Higgs Couplings at a Muon Collider

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IMCC + Snowmass Muon Collider Forum Reports
What is a Muon Collider?
Proton-driven Muon Collider Concept

Muon collider design is driven by finite muon lifetime

Collides fundamental particles, with high luminosity and high energy in the smallest footprint
Current Goal TDR by ~ 2040

Both CERN LDG and Snowmass process conclude no show-stoppers and this is doable with sufficient R&D funding (fingers crossed for P5 in US)
But why Muon Colliders and the Higgs? Don’t we have perfectly good Higgs Factory proposals?
The SM Higgs is an unprecedented particle.

LEP was a Z boson factory and produced
~ 17 Million Z bosons

Higgs Factories produce
~ 1 Million Higgs bosons

Higgs boson Branching Fractions

All major Branching Fractions are $\gtrsim \mathcal{O}(1\%)$

The same Higgs Branching Fractions span 8 to 20 ORDERS OF MAGNITUDE or more!

A Higgs factory is a great start but without the ability to increase luminosity by orders of magnitude we need more Energy
For a first stage LC or any circular Higgs Factory there are effectively no Di-Higgs events produced!

Why does this matter?
Testing the Higgs potential experimentally

\[
\frac{\partial V(h)}{\partial h} \bigg|_{h=v} = 0
\]

\[
\frac{\partial^2 V(h)}{\partial h^2} \bigg|_{h=v} = m_h^2
\]

+ more derivatives = self-interactions

**Experimentally** we look for multi-Higgs production

Can we demonstrate the *qualitatively* new self coupling and test the validity of SM? (BSM later)
Current status of LHC Higgs Potential Measurements?

<table>
<thead>
<tr>
<th>Final state</th>
<th>Collaboration</th>
<th>allowed $\kappa_\lambda$ interval at 95% CL</th>
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<tbody>
<tr>
<td></td>
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<tr>
<td>$b\bar{b}b\bar{b}$</td>
<td>ATLAS</td>
<td>-3.5 – 11.3</td>
</tr>
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<td></td>
<td>CMS</td>
<td>-2.3 – 9.4</td>
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<tr>
<td>$b\bar{b}\tau^+\tau^-$</td>
<td>ATLAS</td>
<td>-2.4 – 9.2</td>
</tr>
<tr>
<td></td>
<td>CMS</td>
<td>-1.7 – 8.7</td>
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<tr>
<td>$b\bar{b}\gamma\gamma$</td>
<td>ATLAS</td>
<td>-1.6 – 6.7</td>
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<td></td>
<td>CMS</td>
<td>-3.3 – 8.5</td>
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<tr>
<td>comb</td>
<td>ATLAS</td>
<td>-0.6 – 6.6</td>
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<tr>
<td></td>
<td>CMS</td>
<td>-1.2 – 6.8</td>
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</table>
Current status of LHC Higgs Potential Measurements?
Why does Energy help with the Higgs?
First way:
Energy helps make more Higgs (and multi-Higgs)
Muon colliders are *also* gauge boson colliders!

Can think of this as $VV$ to $H$ fusion, with $VV$ initial states (PDF like for hadron colliders)

Winner at moderate energies!
Muon colliders are *also* gauge boson colliders!

Can think of this as VV to H fusion, with VV initial states (PDF like for hadron colliders)
Benchmarks in this talk will be using 10 TeV w 10/ab (5 yr run @ design luminosity)
How Many Higgs??

Take this with many grains of salt...

- HL-LHC $\sim 0.35 \times 10^9$
- ILC250/350 $\sim 0.6 \times 10^6$
- FCC-ee 240/365 $\sim 1.2 \times 10^6$
- CEPC 240 $\sim 1.1 \times 10^6$
- CLIC-380 $\sim 0.2 \times 10^6$
- ILC500/1000 $\sim 4.5 \times 10^6$
- CLIC 1500/3000 $\sim 3.4 \times 10^6$

Low energy e+e- Higgs factories
- $\sim 1$ million Higgs

Moderate energy e+e- Higgs factories
- few million Higgs

FCC-hh $\sim 2.7 \times 10^9$
27 billion Higgses

End of LHC ~ O(100) million Higgses!

A Muon Collider gives a great balance of more Higgs, multi-Higgs and low backgrounds

Muon Colliders
- 10 TeV 10/ab $\sim 9.5 \times 10^6$
- 14 TeV 20/ab $\sim 22 \times 10^6$
- 30 TeV 90/ab $\sim 0.12 \times 10^9$
- 100 TeV 100/ab $\sim 0.18 \times 10^9$

10s to 100s of millions of Higgs
If this enhancement is done with “fundamental” particles

You can get an enhanced S/B too!
Blurring the Precision versus Energy Dichotomy!

ONE COLLIDER

TO RULE THEM ALL
Second way:
Energy allows one to probe the Higgs in *multiple* ways
How do we quantify Higgs precision

Kappa fits, EFTs, what else?

What precision we measure an individual channel in can then be combined based on theoretical assumptions
## Typically results in things that look like this

<table>
<thead>
<tr>
<th></th>
<th>HL-LHC</th>
<th>LHeC</th>
<th>HE-LHC</th>
<th>ILC 250</th>
<th>ILC 500</th>
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<th>CLIC 380</th>
<th>CLIC 15000</th>
<th>CLIC 3000</th>
<th>CEPC</th>
<th>FCC-ee 240</th>
<th>FCC-ee/eh/hh</th>
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<tbody>
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<tr>
<td>(\kappa_W) [%]</td>
<td>1.7</td>
<td>0.75</td>
<td>1.4</td>
<td>0.98</td>
<td>1.8</td>
<td>0.29</td>
<td>0.24</td>
<td>0.86</td>
<td>0.16</td>
<td>0.11</td>
<td>1.3</td>
<td>1.3</td>
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<td>1.3</td>
<td>0.9</td>
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<td>0.22</td>
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<td>0.23</td>
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<td>2.5</td>
<td>1.3</td>
<td>0.9</td>
<td>1.5</td>
<td>1.7</td>
</tr>
<tr>
<td>(\kappa_\gamma) [%]</td>
<td>1.9</td>
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<td>1.6</td>
<td>1.2</td>
<td>6.7</td>
<td>3.4</td>
<td>1.9</td>
<td>98*</td>
<td>5.0</td>
<td>2.2</td>
<td>3.7</td>
<td>4.7</td>
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<tr>
<td>(\kappa_{Z\gamma}) [%]</td>
<td>10.</td>
<td>–</td>
<td>5.7</td>
<td>3.8</td>
<td>99*</td>
<td>86*</td>
<td>85*</td>
<td>120*</td>
<td>15</td>
<td>6.9</td>
<td>8.2</td>
<td>81*</td>
</tr>
<tr>
<td>(\kappa_c) [%]</td>
<td>–</td>
<td>4.1</td>
<td>–</td>
<td>–</td>
<td>2.5</td>
<td>1.3</td>
<td>0.9</td>
<td>4.3</td>
<td>1.8</td>
<td>1.4</td>
<td>2.2</td>
<td>1.8</td>
</tr>
<tr>
<td>(\kappa_t) [%]</td>
<td>3.3</td>
<td>–</td>
<td>2.8</td>
<td>1.7</td>
<td>–</td>
<td>6.9</td>
<td>1.6</td>
<td>–</td>
<td>–</td>
<td>2.7</td>
<td>–</td>
<td>–</td>
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<tr>
<td>(\kappa_b) [%]</td>
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<td>3.2</td>
<td>2.3</td>
<td>1.8</td>
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<td>0.48</td>
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<tr>
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<td>4.6</td>
<td>–</td>
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<td>1.7</td>
<td>15</td>
<td>9.4</td>
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<td>320*</td>
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<tr>
<td>(\kappa_\tau) [%]</td>
<td>1.9</td>
<td>3.3</td>
<td>1.5</td>
<td>1.1</td>
<td>1.9</td>
<td>0.70</td>
<td>0.57</td>
<td>3.0</td>
<td>1.3</td>
<td>0.88</td>
<td>1.3</td>
<td>1.4</td>
</tr>
</tbody>
</table>

In this case the assumption is no *new* channels beyond the SM can contribute to the Higgs width.
With Energy we get new observables

$$W^+ W^- \rightarrow t \bar{t}$$

The SM is a *delicate* structure, modification of couplings leads to modifications of amplitudes with deviations that grow with energy.
At a Muon Collider you can probe Higgs multiple ways with Energy!

Why do we care about precision? To find new physics

UV model $\rightarrow \frac{1}{\Lambda^2} \bar{f}_L H f_R H^2 \rightarrow k_f \sim \frac{v^2}{M_{NP}^2}$
At a Muon Collider you can probe Higgs multiple ways with Energy!

\[
\sim \frac{v^2}{M_{NP}^2}
\]

1 % Higgs Precision \(\Rightarrow M_{NP} \lesssim 1 \text{ TeV}\)

Dimensionless couplings \(\lesssim 1\)

Produce the new states that can cause Higgs deviations at the same time!

No need to build separate colliders e.g.
Factory→Discovery machine
You could do it all in one with a Muon collider!
Can you escape this conclusion with strong coupling?

Sure... but a MuC turns out to be ideally suited to search for this as well!
So with all that being said, what do we get for Higgs precision at a Muon Collider?
What has gone into the studies

• Signal and Background fast simulation with muon collider DELPHES card
  • Hard Physics backgrounds - included
  • Beam in Beam (BIB) Background not included
    • DELPHES fast sim compared against full simulation with BIB at 3 TeV and found to give consistent results
  • Collinear backgrounds not fully included but small
• Results I will show assume you can tag forward muons (to discriminate ZBF from WBF)
  • $WW \rightarrow t\bar{t}$ included for top Yukawa
• Signal strengths calculated and then various different theoretical interpretation run
### Higgs Precision Physics

<table>
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<tr>
<th>$\kappa-0$</th>
<th>HL-LHC</th>
<th>LHeC</th>
<th>HE-LHC</th>
<th>ILC</th>
<th>CLIC</th>
<th>CEPC</th>
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<td>0.23</td>
<td>0.22</td>
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<td>$\kappa_g$</td>
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<td>98*</td>
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<td>$\kappa_{Z\gamma}$</td>
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<td>$\kappa_t$</td>
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<td>$\kappa_b$</td>
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<td>0.70</td>
<td>0.57</td>
<td>3.0</td>
<td>1.3</td>
</tr>
</tbody>
</table>

High energy implies one can also test origin of deviations simultaneously - new formalism needed and not fully exploited here.
Other interpretations

• Can of course be recast in terms of EFT coefficients (see IMCC and muC forum for slightly outdated plots)

• What about if you let the Higgs width vary?
  • Notorious flat direction by letting SM couplings increase and adding a new contribution to the Higgs width
    • Can break this degeneracy with an e+e- Higgs factory or a 125 GeV muC
    • Can also break this degeneracy with a 10 TeV muon collider exploiting $VV \rightarrow VV$

• Full exotic Higgs decay program still open to do, $BR_{\text{inv}}$ preliminary results exist
Last but not least a muon collider lets us really improve on Higgs Potential

This is important for getting to the threshold for testing the EW phase transition at EW scale
Conclusions

• A muon collider is an amazing option to study the fundamental questions that the LHC has explicitly presented us about Electroweak symmetry breaking
  • Single Higgs
  • Double Higgs
  • New differential observables
  • Ability to probe precision deviations and their origin in the same collider
• There is still more work to be done, and hopefully with the outcome of P5 in the US and continued/increased support in Europe/CERN we could realize this fundamentally new direction for our field
• If you want your own muon collider swag you can find it here:
  https://www.redbubble.com/people/muon-collider/
Backup
proton - (anti)proton cross sections

\[ \sigma_{\text{jet}}(E_{\text{jet}} > \sqrt{s}/20) \]
\[ \sigma_{\text{jet}}(E_{\text{jet}} > 100 \text{ GeV}) \]

\[ \sigma_{W}, \sigma_{Z}, \sigma_{WW}, \sigma_{ZZ}, \sigma_{VBF} \]

\[ \sigma_{\text{tot}} \]

\[ M_{H} = 125 \text{ GeV} \]

\[ \frac{\text{events/sec}}{L = 10^{33} \text{ cm}^2 \text{s}^{-1}} \]

WJS2012
Figure 4. Stacked $b\bar{b}$ pair invariant mass histograms for the $H \rightarrow b\bar{b}$ analysis after $p_T$ cuts and $b$-tagging at (left) 3 TeV and (right) 10 TeV. The sum of signal and background at 3 TeV is overlayed on the 10 TeV plot for ease of comparison.
<table>
<thead>
<tr>
<th>Process</th>
<th>3 TeV</th>
<th></th>
<th></th>
<th>10 TeV</th>
<th></th>
<th></th>
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</thead>
<tbody>
<tr>
<td></td>
<td>$b\bar{b}$</td>
<td>$c\bar{c}$</td>
<td>$gg$</td>
<td>$b\bar{b}$</td>
<td>$c\bar{c}$</td>
<td>$gg$</td>
</tr>
<tr>
<td>$\mu^+ \mu^- \rightarrow \nu_\mu \bar{\nu}_\mu H; H \rightarrow X$</td>
<td>19000</td>
<td>154</td>
<td>8570</td>
<td>251000</td>
<td>2030</td>
<td>125000</td>
</tr>
<tr>
<td>$\mu^+ \mu^- \rightarrow \mu^+ \mu^- H; H \rightarrow X$</td>
<td>2000</td>
<td>16</td>
<td>951</td>
<td>26700</td>
<td>220</td>
<td>14300</td>
</tr>
<tr>
<td>$\mu^+ \mu^- \rightarrow (\mu^+ \mu^-, \nu_\mu \bar{\nu}_\mu)H; H \not\rightarrow X$</td>
<td>75</td>
<td>52</td>
<td>23400</td>
<td>1310</td>
<td>1040</td>
<td>339000</td>
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<tr>
<td>$\mu^+ \mu^- \rightarrow (\mu^+ \mu^-, \nu_\mu \bar{\nu}_\mu)jj$</td>
<td>2760</td>
<td>183</td>
<td>24900</td>
<td>34700</td>
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<td>355000</td>
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<tr>
<td>$\mu^+ \mu^- \rightarrow \nu_\mu \mu^\pm jj$</td>
<td>3</td>
<td>20</td>
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<td>Others</td>
<td>1440</td>
<td>70</td>
<td>21800</td>
<td>37000</td>
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<tr>
<td>Total Backgrounds</td>
<td>4280</td>
<td>325</td>
<td>88300</td>
<td>73200</td>
<td>5670</td>
<td>1390000</td>
</tr>
</tbody>
</table>

Table 1. Signal and some of the most important backgrounds for VBF $H \rightarrow X$, with $X$ one of ($b\bar{b}$, $c\bar{c}$, $gg$), after applying flavor tagging and analysis cuts. “Others” consists of s-channel and VBF diboson production, $tb$, and $t\bar{t}$. 
Harder to separate hadronic final states

Jet $p_T > 40$ GeV and $|\eta|<2.5$

A.U.

0.07

0.06

0.05

0.04

0.03

0.02

0.01

0.0

50

100

150

200

dijet mass [GeV]

L. Sestini full sim + BIB

10 TeV

No. of Events

40000

35000

30000

25000

20000

15000

10000

5000

0

$M_{WW}$ (GeV)

WWF $h \rightarrow b\bar{b}$

$h$ Bkgs.

Other Bkgs.

PM, M. Forslund Delphes
Full sim+ BIB JER about an order of magnitude worse than CLIC/Delphes
Nevertheless...

3 TeV

Modify Delphes JER to current full SIM + BIB, sensitivity goes from .84% to .95% for Delphes

Full sim closer to original Delphes due to shape test rather than cut and count