Higgs Couplings at Muon Colliders with Delphes

Matthew Forslund

with Patrick Meade

C. N. Yang Institute for Theoretical Physics

January 12, 2022

Single Higgs Production at Muon Colliders

First look at single Higgs precision for a 10 TeV muon collider ($\mathcal{L} = 10\text{ab}^{-1}$) was in the Muon Smasher's Guide (2103.14043)

- Looked at most relevant channels, but was **signal only**

Here we show our preliminary results for most relevant channels including physics backgrounds at 3 TeV (1 ab^{-}1) and 10 TeV (10 ab^{-}1) using Delphes fast simulation

Full simulation studies are under way for several processes (i.e. Higgs 2021: L. Giambastiani, G. Da Molin), but only up to 3 TeV and won't cover all relevant channels.

$b\bar{b}$ and $WW^* \to jj\ell\nu$ (L. Sestini et. al.) will hopefully be key points of comparison for us

Event Generation and Detector Assumptions

Event generation is done mostly using MadGraph5 and showering with Pythia8

Require final state $p_{T,\mu} > 10$ GeV for $ZZ/Z\gamma/\gamma\gamma$F and $WZ/W\gamma$F processes to avoid singularities

Use DELPHES fast muon collider card for the detector:

Hybrid of FCC-hh and CLIC detector cards for efficiencies and reconstruction[1]

Limits detectors to $|\eta| < 2.5$ roughly corresponding to BIB reducing tungsten nozzles with opening $\theta \approx 10^\circ$

Includes hypothetical forward muon detector from $2.5 < |\eta| < 8.0$ with 10% energy resolution

[1] https://indico.cern.ch/event/957299/contributions/4023467/attachments/2106044/3541874/delphes_card_mucol_mdi_.pdf

Flavour Tagging

b-tagging is done using the tight working point (50%) inspired by CLIC (1812.07337)

- c-quark mis-tagging rate $\leq 3\%$
- light quark mistagging rate $\leq 0.5\%$

For c-tagging, we use the tagging rates of ILC reported in (1506.08371). We take 20% as our working point to match the Smasher's Guide.

- b-mistagging rate of flat 1.3%
- light quark mistagging rate of flat 0.66%

We note that the worse mistag rates of the original CLIC design report (1202.5940) yield very similar results.

Event Reconstruction

Events are subject to the same cuts and jet clustering as done in the Smasher's Guide.

We use the Valencia jet clustering algorithm with $\beta = \gamma = 1$ (1607.05039).

Events are clustered in exclusive mode with $R = 0.5$

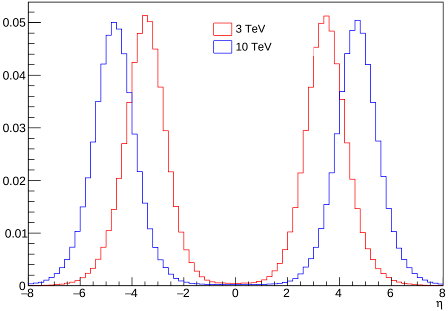
2-body final states required to have both particles satisfying $|\eta| < 2.5$ and $P_T > 40$ GeV.

For 4-body final states, loosen the P_T cut to 20 GeV.

Apply additional process dependent cuts, estimate precision using $\frac{\Delta\sigma}{\sigma} = \frac{\sqrt{N_{sig}+N_{bkg}}}{N_{sig}}$

Forward Muons

To distinguish between W-fusion and Z-fusion, must be able to tag the forward muons beyond the $|\eta| \approx 2.5$ nozzles



For $b\bar{b}$, we include additional results assuming the ability to tag these forward muons. **These are a work in progress and idealised at the moment**.

Event Selection ($b\bar{b}, c\bar{c}, gg(+s\bar{s})$)

Apply an additional correction to b-jet p_T to account for energy losses during reconstruction (1811.02572)

- Smoothly scales 4-momentum by up to $\sim$1.16 at low p_T
- Rough approximation to ATLAS *ptcorr* correction (1708.03299)
- Reproduces a Higgs peak centered near 125 GeV

Apply a similar correction to c-jets

Events that pass the P_T and η cuts are then selected based on an invariant mass cut:

- $100 < M_{b\bar{b}} < 150$ for $b\bar{b}$
- $105 < M_{c\bar{c}} < 145$ for $c\bar{c}$
- $95 < M_{jj} < 135$ for $gg(+s\bar{s})$

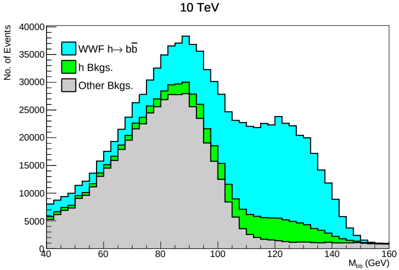
Backgrounds ($b\bar{b}$)

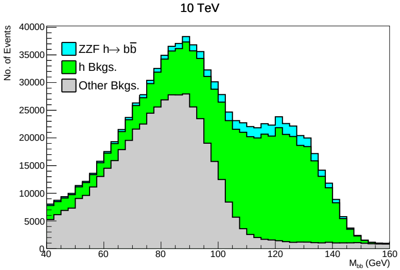
Primary backgrounds: 10 TeV at 10ab^{-1}

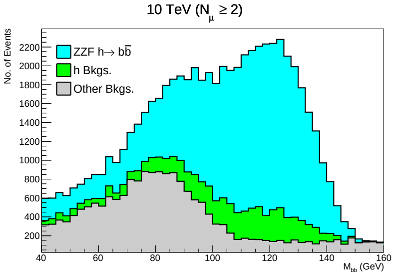
Process	σ (fb)	$A \cdot \epsilon$ (%)	Events
$\mu^+\mu^- \to \nu_\mu\bar{\nu}_\mu H;\ H \to b\bar{b}$	490	5.2	250000
$\mu^+\mu^- \to b\bar{b}(\nu\nu, \mu\mu)$	620	0.56	34000
$\mu^+\mu^- \to \mu^+\mu^- H;\ H \to b\bar{b}$	50	5.2	27000
$\mu\nu WH;\ H \to b\bar{b}$	41	4.0	16000
$(\mu\mu, \nu\nu)ZH;\ H \to b\bar{b}$	21	4.2	8600
Others	-	-	11000

Where others includes VBF WZ, ZZ, tb, tt, and HH

$b\bar{b}$ at 10 TeV







Precision (%)

Energy	*WWF*	*ZZF*	*ZZF* ($N_\mu \geq 2$)
3 TeV	0.84	7.9	2.5
10 TeV	0.24	2.2	0.73

$c\bar{c}, gg(+s\bar{s})$

The dominant backgrounds for $c\bar{c}$ and $gg(+s\bar{s})$ are mostly the same as for $b\bar{b}$ and primarily removed via the M_{jj} cut

Invariant mass resolution critical for distinguishing Z(and W) peaks from the H

$H \to b\bar{b}$ becomes a large irreducible background

Following the same procedure as in $b\bar{b}$, we obtain results for $c\bar{c}$ and $gg(+s\bar{s})$:

Precision (%)

Energy	$c\bar{c}$	$gg(+s\bar{s})$
3 TeV	14	4.2
10 TeV	4.4	1.2

$\tau\tau$

For $H \to \tau\tau$, we take a τ-tagging efficiency of 80% with a jet mistag rate of 2%

Energy losses due to neutrinos in τ-decays make an invariant mass cut alone less useful.

Since all W-fusion carries lots of missing energy, MET is likewise not very useful

We find a $80 < M_{\tau\tau} < 130$ cut combined with $\theta_{\tau\tau} > 20(15)$ at 3(10) TeV cuts down the dominant $\mu\mu \to (\nu\nu, \mu\mu)\tau\tau$ background substantially

We find a precision of 4.5% at 3 TeV and 1.3% at 10 TeV

$WW^* \to jj\ell\nu$

For WW^* and ZZ^*, we generate the full $2 \to 6$ backgrounds such as $\mu\mu \to \nu\nu\ell\ell jj$ using MadGraph.

For $WW^* \to jj\nu\ell$, the story is much the same as $\tau\tau$, as the full M_H cannot be fully reconstructed.

We require two jets and one isolated lepton and apply the mass cuts:

- $5 < M_{jj} < 90$
- $20 < M_{jj\ell} < 110$
- $40 < E_{jj} < 700$, $85 < E_{jj\ell} < 800$ (3 TeV)
- $50 < E_{jj} < 1100$, $90 < E_{jj\ell} < 1600$ (10 TeV)

We find the majority of the background is removed using these cuts

Precision:

- 1.79% (3 TeV)
- 0.48% (10 TeV)

$ZZ^* \to jj\ell\ell$

We apply the cuts:

- $5 < M_{Z^*} < 60$
- $15 < M_Z < 100$
- $50 < M_H < 135$ ($Z \to jj$, $Z^* \to \ell\ell$)
- $80 < M_H < 130$ ($Z^* \to jj$, $Z \to \ell\ell$)

Thanks to the lepton pair, this channel is clean, but statistically limited

Process	No. of Events 3 TeV	No. of Events 10 TeV
$\nu\nu H \to \nu\nu\ell\ell jj$	103	1590
Other VBF Higgs	14	207
$(\ell\ell, \tau\tau)\nu\nu jj$	25	901
$\ell\ell\nu\ell jj$, $t\bar{t}$, tb	15	244

Overall we find a precision of 12% at 3 TeV and 3.4% at 10 TeV.

$\gamma\gamma$

For $\gamma\gamma$, ISR becomes very important, so we include it in event generation by using Whizard.

Require no isolated leptons and a cut of $122 < M_{\gamma\gamma} < 128$

	No. of Events	
Process	3 TeV	10 TeV
$\nu\nu H \to \nu\nu\gamma\gamma$	415	5590
$\mu\mu H \to \mu\mu\gamma\gamma$	34	583
$\nu\nu\gamma\gamma$	321	3890
$\nu\nu\gamma$(+ISR)	264	3290
$\mu\mu\gamma\gamma$	7	35
$\mu\mu\gamma$(+ISR)	38	425

Find a precision of 7.9% at 3 TeV and 2.1% at 10 TeV.

$\mu\mu$

This channel has been analysed at 3 TeV using full simulation[1] (A. Montella), obtaining 38% precision.

For our case, we do a very simple analysis using fastsim:

Require 2 isolated muons with $P_T > 20$, $|\eta| < 2.5$,

Keep events passing a cut of $124 < M_{\mu\mu} < 126$

We find a precision of 44% at 3 TeV and 11% at 10 TeV.

[1] https://indico.cern.ch/event/1030068/contributions/4513645/attachments/2329111/3968454/montella_Higgs_2021.pdf

Preliminary 10 TeV @ 10 ab^{-1} **Smasher's Guide**

Production	Decay	Rate [fb]	$A \cdot \epsilon$ [%]	$\Delta\sigma/\sigma$ [%]	**Signal Only** $\Delta\sigma/\sigma$ [%]
W-fusion	bb	485	5.2	0.24	0.17
	cc	24.4	0.83	4.4	1.7
	$gg(+ss)$	72.2	14	1.2	0.19
	$\tau^+\tau^-$	53.1	3.2	1.3	0.54
	$WW^*(jj\ell\nu)$	52.8	17	0.48	0.30
	$ZZ^*(jj\ell^+\ell^-)$	2.07	7.7	3.4	2.3
	$\gamma\gamma$	1.92	29	2.1	1.3
	$\mu^+\mu^-$	0.18	39	11	0.37
Z-fusion	bb	49.6	5.4	2.2	0.49
	bb ($N_\mu >= 2$)	49.6	4.9	0.73	

Preliminary

Production	Decay	$\Delta\sigma/\sigma$ (%)	
		3 TeV	10 TeV
W-fusion	bb	0.84	0.24
	cc	14	4.4
	$gg(+ss)$	4.2	1.2
	$\tau^+\tau^-$	4.5	1.3
	$WW^*(jj\ell\nu)$	1.8	0.48
	$ZZ^*(jj\ell\ell)$	12	3.4
	$\gamma\gamma$	7.9	2.1
	$\mu^+\mu^-$	44	11
Z-fusion	bb	7.9	2.2
	bb ($N_\mu >= 2$)	2.5	0.73

Preliminary Fit Result [%]

	3 TeV @ 1 ab^{-1}	10 TeV @ 10 ab^{-1}
κ_W	0.45	0.13
κ_Z	3.4	0.96
κ_g	2.4	0.68
κ_γ	4.0	1.1
$\kappa_{Z\gamma}$	–	–
κ_c	7.4	2.3
κ_t	–	–
κ_b	0.99	0.28
κ_μ	22	5.3
κ_τ	2.5	0.71

Where – means it was fixed to the SM (relevant channel still in progress).

Preliminary Fit Result 10 TeV @ 10 ab^{-1} [%]

	10 TeV Muon Collider	with HL-LHC	with HL-LHC + 250 GeV e^+e^-
κ_W	0.13	0.12	0.11
κ_Z	0.96	0.77	0.11
κ_g	0.68	0.64	0.50
κ_γ	1.1	0.84	0.81
$\kappa_{Z\gamma}$	–	–	4.1
κ_c	2.3	2.3	1.4
κ_t	–	3.2	3.2
κ_b	0.28	0.27	0.23
κ_μ	5.3	3.6	3.3
κ_τ	0.71	0.64	0.43

Future Plans

We are finishing the last few relevant channels and should be done soon. Plan to add:

- $WW^* \to 4j$
- $ZZ^* \to 4j, 4\ell$
- $Z(jj)\gamma$
- $t\bar{t}H$

Detailed comparison of these results to full sim still needs to be done for validation.

- However, we have tried to remain conservative with respect to BIB

Next step- measurement of the Higgs width

BACKUPS

Preliminary 3 TeV @ 1 ab^{-1}

Production	Decay	Rate [fb]	$A \cdot \epsilon$ [%]	$\Delta\sigma/\sigma$ [%]
W-fusion	bb	287	6.6	0.84
	cc	14.5	1.1	14
	$gg(+ss)$	42.8	17	4.2
	$\tau^+\tau^-$	31.5	3.9	4.5
	$WW^*(jj\ell\nu)$	31.3	20	1.8
	$ZZ^*(jj\ell^+\ell^-)$	1.23	8.4	12
	$\gamma\gamma$	1.14	37	4.9
	$\mu^+\mu^-$	0.11	52	44
Z-fusion	bb	29.3	6.8	7.9
	bb ($N_\mu >= 2$)	29.3	6.2	2.5

Preliminary Fit Result 3 TeV @ 1 ab^{-1} [%]

	3 TeV Muon Collider	with HL-LHC	with HL-LHC + 250 GeV e^+e^-
κ_W	0.45	0.40	0.33
κ_Z	3.4	1.3	0.12
κ_g	2.4	1.5	0.74
κ_γ	4.0	1.3	1.2
$\kappa_{Z\gamma}$	–	–	4.2
κ_c	7.4	7.3	1.7
κ_t	–	3.2	3.2
κ_b	0.99	0.89	0.44
κ_μ	22	4.7	4.1
κ_τ	2.5	1.3	0.60

Preliminary Fit Result with Forward Muon Tagging [%]

	3 TeV @ 1 ab^{-1}	10 TeV @ 10 ab^{-1}
κ_W	0.44	0.13
κ_Z	1.3	0.38
κ_g	2.4	0.68
κ_γ	4.0	1.1
$\kappa_{Z\gamma}$	–	–
κ_c	7.4	2.3
κ_t	–	–
κ_b	0.98	0.27
κ_μ	22	5.3
κ_τ	2.5	0.71