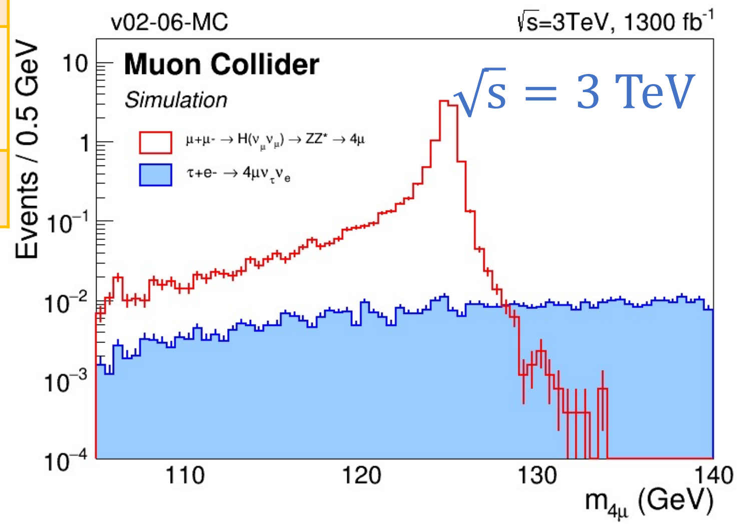
Relative uncertainty on the *HXX* coupling (X any SM particle)

$$\frac{\Delta g_{Hxx}}{g_{Hxx}} = \frac{1}{2}\sqrt{\left(\frac{\Delta\sigma}{\sigma}\right)^2 + \left(\frac{\Delta \frac{g^2_{HWW}}{\Gamma_H}}{\frac{g^2_{HWW}}{\Gamma_H}}\right)^2}$$

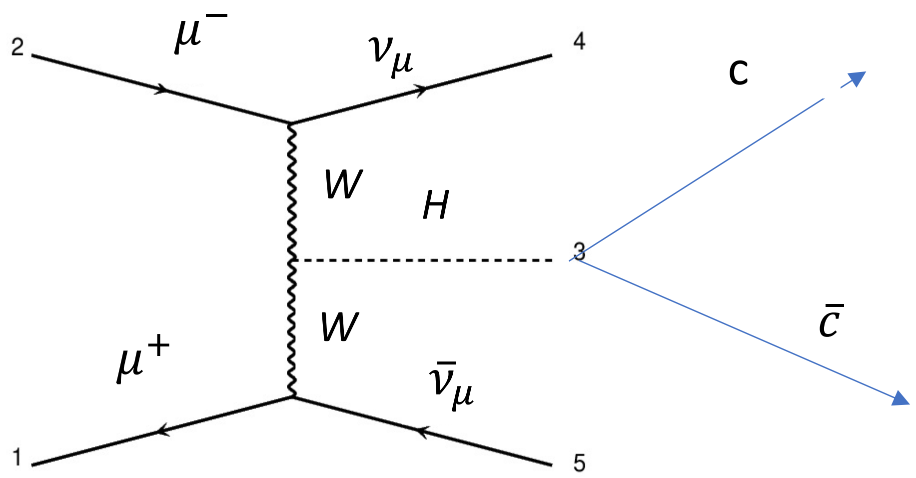
	$\sqrt{s} = 1.5$ TeV L=500fb^{-1}			$\sqrt{s} = 3$ TeV L=1300fb^{-1}		
Results	Z	$\frac{\Delta\sigma}{\sigma}$ (%)	$\frac{\Delta g_{HZZ}}{g_{HZZ}}$	Z	$\frac{\Delta\sigma}{\sigma}$ (%)	$\frac{\Delta g_{HZZ}}{g_{HZZ}}$
Without BIB	3.65	60	**30**	6.91	32	**16**
With BIB	3.08	71	**36**	5.85	37	**19**

- Results can be improved by a factor 2 including all the leptonic channels (assuming same efficiencies)
- Further improvement: inclusions of the fully hadronic final states





Search for $\mathrm{H} \rightarrow c\bar{c}$ at a Muon Collider experiment



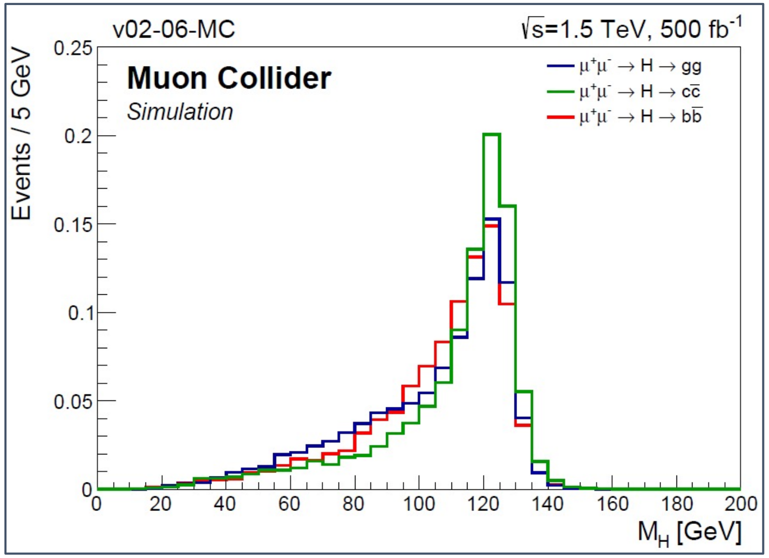
H-to-c-quark coupling at Muon Collider

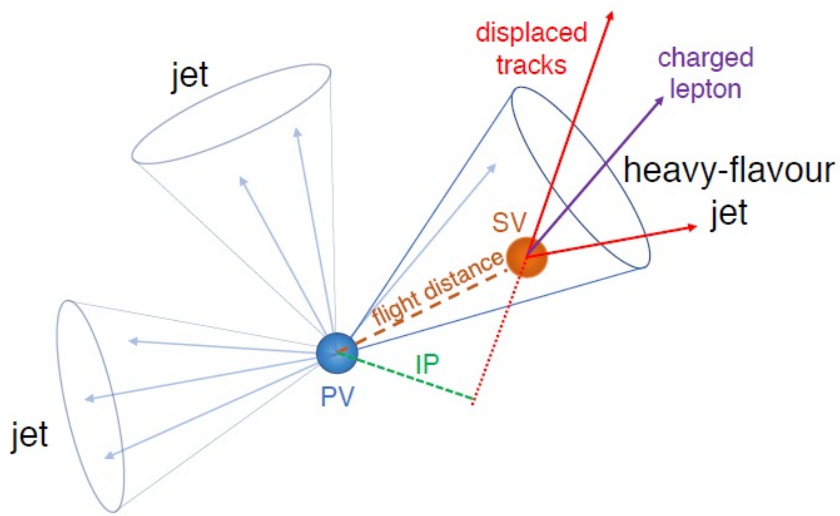
	physics process	σ (fb)	generator
c-jet samples	$\mu^+\mu^- \rightarrow H\nu\bar{\nu} \rightarrow c\bar{c}\ \nu\bar{\nu}$	8.9	pythia
	$\mu^+\mu^- \rightarrow c\bar{c}\ 2leptons$	399	madgraph
b-jet samples	$\mu^+\mu^- \rightarrow H\nu\bar{\nu} \rightarrow b\bar{b}\ \nu\bar{\nu}$	180	pythia
	$\mu^+\mu^- \rightarrow b\bar{b}\ 2leptons$	508	madgraph
light-flavour-jet samples	$\mu^+\mu^- \rightarrow H\nu\bar{\nu} \rightarrow gg\ \nu\bar{\nu}$	26.4	pythia
	$\mu^+\mu^- \rightarrow 2light\ 2leptons$	2.8 . le6	madgraph

$H \rightarrow gg$, $H \rightarrow c\bar{c}$, $H \rightarrow b\bar{b}$

are kinematically indistinguishable.

- Dedicated tagger to discriminate c jets from b and light-flavour ones.
- Heavy-flavour hadron characteristics:
  1. **Secondary vertices (SV)**
  2. **Displaced tracks**
  3. **Low-energy non isolated leptons**

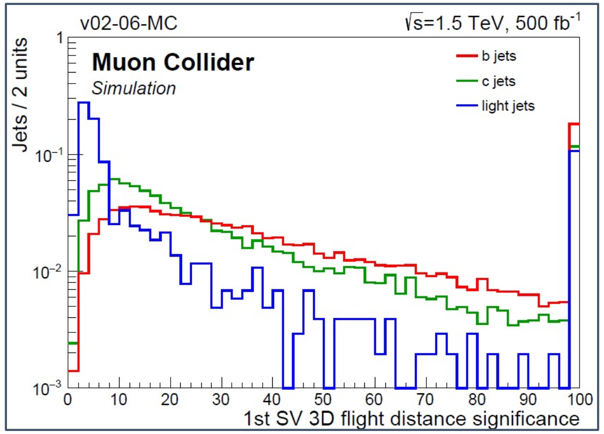




C-jet tagging algorithm: the variables

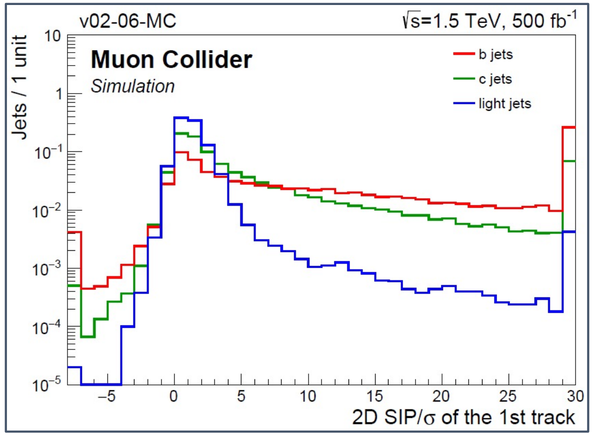
Vertex variables

- Vertex category
- Number of SV, Number of tracks from SV
- 2D and 3D SV flight distance significance
- Corrected mass, Mass-energy fraction
- SV Boost, Energy ratio , ΔR (SV, jet-axis)



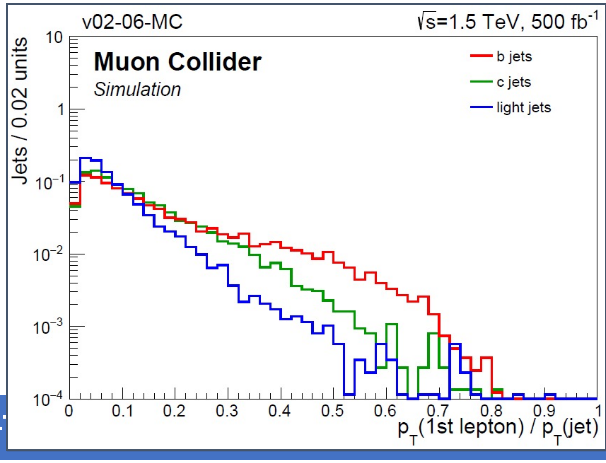
Track variables

- 2D, 3D signed impact parameter (SIP) significance
- Number of tracks in jet
- ΔR (track, jet-axis) ,ΔR (Σ tracks, jet-axis)
- 2D, 3D SIP significance of the first track above invariant mass threshold
- $p_{L-jaxis}$ and $p_{L-jaxis}/p$, $p_{T-jaxis}$ and $p_{T-jaxis}/p, E_T$ (Σtracks) / E_T (jet)

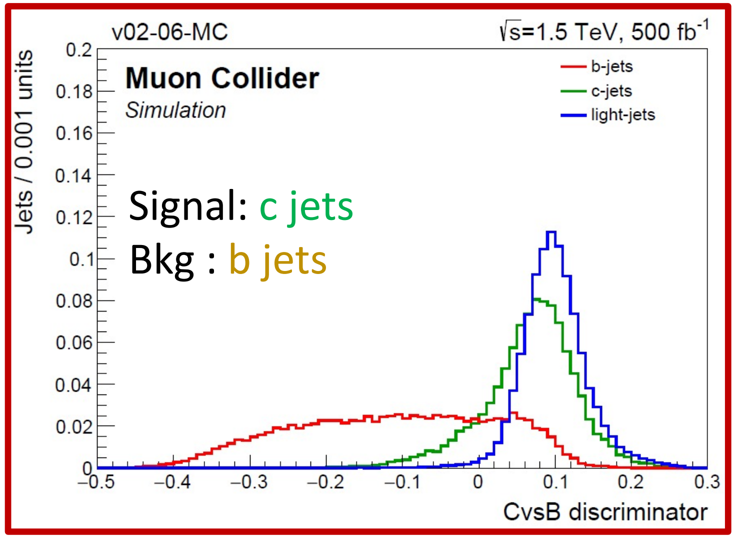


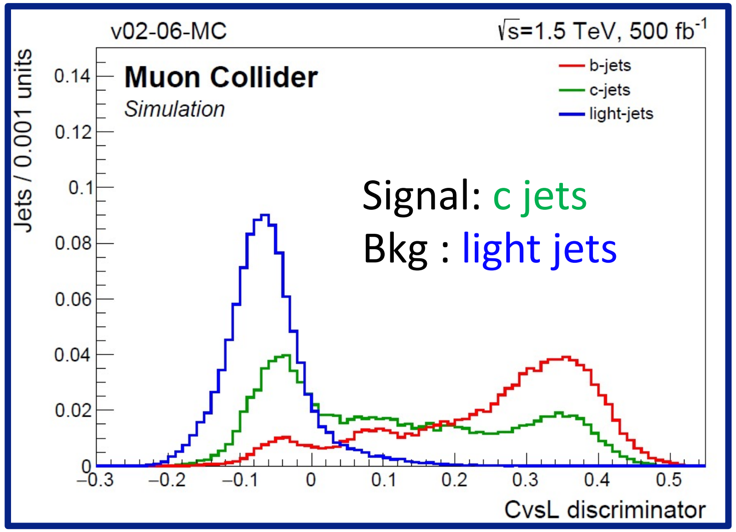
Lepton variables

- Lepton category
- $p_T/p_T(\text{jet})$
- $p_{T-jaxis}$, $p_{L-jaxis}/p(\text{jet})$



C-jet tagging algorithm



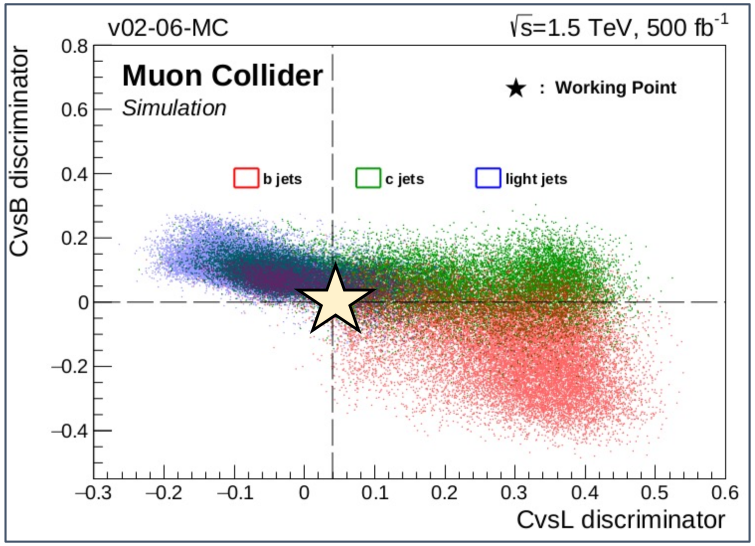


The variables are combined in a single Boosted Decision Tree.

Two independent taggers :

- CvsB : separate c-jets from b-jets
- CvsL : separate c-jets from light flavor

c-tag eff.	b misid. probability MuColl (w/o BIB)	b misid. probability CMS	b misid. probability CLIC (w/o overlay)	light misid. probability MuColl (w/o BIB)	light misid. probability CMS	light misid. probability CLIC (w/o overlay)
50%	7.5%	11%	7%	2.3%	14 %	3 %
60%	10%	14%	11%	6.3%	25 %	6 %
70%	14%	20%	15%	16%	40 %	12 %
80%	19%	26%	23%	31%	55 %	25 %
90%	28%	40%	32%	55%	75 %	52 %



$(CvsL, CvsB)$	c efficiency	b contamination	$light-flav.$ contamination
(0.04, 0.00)	40 %	13 %	5 %

$\mathrm{H} \to c\bar{c}$ preliminary results

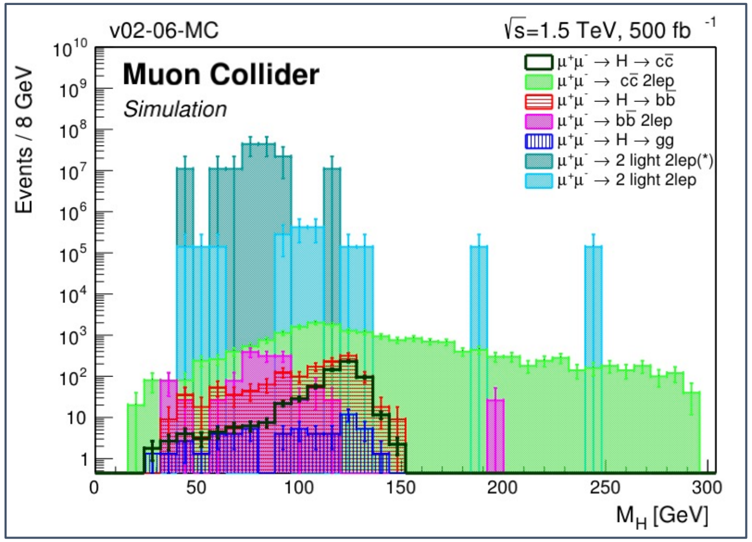
- After flavor tagging, Higgs candidates are built using the two highest pT jets and further topological selections are applied
- $\mathrm{E_H} > 130$ GeV, $\mathrm{pT_H} > 30$ GeV
- $\Delta\mathrm{R}(\mathrm{j_1}, \mathrm{j_2}) < 3$, $\mathrm{m_H} \in [110,130]$ GeV

$\sqrt{s}$ = 1.5 TeV, 500 fb^{-1} (no BIB overlay)		
$S/\sqrt{S+B}$	$\Delta\sigma/\sigma$	$\Delta g_{Hcc}/g_{Hcc}$
9.5	10.5 %	**5.5 %**

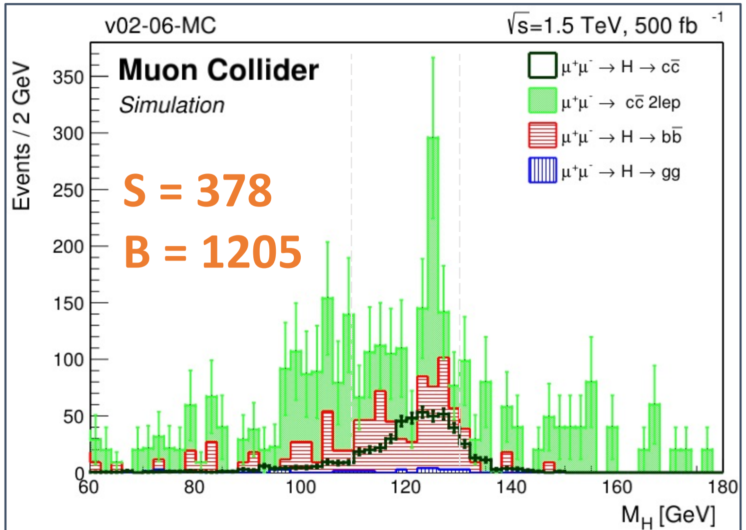
Projection at $\sqrt{s}$ = 3 TeV, 1300 fb^{-1} (assuming same selection efficiencies)		
$S/\sqrt{S+B}$	$\Delta\sigma/\sigma$	$\Delta g_{Hcc}/g_{Hcc}$
20.4	4.9 %	**2.6 %**

CLIC: 350 GeV, 500 fb^{-1}: **6.2** % precision
CLIC: 1.4 TeV, 1500 fb^{-1}: **2.3** % precision

Before topological selections



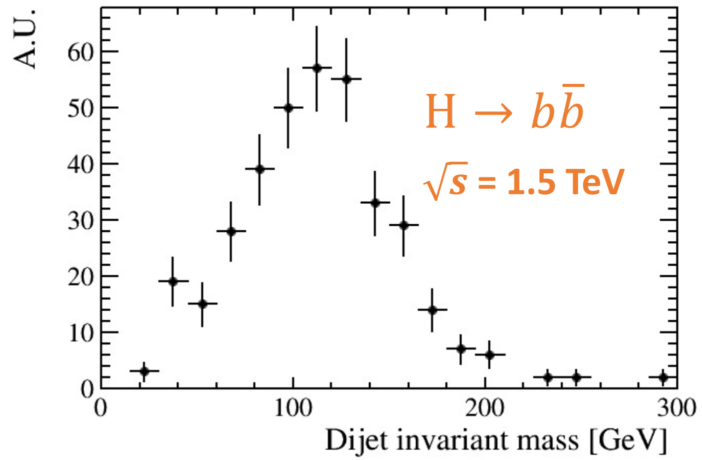
After topological selections



A word on $\mathrm{H} \rightarrow b\bar{b}$

- Feasibility study on $\mathrm{H} \rightarrow b\bar{b}$ performed and published (**2020 JINST 15 P05001**)
- Fully simulated signal and background processes
- BIB accounted and subtracted on a statistical basis from the calorimeter cells
- b-jet tagging based on secondary vertices
  →Able to tag b-jets with a ~60% efficiency and 1-3% of mis-identification.

Process
$\mu^+\mu^- \rightarrow \gamma^*/Z \rightarrow q\bar{q}$
$\mu^+\mu^- \rightarrow \gamma^*/Z\gamma^*/Z \rightarrow q\bar{q}$ +X
$\mu^+\mu^- \rightarrow \gamma^*/Z\gamma \rightarrow q\bar{q}\gamma$



$\sqrt{s}$ [TeV]	A [%]	ϵ [%]	$\mathcal{L}$ [cm^{-2}s^{-1}]	$\mathcal{L}_{int}$ [ab^{-1}]	σ [fb]	N	B	$\frac{\Delta\sigma}{\sigma}$ [%]	$\frac{\Delta g_{Hbb}}{g_{Hbb}}$ [%]
1.5	35	15	$1.25 \cdot 10^{34}$	0.5	203	5500	6700	2.0	1.9
3.0	37	15	$4.4 \cdot 10^{34}$	1.3	324	33000	7700	0.60	1.0
10	39	16	$2 \cdot 10^{35}$	8.0	549	270000	4400	0.20	0.91

Coupling sensitivity is compatible with the one expected by CLIC

Summary and perspectives

- **The Muon Collider is the dream machine for Higgs Physics and beyond**
- First estimate of the precision on the Higgs couplings at the Muon Collider performed with fully simulated and reconstructed samples.
- Both Yukawa couplings and coupling with Z bosons explored
- The precisions obtained at $\sqrt{s}$=3 TeV:
  - **Hbb: 1%**
  - **Hcc: 2.3%**
  - **HZZ: 8%** (only electron and muon final states)

- Precision improves with increasing energy → Muon Collider has the potential to reach higher energy wrt electron-based colliders.

- The reconstruction of final states leptons and jet plays a crucial role.
  - Optimization studies on tracking strategies ongoing
  - Efficient vertexing and reliable jet reconstruction relies on **high granular tracker and calorimeters** → those physics channel will drive the detector design
  - Inclusion of the BIB and impact on the final results under study
  - Study of the Higgs self coupling ongoing

Backup

Jet reconstruction

- Complex task: **tracker info** + **energy deposits in calorimeters**
- Particle reconstruction is performed through Pandora Particle Flow (PF) algorithm → improve the jet energy resolution.
- Output of PF is used for jet clustering: k_T algorithm with radius parameter R = 1.0.