Higgs boson couplings at muon collider

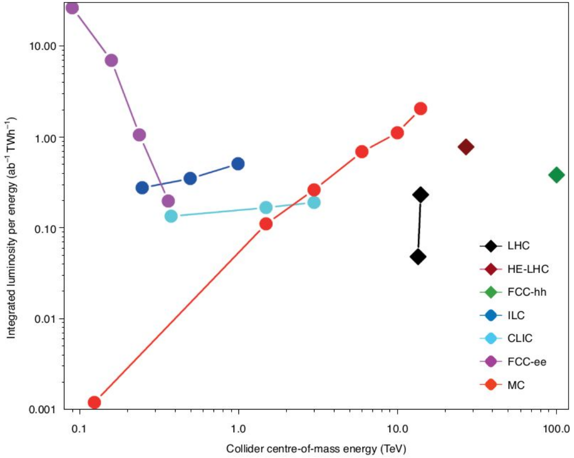
Speaker: Laura Buonincontri
On Behalf of the International Muon Collider Collaboration
23/03/2022

First Pan-African Astro-Particle and Collider Physics Workshop

21-23 March 2022

Why a muon collider

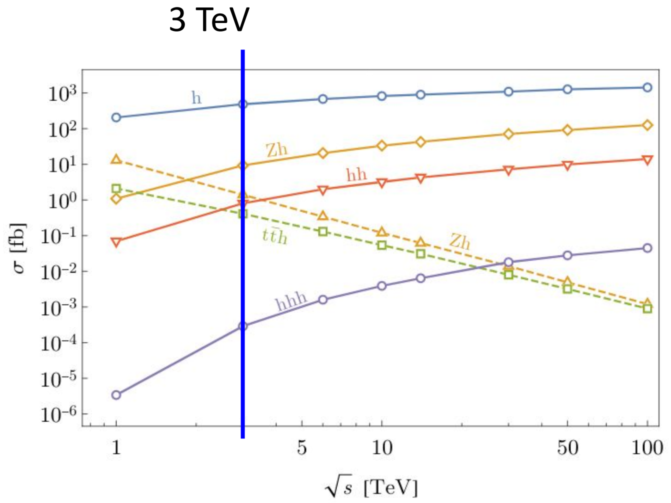
- Lepton colliders allow to exploit the full energy available in the center of mass
- Technologies to reach high energies in $e^+ e^-$ collisions require linear colliders due to synchrotron radiation loss
- Muon collider: above $\sqrt{s}$=2 TeV is expected to be the most energy-efficient choice to reach high energies (very low radiation losses)



- The new International Muon Collider Collaboration is focusing on the baseline designs of a 3 TeV and a 10+ TeV machine with instantaneous luminosities of about 2×10^{34} cm^{-2} s^{-1} and 4×10^{35} cm^{-2} s^{-1} , respectively

Higgs couplings at muon collider

- At high $\sqrt{s}$ the Higgs is mainly produced via Vector Boson Fusion
- At 3 TeV and L = 1 ab^{-1} (4 years of data taking) high production cross sect (500k single Higgs)
- Projected sensitivities on Higgs couplings: obtained with a parametric simulation (in arXiv: 2203.07261)



Coupling	HLLHC	HLLHC + 3 TeV μ-coll. 1 ab^{-1}	HLLHC + 10 TeV μ-coll. 10 ab^{-1}
κ_W	1.7	0.4	0.1
κ_Z	1.5	0.9	0.4
κ_g	2.3	1.4	0.7
κ_γ	1.9	1.3	0.8
κ_c	-	7.4	2.3
κ_b	3.6	0.9	0.4
κ_μ	4.6	4.3	3.4
κ_τ	1.9	1.3	0.6

- Higgs potential after the electroweak symmetry breaking:

$$V = \frac{1}{2} m_h^2 h^2 + \lambda_{SM}(1+\delta\kappa_3) v h^3 + \frac{\lambda_{SM}}{4}(1+\delta\kappa_4) h^4 \qquad \lambda_{SM} = \frac{m_H^2}{2v^2}$$

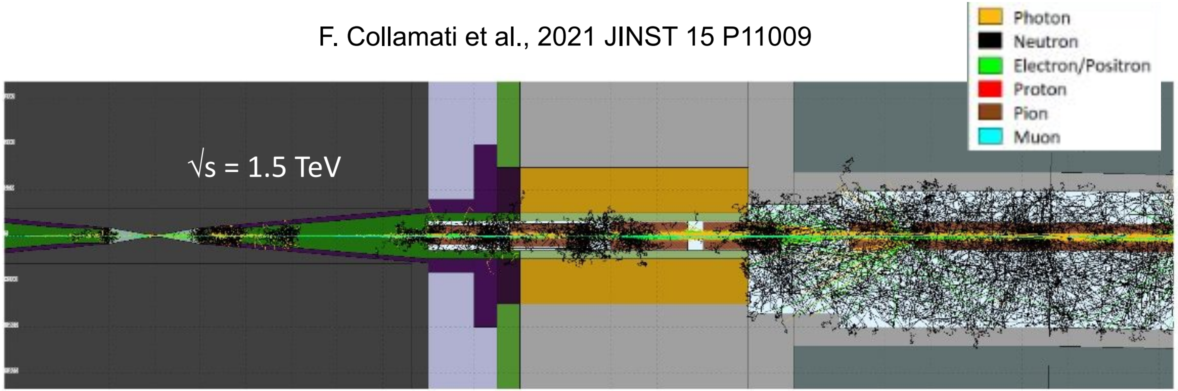
- High rates are accessible for multi-Higgs processes (e.g. at 10 TeV 10 ab^{-1}, 30000 HH events are expected)
- Expected precision on trilinear Higgs self-coupling:
  - $\delta\kappa_3$ ~ 18% at 3 TeV and L = 1 ab^{-1}
  - $\delta\kappa_3$ ~ 4% at 10 TeV and L = 10 ab^{-1} (comparable to 100 TeV hadron collider)

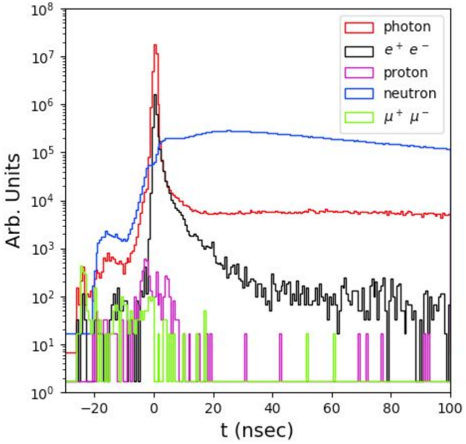
Beam Induced Background by muons beam decay not included in these simulations, evaluation with full simulation is needed!

Detector challenges

- Beam-Induced Background (BIB) caused mainly by μ beam decays: **O(10^8) BIB particles** enter the detector at every bunch crossing
- BIB may affect detector performance if mitigation strategies are not applied, like:
  - Shielding inside detector
  - Proper detector design
- Machine-Detector Interface and BIB studied at √s=1.5 TeV, studies in progress at √s=3 TeV, lower BIB levels seems achievable

F. Collamati et al., 2021 JINST 15 P11009





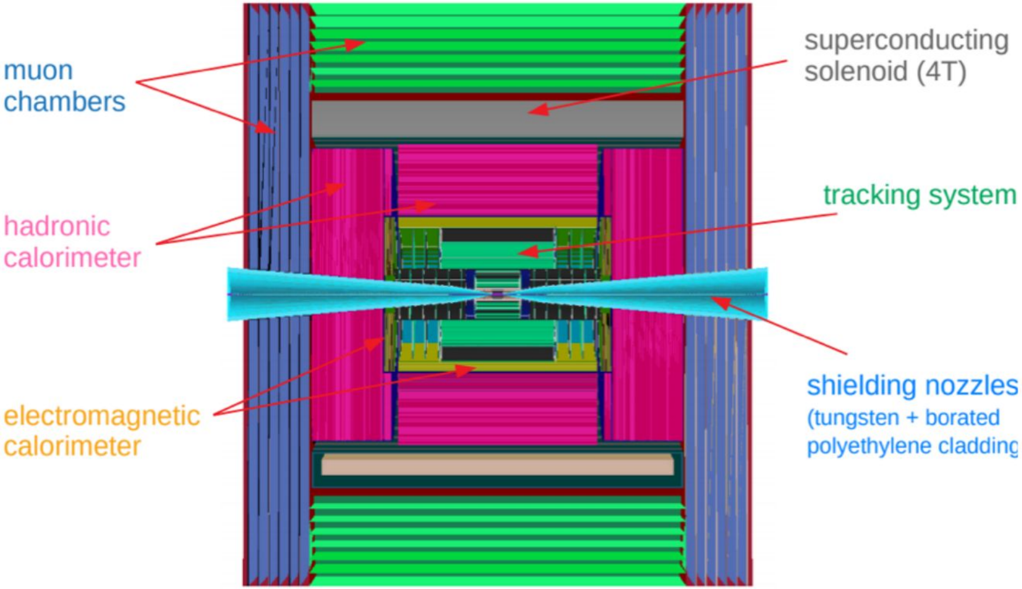
*See Chiara Aimè's talk "Detector performance and physics reach at Muon Collider "

Detector

- Detailed simulation of detector and BIB is crucial to determine detector performance

Challenging object reconstruction:

- Nozzles optimized for $\sqrt{s}$=1.5 TeV
  - The acceptance is expected to be higher at $\sqrt{s}$=3 TeV
- Presence of high hits multiplicity in tracking system due to BIB particles*
- Diffuse BIB background in the calorimeters*
- High multiplicity of hits in the forward regions of the muon chambers, around the nozzles*

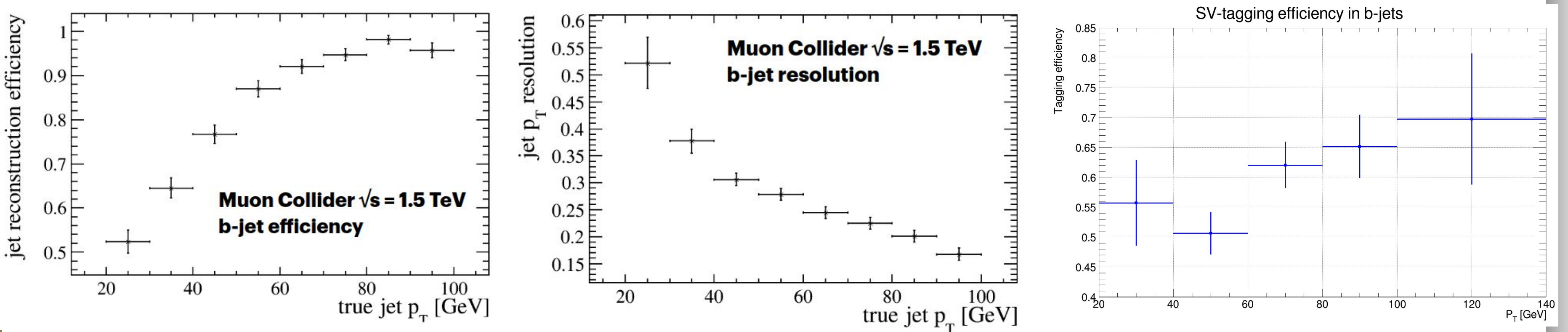


- Higgs physics studies at 3 TeV presented in this talk include BIB at $\sqrt{s}$=1.5 TeV.
- Focus on: $H \to b\bar{b}$, $HH \to b\bar{b}b\bar{b}$, $H \to \mu^+\mu^-$

*See Chiara Aimè's talk "Detector performance and physics reach at Muon Collider "

Jet reconstruction and b tagging efficiencies

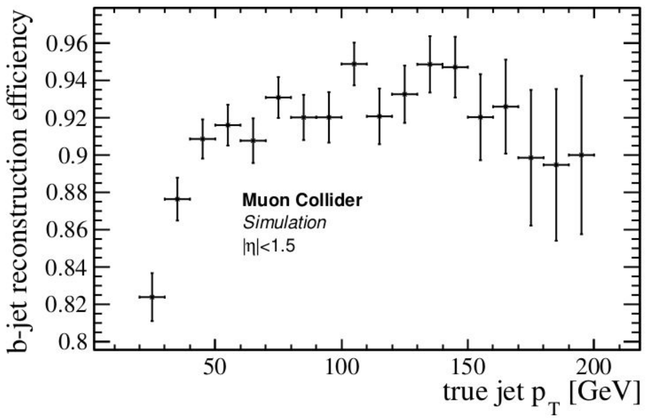
- Key ingredients for the analyzes presented in this talk: jet reconstruction and b tagging
- Jet reconstruction efficiency estimated on $b\bar{b}$-dijet + BIB events:
  - Jets are reconstructed by using calorimeter energy deposits
  - Average energy deposited by BIB in calorimeter cells is subtracted
- Secondary vertices (SV) reconstructed using tracks inside the jet cone. b-jets tagging efficiency: ~ 55%, c jets mis-identification ~ 30%, light+fake jets mis-identification between 0.2% and ~ 10% at high p_T (fake SV due to BIB)

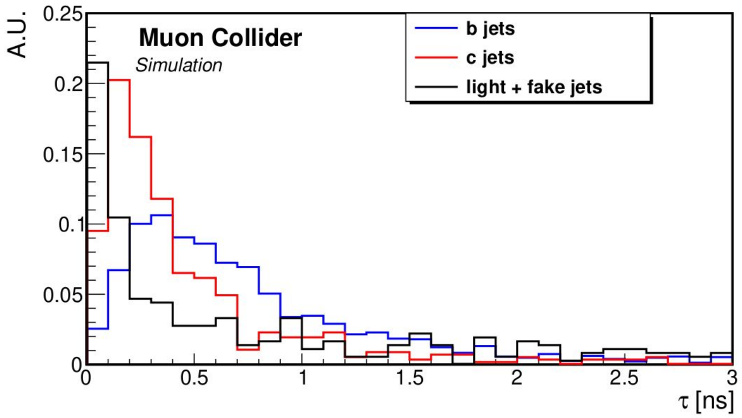


- Such performances are used in the following analyses, but improvements have been already obtained

Improvements in jet and b tagging efficiencies (NEW)

- Improvements in jet reconstruction efficiency:
  - New tracking algorithm allows to reconstruct jets exploiting both tracks and calorimeter clusters
  - Optimization of the energy threshold to subtract BIB (lower energy subtraction)
- Optimization of SV quality cuts (e.g. proper lifetime)
  - b tagging efficiency kept almost the same. Improvements in c jets mis-identification (~20%) and light+fake jets mis-identification (~5% at high p_T)

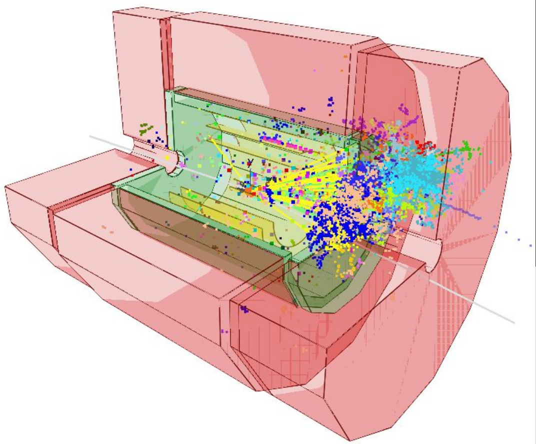




arXiv:2203.07964

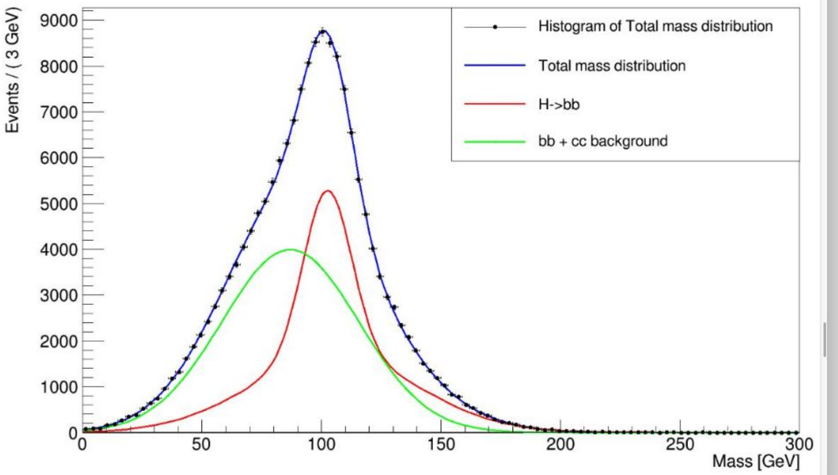
Measurement of σ_H x BR(H→b$\bar{b}$)*

Process*	σ [fb]	Eff_{rec}	Events with $\mathscr{L}_{int} = 1$ ab^{-1}
H→ $b\bar{b}$	324.0	0.244 ± 0.015	79.1k
$b\bar{b}$ + $c\bar{c}$ background	610.7	0.155 ± 0.011	94.8k



- Events selection:
  - both final state jets are required to be tagged
  - M_{jj} <300 GeV
  - $|\eta^{jet}|$<2.5
  - p_T^{jet} > 20 GeV

- Fit of the invariant mass gives an expected statistical uncertainty on **$\sigma(\mu^+\mu^-\to H)\bullet BR(H\to b\bar{b})$ of 0.8% at 3 TeV and 1.0 ab^{-1}**
- CLIC reaches 0.3% with 2.0 ab^{-1} (**)
- Higgs produced forward in the detector and sometimes b jets are reconstructed as a single jet (room for improvements)



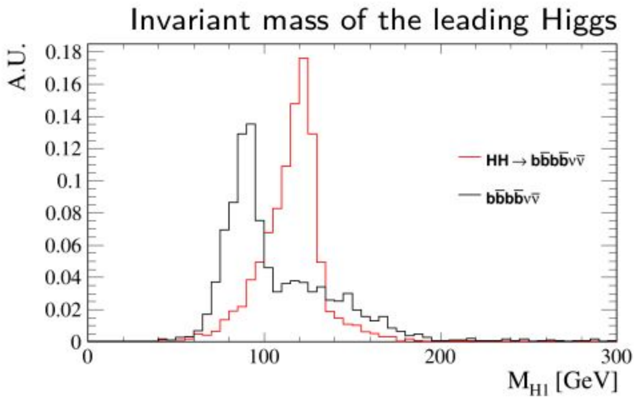
*Study of b- and c- jets identification for Higgs coupling measurement at the Muon Collider, G. Da Molin (master's thesis)

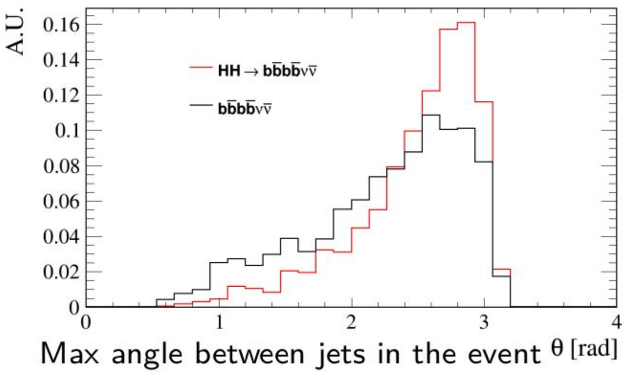
***Higgs physics at the CLIC electron–positron linear collider*, Eur.Phys.J.C 77 (2017) 7, 475

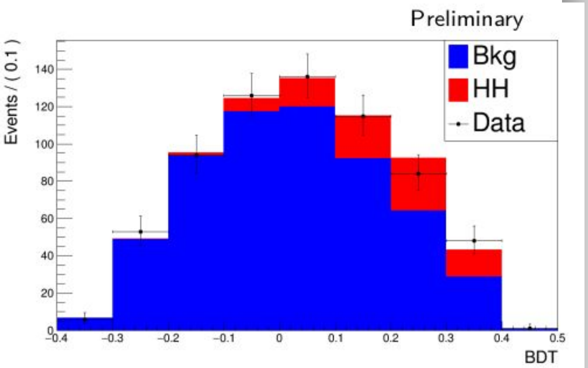
$\mu^+\mu^- \to HH\nu\bar{\nu} \to b\bar{b}b\bar{b}\nu\bar{\nu}$ at 3 TeV

- Simulation performed without BIB but b-tagging efficiency in the presence of BIB is used to weight events
- Event selection requirements:
  - N_{jets} >3 with p_T > 20 GeV
  - Jets paired by minimizing the figure of merit $M = \sqrt{(m_{ij} - m_H)^2 + (m_{kl} - m_H)^2}$
- Kinematical variables can be used to separate the signal from the background ($\mu^+ \mu^- \to b\bar{b}b\bar{b}\nu\bar{\nu}$) by training a BDT
- With L= 1 ab^{-1} at 3 TeV we expect to select 50 HH events and 432 background events
- With a simple fit to the BDT an uncertainty of ~ 30% on **$\sigma(\mu^+\mu^- \to HH\nu\bar{\nu}) \bullet BR(HH \to b\bar{b}b\bar{b})$** has been obtained

Signal	Cross section [fb]
$\mu^+\mu^- \to HH\nu\bar{\nu}$	0.8
Physics background	Cross section [fb]
$\mu^+\mu^- \to b\bar{b}b\bar{b}\nu\bar{\nu}$	3.3
$\mu^+\mu^- \to b\bar{b}H\nu\bar{\nu}$ (signal included)	1.7

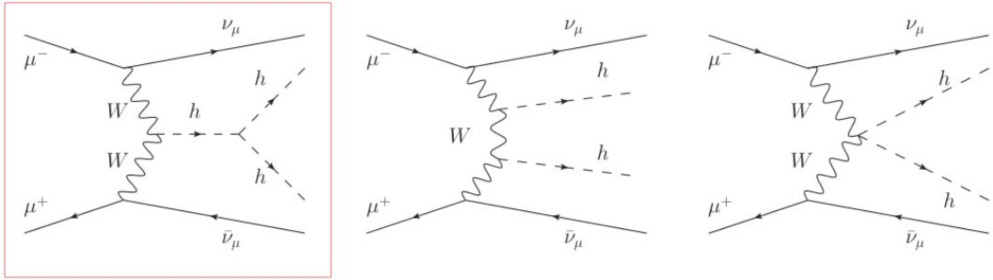


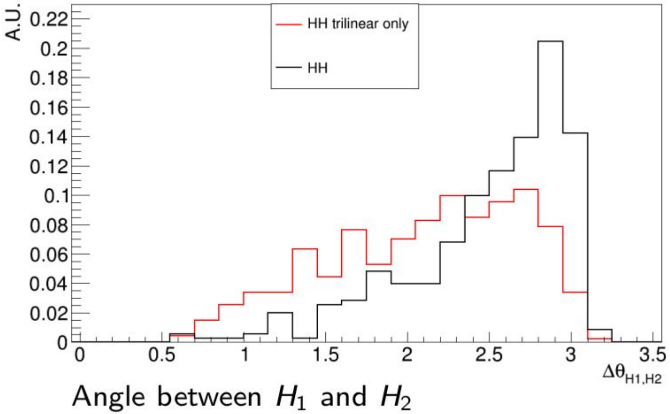




Trilinear coupling uncertainty

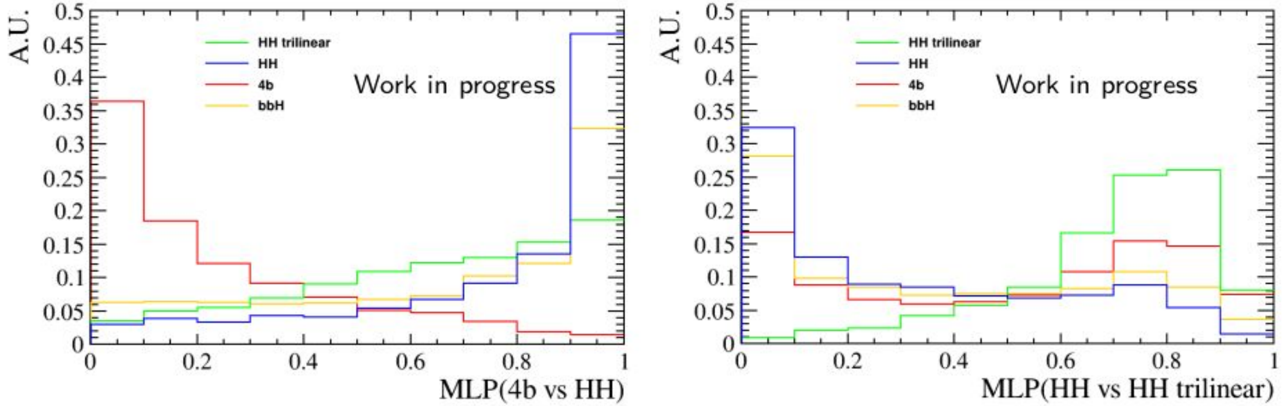
- Generation with WHIZARD and simulation of HH events just with the process mediated by the trilinear coupling
- The kinematic of the HH process is also used to separate the total HH from the HH trilinear-only contribution.





Trilinear coupling uncertainty

- Two Multi Layer Perceptrons (MLP) discriminators are trained to separate:
  - **HH from trilinear vertex vs total HH**
  - **total HH vs 4b background**



- Set of $\mu^+\mu^- \rightarrow HH\nu\bar{\nu} \rightarrow b\bar{b}b\bar{b}\nu\bar{\nu}$ samples generated for different $\kappa = \lambda_3/\lambda_{SM}$ =(0.4, 0.6, 0.8, 1.0, 1.2, 1.4, 1.6)
- Binned likelihood analysis based on pseudo-experiments gives a statistical uncertainty on λ_3 of about **20% at 3 TeV and 1.0 ab^{-1} (at 68% CL)**
- For comparison: CLIC has [-8%,+11%] at 68% CL with 5 ab^{-1} (**)

** *Double Higgs boson production and Higgs self-coupling extraction at CLIC*, Eur. Phys. J. C **80** (2020) no.11, 1010

Measurement of $\sigma_H \times BR(H \to \mu^+\mu^-)$*

*Study of the Physics Potential of the H → $\mu^+\mu^-$ Direct Decay Channel at a 3 TeV Muon Collider, A. Montella (master's thesis)

- Event selection requirements:
  - Two opposite charge muons
  - 10°< θ_μ <170° and p_T^μ > 5 GeV , reject muons from BIB (Most of the BIB hits in the Muon System are located near the nozzles)
- 26 signal and 1100 background events are expected with L=1.0 ab^{-1}
- The statistical uncertainty on **σ(μμ→H)•BR(H→$\mu^+\mu^-$)** is obtained with a fit to the invariant mass: **38% at 3 TeV with L=1.0 ab^{-1}**

SIGNALS

$\mu^+\mu^- \to H\nu_\mu\bar{\nu}_\mu, \quad H \to \mu^+\mu^-$

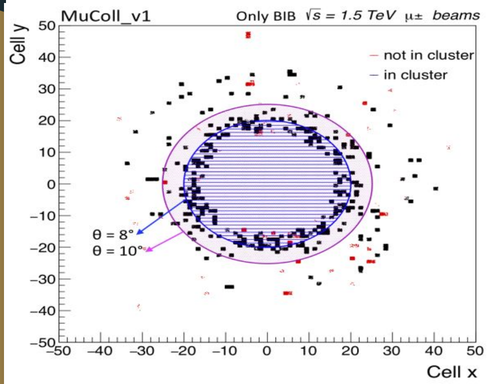
$\mu^+\mu^- \to H\mu^+\mu^-, \quad H \to \mu^+\mu^-$

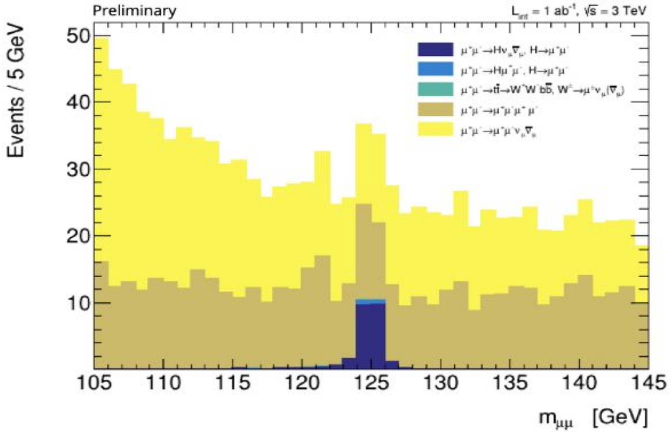
MAIN BACKGROUNDS

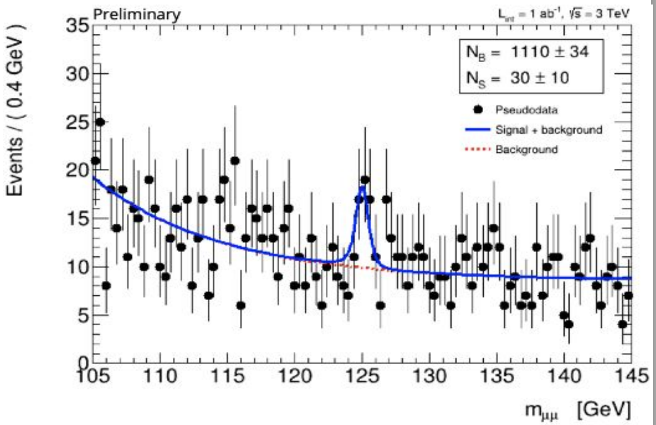
$\mu^+\mu^- \to \mu^+\mu^-\nu_\mu\bar{\nu}_\mu$

$\mu^+\mu^- \to \mu^+\mu^-\mu^+\mu^-$

$\mu^+\mu^- \to t\bar{t} \to W^+W^-b\bar{b}, \quad W^\pm \to \mu^\pm\nu_\mu(\bar{\nu}_\mu)$







Conclusions

- At muon collider muon beams collide at very high center of mass energy, but they decay and produce BIB. Detailed simulation is essential to understand how to deal with BIB in the analyses.

- The evaluation of the uncertainties on the $H \to WW^*$ and $H \to ZZ^*$ cross sections are currently ongoing
- A global fit will allow to determine the uncertainty on Higgs couplings and the Higgs width in a model independent way

- These results are expected to improve with an optimized:
  - jet reconstruction, e.g. study of the longitudinal energy distribution released by the BIB is different from signal
  - overlay with 3 TeV BIB (instead of 1.5 TeV) and dedicated BIB mitigation strategy for 3 TeV