

Higgs pair production at the future LHC runs

Amit Adhikary

Indian Institute of Science, Bangalore, India

Based on

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

With R.K. Barman and B. Bhattacharjee (JHEP 2012 (2020) 179)

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Introduction

Higgs boson has been discovered at the Large Hadron Collider (LHC) in 2012 which is more or less consistent with the Standard Model (SM) Higgs boson. The coupling of Higgs boson to gauge bosons and fermions are being measured with increasing precision at the experiment. There is no direct measurement of Higgs self-coupling till now.

The scalar potential:

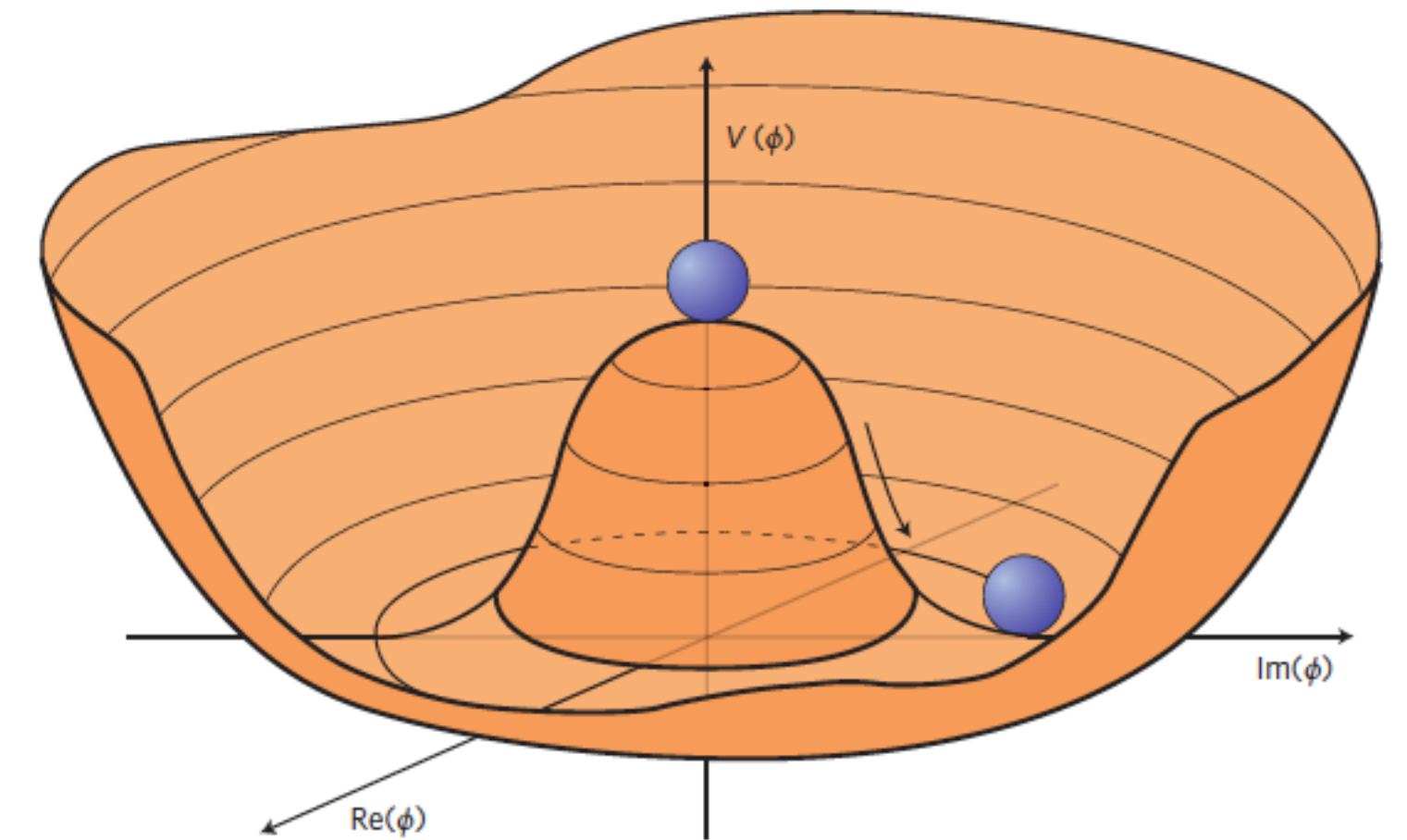
$$V(\Phi) = \mu^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2 \quad \longleftarrow \text{completely arbitrary choice}$$

The only way to reconstruct this potential is by knowing the exact value of λ .

In the SM, with Higgs boson mass of 125 GeV, $\lambda_{SM} = \frac{m_h^2}{2v^2} \sim 0.13$.

Q. Is this the value of Higgs boson self coupling for the spontaneous symmetry breaking mechanism (SSB)?

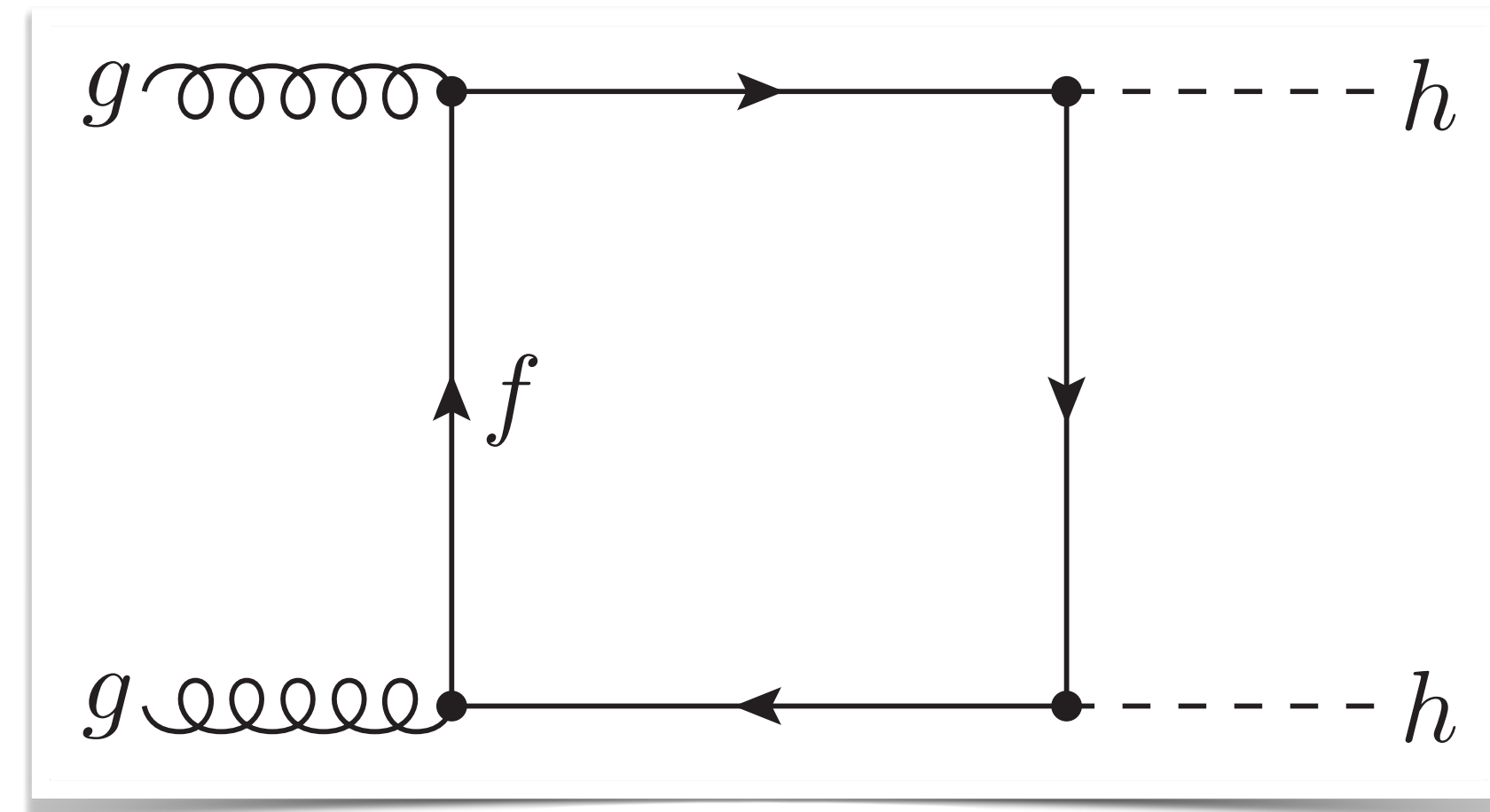
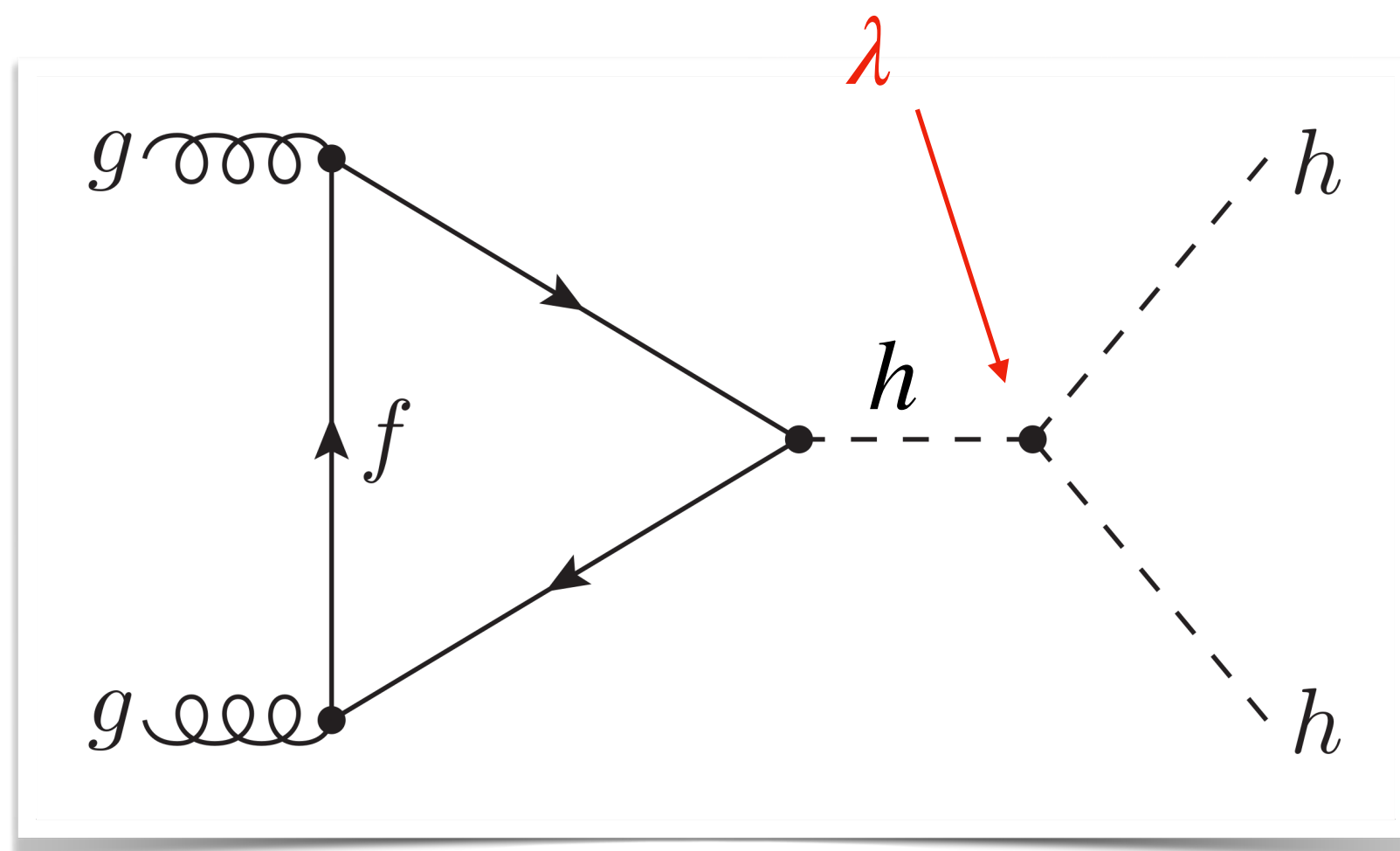
Ans. A direct measurement is necessary at the collider.



Motivation: Higgs boson self-coupling and Higgs pair production

- To probe Higgs self coupling: $\lambda \rightarrow$ we need to produce two Higgs boson from one Higgs boson: $pp \rightarrow hh$.

Dominant production mode at hadron collider: gluon gluon fusion, $gg \rightarrow hh$.



Cancellation between triangle and box diagrams \rightarrow very small production cross-section.

Di-Higgs production at HL-LHC

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

Channels are chosen based on their production rate and cleanliness.

The selected 11 possible final states are,

- $b\bar{b}\gamma\gamma$
- $b\bar{b}\tau\tau \rightarrow (a) \tau_h\tau_h, (b) \tau_h\tau_\ell$ and $(c) \tau_\ell\tau_\ell$
- $b\bar{b}WW^* \rightarrow (a) b\bar{b}\ell jj + \cancel{E}_T$ and $(b) b\bar{b}\ell\ell + \cancel{E}_T$
- $WW^*\gamma\gamma \rightarrow (a) \ell jj\gamma\gamma + \cancel{E}_T$ and $(b) \ell\ell\gamma\gamma + \cancel{E}_T$
- $WW^*WW^* \rightarrow (a) 2\ell 4j + \cancel{E}_T, (b) 3\ell 2j + \cancel{E}_T$ and $(c) 4\ell + \cancel{E}_T$

Standard cut-based analysis (Follow CMS/ATLAS analysis whenever available).

Multivariate analysis using Boosted Decision Tree (BDT) algorithm.

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

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

Cut-based Analysis

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

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

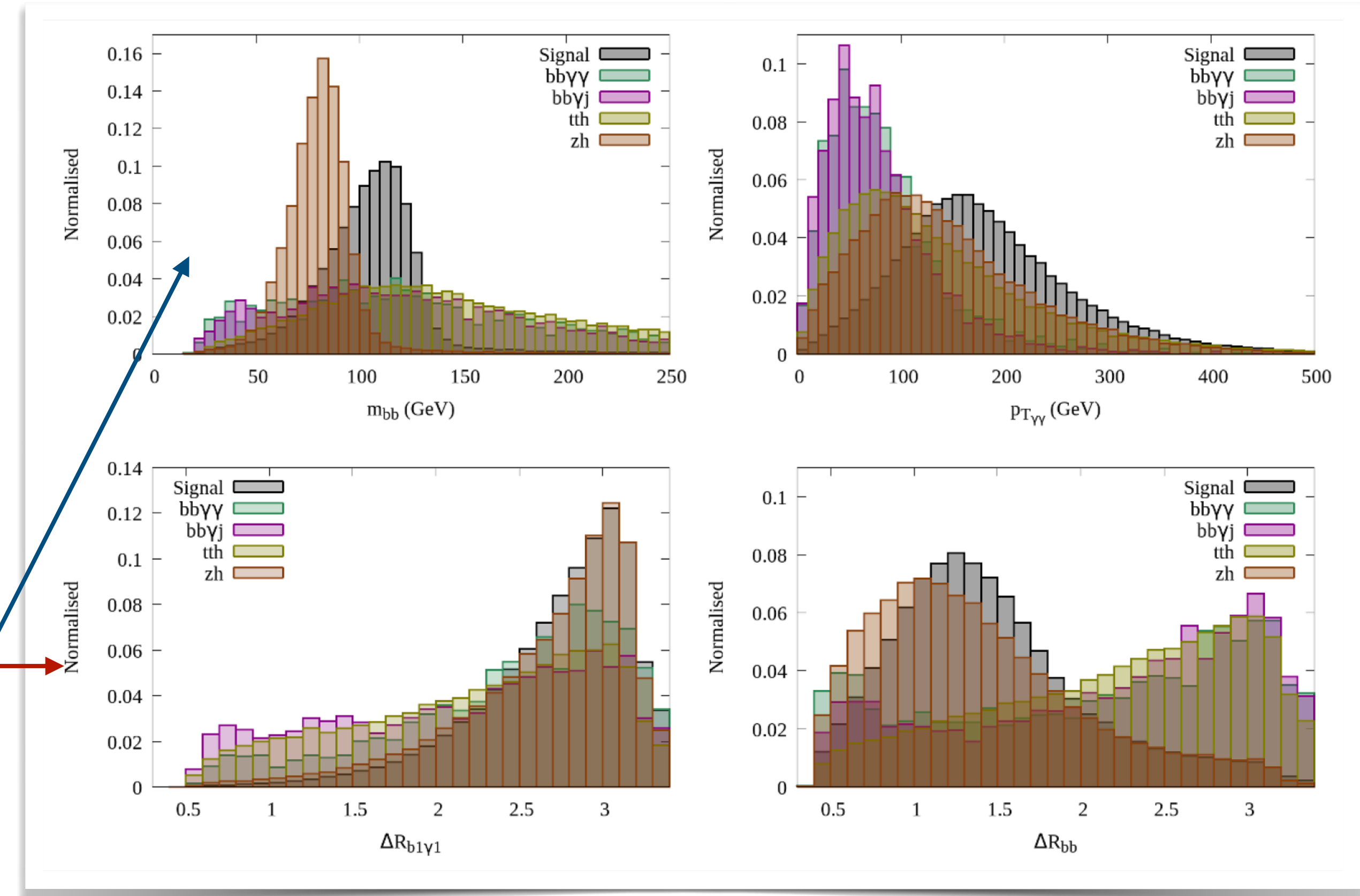


Fig. Normalised distributions of m_{bb} , $p_{T,\gamma\gamma}$, $\Delta R_{b1\gamma1}$, ΔR_{bb} .

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

BDT Analysis

Kinematic variables used:

$$m_{bb}, p_{T,\gamma\gamma}, \Delta R_{\gamma\gamma}, p_{T,bb}, \Delta R_{b_1\gamma_1}, p_{T,\gamma_1}, \Delta R_{bb},$$

$$p_{T,\gamma_2}, \Delta R_{b_2\gamma_1}, \Delta R_{b_2\gamma_2}, p_{T,b_1}, \Delta R_{b_1\gamma_2}, p_{T,b_2}, \cancel{E}_T,$$

Results:

Sl. No.	Process	Events
Background	$hb\bar{b}$	2.75
	$t\bar{t}h$	14.85
	Zh	12.28
	$b\bar{b}\gamma\gamma^*$	34.46
	Fake 1	14.25
	Fake 2	8.46
	Total	87.05
	Signal ($hh \rightarrow 2b2\gamma$)	16.46
	Significance (S/\sqrt{B})	1.76

$$\text{Event rate} = \text{cross-section} * \text{Branching ratio} * \text{Efficiency} * L .$$

The other search channels

- $pp \rightarrow hh \rightarrow b\bar{b}\tau\tau : b\bar{b}\tau_h\tau_h, b\bar{b}\tau_h\tau_\ell, b\bar{b}\tau_\ell\tau_\ell$, dominant background is $t\bar{t}$.
 - Signal significance after BDT analysis: $\tau_h\tau_h = 0.74$, $\tau_h\tau_\ell = 0.49$, $\tau_\ell\tau_\ell = 0.08$.
- $pp \rightarrow hh \rightarrow b\bar{b}WW^*$: Semi-leptonic and fully leptonic channels, dominant background is $t\bar{t}$.
 - Signal significance after BDT analysis: leptonic = 0.62, semi-leptonic = 0.13.
- $pp \rightarrow hh \rightarrow WW^*\gamma\gamma$: 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.
- $pp \rightarrow hh \rightarrow WW^*WW^*$: 3 channels: (a) 2 lepton, (b) 3 lepton and (c) 4 lepton final states.
 - more lepton \rightarrow low rate, more jets \rightarrow lose cleanliness, signal significance < 1.
- Combined signal significance $\sim 2.1\sigma$.

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:

- $b\bar{b}\gamma\gamma$
- $b\bar{b}\tau\tau \rightarrow \tau_h\tau_h$
- $b\bar{b}WW^* \rightarrow b\bar{b}ll + \cancel{E}_T$
- $WW^*\gamma\gamma \rightarrow ll\gamma\gamma + \cancel{E}_T$
- $b\bar{b}ZZ^* \rightarrow (a) b\bar{b}4l' + \cancel{E}_T$ and $(b) b\bar{b}2e2\mu + \cancel{E}_T$
- $b\bar{b}\mu\mu$

Multivariate analysis:

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

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

Acceptance cuts

$$N_b \text{ jets} = 2, N_\gamma = 2$$

$$122 \text{ GeV} < m_{\gamma\gamma} < 128 \text{ GeV}$$

$$\Delta R_{b\gamma} > 0.2$$

$$m_{bb} > 50 \text{ GeV}$$

Kinematic variables in BDT, XGBoost and DNN Analysis:

$$m_{bb}, \Delta R_{\gamma\gamma}, \Delta R_{bb}, p_{T,bb}, p_{T,\gamma\gamma}, \Delta R_{bb\gamma\gamma}, p_{T,hh}, \Delta R_{b_i\gamma_i},$$

$$m_{hh}, p_{T,b_{1,2}}, p_{T,\gamma_{1,2}}, \cancel{E}_T, \cos\theta^*, \cos\theta_{\gamma_1 h}$$

Signal significance, S/\sqrt{B} :

BDT ~ 9.4 , DNN ~ 10 , XGBoost ~ 12.5

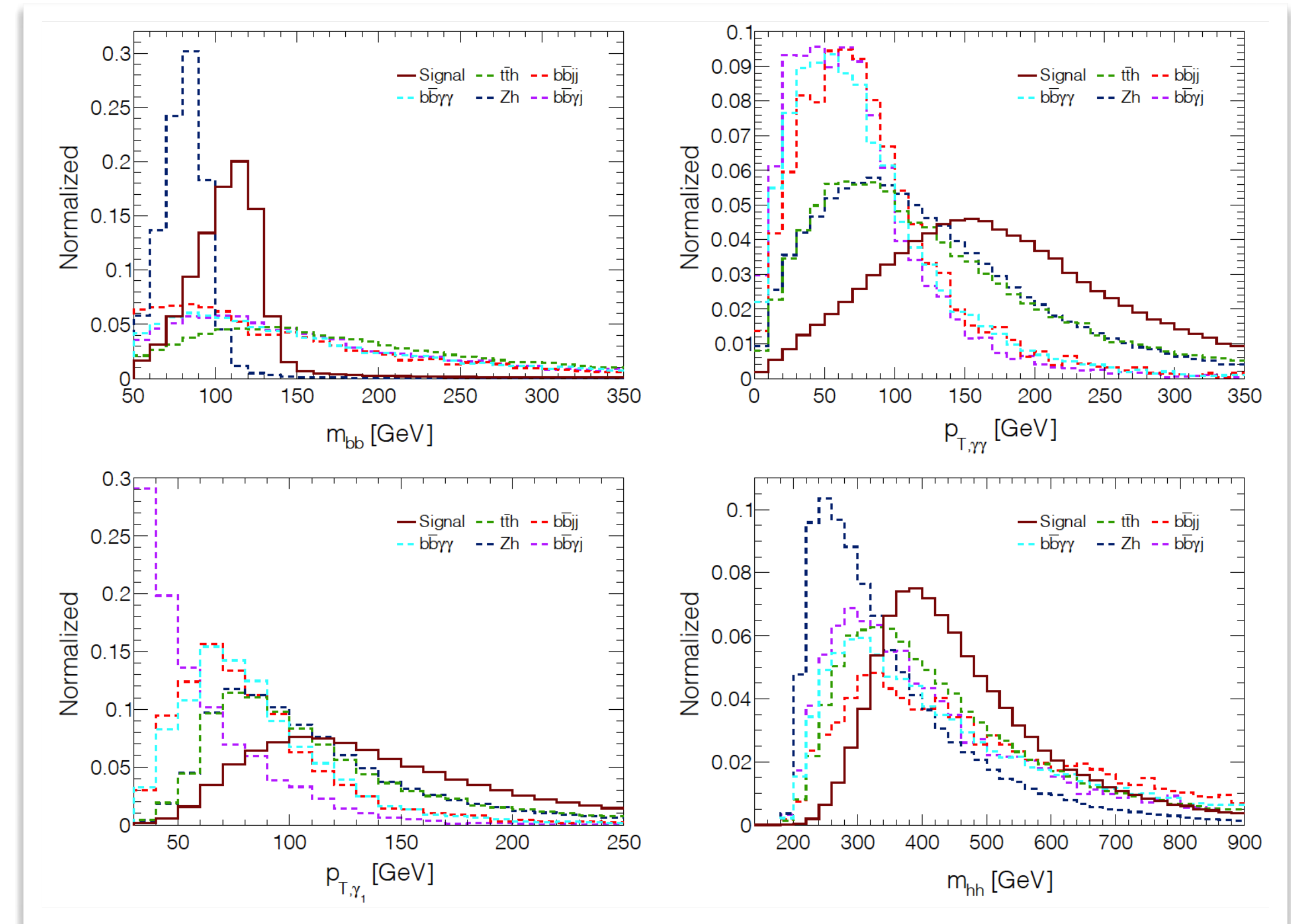


Fig. Normalised distributions of m_{bb} , $p_{T,\gamma\gamma}$, p_{T,γ_1} , m_{hh} .

The other search 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, New variables used:

$$\log T, \log H, M_{T2}^{(b)}, M_{T2}^{(\ell)}, \sqrt{\hat{s}_{min}^{(\ell\ell)}}, \sqrt{\hat{s}_{min}^{(bb\ell\ell)}}, p_{T,\ell_{1/2}}, \cancel{E}_T, m_{\ell\ell}, m_{bb}, \Delta R_{\ell\ell}, \Delta R_{bb}, p_{T,bb}, p_{T,\ell\ell}, \Delta\phi_{bb\ell\ell}.$$

- $WW^*\gamma\gamma$: 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 the Higgs self-coupling from SM

- Changing $k_\lambda = \lambda/\lambda_{SM} \rightarrow$ 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 $k_\lambda = [-2,4]$.

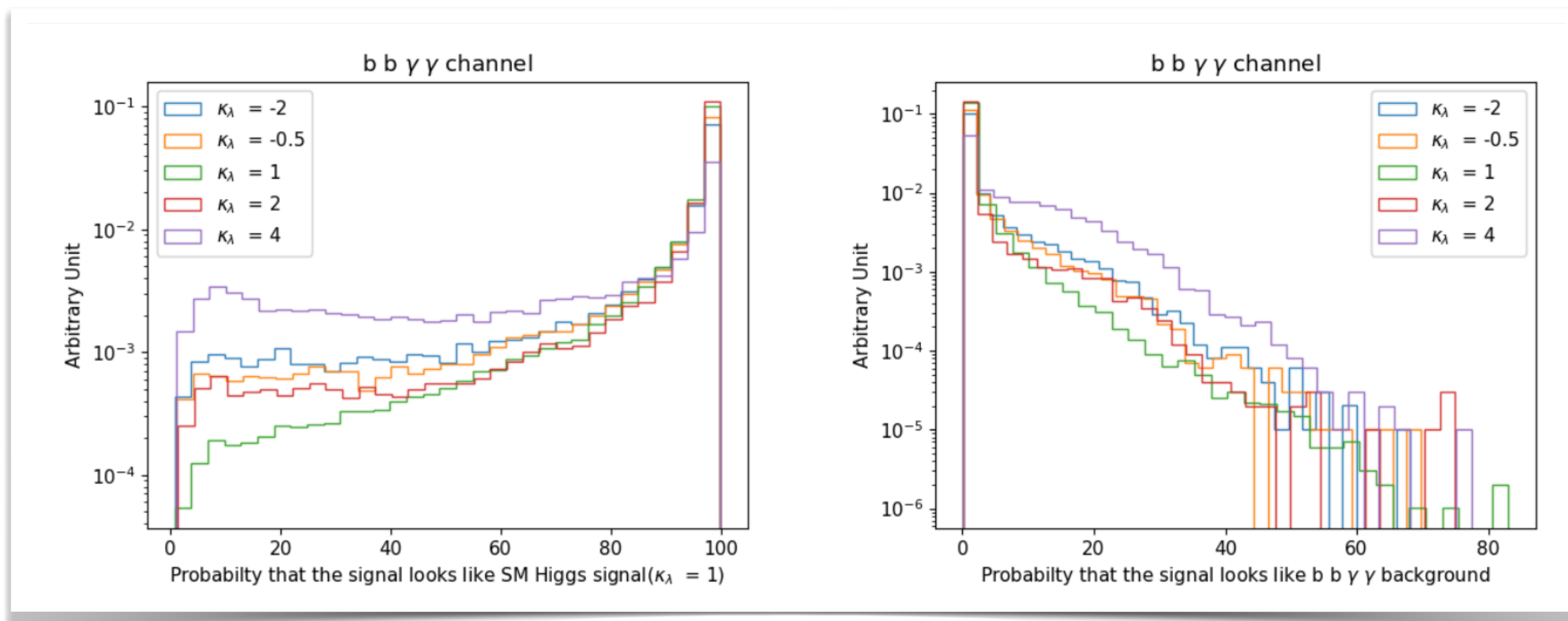


Fig. Normalised distributions illustrating the probability that the signal events look like the respective SM di-Higgs signal (left) and dominant SM backgrounds (right).

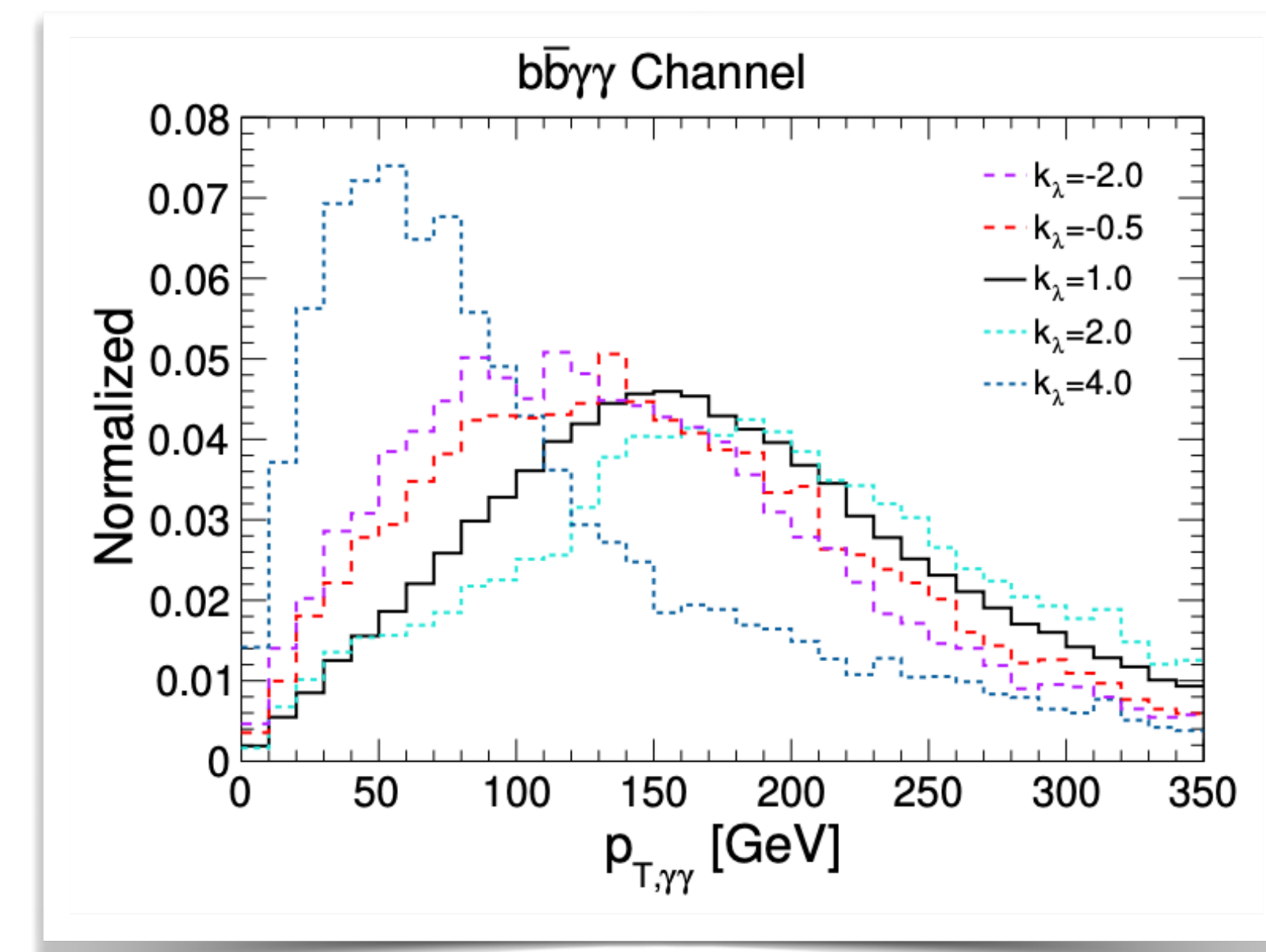


Fig. Normalised distribution of $p_{T,\gamma\gamma}$.

Summary

- The prospect of observing Higgs pair production is bleak at the HL-LHC.
- Combining various di-Higgs search channels \rightarrow better final result. We got signal significance $\sim 2.1\sigma$.
- HL-LHC \rightarrow HE-LHC : di-Higgs production rate can improve by a factor of ~ 3 .
- The HE-LHC can probe the Higgs self-coupling, with signal significance $> 10\sigma$.
- The HE-LHC will be sensitive in the range of Higgs self-coupling, $k_\lambda = [-2,4]$.

Thank you