Prospects of non-resonant Higgs pair production at the HL-LHC and HE-LHC

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With S. Banerjee, R.K. Barman, B. Bhattacherjee and S. Niyogi (arXiv:1712.05346)

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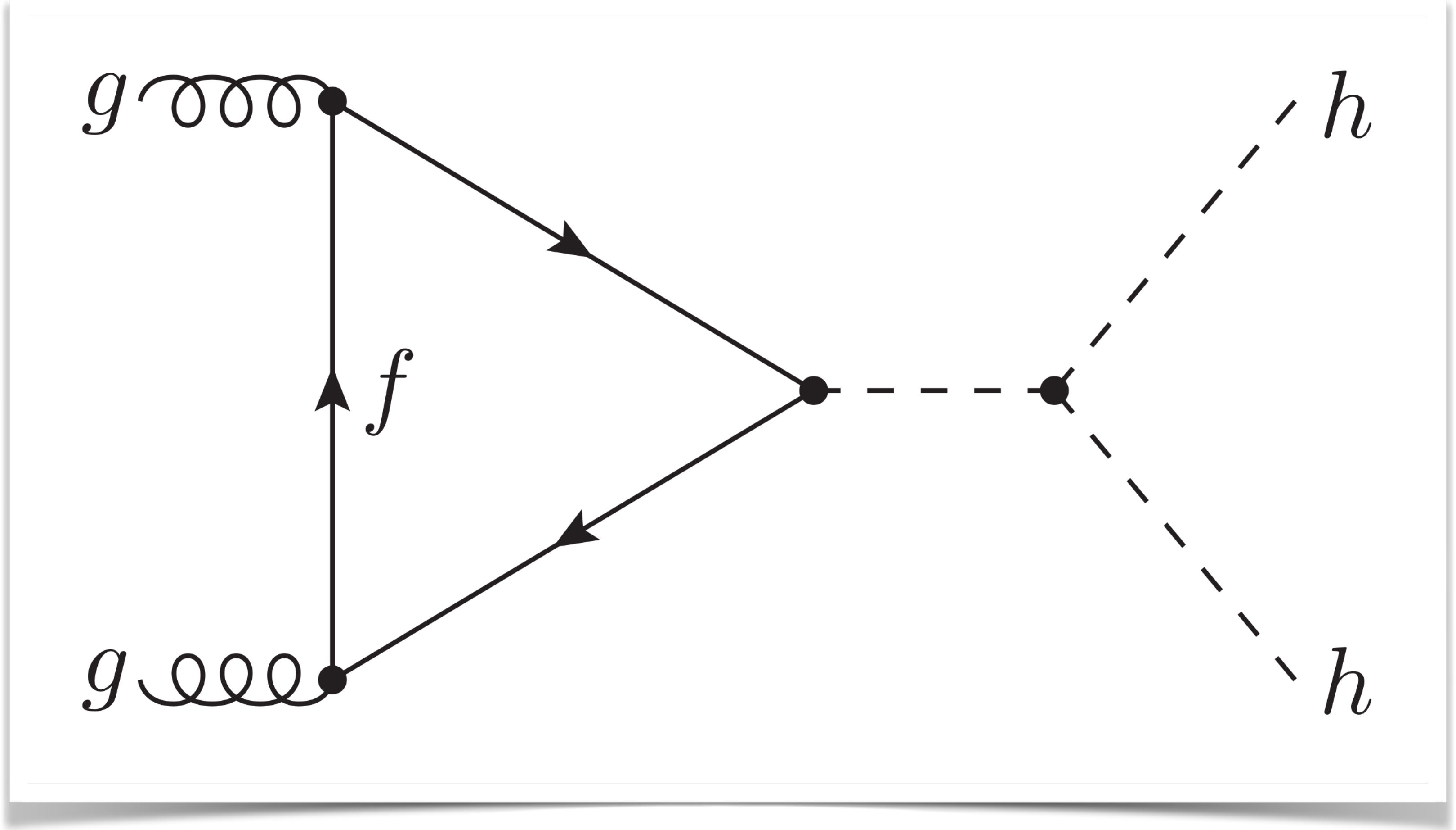
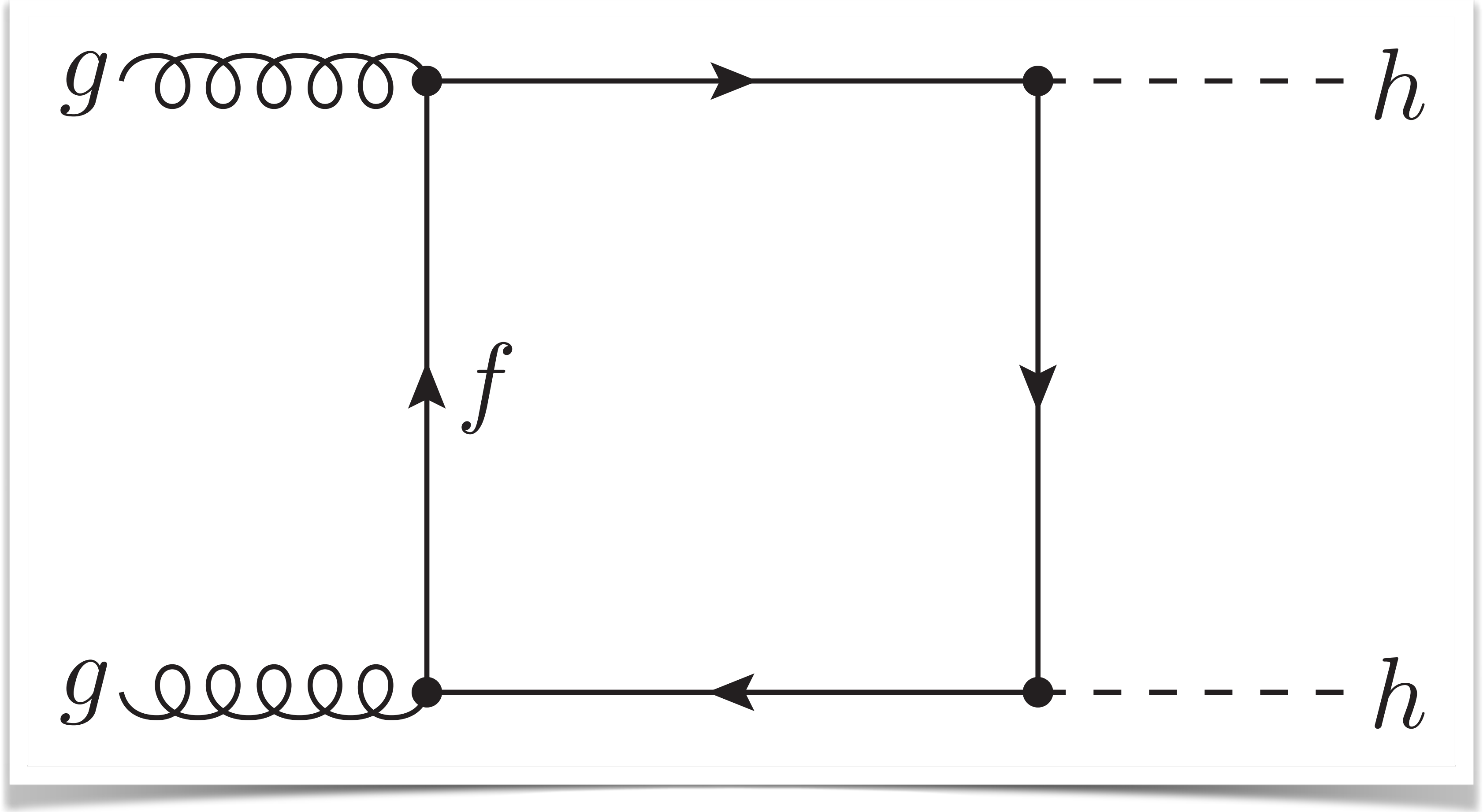
Introduction

- Higgs boson has been discovered at the LHC in 2012 which is more or less consistent with Standard Model
- The coupling to gauge bosons and fermions are being measured with great precision
- In Standard Model, the Higgs self coupling (λ) has a value, fixed by the Higgs mass and VEV
- The value of λ determines the structure of the Higgs potential
- There is no direct measurement of Higgs self-coupling till now

Motivation





- To probe Higgs self coupling → Higgs pair production
- Cancellation between triangle and box diagrams → small production cross-section

Di-Higgs production at HL-LHC

- HL-LHC: 14 TeV @ 3 ab^{-1}, $\sigma(gg \to hh) = 36.69$ fb [CERN Twiki]
- Channels based on production rate and cleanliness
- 11 possible final states:
  - $b\bar{b}\gamma\gamma$
  - $b\bar{b}\tau\tau \to (a)\ \tau_h\tau_h$, $(b)\ \tau_h\tau_\ell$ 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 analysis (Follow CMS/ATLAS analysis whenever available)
- Multivariate analysis using Boosted Decision Tree (BDT) algorithm

Di-Higgs production at HL-LHC: 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: $b\bar{b}jj$, $b\bar{b}j\gamma$, $jj\gamma\gamma$, $c\bar{c}jj$, $c\bar{c}j\gamma$

Cut-based Analysis:

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

- Signal Significance, $S/\sqrt{B}$ = 1.46

BDT Analysis:

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

- Signal Significance, $S/\sqrt{B}$ = 1.76

Di-Higgs production at HL-LHC: The $b\bar{b}\gamma\gamma$ channel

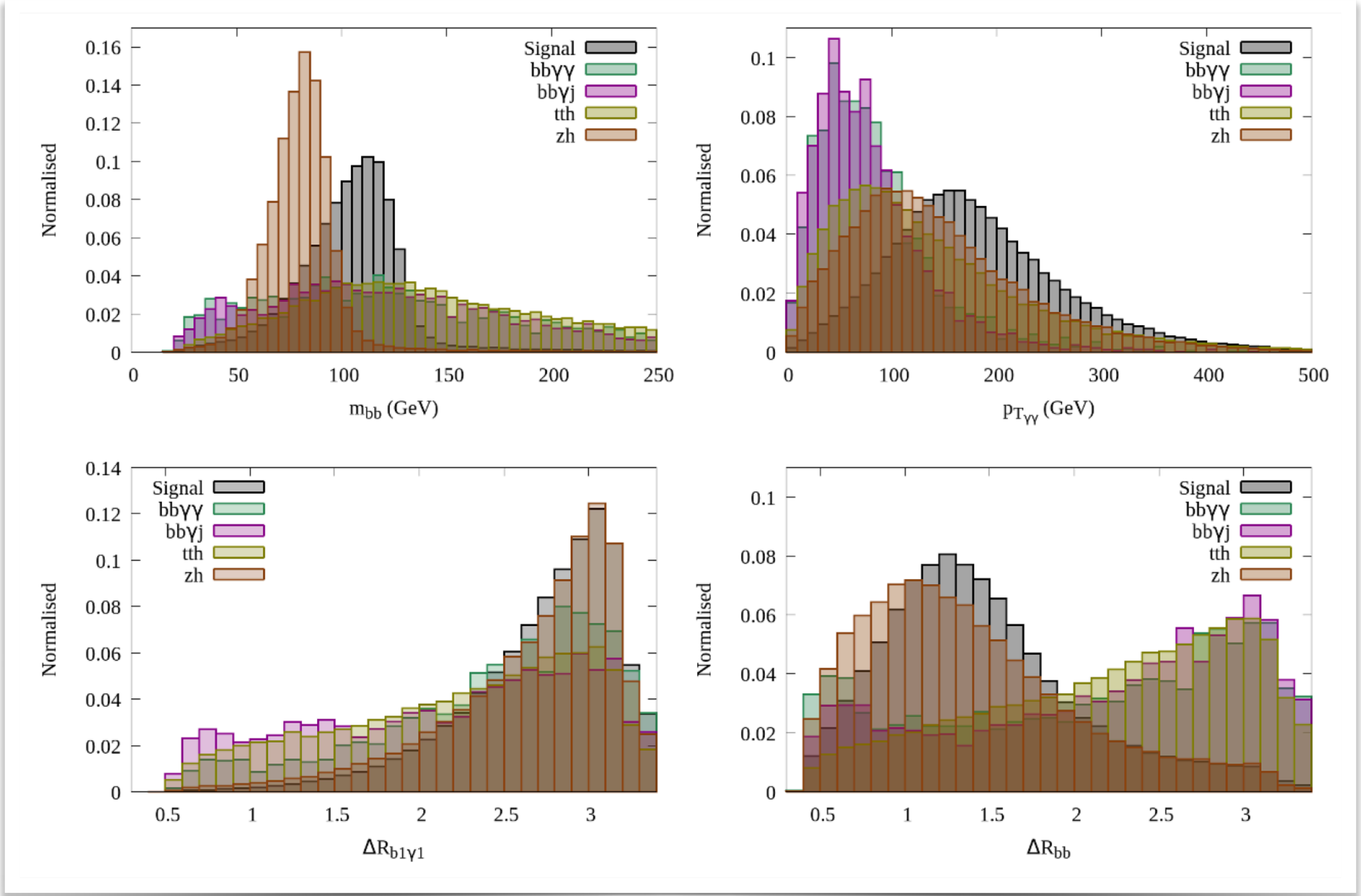


Fig. Normalised distributions of m_{bb}, $p_{T,\gamma\gamma}$, $\Delta R_{b1\gamma1}$, ΔR_{bb}

Di-Higgs production at HL-LHC: The other channels

- $b\bar{b}\tau\tau$: $t\bar{t}$, Significance: $\tau_h\tau_h = 0.74,\ \tau_h\tau_\ell = 0.49,\ \tau_\ell\tau_\ell = 0.08$

- $b\bar{b}WW^*$: $t\bar{t}$, Significance: leptonic = 0.62, semi-leptonic = 0.13

- $WW^*\gamma\gamma$: $t\bar{t}h$, < 5 Signal events, S/B: leptonic = 0.40, semi-leptonic = 0.11

- WW^*WW^* : more lepton → low rate, more jets → lose cleanliness, Significance < 1

- Combined significance $\sim 2.1\sigma$

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

Ans. Kinematics of new physics may overlap with SM / Overlap is not significant but overall rate is large

Di-Higgs production at HE-LHC

- HE-LHC: 27 TeV @ 15 ab^{-1}, $\sigma(gg \rightarrow hh) = 139.9$ fb [CERN Twiki]
- 7 possible final states:
  - $b\bar{b}\gamma\gamma$
  - $b\bar{b}\tau\tau \rightarrow \tau_h\tau_h$
  - $b\bar{b}WW^* \rightarrow b\bar{b}\ell\ell + \not{E}_T$
  - $WW^*\gamma\gamma \rightarrow \ell\ell\gamma\gamma + \not{E}_T$
  - $b\bar{b}ZZ^* \rightarrow (a)\ b\bar{b}4\ell' + \not{E}_T$ 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)

Di-Higgs production at HE-LHC: The $b\bar{b}\gamma\gamma$ channel

Acceptance cuts
$N_{b\ jets} = 2, \ N_\gamma = 2$
$122 \text{ GeV} < m_{\gamma\gamma} < 128 \text{ GeV}$
$\Delta R_{b\gamma} > 0.2$
$m_{bb} > 50 \text{ GeV}$

Kinematic variables in BDT, XGBoost and DNN Analysis:

$$m_{bb},\ \Delta R_{\gamma\gamma},\ \Delta R_{bb},\ p_{T,bb},\ p_{T,\gamma\gamma},\ \Delta R_{bb\ \gamma\gamma},\ p_{T,hh},\ \Delta R_{b_i\gamma_i},\ m_{hh},\ p_{T,b_{1,2}},\ p_{T,\gamma_{1,2}},\ \not{E}_T,\ \cos\theta^*,\ \cos\theta_{\gamma_1 h}$$

Signal Significance, $S/\sqrt{B}$:

BDT = 9.8

DNN = 10.4

XGBoost = 13.1 (97% probability cut)

= 9.7 (95% probability cut)

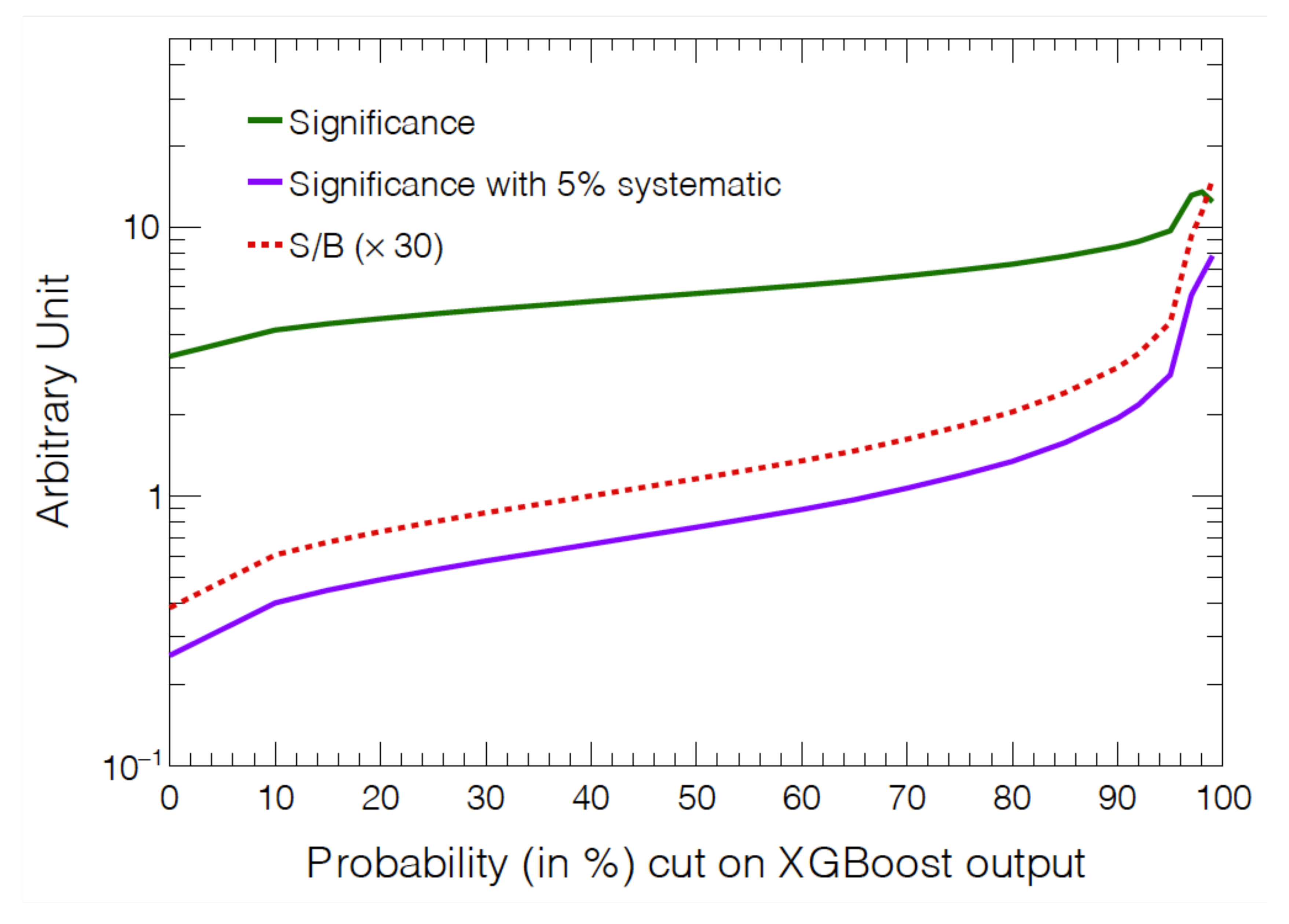


Fig. Variation of significance and S/B with the probability cut on XGBoost output.

Di-Higgs production at HE-LHC: The $b\bar{b}\gamma\gamma$ channel

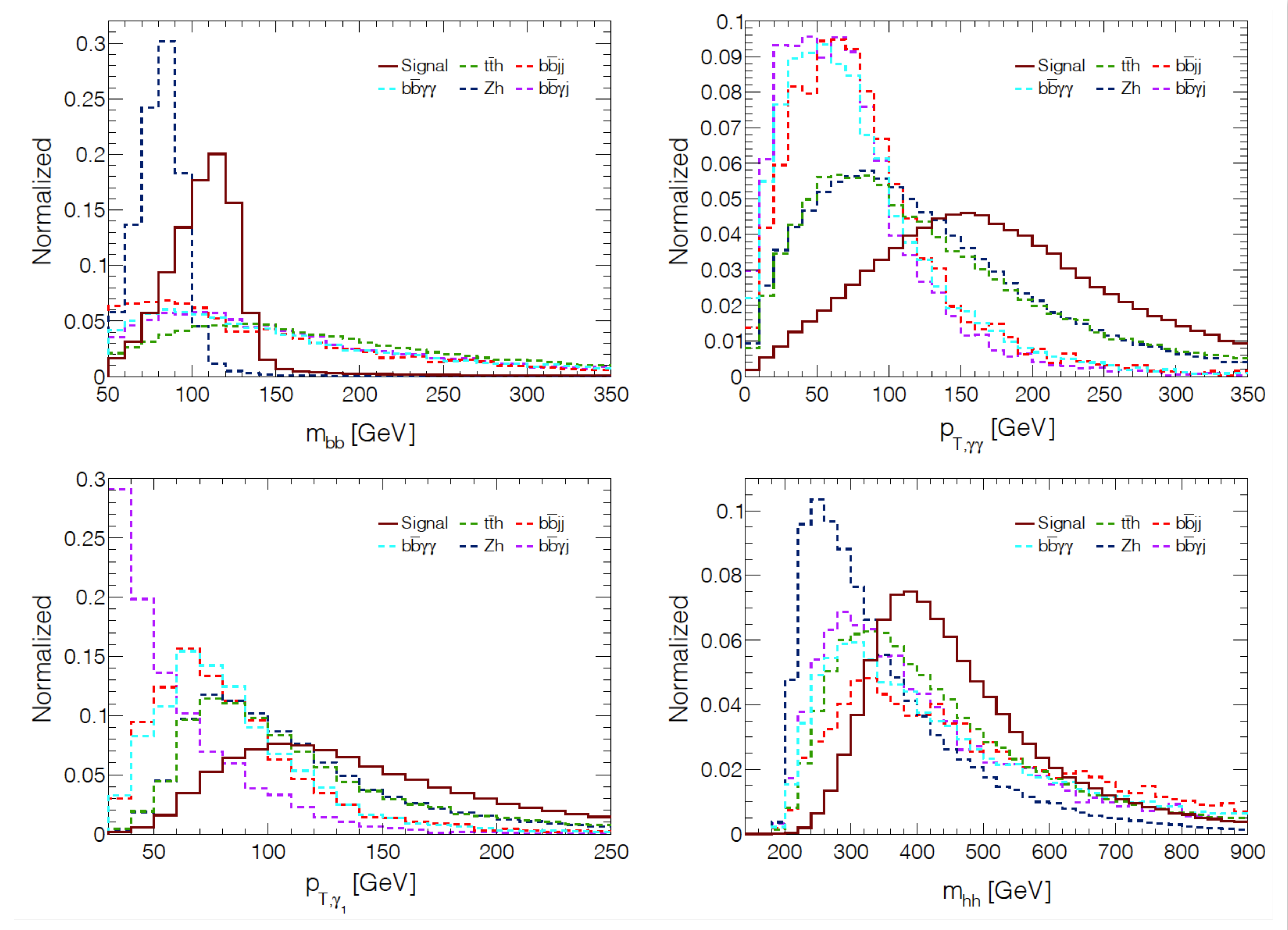


Fig. Normalised distributions of m_{bb}, $p_{T,\gamma\gamma}$, p_{T,γ_1}, m_{hh}

Di-Higgs production at HE-LHC: The other channels

- $b\bar{b}\tau\tau$: Significance: BDT = 2.8, DNN = 4.3, XGBoost = 4.8

- $b\bar{b}WW^*$: Significance: BDT = 1.5, DNN = 1.4, XGBoost = 2.7, Extra new variables used:

$$\boxed{\begin{aligned} &logT,\ logH,\ M_{T2}^{(b)},\ M_{T2}^{(\ell)},\ \sqrt{\hat{s}_{min}^{(\ell\ell)}},\ \sqrt{\hat{s}_{min}^{(bb\ell\ell)}},\ p_{T,\ell_{1/2}},\ \not{E}_T,\ m_{\ell\ell},\ m_{bb},\\ &\qquad \Delta R_{\ell\ell},\ \Delta R_{bb},\ p_{T,bb},\ p_{T,\ell\ell},\ \Delta\phi_{bb\ \ell\ell}.\end{aligned}}$$

- $WW^*\gamma\gamma$: 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)

- Changing $k_\lambda = \lambda/\lambda_{SM} \rightarrow$ modifies the kinematics of di-Higgs final state. Our projections indicate that the HE-LHC would be sensitive to the entire range of $k_\lambda = [-2,4]$ through direct searches in the non-resonant di-Higgs search channels.

Summary

- It is very important to directly probe Higgs pair production to understand the Higgs potential
- At the HL-LHC, the di-Higgs search yields a combined signal significance of $\sim 2.1\sigma$
- New physics can contaminate the small number of events from di-Higgs signal
- HL-LHC $\rightarrow$ HE-LHC : di-Higgs production rate can improve by a factor of ~ 4
- The Higgs pair production can be probed with discovery potential at the HE-LHC
- At the HE-LHC, di-Higgs search will be sensitive to variation in $k_\lambda = [-2,4]$