Summary of physics results with detector full simulation

Speaker: Laura Buonincontri
21 June 2023

Outlook

- Higgs physics full simulation studies
  - Results at 3 TeV on σ x BR and trilinear
  - State of the art of Higgs width measurements
  - Fit to σ x BR measurements, uncertainty on couplings
- Beyond the standard model full simulation studies
  - Search for Wino and higgsino dark matter with disappearing tracks
  - Study of dark-SUSY
  - Search for the associated production of a dark photon (DP) or an axion-like particle (ALP)

- Full simulation studies include BIB, unless otherwise specified
  - BIB events 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

Full simulation at a 3 TeV Muon Collider Detector

Challenging events reconstruction in the presence of the BIB*:

- Nozzles are fundamental to mitigate BIB, but also reduce acceptance
- High hits multiplicity in tracking system due to BIB particles
- Diffused BIB background in the calorimeters:
- **Fake secondary vertices** (SV) due to BIB, that affects flavour tagging
- High multiplicity of hits in the forward regions of the muon chambers

➔ **Loss of tracking, jets, photon, electron, muons reconstruction efficiency** in the forward region and low p_T

➔ BIB produces **fake tracks**, **fake jets and fake SV** that have to be removed in the analysis

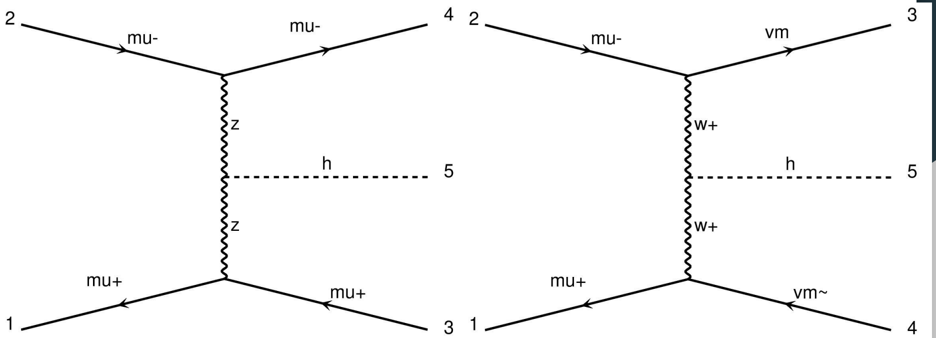
➔ BIB worsen energy resolution

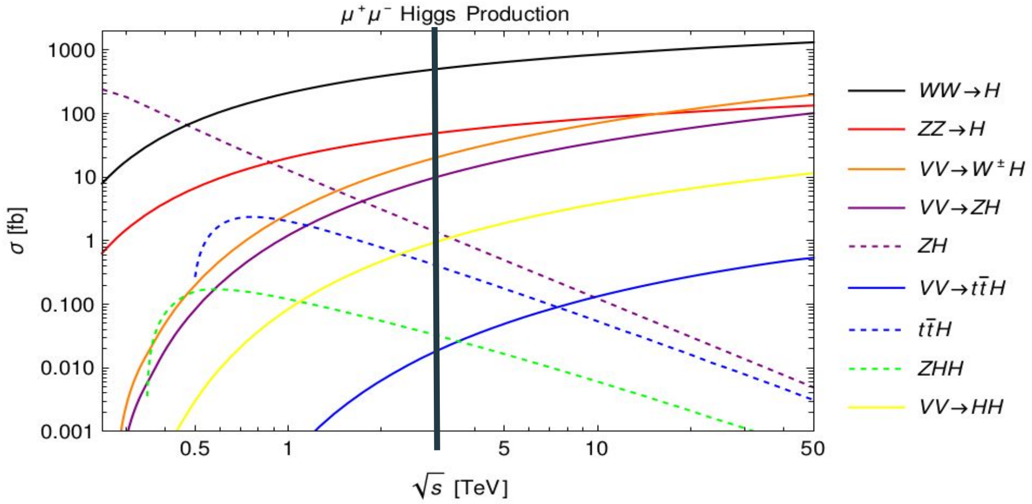
*See C. Aimè's talk: https://indico.cern.ch/event/1250075/contributions/5349959/

Higgs physics studies

Higgs at a muon collider

- At multi-TeV energy, Higgs mainly produced by Vector Boson Fusion (VBF)
- 1 ab^{-1} @ 3 TeV Muon Collider considered in this presentation
- ~500k events expected with 1 ab^{-1} @ 3 TeV



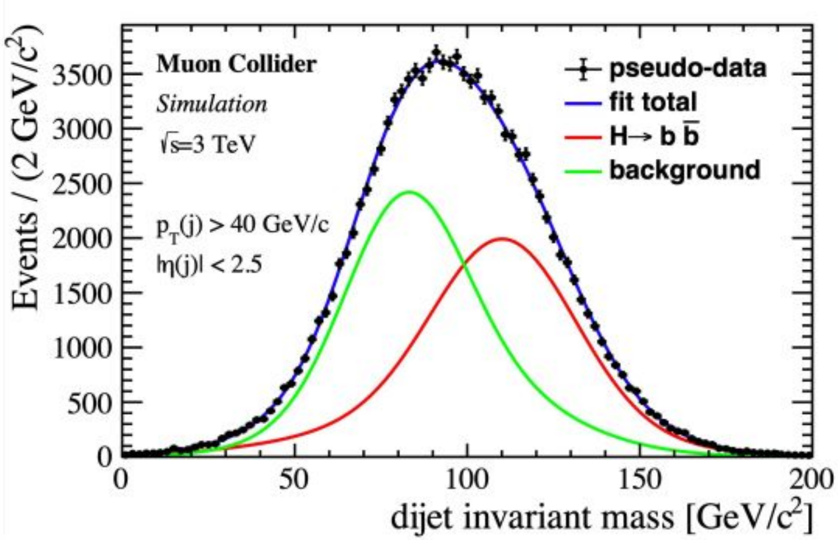


Measurement of σ_H x BR($H \to b\bar{b}$)

L. Sestini

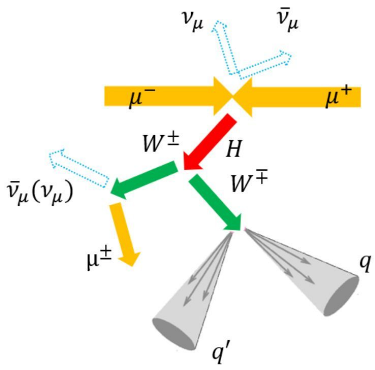
- Signal: $\mu^+\mu^- \to (H \to bb) + X$ and background $\mu^+\mu^- \to qq + X$ (q=b,c) generated with Whizard+Pythia8
  - background mainly from $Z \to bb$ and $Z \to cc$
- Preliminary cuts to remove fake jets in the analysis
- Two jets with a Secondary Vertex tag are required.
  - Background from light jets considered negligible
- Events selection:
  - both final state jets are required to be tagged
  - $|\eta^{jet}| < 2.5$
  - $p_T^{jet} > 40$ GeV
- S= 59 500, B=65 400 in 1 ab^{-1}
- Signal yield from template fit to pseudo-experiments invariant mass
- Statistical relative uncertainty on

  σ x BR = 0.75%



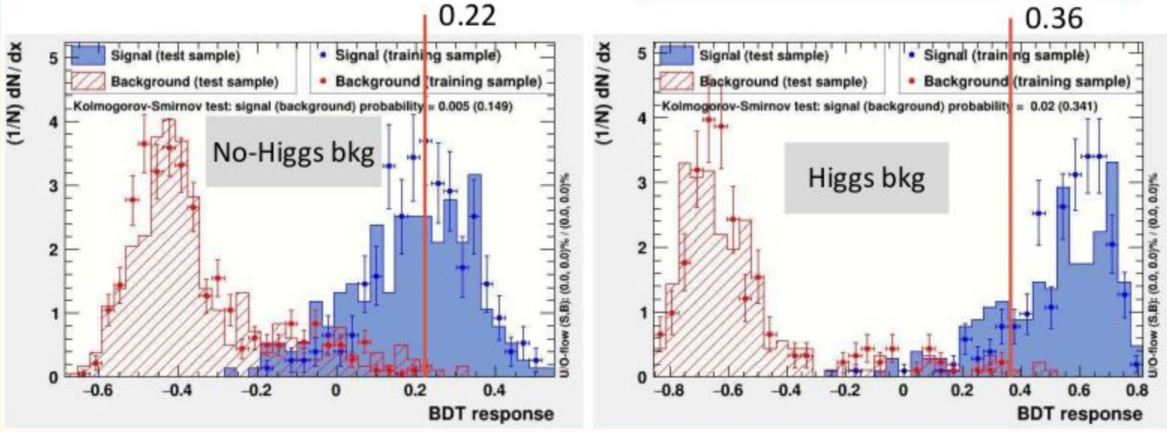
http://hdl.handle.net/20.500.12608/28559

Measurement of $\sigma_H \times BR(H\text{->}WW^*)$



- Events selection:
  - preliminary cuts to remove fake jets in the analysis
  - at least two jets in final state with $p_T^{jet} > 20$ GeV and $|\eta^{jet}|<2.5$
  - at least one muon in final state with $p_T^{\mu} > 10$ GeV and $10° < \Theta^{\mu} < 170°$
- Signal and backgrounds (with and without Higgs) simulated with Whizard+Pythia8
- Cuts on two BDTs to select signal vs backgrounds
- S=2430, B=2600 in 1 ab $^{-1}$

Event	Expected Events
$\mu^+\mu^- \to H + X \to WW^* + X \to qq\mu\nu + X$	2430 ± 150
$\mu^+\mu^- \to qq\mu\nu$	2600 ± 1300
$\mu^+\mu^- \to qqll$	< 100 $C.L. = 68\%$
$\mu^+\mu^- \to qq\nu\nu$	< 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 $C.L. = 68\%$



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

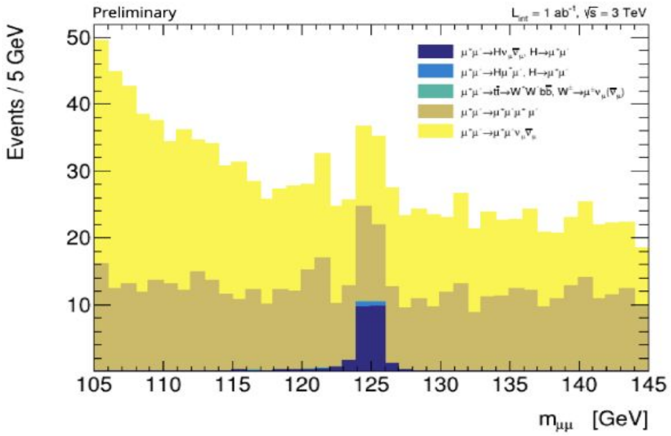
Measurement of $\sigma_H \times BR(H \to \mu^+\mu^-)$

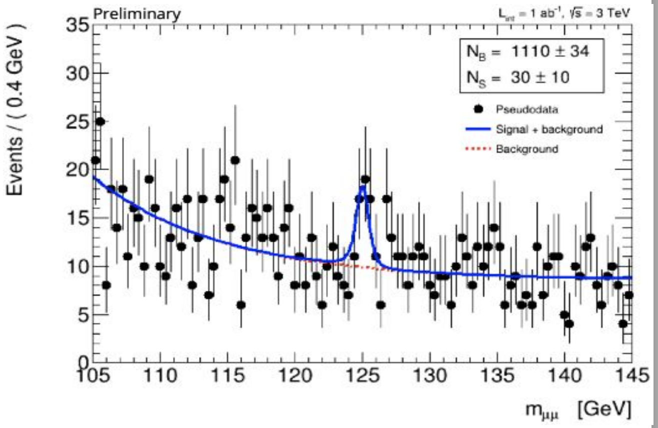
https://doi.org/10.22323/1.398.0579

(*)https://indico.cern.ch/event/1283532/

- Event selection requirements:
  - Two opposite charge muons with $p_T^{\mu} > 5$ GeV
  - $10° < \theta_\mu < 170°$ to reject fake hits from BIB
- 26 signal and 1100 background events are expected with $L=1.0\ ab^{-1}$
- Selection cuts on two BDTs trained to discriminate signal from the backgrounds
- The statistical uncertainty on **$\sigma(\mu\mu \to H) \cdot BR(H \to \mu^+\mu^-)$** is obtained with a fit to the invariant mass: **38% at 3 TeV with $L=1.0\ ab^{-1}$**
- Analysis performed without BIB, but BIB effects are negligible (*)

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





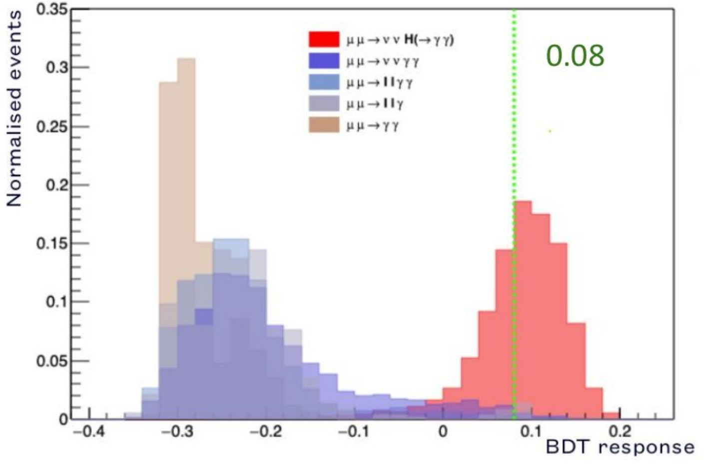
Measurement of σ_H x BR(H→γγ)

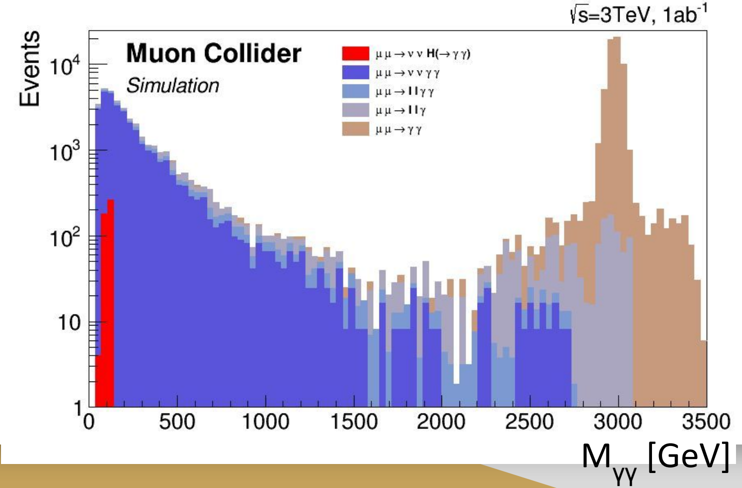
D. Zuliani

- Signal and backgrounds generated with MG5+Pythia8
- Preliminary result: No BIB at the moment
- Event selection requirements:
  - Two photons in acceptance with p_T^γ > 10 GeV and E^γ>15 GeV
  - Most energetic photon with p_T^γ > 40 GeV
- 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

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

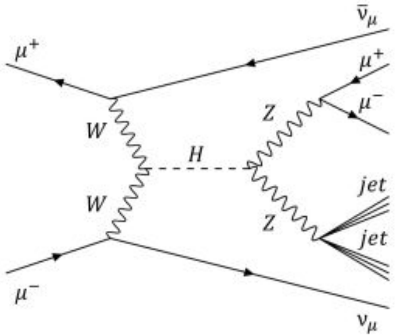


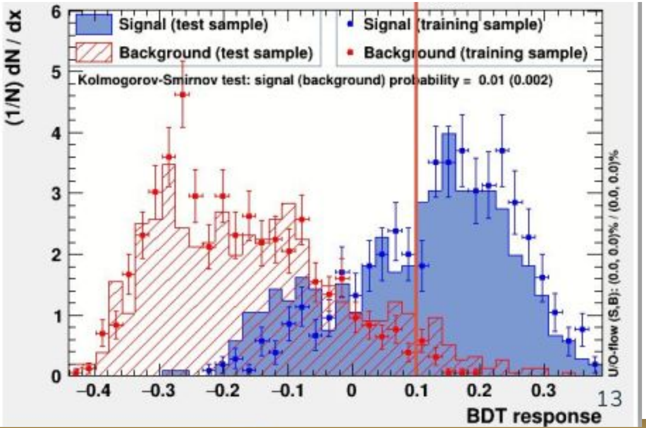


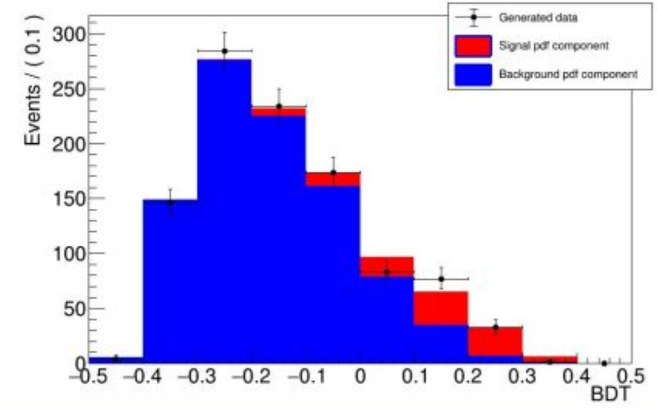
Measurement of $\sigma_H \times BR(H \to ZZ)$

L. Mareso in https://indico.cern.ch/event/1197844/

- Events selection:
  - preliminary cuts to remove fake jets in the analysis
  - at least two jets candidates with $p_T^{jet} > 15$ GeV
  - at least two muons candidates with $p_T^{\mu} > 10$ GeV outside the jets cone
- Signal generated with MG5+Pythia8, while inclusive $\mu^+ \mu^- \to \nu\nu\mu^+ \mu^- jj$ background (excluding signal) is generated with Whizard+Pythia8
- BDT used to classify signal vs background
- Resolution obtained with cut-based approach and with fit of BDTs, giving the same result







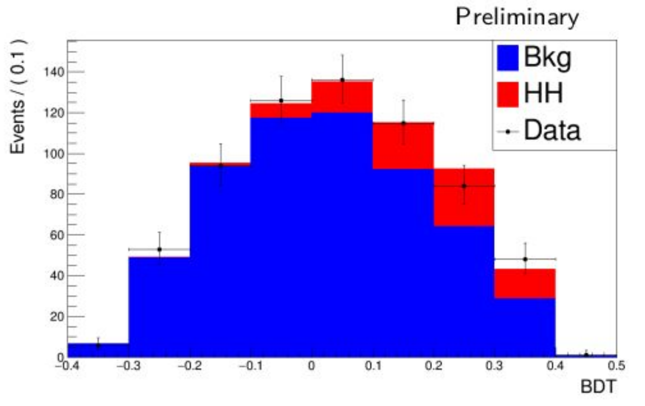
$$\frac{\Delta\sigma}{\sigma} = 17\%$$

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

http://hdl.handle.net/20.500.12608/22861

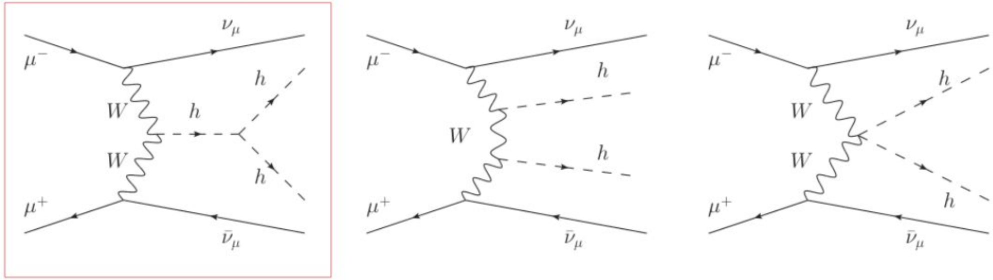
- Simulation performed without BIB:
  - b-tagging efficiency in the presence of BIB is used to weight events
  - Full simulation with BIB ongoing
- Event selection requirements:
  - N_{jets} >3 with p_T > 20 GeV
  - Jets paired by minimizing the figure of merit $M = \sqrt{(m_{ij} - m_H)^2 + (m_{kl} -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

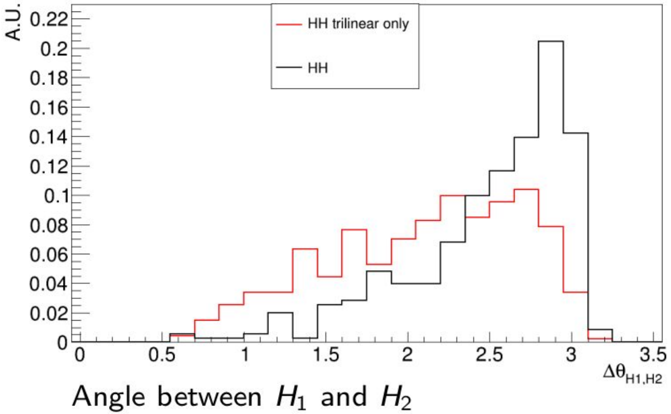
Signal	Cross section [fb]
$\mu^+\mu^- \rightarrow HH\nu\bar{\nu}$	0.8
Physics background	Cross section [fb]
$\mu^+\mu^- \rightarrow b\bar{b}b\bar{b}\nu\bar{\nu}$	3.3
$\mu^+\mu^- \rightarrow b\bar{b}H\nu\bar{\nu}$ (signal included)	1.7



Trilinear coupling uncertainty

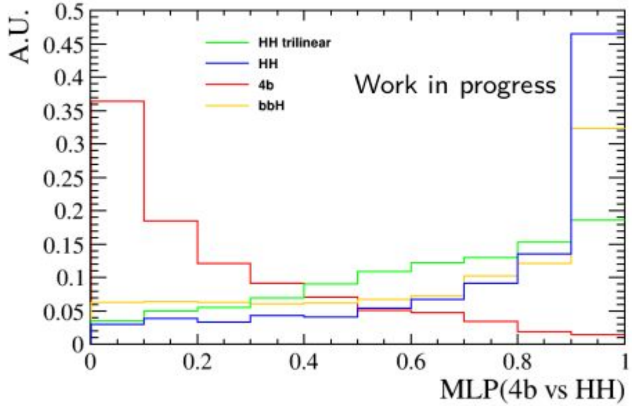
- Generation with WHIZARD and simulation of HH events just with the process mediated by the trilinear coupling
- The kinematic of the HH process is also used to separate the total HH from the HH trilinear-only contribution.

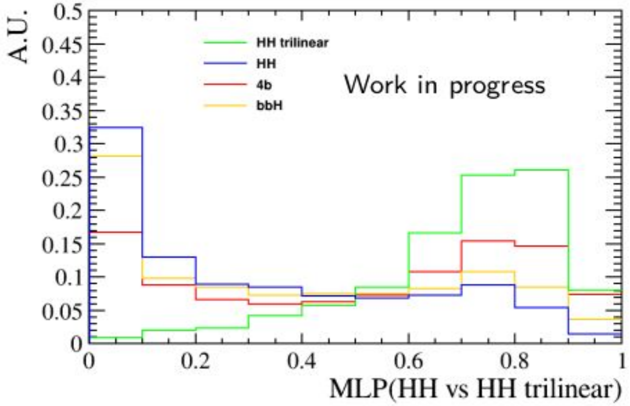




Trilinear coupling uncertainty

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





- Set of signal samples generated for different $\kappa = \lambda_3 / \lambda_{SM}$ hypothesis
- Statistical uncertainty on λ_3 of about **20% at 3 TeV and 1.0 ab^{-1} (at 68% CL)** obtained with a likelihood scan

** *Eur.* Phys. J. C **80** (2020) no.11, 1010

Comparison with CLIC

Measurement	Statistical precision	
	1.4 TeV 1.5 ab^{-1}	3 TeV 2.0 ab^{-1}
$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to b\bar{b})$	0.4%	0.3%
$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to \mu^+\mu^-)$	38%	25%
$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to \gamma\gamma)$	15%	10%*
$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to WW^*)$	1.0%	0.7%*
$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to ZZ^*)$	5.6%	3.9%*

Measurement	Statistical precision 350 GeV 500 fb^{-1}
$\sigma(ZH) \times BR(H \to b\bar{b})$	0.86%
$\sigma(ZH) \times BR(H \to WW^*)$	5.1%
$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to b\bar{b})$	1.9%

$$\frac{\Delta[\sigma(HH\nu_e\bar{\nu}_e)]}{\sigma(HH\nu_e\bar{\nu}_e)} = 44\% \text{ at } 1.4\,\text{TeV},\ 20\% \text{ at } 3\,\text{TeV}$$

$\Delta\lambda/\lambda$ [-8%,+11%] at 68% CL with 5 ab^{-1} (**)

Muon Collider 1 ab^{-1} @ 3 TeV	
H->WW	2.9%
H->ZZ	17%
H->bb	0.75%
H->μμ	38%
H->γγ	8.9%
HH->4b	30%
λ_3	20%

Differences:

- H→bb from combined measurement of hadronic Higgs decays
- H→ZZ* with llqq final state, and l = {e, μ, τ}
- H→WW* with qqqq and lνqq final state, and l = {e, μ}

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

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

Higgs width measurement via the recoil mass method

Recoil mass method, tested for 3 TeV muon collider:

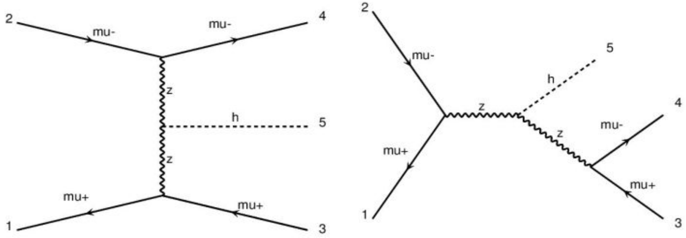
- Γ_H can be extracted with proper ratio of σ and σ×BR
- Higgs produced via $\mu^+\mu^- \rightarrow H\mu^+\mu^-$ (ZBF+Higgsstrahlung)

Processes

$$\sigma(\mu^+\mu^- \to \mu^+\mu^- H) \propto g^2_{HZZ}$$

$$\sigma(\mu^+\mu^- \to \nu\nu H) \times BR(H \to WW) \propto \frac{g^4_{HWW}}{\Gamma_H}$$

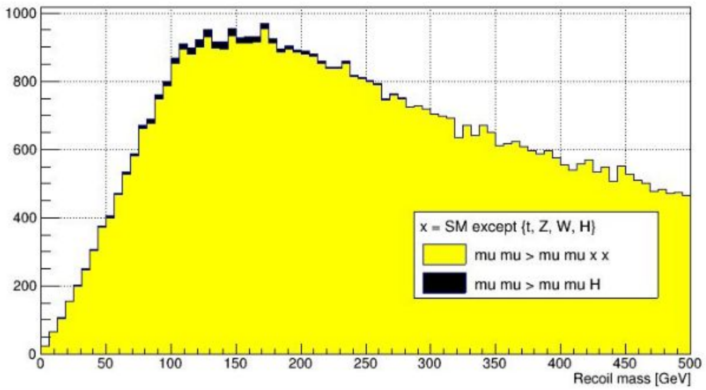
$$\sigma(\mu^+\mu^- \to \nu\nu H) \times BR(H \to ZZ) \propto \frac{g^2_{HWW}\, g^2_{HZZ}}{\Gamma_H}$$



$$\frac{(\sigma(\mu^+\mu^- \to \nu\nu H) \times BR(H \to WW)) \times (\sigma(\mu^+\mu^- \to \mu^+\mu^- H))^2}{(\sigma(\mu^+\mu^- \to \nu\nu H) \times BR(H \to ZZ))^2} \propto \Gamma_H$$

- The H peak is reconstructed as the recoil mass distribution:

$$M_H^2 = E_{CM}^2 + M_{\mu\mu}^2 - 2\, E_{\mu\mu} \cdot E_{CM}$$

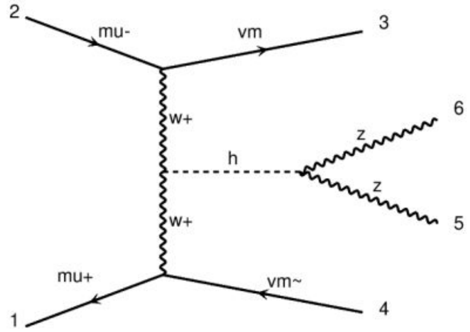


- S =345.8, B = 25554, S/sqrt(S+B) = 2.2
- When E_{CM} is increased, $M_{\mu\mu}$ and $E_{\mu\mu}$ grow, difference between large terms
- Poor energy resolution in the forward region
- Should get worse at higher energies

L. Giambastiani: https://indico.cern.ch/event/1103957/

Indirect measurement of the Higgs width

- Indirect measurement of Higgs width similar to the one used by LHC
- Consider WBF and ZBF processes μμ⟶VV+X (V=W,Z)
- Include diagrams sensitive to the couplings of the Higgs to vector bosons (H is off-shell)
- These processes are generated with Monte Carlo for different hypothesis of a coupling modifier introduced on g_{HZZ} and g_{HWW}
- The resolution on the coupling modifier (*k*) can be obtained with a likelihood scan
- The resolution on the Higgs width can be determined knowing the resolution on k and on the on-shell cross section (shown before)



$$\frac{\sigma^{on-shell}(W^+W^- \to H \to ZZ)}{\sigma^{on-shell}_{SM}(W^+W^- \to H \to ZZ)} \propto \frac{k^4}{\Gamma_H/\Gamma_H^{SM}}$$

$$k = \frac{g_{HVV}}{g^{SM}_{HVV}}$$

- Study performed via fast simulation considering all possible final states: 4j, $l^{\pm} \nu_{\ell}$ jj and l^+l^- jj (see M. Forslund and P. Meade*)

$$\Delta\Gamma = 4.0\% \text{ at } 10 \text{ TeV}$$

$$\Delta\Gamma = 58\% \text{ at } 3 \text{ TeV}$$

*https://indico.fnal.gov/event/56615/contributions/255035/attachments/162410/214663/MC_HPrec_ForTalk.pdf

L. Giambastiani

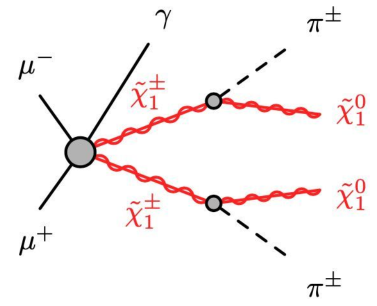
Higgs couplings from full sim

- Previous measurements of σ x BR 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 (SM Γ_H) $1\ \mathrm{ab}^{-1}$ @ 3 TeV	CLIC $0.5\ \mathrm{ab}^{-1}$ @ 350 GeV + $1.5\ \mathrm{ab}^{-1}$ @ 1.4 TeV + $2\ \mathrm{ab}^{-1}$ @ 3 TeV
Γ_H	SM	3.5%
g_{HZZ}	7.9%	0.8%
g_{HWW}	0.8%	0.9%
g_{Hbb}	0.8%	0.9%
$g_{H\mu\mu}$	19.0%	7.8%
$g_{H\gamma\gamma}$	4.2%	3.2%

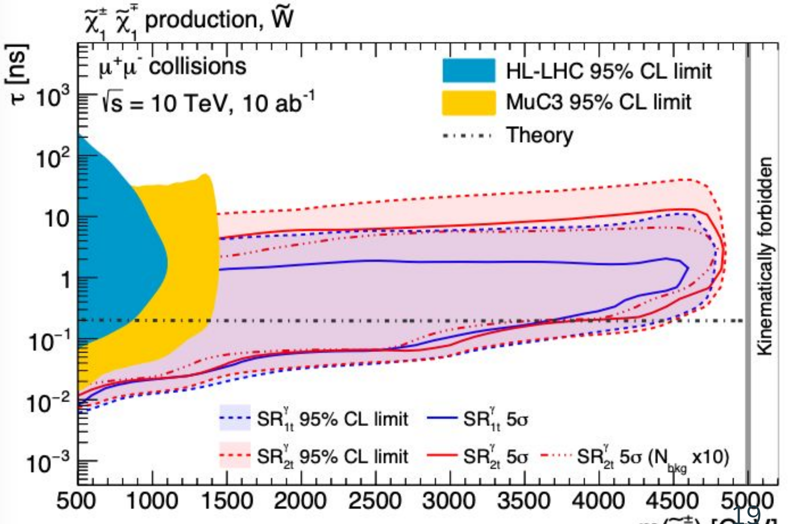
Beyond the Standard Model searches

Wino and higgsino dark matter with disappearing tracks



- Signal (MG5+ Pythia): pairs of charged LLPs (chargino) with decay lengths < 1 m, at $\sqrt{s}$ = 3 TeV (1 ab^{-1}) and $\sqrt{s}$ = 10 TeV (10 ab^{-1})
  - track with no hits in outermost layers of the tracking system
  - no energy deposits in calorimeters or muon system associated to it
- Background:
  - BIB: disappearing tracks from fake hits combination, fully simulated
  - SM: most significant is $\mu^+\mu^- \rightarrow \nu\nu$
- Average number of fake tracks due to BIB ~ 0.08/event exploiting double layer layout and quality requirements on tracks
- Efficiency on signal disappearing tracks: 90% in the central region
- Two signal regions, based on tracklet multiplicity

Requirement / Region	SR^{γ}_{1t}	SR^{γ}_{2t}
Vetoes	leptons and jets	
Leading tracklet p_T [GeV]	> 300	> 20
Leading tracklet θ [rad]	$[2/9\pi, 7/9\pi]$	
Subleading tracklet p_T [GeV]	-	> 10
Tracklet pair Δz [mm]	-	< 0.1
Photon energy [GeV]	> 25	> 25

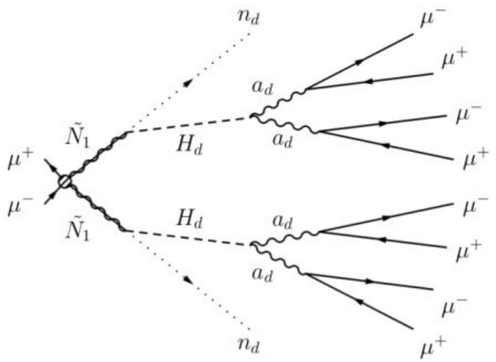


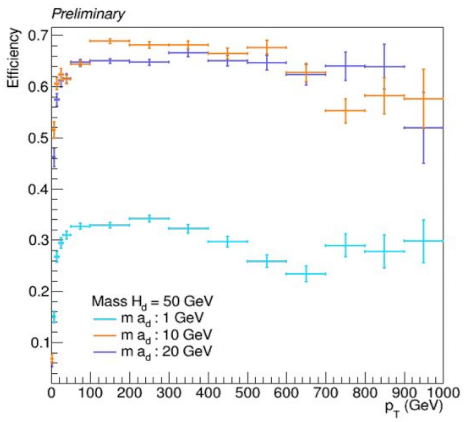
https://doi.org/10.1007/JHEP06(2021)133

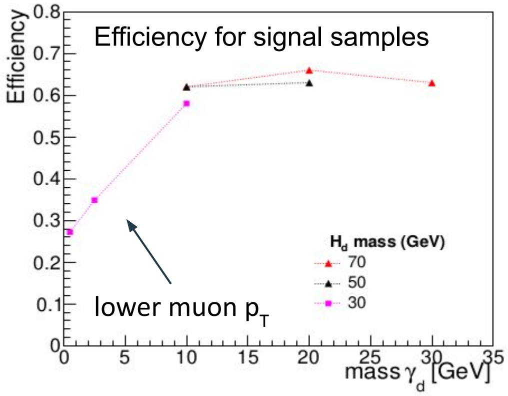
Study of dark-SUSY at 3 TeV

C. Aimè
https://doi.org/10.22323/1.398.0644

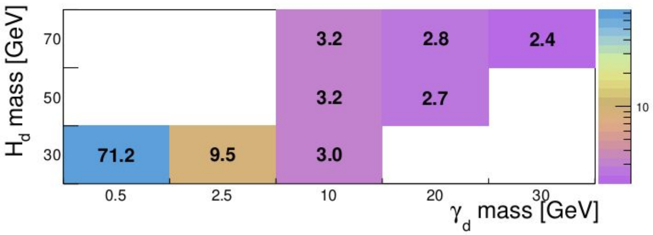
- Signal generated with MG5
- A MSSM lightest neutralino decays in two dark photons through a dark Higgs boson (8 final state muons)
- Events full simulated without BIB and selected:
  - 8 muons in the final state
  - muons paired by requiring a minimum difference between the reconstructed dark photon and dark Higgs masses
- 8 muons background found to be negligible
- 8 muons + 2 neutrinos background not possible to generate







Signal yield for 1 ab^{-1}

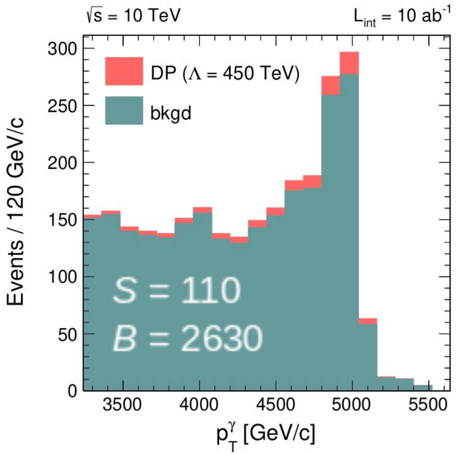


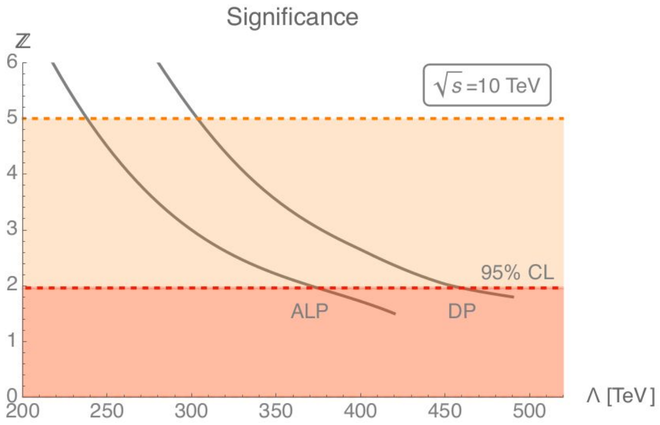
➔ Reconstruction efficiency of processes with n-muons in final state with BIB to be determined!

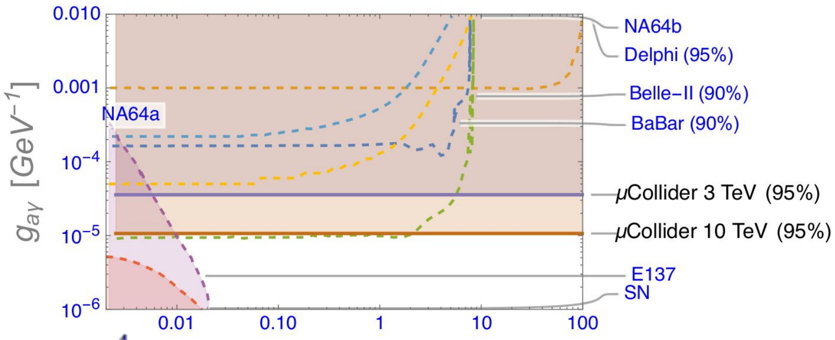
Monochromatic single photon events

https://doi.org/10.1103/PhysRevD.105.075008

- Search for the associated production of a dark photon (DP) or an axion-like particle (ALP) with a photon at $\sqrt{s}$ = 3 TeV (1 ab^{-1}) and $\sqrt{s}$ = 10 TeV (10 ab^{-1})
- Signals and background generated with MG5+Pythia
- At high energies the production cross sections depend on a single effective energy scale: $\sigma \propto 1/\Lambda^2$
- Experimental signature is a single monochromatic photon
- Background $\mu^+\mu^- \rightarrow \gamma\nu\nu$
- Events full simulated without BIB, but high energy single photon is required:
  - E_γ > 1450 GeV and 40° < θ_γ < 140° for 3 TeV
  - E_γ > 4800 GeV and 40° < θ_γ < 140° for 10 TeV







$$g_{a\gamma} = \frac{4}{\Lambda}$$

Conclusions and final considerations

Conclusions and next steps

- This talk shows many physics studies, both for Standard Model and Beyond the Standard Model
- Many Higgs physics studies can be improved:
  - Electronic and muonic decay channels (i. e. $H \to ZZ$ and $H \to WW$)
  - Forward detectors to tag ZBF production
- Some Higgs decay channel are still to be studied, like $H \to \tau\tau$
- Others need further studies, like $H \to cc$:
  - b- and c-jets have a different internal structure due to the different quarks composition
  - A Deep Neural Network to exploit the different flavour distributions inside the jets could be a promising technique*, but more studied are needed
- Precision on ttH production at 3 and 10 TeV for the direct measurement of the top Yukawa coupling investigated via fast simulation*
  - Large multiplicity final states (8 jets or 6 jets + 1 lepton in final state)
  - Signal precision on ttH(bb): ~ 61% at 3 TeV, ~53% at 10 TeV*
- The Muon Collider have a great potential in studying also BSM physics
- At 3 TeV and 1 ab^{-1} the precision on Γ_H measurement is worse than the HL-LHC precision
  - expected large improvements by going to 10 TeV

*https://doi.org/10.1007/JHEP08(2022)185

Backup