24th Vietnam School of Physics Quy Nhon

Revisiting the non-resonant Higgs pair production at the HL-LHC

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- Motivation
- Non resonant di-Higgs production
- Contaminations from new physics

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• Summary and Conclusions

- The nature of the discovered boson is more or less consistent with the Standard Model Higgs boson
- Its combined (CMS + ATLAS) mass, from run-I data, is measured to be 125.09 GeV<sup>1</sup> in the h  $\rightarrow \gamma\gamma$  and the h  $\rightarrow ZZ^* \rightarrow 4\ell$  channels

- A CP-even spin zero hypothesis is favoured<sup>2</sup>
- Direct measurement of self-coupling at collider

Motivation

$$\mathcal{V} = rac{1}{2}{m_h}^2 h^2 + \lambda v h^3 + \lambda h^4$$

$$[m_h=125 \text{ GeV}] \Downarrow [v=246 \text{ GeV}]$$

$$\lambda^{\text{SM}} = \frac{{m_h}^2}{2v^2} \sim 0.13$$



• Higgs pair production can directly probe Higgs self coupling



Small di-Higgs cross-section in SM ( $\sim 39.56~{\rm fb})^3 \leftarrow$  partial cancellation of triangle and box diagram contributions

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<sup>3</sup>deFlorian et. al., 2013; Borowka et. al., 2016

#### Non resonant di-Higgs production

- We choose channels based on the rate and cleanliness
- We consider 11 channels •  $b\bar{b}\gamma\gamma$ 
  - $b\bar{b}\tau^+\tau^- \rightarrow b\bar{b}\tau_h\tau_h + \not\!\!{E}_T, \ b\bar{b}\tau_h\ell + \not\!\!{E}_T, \ b\bar{b}\ell\ell + \not\!\!{E}_T$
  - $b\bar{b}WW^* \rightarrow b\bar{b}\ell jj + \not\!\!{E}_T, \ b\bar{b}\ell\ell + \not\!\!{E}_T$

• WW\*
$$\gamma\gamma \rightarrow \ell j j \gamma\gamma + \not{\!\!\!E}_T, \ \ell \ell \gamma \gamma + \not{\!\!\!\!E}_T$$

- $WW^*WW^* \rightarrow \ell^{\pm}\ell^{\pm}jjjj + \not\!\!\!E_T, \ \ell\ell\ell jj + \not\!\!\!\!E_T, \ \ell\ell\ell\ell + \not\!\!\!\!\!E_T$
- 4 $\tau$ , WW\* $\tau^+\tau^-$ , ZZ\* $\tau^+\tau^-$ , 4 $\gamma$ , ZZ\* $\gamma\gamma$ , 4Z may be important at 100 TeV colliders
- Follow CMS and ATLAS analyses (when available) and optimise upon them
- HL-LHC : 14 TeV @ 3 *ab*<sup>-1</sup>

# Non resonant di-Higgs production : $b\bar{b}\gamma\gamma$

- low rate but cleanest
- Major backgrounds :  $b\bar{b}\gamma\gamma$ ,  $t\bar{t}h$ ,  $b\bar{b}h$ , Zh
- Dominant Fakes :  $b\bar{b}jj$ ,  $b\bar{b}j\gamma$ ,  $jj\gamma\gamma$ ,  $c\bar{c}jj$ ,  $c\bar{c}j\gamma$



- Significance :  $S/\sqrt{B} = 1.46$
- Changing to : 90 GeV  $< m_{bb} < 130$  GeV,  $S/\sqrt{B} = 1.64$

#### <sup>5</sup>ATL-PHYS-PUB-2017-001

# Non resonant di-Higgs production : $b\bar{b}\gamma\gamma$

- Multivariate technique (BDT algorithm) employed to further optimise search
- Variables chosen :

•  $S/\sqrt{B} = 1.76$ , CMS (ATLAS) projection :  $1.6\sigma$  (1.05 $\sigma$ )



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# Non resonant di-Higgs production : $b\bar{b}\tau^+\tau^-$

• Major backgrounds : tī,  $\ell\ell b\bar{b},\, hb\bar{b},\, Zh,\, t\bar{t}X,\, b\bar{b}jj$ 

•  $\tau_h \tau_h$ :  $S/\sqrt{B} = 0.74, \tau_h \tau_\ell$ :  $S/\sqrt{B} = 0.49, \tau_\ell \tau_\ell$ :  $S/\sqrt{B} = 0.08$ 



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# Non resonant di-Higgs production : $b\bar{b}WW^*$

- Major backgrounds: tī, W $b\bar{b}$  + jets,  $\ell\ell b\bar{b}$
- Leptonic :  $S/\sqrt{B} = 0.62$ , CMS projection :  $S/\sqrt{B} = 0.59$
- Semi-leptonic :  $S/\sqrt{B} = 0.13$



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### Non resonant di-Higgs production : $\gamma \gamma WW^*$ leptonic

- Major backgrounds :  $t\bar{t}h$ , Wh + jets
- b-jet veto applied
- Leptonic : S/B = 0.40 and < 1 signal event  $\rightarrow$  more luminosity/energy



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• Semi-leptonic : S/B = 0.11 and < 5 signal event  $\rightarrow$  more luminosity/energy



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- $\bullet \mbox{ more } \ell \rightarrow \mbox{ low rate and more } j \rightarrow \mbox{ lose cleanliness }$
- Major background : WZ, tī, tīX, Vh, VVV,  $W^{\pm}W^{\pm}$ , 4 $\ell$
- $SS2\ell$  :  $S/\sqrt{B} = 0.11$
- $3\ell$  :  $S/\sqrt{B} = 0.20$

#### Non resonant di-Higgs production : Summary

- $\bullet\,$  Bleak prospects for discovering SM non-resonant di-Higgs channel at HL-LHC with  $3~ab^{-1}$  data
- $b\bar{b}\gamma\gamma$  is cleanest  $(S/B \sim 0.19)$ , but suffers from small rate
- Combined significance  $\sim 2.1\sigma$  from all these channel
- Purely leptonic case of  $b\bar{b}WW^*$  shows promise  $(S/\sqrt{B}=0.62)$  but needs better handle over backgrounds
- Both semi-leptonic and leptonic channels for  $\gamma\gamma WW^*$  show excellent  $S/B \rightarrow$  need larger luminosity or higher energy colliders

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• SM di-Higgs signal events are rather small for most final states

Q: How much contamination possible once multivariate analysis performed to maximise SM di-Higgs?

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A: If new physics kinematic variables overlap with SM counterpart or If overlap is not significant but overall rate is large

#### Contaminations from new physics

- Double Higgs production,  $pp \rightarrow hh(+X)$  through resonant or non-resonant production modes
  - $pp \rightarrow H \rightarrow hh$
- Single Higgs production in association with some other particles,  $pp \rightarrow h + X$

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- $pp \rightarrow A \rightarrow Zh$
- Null Higgs scenario,  $pp \to X$ 
  - $pp \rightarrow H \rightarrow t\bar{t}$ •  $pp \rightarrow \bar{t}bH^+/t\bar{b}H^-$
- Cross-section upper limit defined as:  $S_{NP}^{UL}/\sqrt{B_{SM}} > N\sigma$

#### Contaminations from new physics : hh(+X)

• Order 100 fb cross-section for resonant Higgs mass  $\geq 400~{\rm GeV} \rightarrow$  Contaminates SM di-Higgs expectation to at least  $2\sigma$ 



• Green(blue) region indicate upper limit on cross-section to contaminate SM yield at  $2\sigma(5\sigma)$ :  $B_{SM}$  contains SM di-Higgs

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### Contaminations from new physics : h(+X)



•  $A \rightarrow Zh$  contaminates the SM signals to a lesser degree; Possible reason: Reconstructed Z -peak is shifted from the reconstructed Higgs peak and  $m_{bb}$ is an important discriminatory variable for all such searches involving a b-jet pair •  $H \rightarrow t\bar{t}$  for  $m_H > 2m_t$  may contaminate  $b\bar{b}\tau^+\tau^-$  and  $b\bar{b}WW^*$ 



• Weaker bounds because  $m_{bb}$  is different for  $t\bar{t}$ , Require a large production cross-section for heavy resonant scalar in order to contaminate appreciably



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- Search for Higgs pair production is an important enterprise to understand the Higgs cubic coupling
- $\bullet\,$  Non-resonant di-Higgs searches at the HL-LHC yields a significance of  $\sim 2.1\sigma\,$
- Contaminations to SM non-resonant di-Higgs channels from resonance Higgs,  $A \rightarrow Zh$ ,  $H \rightarrow t\bar{t}$ , charged Higgs production etc. possible

# Thank You

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- Di-Higgs samples and backgrounds generated at LO with MG5 aMC@NLO
- Signal samples decayed using Pythia-6
- NN23LO parton distribution function employed
- Default factorisation and renormalisation scales used
- Shower + hadronisation using Pythia-6
- Delphes-3.4.1 used for detector simulation
- Jets: anti-kT algorithm,  $p_T > 20$  GeV, R = 0.4 (FastJet)
- Total energy around  $\ell, \mu, \gamma$  required to be <12%, 25%, 12% within  $\Delta R=0.5$

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• b-tag efficiency: 70%,  $j \rightarrow b: 1\%, \ c \rightarrow b: 30\%$