# **INTERFERENCE EFFECTS IN HIGGS DECAYS**



#### DANIEL STOLARSKI

**DS, R. Vega-Morales, Phys.Rev.D.86, 117504 (2012)[arXiv: 1208.4840]. Yi Chen, DS, R. Vega-Morales, Phys.Rev.D.92, 053003 (2015)[arXiv:1505.01168]. Y. Chen, J. Lykken, M. Spiropulu, DS, R. Vega-Morales, [arXiv:1608.02159]. And work in progress.**

Theory Canada 14 June 1, 2019

## **A NEW PARTICLE**

July 2012:



#### **HIGGS MECHANISM** do a nature of the charged-current weak interactions were of the charged-current weak interactions were of the c reconciled with the finite mass of the finite mass of the electron. The generation of the generation of the ge

There is no theoretical principle that determines the size of this Yukawa Entire universe is a superconductor, condensate of  $t_{\text{max}}$  that talled to formiona. W  $7$  but not ring that talks to remind something that talks to fermions, W, Z but not photon.

> γ wwwwwwwwwwwwwwwwww



**Anderson, 1963**

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> γ wwwwwwwwwwwwwwwwww



**Anderson, 1963**

Endlort Higge-and others by Brout, Englert, Higgs and others. One model is an elementary scalar field proposed

#### **DISCOVERY MODES**

$$
h \to \gamma \gamma \qquad h \to 4e/4\mu/2e2\mu
$$

All final states are light!

Higgs is supposed to be responsible for mass…

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All final states are light!

Higgs is supposed to be responsible for mass…

Second order quantum effect:

$$
E_n^2 = \sum_{m \neq n} \frac{\left| \langle \psi_m^0 | H' | \psi_n^0 \rangle \right|^2}{E_n^0 - E_m^0}
$$

**Griffiths,** *Quantum Mechanics, Eq. 6.15*

#### **DISCOVERY MODES**

 $h \rightarrow \gamma \gamma$   $h \rightarrow 4e/4\mu/2e2\mu$ 



### **IS IT THE HIGGS?**

Consistent with the Higgs, but could also be something else.

Neutral pion decays to two photons and four electrons, but its just a bound state of quarks.



### **WARM UP EXERCISE**

Assume parity even scalar:





 $h Z^{\mu} Z_{\mu}$ 

### **KINEMATIC DISTRIBUTIONS**

Study  $h \rightarrow 4e/4\mu/2e2\mu$ :

Each event is characterized by five different variables.



In  $h\to \gamma\gamma$ , conservation of 4-momentum means there is no additional information.

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#### KINEMATIC DISTRIBUTIONS  $\frac{1}{0}$  1  $\frac{2}{3}$   $\frac{4}{4}$  5  $\frac{1}{5}$  $10^{-1}$ <sup>0</sup> <sup>1</sup> <sup>2</sup> <sup>3</sup> <sup>4</sup> <sup>5</sup> <sup>6</sup> 0.00

Distributions encode information about tensor structure.



FIG. 1: *(a) Two decay planes of Z<sup>i</sup>* ! `*<sup>i</sup>* **117504 (2012) [arXiv:1208.4840].DS, R. Vega-Morales, Phys.Rev.D.86,** 



 $a_{Z\gamma}$ 

 $a_{\text{Z}\gamma}$ 

well below MZ different scenarios.

well below M<sup>Z</sup> diers for erent scenarios.

*as*

*as*

*ah ah*

#### **LIKELIHOOD DISTRIBUTION**  $\begin{array}{c|c} \hline \textbf{1.0} \\ \hline \textbf{1.0} \end{array}$  $\mathbf{p}(\mathbf{p}, \mathbf{p})$  for each operator  $\mathbf{p}(\mathbf{p}, \mathbf{p})$  for each operator and a sympathy  $\mathbf{p}(\mathbf{p}, \mathbf{p})$ a Le normalization is computed with the Mi cuts of Mi c des above because they are in the independent of Lorentz and Lorentz are in the independent of Lorentz and Lor<br>Independent of Lorentz and frame. Taking the pT and  $\frac{1}{2}$  and

Can do statistical testing among different discrete hypotheses using FIG. 2. Normalized distribution for cos θ in the a<sup>h</sup> scenario. The blue (solid) curve is the same as the theory curve from Fig. 1, the red (dashed) histogram is the red (dashed) historical second in the red (dashed) historical second<br>The red of the distribution for contraction for contraction for contraction for contraction for contraction fo<br>  $\blacksquare$ further work.

#### I stical example for 50 events: Example for 50 events:



*b*  $\mathbf{y}$ 

#### **DATA**

Evidence for the Higgs:

This data is a bit old…



#### **DATA**

Recent measurements assume:

SM Higgs + deviations.



**CMS, arXiv:1901.00174.**

#### **IS IT THE HIGGS?**

Properties of new boson agree with SM Higgs at ~20% level.

SM predicts all properties of the Higgs.

Even small deviations in Higgs properties imply new terms in the Lagrangian of nature.

$$
\mathcal{L}=?
$$

Problems with the Standard Model:

• Dark Matter



Problems with the Standard Model:

- Dark Matter
- Baryon asymmetry of the universe



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- Dark Matter
- Baryon asymmetry of the universe
- Neutrino mass
- Inflation
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Experimental studies of the Higgs could give insights into these problems.

# **COUPLING TO GAUGE BOSONS**

Kinematic distributions can reveal more than just rate measurements can.

Put this to use in interference effects.



After the *W* and top, the next largest contribution tree level effect. Leading quantum effect (one-loop) interferes with

# **COUPLING TO GAUGE BOSONS**

Two diagrams contain different Higgs couplings.

Can use this to measure gauge-Higgs structure.



## **TREE-LEVEL MEASUREMENTS**

Can also measure these couplings at tree level.



#### Tree-level effects are much bigger than quantum effects, what's the point?

## **TREE-LEVEL MEASUREMENTS**

Define the ratio of those two couplings:  $λ$ <sub>*WZ*</sub>  $\equiv$ *ghWW ghZZ*

Tree level measurement:



## **TREE-LEVEL MEASUREMENTS**

Tree level processes have no information about sign of  $\lambda_{WZ}$ .



Ratio of couplings to gauge bosons dictated by SM custodial isospin symmetry.

$$
\vec{W} = \left(\begin{array}{c} W^+ \\ Z^0 \\ W^- \end{array}\right)
$$

Ratio of couplings to gauge bosons dictated by SM custodial isospin symmetry.





Ratio of couplings to gauge bosons dictated by SM custodial isospin symmetry.

Also dictates ratio of masses of gauge bosons.





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#### **REVIEW**

$$
SM: SU(2)_L \times SU(2)_R \to SU(2)_C
$$

Explicit breakings: hypercharge and Yukawas.

$$
\textsf{W} \textsf{ and } \textsf{Z} \textsf{ are } \textsf{3} \textsf{ under } \textsf{SU}(2)_{\textsf{C}}.\ \ \vec{W} = \left(\begin{array}{c} W^+ \\ Z^0 \\ W^- \end{array}\right)
$$

SM Higgs: 
$$
(2,2) = 3 + 1
$$
  
Longitudinal  
modes.

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#### H = **(n, m)** under L x R

responsible for breaking  $SU(2)_L \times SU(2)_R \rightarrow SU(2)_C$ .

**Low and Lykken, [arXiv:1005.0872].**

#### H = **(n, m)** under L x R

responsible for breaking  $SU(2)_L \times SU(2)_R \rightarrow SU(2)_C$ .

There is a neutral state under C.

#### **n = m.**

**Low and Lykken, [arXiv:1005.0872].**

#### $H = (n, n)$  under  $L \times R$ .

#### H = **1 + 3 + 5 + … + (2n+1)** under C.

**n = 3** simplest non-SM model. **Georgi and Machacek, PLB 1985.**

Triplet of  $SU(2)_L$  triplets with Y=+1, 0, -1.

Avoids usual problems of electroweak triplets.

#### $H = (n, n)$  under  $L \times R$ .

#### H = **1 + 3 + 5 + … + (2n+1)** under C.

The H(125) decays to a pair of gauge bosons.



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Which of the above representations can do that?

#### $H = (n, n)$  under  $L \times R$ .

#### H = **1 + 3 + 5 + … + (2n+1)** under C.

#### $N$  eed:  $H \otimes W \otimes W = 1$  under C.
### **GENERAL EWSB**

$$
H = (n, n)
$$
 under L x R.

#### H = **1 + 3 + 5 + … + (2n+1)** under C.

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$$
\overrightarrow{W} \otimes \overrightarrow{W} = 3 \otimes 3 = 1 \oplus 3 \oplus 5
$$
  
Isospin 1

## **GENERAL EWSB**

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Reduced possibilities for H to finite set.

Let's look at the couplings for the different possibilities.

Look up Clebsch-Gordan coefficients.



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 $\overline{2}$ 

 $1/2$ 

 $\overline{2}$ 

 $0 - 1 \vert 1/2 \vert$ 

 $\sin 2$ 

 $1/2$ 

 $+1$  | 1/2  $-1/2$ 

 $\overline{O}$ 

 $\overline{2}$ 

 $\Omega$ 

 $-1$ | 1/6

 $\Omega$ 

Isospin 2

 $1\times$ 

 $+1 +$ 

 $-1$  0  $1/2$   $-1/2$   $-2$ 

#### Y 1 <sup>2</sup> = − **2 COUPLINGS**

4

2π

Can compute ratios of couplings for **1** and **5**.



d j <sup>m</sup>′,m = (−1)m−m′  $H_1 (2 W^+ W^- + Z Z)$   $H_5 (W^+ W^- - Z Z)$  $\lambda_{WZ} = +1$   $\lambda_{WZ} = -1/2$ 

Two cases predict opposite signs!

# **H(125)**

Let's measure the sign:

Rate measurements insensitive to sign.

Can use interference





### **HUMBLEBRAG**

#### PHYSICAL REVIEW LETTERS

**Highlights** 

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#### **EDITORS' SUGGESTION**

#### Golden Probe of Electroweak Symmetry **Breaking**

Four-lepton decays of the Higgs boson could be used to probe a key parameter of electroweak symmetry breaking.

Yi Chen et al. Phys. Rev. Lett. 117, 241801 (2016)



Vol. 117, Iss. 24 - 9 December 2016

#### **View Current Issue**

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Vol. 117, Iss. 23 - 2 December 2016 Vol. 117, Iss. 22 - 25 November 2016 Vol. 117, Iss. 21 - 18 November 2016 Vol. 117, Iss. 20 - 11 November 2016

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Meet The Editors **AGU Fall Meeting** 



#### ON THE COVER

Reversion of a Parent  $\{130\}\langle 310\rangle_{a^2}$ Martensitic Twinning System at the Origin of  $(332)(113)<sub>6</sub>$  Twins Observed in Metastable  $\beta$ **Titanium Alloys** 

December 9, 2016

Electron backscattered diffraction inverse pole figure map of stressinduced martensite microstructure showing large bands that indicate a

## **MEASURING THE SIGN**

#### Build up likelihood with data.

Will now be function of continuous parameter  $\lambda_{WZ}$ .

What is probability that it is negative?

**Y. Chen, J. Lykken, M. Spiropulu, DS, R.** 2,000 events **Vega-Morales, Phys.Rev.Lett.117, no. 24, 241801, 2016 [arXiv:1608.02159].**

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### **MEASURING THE SIGN**



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### **TOP YUKAWA**

Next largest interference effect: the top quark.



SM predicts this coupling is P and CP even.

Can we test that with data?

#### **TOP YUKAWA**



*ht* ¯(*y* + *i y* ˜ *γ*5 ) *t*  $SM y \approx 1 \& \tilde{y} \approx 0$ 

Equivalent to measurement of phase of Yukawa.

Rate measurements only sensitive to  $y^2 + \tilde{y}^2$ .

Make non-trivial measurements using interference.

#### **SENSITIVITY**



# **HIGH LUMINOSITY**

8,000 events ~ 3,000 fb-1

Better constraint.

If there is anomaly, will help characterize.

![](_page_50_Figure_4.jpeg)

t

### **100 TEV?**

![](_page_51_Figure_1.jpeg)

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# **LEPTON COLLIDER**

Can we do this at a lepton collider?

Cleaner environment…

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Cleaner environment…

 $\sigma(e^+e^- \to Zh, \sqrt{s} = 240 \,\text{GeV}) \simeq 300 \,\text{fb}$  $\mathcal{L}(\text{TLEP}) \simeq 500$ /fb/year  $BR(h \rightarrow 4\ell) \simeq 10^{-4}$ 

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 $\mathcal{L}(\text{TLEP}) \simeq 500$ /fb/year

 $BR(h \rightarrow 4\ell) \simeq 10^{-4}$ 

15 events per year.

#### **CROSSING SYMMETRY**

![](_page_55_Figure_1.jpeg)

Can probe same coupling with crossed diagram.

No longer have to pay branching ratio penalty.

#### **CROSSING SYMMETRY** di↵erential cross sections for several <sup>p</sup>*se*+*e* and set the corresponding parameter *<sup>t</sup>* or *<sup>a</sup>* equal to 1. From the figure, it is quite clear that the di↵erential cross sections arising from

![](_page_56_Figure_1.jpeg)

**See for example: Shen and Zhu, arXiv:1504.05626.**

![](_page_56_Figure_3.jpeg)

### **TOP AND W LOOPS**

![](_page_57_Figure_1.jpeg)

our signal and fit for the parameters in Eq. (2), while we substitute one for the other. Top and W contribute to same operators, can

What happens if you float both couplings? We can further characterize the 'background' in *<sup>M</sup>*<sup>1</sup>

#### **FIT BOTH COUPLINGS**

7

![](_page_58_Figure_1.jpeg)

# **ACCESS HIGGS POTENTIAL**

Currently we have no information about Higgs potential.

SM uses Mexican hat, but no direct evidence for that.

![](_page_59_Figure_3.jpeg)

Triple Higgs coupling (HHH) is a measure of third derivative of potential at the minimum.

First direct measurement of structure of potential.

#### **TRIPLE HIGGS COUPLING** *Z* left is the tree-level contribution mediated by the *<sup>Z</sup>* boson pairs,mentum <sup>e</sup>↵ects ply by the cays to *h hV V*  $\blacksquare$  mediated the respectively. *h hV V* e↵ective couplings*Z* bosonrespectively. weak sendisentan- $\sim$ tributions in the contribution of the cont *h* ! the  $\overline{\phantom{a}}$  $\mathbf{H}$ ential crossc.  $\blacksquare$  possibilitydetails of thisCommentsbeen discussed,loop generated enerically define the control of the contr attempting*Z*

![](_page_60_Figure_1.jpeg)

rrections.  $\mathcal{L}$ iO CO  $\overline{\phantom{a}}$  $\overline{I}$  *tiple* L iggs coupling al Triple *h*  $f$ Triple Higgs coupling also comes into<br>corrections. **Triple riggs C**<br>corrections. *on-shell* s in lso c  $5<sup>o</sup>$ *h*  $\mathbf{F}$ couples gs coup<br>s.<br>ibutes  $\overline{a}$  $\ddot{\phantom{0}}$ ।ggs<br>ions. thisHiggs<sup></sup> assess More  $\mathsf{f}(\mathsf{f})$  $\frac{1}{g}$  also comes COLI ing also come oup  $\cdots$ o $\cdots$ simples in the ended<br>Biggs continued in the set of the se theseTriple Higgs coupling also comes into NLO Eq.tic iis.<br>T  $\overline{\phantom{a}}$ rre ton Gutions.<br>
Waliofari *<sup>W</sup> <sup>Z</sup>* iscorrections.

 $\overline{\phantom{a}}$ *g Dnl*  $\overline{\ }$  couplings dicult.mentumwhen  $Z$ 's are in final ibutes **'** vıı∪ıı *(* bu<sup>-</sup>  $\overline{\mathbf{u}}$ Only *Z* computed $\overline{\mathsf{in}}$ vhen Z's are tes wh  $It$  $\overline{a}$ erik<br>Irik ntributes when Z's are in fir  $\overline{\mathbf{z}}$  anuisa<br>Le analysis of *<sup>W</sup> <sup>Z</sup>*. Asites w  $\overline{\phantom{a}}$  statisticsul obtained, the control of th **Daly contriber**  the dominated $\theta$ te.<br>*on-shell* **and**  $\alpha$  pairs of  $\alpha$  pairs of  $\alpha$  pairs. Only contributes when Z's are in final state.

#### **Work in progress.**  <u>vork in pr</u> nuisance cays to *on-shell* and *<sup>Z</sup>* pairs.tributions in the contract of examplei pr  $\frac{1}{2}$ orl rv ( pseudoscalar<br>pseudoscalar<br>pseudoscalar **The Work in progress.**  $\ddot{\phantom{0}}$ pling *<sup>g</sup><sup>W</sup>* will

Thealready

Ideally

#### **HIERARCHY PROBLEM** relatively light charginos and neutralinos in the superpartner spectrum. (Of course, after EWSB, these physical states may also contain admixtures of electroweak gauginos.)

SM Higgs has a hierarchy problem.

Quantum correction make Higgs mass sensitive to high scale physics. Washin contain states may also contain a state of electronic states of electronic states of electronic states o

SM is fine-tuned to 1 part in 1032.

![](_page_61_Figure_4.jpeg)

## **CANCELLATION**

Adding new particles can cancel sensitivity (to a log).  $\mathbb{R}$  best physical states may also contain admixtures of electroweak gauginos.

![](_page_62_Figure_2.jpeg)

$$
E_{\rm self} \sim \frac{y}{2\pi} m_t \log(\Lambda/m_t)
$$

Particle has to have same coupling to the Higgs. (Supersymmetry is most famous example).

### **BSM PHYSICS**

Can use Higgs coupling to stop to directly probe other fields that couple to Higgs.

![](_page_63_Figure_2.jpeg)

Independent of decay, do not have to carry colour.

**Work in progress with Paul Smith.**

# **CONCLUSIONS**

- Kinematic distributions in  $h \to 4\ell \,$  can provide unique and complementary tests of the SM.
- NLO contributions make this channel sensitive to large Higgs couplings.
- Can probe non-standard custodial representations of custodial symmetry.
- Sensitivity to CP violation in the top-Higgs sector.

# **THANK YOU**

# **MATRIX ELEMENT METHOD**

For a given  $h \to 4\ell$  event, can compute probability of that even given underlying theory.

![](_page_66_Figure_2.jpeg)

# **MATRIX ELEMENT METHOD**

For a given  $h \to 4\ell$  event, can compute probability of that even given underlying theory.

$$
P(\vec{\phi}|a_i) = \frac{|\mathcal{M}(\vec{\phi})|^2}{\int d\vec{\phi} |\mathcal{M}(\vec{\phi})|^2}
$$

For N events, can compute likelihood for different underlying theories.

![](_page_67_Picture_4.jpeg)

#### **KINEMATIC DISTRIBUTIONS** 95 Σ

#### Get better discrimination with more events.  $\mathsf{L}$

![](_page_68_Figure_2.jpeg)

#### **KINEMATIC DISTRIBUTIONS** 95 Σ

Get better discrimination with more events.  $\mathsf{L}$ 

![](_page_69_Figure_2.jpeg)

#### **RATE MEASUREMENTS** METARA YA NETE N THE INJE A CHID ENJEMPLY  $\mathbf{H} = \mathbf{H} \mathbf{H} + \mathbf{H} \mathbf{H}$

0 0.5 1 1.5 2

![](_page_70_Figure_1.jpeg)

### **BIG PICTURE**

At discovery, rate measurements pointed to 4 lepton coming from tree level and 2 photon at one loop.

Could imagine a tuned model:

$$
c_B s B^{\mu\nu} B_{\mu\nu} \qquad c_W s W^{a\mu\nu} W^a_{\mu\nu}
$$
## **BIG PICTURE**

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$$
c_B s B^{\mu\nu} B_{\mu\nu} \qquad c_W s W^{a\mu\nu} W^a_{\mu\nu}
$$

Worthwhile to test SM and rule out all other logical possibilities.

Techniques become extremely important if there is an anomaly.

## **BIGGER THAN YOU THINK**

Photon in final state makes NLO effect larger than naive one-loop size.

Can look in regions of phase space away from Z peak for lepton pairs.

Photon coupling to leptons bigger than for Z.



## **EDM BOUNDS**

Can place strong bounds on CP violation from EDMs.



Figure 2. Left: Present constraints on *<sup>t</sup>* and ˜*<sup>t</sup>* from the electron EDM (blue), the neutron **Brod, Haisch, Zupan, [arXiv:1310.1385].**

## **EDM BOUNDS**

Depend on knowing Higgs coupling to first generation.



Brod, Haisch, Zupan, [arXiv:1310.1385].

#### **SENSITIVITY** where *M*`` are all six lepton pair invariant masses and we explicitly removed by removed and the sign same flavor of  $\mathbf{c}$ (OSSF) lepton pairs that have *M*`` in the range 8*.*8 kinematic shapes of the *ZZ*, *Z*, and intermediate states [67, 68].

 $M_{0.0011}$  consequent  $\alpha$ Measurement gets better with more no background into the sample. It is the sample of the sample. It is the same sample. It is the same sample. I events.

Retter sensitivity to  $\sim$  single single likelihood and fit for the background fraction fraction fraction  $\sim$ pseudo-scalar  $\frac{1}{2}$  the parameters in Eq. (13). The background fractions in Eq. (13). The background fractions in Eq. (13). The background fractions in  $\frac{1}{2}$ coupling. Better sensitivity to

traction framework including the building of the signal Need large number of  $\bullet$  found in  $\bullet$ events.

Chen, DS, Vega-Morales, [arXiv Chen, DS, Vega-Morales, [arXiv:1505.01168].



# **EXPERIMENTA**

CMS cuts optimized for discovery:

 $M_1 > 40$ ,  $M_2 > 12$ ,  $M_{\ell\ell} > 4$ 

Want to gain sensitivity to NLO effects.





 $M<sub>1</sub>$  (GeV)

#### **EXPERIMENTAL CUTS** which are much larger than the t-channel *qq*¯ ! ! 4` (red) and *qq*¯ ! *ZZ* ! 4` (blue) components. This leads us to suspect that including the non-Higgs background

CMS cuts optimized for discovery:  $M_1 > 40$ ,  $M_2 > 12$ ,  $M_{\ell\ell} > 4$ 

Modified "Relaxed - Υ"  $M_{\ell\ell} > 4$ ,  $M_{\ell\ell}$ (OSSF)  $\notin$  (8*.*8*,* 10*.8*)

S/B gets worse, but sensitivity improves.

*qq*¯ ! 4` background including *pdfs*. We plot the total background  $\mathbf{b}$  and compare it to the result from a large Mad- $\mathbf{b}$ **Chen, Harnik, Vega-Morales, [arXiv:1503.05855].**



### **DI-HIGGS**

Traditional way to measure triple Higgs coupling is via di-Higgs production.

on is quite small.  $,$   $\overline{0}$ Cross section is quite small.



### **Baglio, et. al. [arXiv:1212.5581].**



#### LHC PROSPECTS (2014), 1310.1084. [69] G. Aad et al. (ATLAS), Phys.Rev.Lett. 114, 081802 (2015), 1406.5053.

Theorist studies are more optimistic (still need HL). [72] Tech. Rep. CMS-PAS-HIG-13-032, CERN, Geneva (2014), URL

#### Studies in bbγγ, bbττ, bbWW, 4b, ranging from 2-6σ significance.  $\overline{7}$  Tech. Rep. Atlantic  $\overline{7}$ [75] S. Das, *Searches for higgs pair production using the cms detector*,

[76] U. Baur, T. Plehn, and D. L. Rainwater, Phys.Rev. D69, 053004 (2004), hep-ph/0310056.

https://indico.mitp.uni-mainz.de/getFile.py/access?contribId=3&sessionId=

- [77] J. Baglio, A. Djouadi, R. Grber, M. Mhlleitner, J. Quevillon, et al., JHEP 1304, 151 (2013), 1212.5581.
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- [79] V. Barger, L. L. Everett, C. Jackson, and G. Shaughnessy, Phys.Lett. B728, 433 (2014), 1311.2931.
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- [83] D. E. Ferreira de Lima, A. Papaefstathiou, and M. Spannowsky, JHEP 1408, 030 (2014), 1404.7139.

## **LHC PROSPECTS**

#### Preliminary studies by experiments show that reliminary studies by experiments show that<br>Measurement is very difficult even at high-lumi.  $F = 211511.533110.781111711$

**ECFA Results**



# **COUPLING SENSITIVITY Limit Setting**



> Based on these results, we should be able to exclude values of the selfcoupling strength larger than 8.7xSM, and smaller than -1.3xSM

#### **Talk by N. Styles at MITP.**

#### **OTHER LOOP PROCESSES** *H H V V H H V V*

Triple Higgs coupling appears in many loop processes including Higgs production and Higgs decay to photons. for processes involving massive vector bosons in the final or in the intermediate states (VBF, *HV* and *H* ! *V V* ⇤ ! 4*f*).



#### the full 2-loop diagrams involving a top-quark loop and a *h*<sup>3</sup> vertex that arises from the insertion of *O*6. A prototype graph of such a contribution is shown in Figure 1. After v:1607.03773]. Degrassi et.al. [arXiv:1607.04521]. Figure 5: Diagrams contributing to the *C*<sup>1</sup> coecient in (*H* ! ). The **Gorbahn and Haisch [arXiv:1607.03773]. Degrassi et.al. [arXiv:1607.04521].**

## **OTHER LOOP PROCESSES**

### Constraints are similar(ly bad).



### Gorbahn and Haisch [arXiv:1607.03773]. Degrassi et.al. [arXiv:1607.04521].

#### **DETAILS** to the *Z* and  $\blacksquare$ shown to greatly improve the sensitivity to the *Z* and the fit for the 1 allowed region in the *y<sup>t</sup> y*˜*<sup>t</sup>* plane for a range of data set sizes. The allowed parameter space *h* ! *Z* (thick pink band) [106] searches which start to become relevant at this luminosity. We can see at this stage that *h* ! 4` is also starting to become a useful

- 115  $\text{GeV} < M_{4\ell} < 135 \text{ GeV}$  $\sim 115 \text{ CeV} \times M_{\odot} \times 125 \text{ CeV}$  $\text{Im}\omega \cdot \sin \psi$
- $p_T$  > (20, 10, 5, 5) GeV for lepton  $p_T$  ordering, and it is the interesting of the interesting of the interesting  $\mathbf{I}$
- $|\eta_{\ell}| < 2.4$  for the lepton rapidity, turquoise ellipses) using these optimized cuts. This also consider these optimized cuts. This also consider th<br>This also consider the cuts. This also consider the cuts. This also consider the cuts. This also consider the
- $\bullet$   $M_{\ell\ell} > 4$  GeV,  $M_{\ell\ell}$ (OSSF)  $\notin (8.8, 10.8)$  GeV,



$$
\mu(th) \simeq y_t^2 + 0.42 \tilde{y}_t^2
$$
  
\n
$$
\mu(h \to \gamma \gamma) \simeq (1.28 - 0.28 y_t)^2 + (0.43 \tilde{y}_t)^2
$$
  
\n
$$
\mu(h \to Z\gamma) \simeq (1.06 - 0.06 y_t)^2 + (0.09 \tilde{y}_t)^2,
$$

measurement given by, and the second control of the second control o