Probing di-Higgs using machine learning techniques

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Based on

JHEP 07 (2018) 116, with S. Banerjee, R.K. Barman, B. Bhattacherjee and S. Niyogi

JHEP 12 (2020) 179, with R.K. Barman and B. Bhattacherjee

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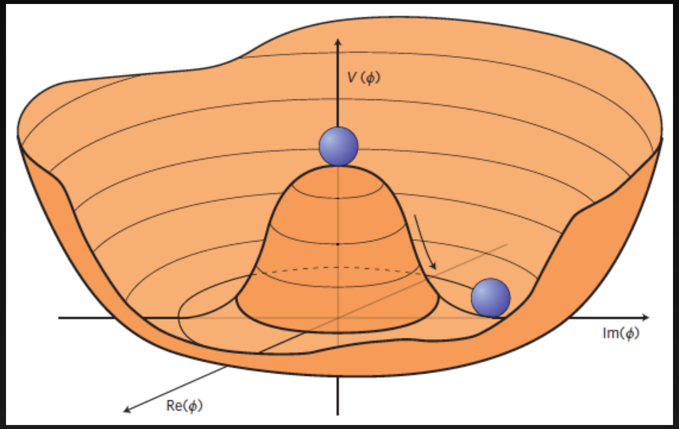
Introduction

In Standard Model (SM), the Higgs potential looks like,

$$V(\Phi) = \mu^2\Phi^\dagger\Phi + \lambda(\Phi^\dagger\Phi)^2 \xrightarrow{\text{completely arbitrary choice}}$$

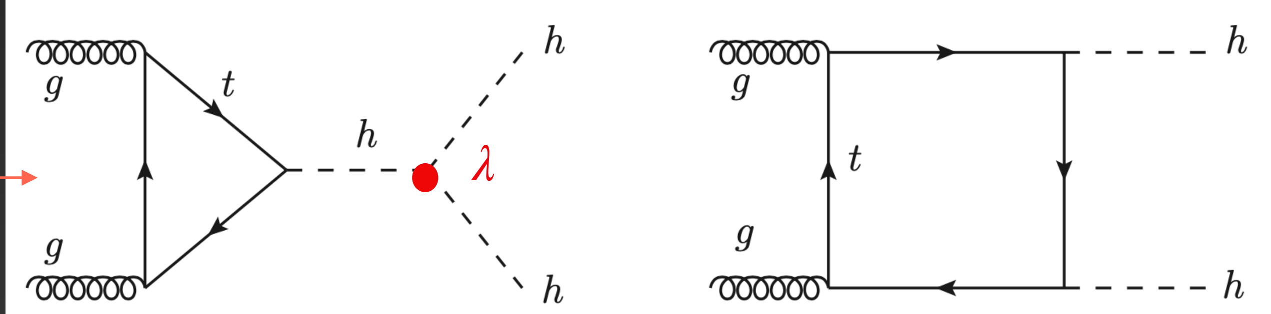


The only way to reconstruct this potential is by knowing the exact value of Higgs self-coupling, λ .

There is no direct measurement of Higgs self-coupling yet.

A direct probe of Higgs self coupling, λ is to produce two Higgs boson from one Higgs boson, called (non-resonant) Higgs pair production or di-Higgs production, $pp \rightarrow hh$.

Destructive interference between triangle and box diagrams → very small production cross-section. →



Triangle Box

Di-Higgs production at HL-LHC

HL-LHC: $\sqrt{s} = 14$ TeV and 3 ab^{-1} of integrated luminosity, $\sigma(gg \to hh) = 36.69$ fb [CERN Twiki].

Channels are chosen based on their production rate and cleanliness.

The selected 11 possible final states are,

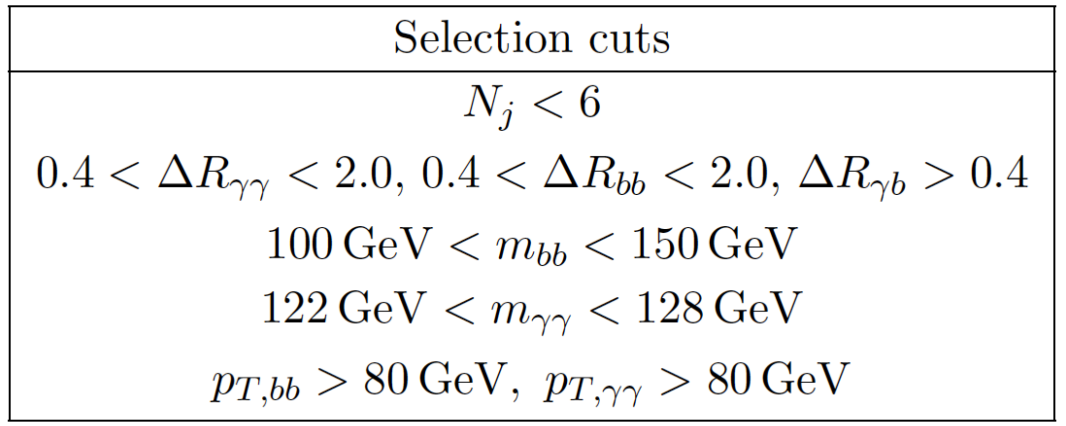
- $b\bar{b}\gamma\gamma$
- $b\bar{b}\tau\tau \to (a)\ \tau_h\tau_h$, $(b)\ \tau_h\tau_\ell$ and $(c)\ \tau_\ell\tau_\ell$
- $b\bar{b}WW^* \to (a)\ b\bar{b}\ell jj + \not{E}_T$ and $(b)\ b\bar{b}\ell\ell + \not{E}_T$
- $WW^*\gamma\gamma \to (a)\ \ell jj\gamma\gamma + \not{E}_T$ and $(b)\ \ell\ell\gamma\gamma + \not{E}_T$
- $WW^*WW^* \to (a)\ 2\ell 4j + \not{E}_T$, $(b)\ 3\ell 2j + \not{E}_T$ and $(c)\ 4\ell + \not{E}_T$

Standard cut-based and Multivariate analysis using Boosted Decision Tree (BDT) algorithm.

The $b\bar{b}\gamma\gamma$ channel

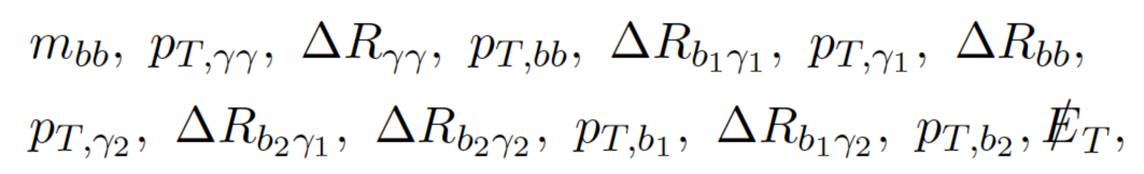
- $pp \to hh \to b\bar{b}\gamma\gamma$: Clean channel but low production rate
- Major backgrounds: $b\bar{b}\gamma\gamma$, $t\bar{t}h$, $b\bar{b}h$, Zh
- Fake backgrounds: $b\bar{b}jj$, $c\bar{c}\gamma\gamma$, $jj\gamma\gamma$, $b\bar{b}j\gamma$, $c\bar{c}j\gamma$

Cut-based Analysis



Selection cuts
$N_j < 6$
$0.4 < \Delta R_{\gamma\gamma} < 2.0,\ 0.4 < \Delta R_{bb} < 2.0,\ \Delta R_{\gamma b} > 0.4$
$100\ \text{GeV} < m_{bb} < 150\ \text{GeV}$
$122\ \text{GeV} < m_{\gamma\gamma} < 128\ \text{GeV}$
$p_{T,bb} > 80\ \text{GeV},\ p_{T,\gamma\gamma} > 80\ \text{GeV}$

BDT Analysis (20% improvement)



$$m_{bb},\ p_{T,\gamma\gamma},\ \Delta R_{\gamma\gamma},\ p_{T,bb},\ \Delta R_{b_1\gamma_1},\ p_{T,\gamma_1},\ \Delta R_{bb},$$
$$p_{T,\gamma_2},\ \Delta R_{b_2\gamma_1},\ \Delta R_{b_2\gamma_2},\ p_{T,b_1},\ \Delta R_{b_1\gamma_2},\ p_{T,b_2},\ \not{E}_T,$$

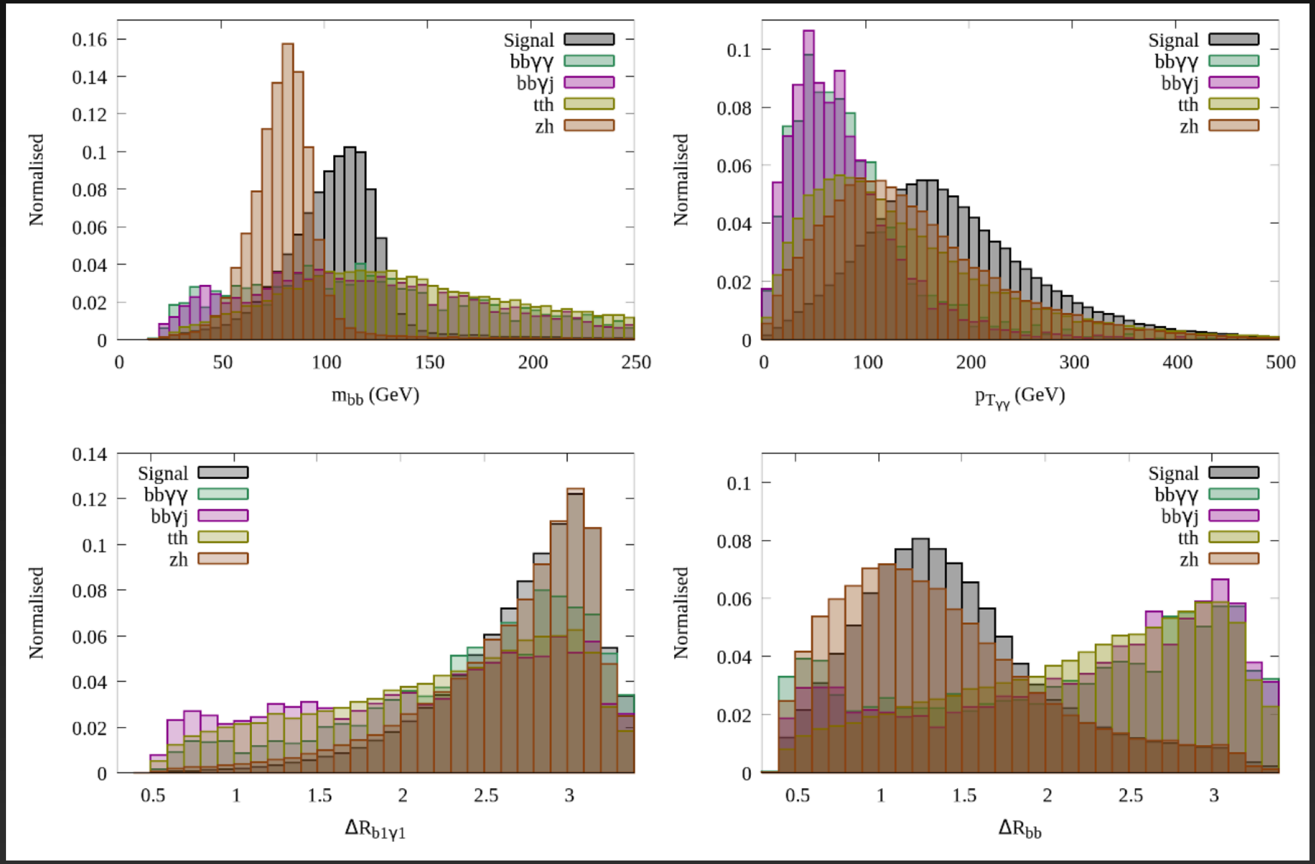


Fig. Normalised distributions of m_{bb}, $p_{T,\gamma\gamma}$, $\Delta R_{b1\gamma1}$, ΔR_{bb}.

The other search channels

- $pp \to hh \to b\bar{b}\tau\tau$: $b\bar{b}\tau_h\tau_h$, $b\bar{b}\tau_h\tau_\ell$, $b\bar{b}\tau_\ell\tau_\ell$, dominant background is $t\bar{t}$.
  - Signal significance after BDT analysis: $\tau_h\tau_h = 0.74$, $\tau_h\tau_\ell = 0.49$, $\tau_\ell\tau_\ell = 0.08$.
- $pp \to hh \to b\bar{b}WW^*$: Semi-leptonic and fully leptonic channels, dominant background is $t\bar{t}$.
  - Signal significance after BDT analysis: leptonic = 0.62, semi-leptonic = 0.13.
- $pp \to hh \to WW^*\gamma\gamma$: Semi-leptonic and fully leptonic channels, dominant background is $t\bar{t}h$.
  - < 5 Signal events, S/B: leptonic = 0.40, semi-leptonic = 0.11.
- $pp \to hh \to WW^*WW^*$: 3 channels: (a) 2 lepton, (b) 3 lepton and (c) 4 lepton final states.
  - more lepton → low rate, more jets → lose cleanliness, signal significance < 1.
- Combined signal significance $\sim 2.1\sigma$ (without systematics).

Di-Higgs production at HE-LHC

HE-LHC: 27 TeV @ 15 ab^{-1}, $\sigma(gg \to hh) = 139.9$ fb [CERN Twiki] .

7 di-Higgs final states are chosen:

- $b\bar{b}\gamma\gamma$
- $b\bar{b}\tau\tau \to \tau_h\tau_h$
- $b\bar{b}WW^* \to b\bar{b}ll + \not{E}_T$
- $WW^*\gamma\gamma \to ll\gamma\gamma + \not{E}_T$
- $b\bar{b}ZZ^* \to (a)\ b\bar{b}4l' + \not{E}_T$ and $(b)\ b\bar{b}2e2\mu + \not{E}_T$
- $b\bar{b}\mu\mu$

Multivariate analysis:

- Boosted Decision Tree (BDT) algorithm
- XGBoost toolkit
- Deep Neural Network (DNN)

Analysis Results

- $b\bar{b}\gamma\gamma$: Significance ($S/\sqrt{B}$): BDT $\sim$ 9.4 , DNN $\sim$ 10 , XGBoost $\sim$ 12.5.
- $b\bar{b}\tau\tau$: Significance: BDT = 2.8, DNN = 4.3, XGBoost = 4.8.
- $b\bar{b}WW*$: Significance: BDT = 1.5, DNN = 1.4, XGBoost = 2.7
- $WW*\gamma\gamma$: Significance: BDT = 1.7, XGBoost = 2.1.
- $b\bar{b}ZZ*$: $t\bar{t}h$, Combined significance from both final states: BDT = 1.2, XGBoost = 1.4.
- $b\bar{b}\mu\mu$: $t\bar{t}$, $b\bar{b}\mu\mu$, Significance < 1.
- Combined significance $\sim 10\sigma$ (BDT), $\sim 14\sigma$ (XGBoost) .

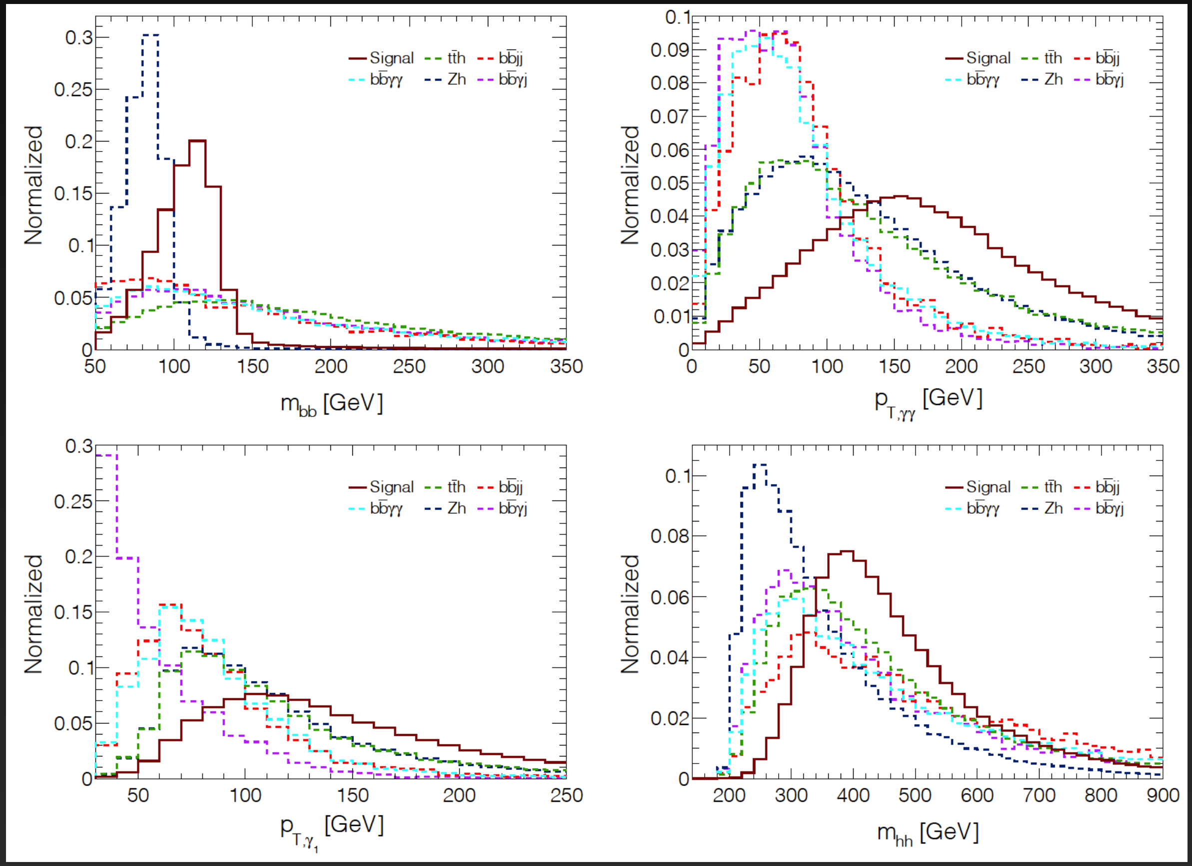


Fig. Normalised distributions of m_{bb}, $p_{T,\gamma\gamma}$, p_{T,γ_1}, m_{hh} in the $b\bar{b}\gamma\gamma$ channel.

Changing the Higgs self-coupling from SM

- Changing $\kappa_\lambda = \lambda/\lambda_{SM} \rightarrow$ modifies the kinematics of di-Higgs final state.
- Channels explored: $b\bar{b}\gamma\gamma$, $b\bar{b}\tau\tau$, $b\bar{b}WW*$.
- The HE-LHC would be sensitive to the entire range of $\kappa_\lambda = [-2,4]$.

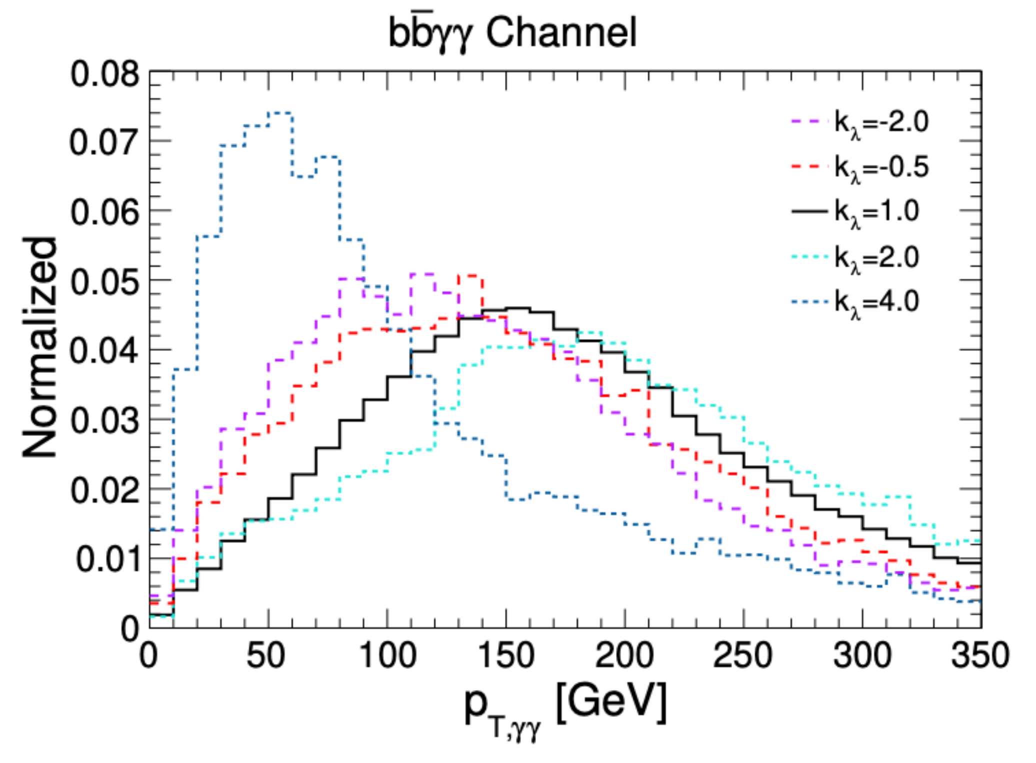


Fig. Normalised distribution of $p_{T,\gamma\gamma}$.

Conclusion

- At the HL-LHC, combining various di-Higgs search channels → better final result. Further, a combination of ATLAS and CMS results will provide improved discovery potential.
- HL-LHC → HE-LHC: di-Higgs production rate increases by a factor of ~ 3.
- The HE-LHC can probe the Higgs self-coupling, with signal significance $> 10\sigma$, without any systematics. The signal significance reduces to almost 5σ with a systematic uncertainty of 5%.
- The HE-LHC will be sensitive in the range of Higgs self-coupling, $k_\lambda = [-2,4]$.

Thank you

Detector Simulation at HE-LHC

- Signal and backgrounds are generated at LO with MG5 aMC@NLO.
- NNPDF2.3LO PDF is used. Showering and hadronisation is done with Pythia8.
- Delphes is utilised for fast detector simulation. The default ATLAS card is used with the following modifications.
- Jets: anti-kT algorithm with radius parameter $R = 0.4$ and $p_T^j > 20$ GeV in FastJet framework.
- Isolation: The p_T sum of the surrounding objects within $\Delta R = 0.2$ must be $< 20\,\%$ of the lepton or photon p_T, with $|\eta| \leq 4.0$; and $p_T > 5$ GeV and $p_T > 10$ GeV, respectively.
- b-tag efficiency is $70\,\%$. The $c \to b$ and $j \to b$ fake rates are $3\,\%\,(4\%)$ and $0.15\,\%\,(0.12\%)$ for a c-jet or light jet having $p_T = 30 - 90$ GeV (> 90 GeV), respectively.