High precision Higgs physics at high energy muon colliders

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Muon Colliders

In the last few years, there has been a resurgence of interest in muon colliders

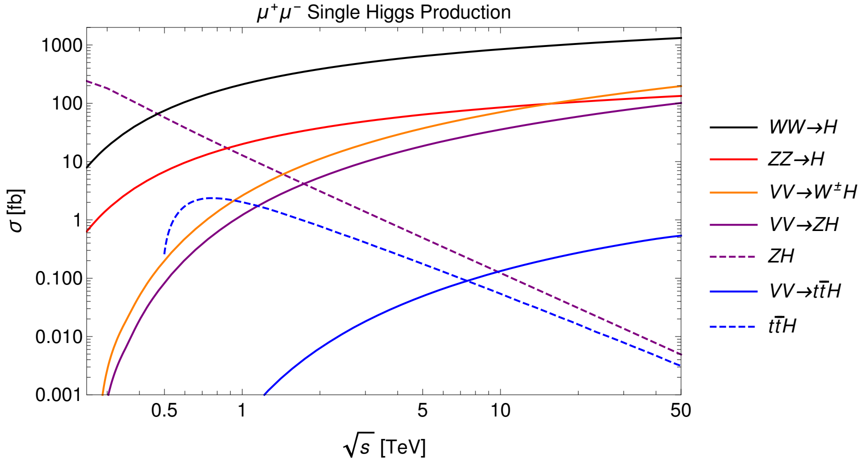
BIB seems to be under control (tungsten nozzles, detector technology advancements)

Potential bridge to the energy/precision dichotomy

How well can a muon collider do for single Higgs precision including backgrounds?

Compare to signal-only results in (2103.14043)

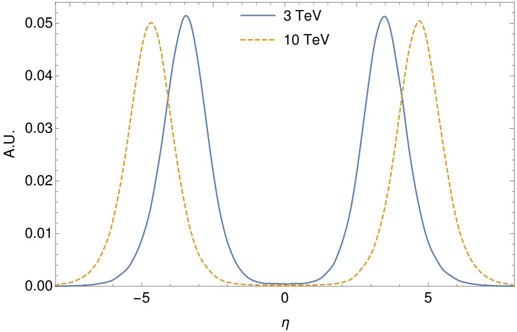
Single Higgs Production at Muon Colliders



We look at all of the relevant decays of $WW \to H$ and $ZZ \to H$.

Forward Muons

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



For *ZZ*-fusion, we include results considering tagging up to $|\eta| \leq 6$.

Event Generation and Detector Assumptions

Event generation is done mostly using MadGraph5 and showering with Pythia8

Use Delphes fast muon collider card for the detector:

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

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

- Loosen to $p_T > 20$ GeV for non-hadronic 4-body final states.

Apply flavour tagging, additional process dependent cuts, estimate precision using $\frac{\Delta\sigma}{\sigma} = \frac{\sqrt{S+B}}{S}$

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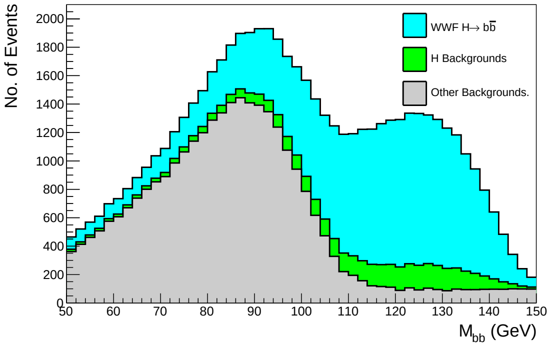
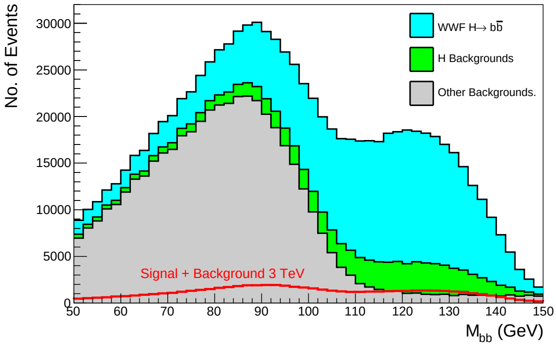
[1] `https://indico.cern.ch/event/957299/contributions/4023467/attachments/2106044/3541874/delphes_card_mucol_mdi_.pdf`

Hadronic Processes: $b\bar{b}$

3 TeV



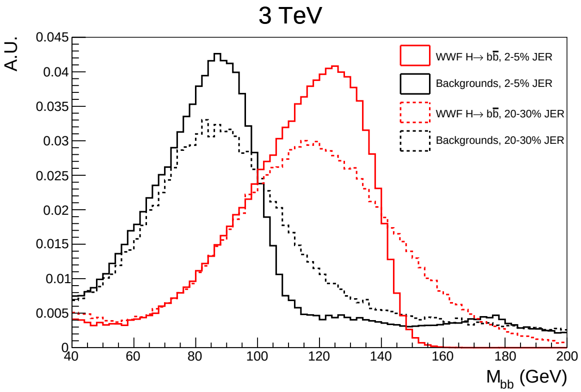
10 TeV



Precision (%)

Energy	WWF	ZZF	ZZF ($N_\mu \geq 2$)
3 TeV	0.84	7.9	2.6
10 TeV	0.24	2.2	0.77

Estimating the Effects of the BIB



The additional spreading roughly doubles the background contribution from the Z peak: 0.84% → 0.95% precision.

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

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 an M_{jj} cut

$H \to b\bar{b}$ 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

$\tau^+\tau^-$ follows a similar strategy with similar backgrounds, adding $\theta_{\tau\tau} > 15(20)$ cuts, to get 4.5(1.3)% precision.

WW^*, ZZ^*

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

Consider WW-fusion $WW^* \to (\ell\nu jj, 4j)$, $ZZ^* \to (4\ell, 2\ell 2j, 4j)$ and ZZ-fusion $WW^* \to 4j$

The $4j$ final states have an enormous background from $H \to b\bar{b}, gg$ from exclusive clustering, completely overwhelming all other backgrounds.

Number of Events

Process	3 TeV			10 TeV		
	$4j$	$2j2\ell$	4ℓ	$4j$	$2j2\ell$	4ℓ
$\mu^+\mu^- \to \nu_\mu\bar{\nu}_\mu H;\ H \to ZZ^* \to X$	124	103	5	2910	1590	66
$\mu^+\mu^- \to \mu^+\mu^- H;\ H \to ZZ^* \to X$	3	9	0	315	151	8
Others	6700	50	0	208000	1370	2

$t\bar{t}H$

This process requires special care

Select events with four b-tagged $p_T > 20$ jets and ≤ 1 leptons, apply various cuts on $E_{W,t,H}$, $m_{W,t,H}$

Obtain a precision of 61% at 3 TeV and 53% at 10 TeV

(Different y_t dependence at 3 and 10 TeV)

Number of Events

Process	3 TeV		10 TeV	
	SL	Had	SL	Had
$t\bar{t}H;\ H \to b\bar{b}$	34	63	49	59
$t\bar{t}H;\ H \not\to b\bar{b}$	9	21	6	11
$t\bar{t}$	609	2070	502	1440
$t\bar{t}Z$	207	362	530	663
$t\bar{t}b\bar{b}$	9	21	15	18

Fit Result [%]

	3 TeV @ 1 ab^{-1}	10 TeV @ 10 ab^{-1}
κ_W	0.45	0.13
κ_Z	3.4	0.94
κ_g	2.4	0.67
κ_γ	3.9	1.1
$\kappa_{Z\gamma}$	37	10
κ_c	7.5	2.3
κ_t	35	53
κ_b	0.98	0.27
κ_μ	22	5.4
κ_τ	2.5	0.71

We keep Γ_H fixed to the standard model in this fit

Forward tagging mainly affects κ_Z:

- 3.4% → 1.3%
- 0.94% → 0.40%

The full $\Delta\sigma/\sigma$ precisions for all channels in backups

Conclusion

At the level of fast simulation, muon colliders appear competitive with most proposed colliders for single Higgs couplings, especially at 10 TeV.

BIB effects are unlikely to significantly change these results.

Still need the width to break the degeneracy: will hopefully have results in this direction soon!

The real strength of a high energy muon collider is to simultaneously push the energy regime alongside precision

BACKUPS

Flavour Tagging

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

- c-quark mistagging 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.

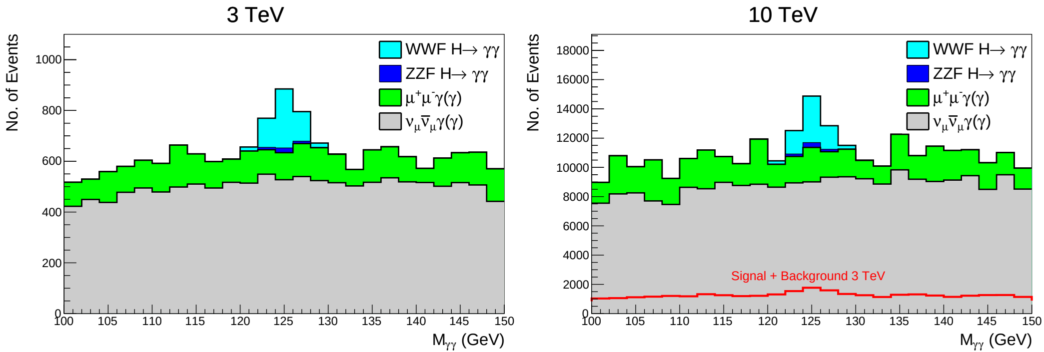
- b-quark mistagging rate of flat 1.3%
- light quark mistagging rate of flat 0.66%

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

$\gamma\gamma$ and $Z\gamma$

For $\gamma\gamma$ and $Z\gamma$, ISR becomes very important, so we include it via Whizard

For $\gamma\gamma$, require no isolated leptons and a cut of $122 < M_{\gamma\gamma} < 128$.



The $Z(jj)\gamma$ process has similar backgrounds the hadronic modes with added ISR backgrounds, but much messier and with more complicated cuts.

	3 TeV @ 1 ab^{-1}	10 TeV @ 10 ab^{-1}
$b\bar{b}$	0.84	0.24
$c\bar{c}$	14	4.4
gg	4.2	1.2
$\tau^+\tau^-$	4.5	1.3
$WW^*(jj\ell\nu)$	1.8	0.50
$WW^*(4j)$	5.7	1.4
$ZZ^*(4\ell)$	48	13
$ZZ^*(jj\ell\ell)$	12	3.5
$ZZ^*(4j)$	67	16
$\gamma\gamma$	7.7	2.1
$Z(jj)\gamma$	73	20
$\mu^+\mu^-$	43	11

WW-Fusion $\Delta\sigma/\sigma$ [%]

ZZ-Fusion $\Delta\sigma/\sigma$ [%]

	3 TeV @ 1 ab^{-1}	10 TeV @ 10 ab^{-1}
$b\bar{b}$	7.9	2.2
$b\bar{b},\ (N_\mu \geq 2)$	2.6	0.77
$WW^*(4j)$	49	12
$WW^*(4j),\ (N_\mu \geq 2)$	17	4.3
$t\bar{t}H$ $\Delta\sigma/\sigma$ [%]		
$b\bar{b}$	61	53

Fit Result [%]

	$\mu^+\mu^-$		$+$ HL-LHC		$+$ HL-LHC $+$ $250\,\mathrm{GeV}$ e^+e^-	
	3 TeV	10 TeV	3 TeV	10 TeV	3 TeV	10 TeV
κ_W	0.45	0.13	0.39	0.12	0.34	0.11
κ_Z	3.4	0.94	1.3	0.77	0.12	0.11
κ_g	2.4	0.67	1.5	0.63	0.76	0.50
κ_γ	3.9	1.1	1.3	0.84	1.2	0.81
$\kappa_{Z\gamma}$	37	10	37	10	4.1	3.8
κ_c	7.5	2.3	7.4	2.3	1.8	1.4
κ_t	35	53	3.2	3.2	3.2	3.2
κ_b	0.98	0.27	0.88	0.27	0.45	0.23
κ_μ	22	5.4	4.7	3.6	4.1	3.3
κ_τ	2.5	0.71	1.3	0.64	0.63	0.43

Fit Result [%] with Forward Muon Tagging

	$\mu^+\mu^-$		+ HL-LHC		+ HL-LHC + $250\,\mathrm{GeV}$ e^+e^-	
	3 TeV	10 TeV	3 TeV	10 TeV	3 TeV	10 TeV
κ_W	0.44	0.13	0.39	0.12	0.34	0.11
κ_Z	1.3	0.40	0.94	0.38	0.12	0.11
κ_g	2.4	0.67	1.5	0.63	0.76	0.50
κ_γ	3.9	1.1	1.3	0.83	1.2	0.81
$\kappa_{Z\gamma}$	37	10	37	10	4.1	3.8
κ_c	7.5	2.3	7.4	2.3	1.8	1.4
κ_t	35	52	3.2	3.2	3.2	3.2
κ_b	0.96	0.27	0.86	0.26	0.45	0.23
κ_μ	22	5.4	4.7	3.6	4.1	3.3
κ_τ	2.5	0.71	1.3	0.64	0.63	0.43

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

	Signal Only (2103.14043)	With Backgrounds
κ_W	0.06	0.13
κ_Z	0.23	0.94
κ_g	0.15	0.67
κ_γ	0.64	1.1
$\kappa_{Z\gamma}$	1.0	10
κ_c	0.89	2.3
κ_t	6.0	53
κ_b	0.16	0.27
κ_μ	2.0	5.4
κ_τ	0.31	0.71