Probing the nature of electroweak symmetry breaking with Higgs boson pairs in ATLAS

31st Lepton Photon Conference, 2023 July 17th-21st Yu Nakahama on behalf of the ATLAS Collaboration

Higgs potential and self-coupling

• The Higgs potential:

$$V(\phi) = -\mu^2 \phi^2 + \lambda \phi^4$$

Our universe lives in the minimum.
 The potential can be expanded around the minimum

$$V(h) \simeq \frac{1}{2}m_H^2 h^2 + \lambda v h^3 + \cdots$$

Mass term (measured) Self-coupling term (not measured)

- The self-coupling represents the shape of the potential, the nature of EW symmetry breaking.
- The λ can be measured directly in Higgs pair production processes.
 - If λ is not consistent with the SM prediction (λ_{SM}), it might indicate new physics.
 - The coupling modifier k_λ is defined as $\lambda/\lambda_{SM.}$
 - The destructive interference between triangle and box diagram means x-sec is tiny







Higgs potential and self-coupling

- We have a prediction for the shape from the SM.
- However, other shapes of the potential still allow for Electroweak Symmetry Breaking. Such other shapes could reveal evidence for Electroweak Baryogenesis, or hints to vacuum stability, BSM, ...



HH signatures

- The small HH cross-section means multiple final states must be used.
 - Balance between cleanness (low background) and branching ratio decides search channels.

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- This talk focuses on 3 most sensitive channels and combination with the full Run2 data at 13 TeV.

bbbb: arXiv:2301.03212 Accepted by PRD bbWW (not shown): Phys. Lett. B 801 (2020) 13145 bbττ : JHEP 07 (2023) 040

bbyy: PRD 106 (2022) 052001

Combination:

Phys. Lett. B 843 (2023) 137745,

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ZZ bb ww TT YY final 34% bb decay state ww 25% 4.6% probability 2 7.3% 2.7% 0.39% ττ niggs ZZ 3.1% 1.1% 0.33% 0.069% 0.012% 0.0005% 0.26% 0.10% 0.028% YY

higgs 1 decay

HH→bbγγ search

- Largest BR (H \rightarrow bb) + high resolution (H $\rightarrow \gamma\gamma$)
- Dominant backgrounds
 - $\gamma\gamma$ + jets continuum, small contribution from single Higgs
- 4 categories, defined based on
 - Mass m_{HH} (>350 GeV, <350 GeV)
 - BDT score (low, high purity)



• Fit to $m_{\gamma\gamma}$ in 4 SRs simultaneously



HH→bbττ search

- A good balance on relatively large BR (H→bb) x BR (H→ττ) and cleanness of m_{ττ} reconstruction
- Dominant backgrounds
 - taus from ttbar and $Z(\rightarrow \tau \tau)$ + heavy flavor jets
 - fake taus from multijet and ttbar

s = 13 TeV, 139 fb

Signal Region

• 3 categories by tau decay modes: T_{had}T_{had}, T_{lep}T_{had}, T_{lep}T_{lep}

- X (m = 500 GeV)

X (m = 1000 GeV)

 $(X \rightarrow HH) = 1 \text{ nh}$

 $Z \rightarrow \tau \tau + (bb, bc, cc)$

Uncertainty Pre-fit background

→ T., fakes (M.

fakes (tt)

m_{Her} [GeV]

- Fits to BDT score shape.
 - Data agrees well with background prediction.





Require 1 or 2 T: $m_{TT} > 60 \text{ GeV}$



Require two b-tagged jets

HH→bbbb search

arXiv:2301.03212, accepted by PRD

Run: 350013 Event: 1556168518 2018-05-11 01:39:26 CEST

4 b-tagged jets for resolved

2 large-R jets for boosted signature.

Forward jets used to split into ggF and VBF regions



- Exploits the decay mode with the largest BR.
- Dominant background: multi-jet (~95%)
- 6 categories, driven by (m_{H1}, m_{H2}) place and $d\eta_{HH}$

Statistical combination

• Combination of three channels (hh \rightarrow bb $\gamma\gamma$, bb $\tau\tau$, bbbb) to achieve ultimate sensitivity



• Observed (expected) 95% CL on the signal strength is 2.4 (2.9) x SM prediction.

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Statistical combination

Combination of three channels (hh \rightarrow bbyy, bb $\tau\tau$, bbbb) achieves ultimate sensitivity.



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HH+H combination

 Single Higgs boson production is also sensitive to k_λ through loop corrections e.g.



• The statitical combination of HH and H searches achieves the most stringient constraint on k_{λ} and a less model-dependent interpretation.



EFT Interpretations

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- The HH results are also interprated in the context of Effective Field Theories (EFTs).
- The Higgs EFT (HEFT) includes 2
 additional effective coupling parameters.

Combined limits on 7 HEFT benchmarks (with m_{HH} shape features) and 2 couplings.



Prospects





Significance of 3.4 σ (4.9 σ), assuming the baseline (no systematic uncertainties) scenario.



The 1 σ confidence interval on κ_{λ} : [0.5, 1.6]

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Conclusion

- Search for Higgs boson pairs is the excellent probe to the shape of the Higgs potential, which is the nature of electroweak symmetry breaking.
- A combination of the three most sensitive channels achieves 95% CL upper limit on μ_{HH} at 2.4 x SM prediction.
- Further combination of HH and H improves constraints
 e.g. Higgs self-coupling k_λ∈[-0.4, 6.3] at 95% CL.
- Further studies (e.g. EFT, more channels) performed to cover plenty of phase space.
- HH observation is likely possible with the HL-LHC dataset (maybe earlier).
- Many more exciting results are expected in the near future.