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Prospects of Higgs pair production at the HL-LHC

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Outline of this talk

- HL-LHC prospects of non-resonant di-Higgs searches.
- A qualitative analysis of the sensitivity of di-Higgs search strategies on λ_{hhh}.
- Contamination to di-Higgs final states from BSM scenarios.

Motivation

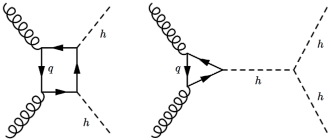
- The CMS and ATLAS collaborations have unambiguously confirmed the existence of a scalar boson at 125 GeV.
- Numerous studies performed to measure the Higgs coupling with SM particles.
- The Higgs self-coupling, λ_{hhh} still remains elusive.
- The only direct probe of λ_{hhh} in SM is offered by the non-resonant Higgs pair production process, where the final state Higgs eventually decays into SM particles.
- Precise measurement of λ_{hhh} is extremely challenging because of the small SM di-Higgs production cross-section.
- In the SM, the di-Higgs production proceeds through top-quark loop in the *ggF* mode.

Direct measurement is challenging :

Small SM production cross-section : $\sigma_{gghh_{SM}} = 39.56^{+7.32\%}_{-8.38\%}$ (at 14 TeV).[a]

Other di-Higgs production modes furnish even smaller cross-sections ~ 1 fb

[a] Borowka et. al., 2016



However, phenomenologically rich final states can emerge, offering a possibility to improve the discovery potential through highly optimized search strategies.

Current limits from non-resonant di-Higgs searches:

- ATLAS : 13.3 fb^{-1} : $4b$: $\sim$ 29 times.
- ATLAS : 36.1 fb^{-1} : $4b$: $\sim$ 13 times
- CMS : 35.9 fb^{-1} : $2b2\tau$: $\sim$ 30 times.
- CMS : 35.9 fb^{-1} : $2b2\gamma$: $\sim$ 19 times.

Strategy

- Optimize the di-Higgs search strategy using both, cut-based analysis and multivariate techniques, for a multitude of di-Higgs final states:

1. $b\bar{b}\gamma\gamma$
2. $b\bar{b}\tau_h\tau_h$
3. $b\bar{b}\tau_h\tau_l$
4. $b\bar{b}\tau_l\tau_l$
5. $b\bar{b}W^+W^- \to b\bar{b}l\nu jj$
6. $b\bar{b}W^+W^- \to b\bar{b}l\nu l\nu$
7. $W^+W^-\gamma\gamma \to l\nu jj\gamma\gamma$
8. $W^+W^-\gamma\gamma \to l\nu l\nu\gamma\gamma$
9. $4W \to ss2l$
10. $4W \to 3l$
11. $4W \to 4l$

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

The small signal rate is compensated by a very clean signature.

Backgrounds

- Dominant background : **QCD-QED** $b\bar{b}\gamma\gamma$.
  Pure QED contribution is roughly $\sim O(1\%)$ of the QCD-QED counterpart.
- Associated production of Higgs with bottom and top quarks :$b\bar{b}h$, $t\bar{t}h$.
- Associated production of Higgs with Z-boson : Zh.
- Fake backgrounds : $c\bar{c}\gamma\gamma$, $jj\gamma\gamma$, $b\bar{b}jj$, $b\bar{b}j\gamma$, $c\bar{c}j\gamma$.
  $$N^{c\bar{c}\gamma\gamma\ (jj\gamma\gamma)} = (N^{c\bar{c}\gamma\gamma\ (jj\gamma\gamma)}_{\rm ATLAS}/N^{b\bar{b}\gamma\gamma}_{\rm ATLAS}) \cdot N^{b\bar{b}\gamma\gamma}$$
  $$N^{c\bar{c}j\gamma} = (N^{c\bar{c}j\gamma}_{\rm ATLAS}/N^{b\bar{b}j\gamma}_{\rm ATLAS}) \cdot N^{b\bar{b}j\gamma}.$$

Event selection

- Exactly 2 b-tagged jets and exactly 2 γ.
- $p_T^{b_1} > 40$ GeV and $p_T^{b_2} > 30$ GeV.
- $|\eta_{b_1,b_2}| < 2.4$.
- $p_T^{\gamma} > 30$ GeV and $|\eta_\gamma| < 1.37$, $1.52 < |\eta_\gamma| < 2.37$.
- Veto : Isolated leptons with $p_T > 25$ GeV and $|\eta| < 2.5$.

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

Selection cuts

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

Significantly reduces the $t\bar{t}h$ background, when either or both top quarks decay hadronically.

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

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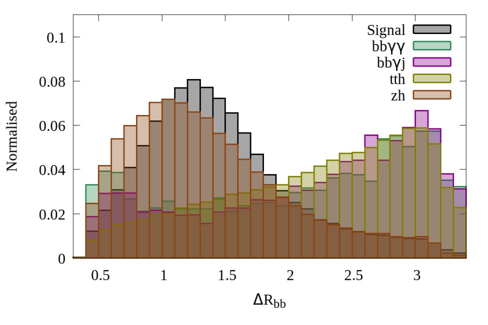
- $N_j < 6$
- $0.4 < \Delta R_{\gamma\gamma} < 2.0$, $0.4 < \Delta R_{bb} < 2.0$, $\Delta R_{\gamma b} > 0.4$
- $p_{T,bb} > 80$ GeV, $p_{T,\gamma\gamma} > 80$ GeV
- 100 GeV $< m_{bb} < 150$ GeV, 122 GeV $< m_{\gamma\gamma} < 128$ GeV

Highly effective in tackling the QED-QCD $b\bar{b}\gamma\gamma$ and fake backgrounds.



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

Selection cuts

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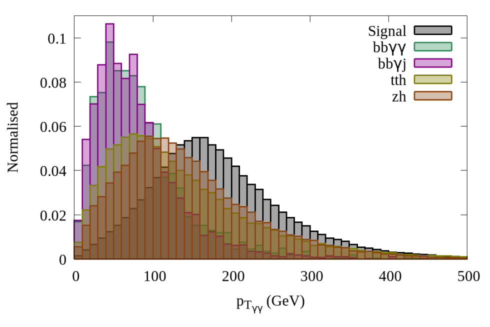
- $0.4 < \Delta R_{\gamma\gamma} < 2.0$, $0.4 < \Delta R_{bb} < 2.0$, $\Delta R_{\gamma b} > 0.4$
- $p_{T,bb} > 80$ GeV, $p_{T,\gamma\gamma} > 80$ GeV
- 100 GeV $< m_{bb} < 150$ GeV, 122 GeV $< m_{\gamma\gamma} < 128$ GeV

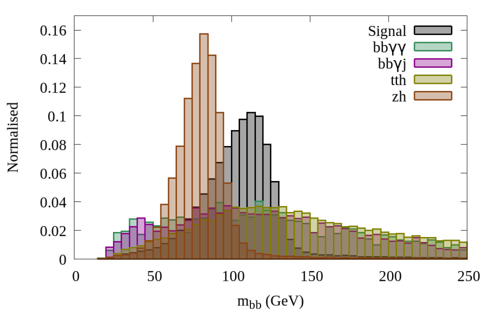
Effective in reducing the QED-QCD $b\bar{b}\gamma\gamma$, fake backgrounds and $t\bar{t}h$ backgrounds.



Selection cuts

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

Eliminates a significant chunk of Zh and $b\bar{b}h$ background.



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

The cut flow table

Cut flow	Event rates with 3000 fb^{-1} of integrated luminosity							$\frac{S}{\sqrt{B}}$
	Signal	SM Backgrounds						
	$hh \to 2b2\gamma$	$hb\bar{b}$	$t\bar{t}h$	Zh	$b\bar{b}\gamma\gamma*$	Fake 1	Fake 2	
$2b + 2\gamma$	31.63	21.20	324.91	39.32	25890.31	1141.18	393.79	0.19
lepton veto	31.63	21.20	255.66	39.32	25889.94	1141.18	393.79	0.19
$N_j < 6$	31.04	21	192.05	39.23	25352.78	1064.64	167.32	0.19
ΔR cuts	22.19	7.75	38.71	23.48	4715.21	130.10	28.81	0.31
m_{bb}	12.71	1.53	13.80	1.09	862.37	22.11	6.88	0.42
$m_{\gamma\gamma}$	12.36	1.5	13.16	1.06	26.54	22.11	6.88	1.46
$p_{T,bb}, p_{T,\gamma\gamma}$	12.32	1.48	13.03	1.06	26.54	21.82	6.88	1.46

Signal significance : $\frac{S}{B} = 0.17$ and $\frac{S}{\sqrt{B}} = 1.46$.

[0] $b\bar{b}\gamma\gamma* : b\bar{b}\gamma\gamma + c\bar{c}\gamma\gamma + jj\gamma\gamma$

[0] Fake 1: $b\bar{b}j\gamma + c\bar{c}j\gamma$, Fake 2: $b\bar{b}jj$.

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

Implications from $\not{E}_T$ cut and modified range of $m_{b\bar{b}}$

- The signal lacks any $\not{E}_T$ source.
- Leptonically decaying W-bosons in $t\bar{t}h$ can result in $\not{E}_T$.

Applying, $\not{E}_T < 50$ GeV

	Process	Events
Background	$hb\bar{b}$	1.31
	$t\bar{t}h$	7.87
	Zh	1.03
	$b\bar{b}\gamma\gamma*$	23.18
	Fake 1	20.69
	Fake 2	6.52
	Total	60.60
Signal ($hh \to 2b2\gamma$)		11.75
Significance ($S/\sqrt{B}$)		1.51

- Jet energy corrections can result in a shift in the $m_{b\bar{b}}$ distributions.

Applying, m_{bb} **:** $90GeV < m_{bb} < 130$ **GeV**

	Process	Events
Background	$hb\bar{b}$	1.55
	$t\bar{t}h$	11.91
	Zh	4.43
	$b\bar{b}\gamma\gamma*$	28.41
	Fake 1	22.39
	Fake 2	7.25
	Total	75.94
Signal ($hh \to 2b2\gamma$)		14.27
Significance ($S/\sqrt{B}$)		1.64

A multivariate analysis is also performed by utilising the Boosted Decision Tree (BDT) algorithm.

Variables used

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

The most effective variables in isolating the signal and backgrounds:
$m_{bb},\ p_{T,\gamma\gamma},\ \Delta R_{b_1\gamma_1},\ \Delta R_{bb}$

Features a $\sim 20\%$ improvement in signal significance.

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 ($hh \to 2b2\gamma$)		16.46
Significance ($S/\sqrt{B}$)		1.76

The $b\bar{b}\tau^+\tau^-$ channel

The τ leptons can decay either leptonically (34%) and hadronically.
Three final states : $b\bar{b}\tau_l\tau_l$, $b\bar{b}\tau_l\tau_h$, $b\bar{b}\tau_h\tau_h$.

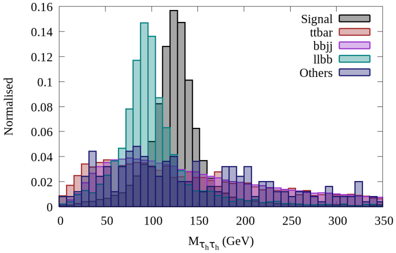
Background

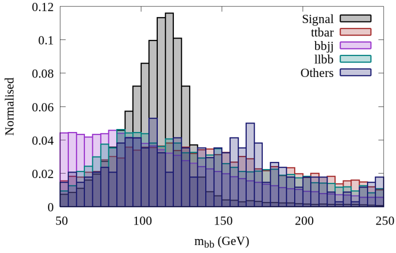
- Dominant background : $t\bar{t}$

  Contributions arise from hadronic, leptonic and semi-leptonic decay modes of $t\bar{t}$.
- $b\bar{b}Z^*/\gamma^* \to b\bar{b}\tau^+\tau^-$.
- $b\bar{b}h$.
- Zh.
- Associated production of bosons with $t\bar{t}$ pair : $t\bar{t}h$, $t\bar{t}W$, $t\bar{t}Z$
- Fake backgrounds : $b\bar{b}jj$.
- Other potential sources can be $W(\to \tau\nu) + \text{jets}$, Wh, WZ, $h \to ZZ^*$, however, are neglected because of small rates.

The $b\bar{b}\tau^+\tau^-$ channel

- The signal is marred by an extremely large $t\bar{t}$ background.
- Cut-based analysis, motivated from a similar search by ATLAS, results in a signal significance of $\sim$ 0.44, 0.26 and 0.044, for $b\bar{b}\tau_h\tau_h$, $b\bar{b}\tau_l\tau_h$ and $b\bar{b}\tau_l\tau_l$, respectively.
- Imposing an additional cut on $M_{\tau\tau} < 200$ GeV improves $S/\sqrt{B}$ to 0.65, 0.44 and 0.07.
- Multivariate analysis performed using the variables :
  $\tau_h\tau_h$: $p_{T,bb}$, m_{bb}, ΔR_{bb}, $M_{\tau_h\tau_h}$, m_{T2}, $\Delta\phi_{\tau_{h_1}\not{E}_T}$, $m_{hh}^{\rm vis}$, $p_{T,hh}^{\rm vis}$, $\Delta R_{hh}^{\rm vis}$,
  $\tau_h\tau_l$: $p_{T,bb}$, m_{bb}, ΔR_{bb}, $M_{\tau_h\tau_l}$, m_{T2}, $\Delta\phi_{\tau_h\not{E}_T}$, $\Delta\phi_{\tau_\ell\not{E}_T}$, $m_{hh}^{\rm vis}$, $\Delta R_{hh}^{\rm vis}$
  $\tau_l\tau_l$: $p_{T,bb}$, m_{bb}, ΔR_{bb}, $M_{\tau_l\tau_l}$, m_{T2}, $\Delta\phi_{\tau_{\ell_1}\not{E}_T}$, $\Delta\phi_{\tau_{\ell_2}\not{E}_T}$, $m_{hh}^{\rm vis}$
  results in a signal significance of 0.74, 0.49 and 0.077, respectively.





The $b\bar{b}W^+W^-$ channel

Three possible final states :

- Fully leptonic : $b\bar{b}ll + \not{E}_T$. **Cleaner signature and lesser background.**
- Semi leptonic : $b\bar{b}l +$ *jets* $+ \not{E}_T$.
- Hadronic : $b\bar{b} +$ *jets*..

Backgrounds

- Dominant background : $t\bar{t}$
  Fully leptonic $t\bar{t}$ contributes as dominant background to $b\bar{b}ll + \not{E}_T$.
  Leptonic and semi-leptonic contributes as dominant background to $b\bar{b}l +$ *jets* $+ \not{E}_T$.
- Second most dominant background for the semi-leptonic case : $Wb\bar{b} + jets$
- Other contributing backgrounds : $llb\bar{b}$, $b\bar{b}h$, $t\bar{t}h$, $t\bar{t}V$, Vh, $Vb\bar{b}$ and VVV

The $2b2l + \not{E}_T$ channel :

Multivariate analysis is performed using BDT algorithm.

Variables used :

$$p_{T,\ell_{1/2}},\ \not{E}_T,\ \mathrm{m}_{\ell\ell},\ \mathrm{m}_{\mathrm{bb}},\ \Delta\mathrm{R}_{\ell\ell},\ \Delta\mathrm{R}_{\mathrm{bb}},\ \mathrm{p}_{\mathrm{T,bb}},\ \mathrm{p}_{\mathrm{T},\ell\ell},\ \Delta\phi_{\mathrm{bb}\ \ell\ell},$$

- The BDT algorithm is trained by using the signal sample and the $t\bar{t}$ background only.
- Best discriminatory variables : m_{bb}, $m_{\ell\ell}$, $p_{T,bb}$ and $p_{T,\ell\ell}$

Sl. No.	Process	Events
Background	$t\bar{t}$ lep	2080.52
	$t\bar{t}h$	131.66
	$t\bar{t}Z$	106.31
	$t\bar{t}W$	35.97
	$hb\bar{b}$	~ 0
	$\ell\ell b\bar{b}$	842.72
	Total	3197.18
Signal ($hh \to b\bar{b}WW \to b\bar{b}\ell\ell + \not{E}_T$)		35.20
Significance ($S/\sqrt{B}$)		0.62

The $b\bar{b}W^+W^-$ channel

The $1l2j2b + \not{E}_T$ channel :

- Dominant background : Semi-leptonic and leptonic decays of $t\bar{t}$
- Input variables used :

$$p_{T,\ell},\ \not{E}_T,\ \mathrm{m_{jj}},\ \mathrm{m_{bb}},\ \Delta\mathrm{R_{jj}},\ \Delta\mathrm{R_{bb}},\ \mathrm{p_{T,bb}},\ \mathrm{p_{T,\ell jj}},\ \Delta\phi_{\mathrm{bb}\ \ell\mathrm{jj}},\ \Delta\mathrm{R}_{\ell\ \mathrm{jj}},$$

where $p_{T,\ell jj}$ refer to the p_T of the ℓjj system (Eg., for the signal, ensuing from the $h \to WW^* \to \ell\nu jj$ decay).

- Background training is performed using $t\bar{t}$.
- The best discriminatory observables : m_{bb}, p_{T,ℓ_1}, $p_{T,bb}$ and $\not{E}_T$.

Sl. No.	Process	Events
Background	$t\bar{t}$ semi-lep	866990.56
	$t\bar{t}$ lep	96147.82
	$t\bar{t}h$	4508.25
	$t\bar{t}Z$	5192.52
	$t\bar{t}W$	2949.65
	$Wb\bar{b} + \mathrm{jets}$ [LO]	121313.52
	$\ell\ell b\bar{b}$	5780.47
	Total	1102882.79
Signal ($hh \to 2b2W$)		134.34
Significance ($S/\sqrt{B}$)		0.13

The $W^+W^-\gamma\gamma$ channel

We analyse two different final states : • Fully leptonic : $\ell^+\ell^-\gamma\gamma + \not{E}_\mathrm{T}$. • Semi-leptonic : $\ell jj\gamma\gamma + \not{E}_\mathrm{T}$.

Features smaller signal yield, however, has lesser background.

The pure leptonic decay :

Backgrounds : • $t\bar{t}h$, • Zh, • $ll\gamma\gamma$.

- Variables for multivariate analysis :

$$p_{T,\ell_{(1,2)}},\ \not{E}_\mathrm{T},\ \mathrm{m}_{\ell\ell},\ \mathrm{m}_{\gamma\gamma},\ \Delta\mathrm{R}_{\gamma\gamma(\ell\ell)},\ \mathrm{p}_{\mathrm{T},\ell\ell},\ \mathrm{p}_{\mathrm{T},\gamma\gamma},\ \Delta\phi_{\ell\ell\ \gamma\gamma}, \tag{1}$$

- Best discriminating variables : $m_{\ell\ell}$, $\not{E}_\mathrm{T}$, $p_{T,\gamma\gamma}$, $m_{\gamma\gamma}$

Sl. No.	Process	Events
Background	$t\bar{t}h$	0.89
	Zh + jets	0.20
	$\ell\ell\gamma\gamma$ + jets	0.33
Total		1.42
Signal		0.57

- Features one of the best $\frac{S}{B}$ values ~ 0.40.
  Has the potential to become an important channel for HE-LHC owing to higher $\frac{S}{B}$.

The $W^+W^-\gamma\gamma$ channel

The semi-leptonic case :

Backgrounds

- Irreducible background : $l\nu\gamma\gamma$ ($\sigma = 3.28$ fb)
- Mis-identified background : $ll\gamma\gamma$ ($\sigma = 1.05$ fb)
  - Both, generated with $120\ \mathrm{GeV} < m_{\gamma\gamma} < 130\ \mathrm{GeV}$
- Other important backgrounds: $t\bar{t}h$, Zh+jets, Wh

Variables used : p_{T,ℓ_1}, $\not{E}_{\mathrm{T}}$, $\mathrm{m}_{\gamma\gamma}$, $\Delta\mathrm{R}_{\gamma\gamma}$, $\mathrm{p}_{\mathrm{T},\gamma\gamma}$, $\mathrm{p}_{\mathrm{T},\ell\mathrm{j}}$, $\Delta\phi_{\ell\mathrm{j}\ \gamma\gamma}$, $\Delta\mathrm{R}_{\ell\mathrm{j}}$, m_{T}

Most discriminating variables :
$\Delta R_{\ell j}$, $p_{T,\gamma\gamma}$, $m_{\gamma\gamma}$ and m_T

Sl. No.	Process	Events
Background	$t\bar{t}h$	6.49
	Zh + jets	1.71
	Wh + jets	5.13
	$\ell\nu\gamma\gamma$ + jets	2.57
	$\ell\ell\gamma\gamma$ + jets	1.07
	Total	16.97
Signal		1.85

The $4W$ channel

We choose these final states :
• Same-sign di-leptons ($SS2\ell$): $\ell^{\pm}\ell^{\pm} + 4j + \not{E}_T$, • Tri-leptons ($3\ell$) : $3\ell + 2j + \not{E}_T$,
• Four leptons (4ℓ) : $4\ell + \not{E}_T$.

Backgrounds

- SS2l :
  - Dominant backgrounds : $WZ(W \to \ell\nu, Z \to \ell\ell)$ and same-sign W-pair.
  - Other important ones : Vh, $t\bar{t}X$ $(X = W^{\pm}, Z, h)$, • Fakes : $t\bar{t}$.
- 3l :
  - Dominant backgrounds : Wh, WZ, • Fake backgrounds : $t\bar{t}$
  - Others : Zh $(Z \to \ell\ell, h \to W^+W^-)$, $t\bar{t}X$ $(X = W^{\pm}, Z, h)$ and ZZ
- 4l :
  - Fake backgrounds : $t\bar{t}$ • Other important backgrounds : Wh, $t\bar{t}h$, $t\bar{t}$, ZZ and Zh

Variables used for multivariate analysis :

- SS2l: $m_{\ell^{\pm}\ell^{\pm}}$, $\Delta R_{\ell_i j_k}$, m_{jj}.
- 3l: $m_{\ell_i\ell_j}$, $\Delta R_{\ell_i\ell_j}$, $m_{\ell\ell\ell}$, $m_{\rm eff}$, $\not{E}_T$, p_{T,ℓ_i}, $n_{\rm jet}$.

The $4W$ channel

We choose these final states :
• Same-sign di-leptons ($SS2\ell$): $\ell^\pm\ell^\pm + 4j + \not{E}_T$, • Tri-leptons ($3\ell$) : $3\ell + 2j + \not{E}_T$,
• Four leptons (4ℓ) : $4\ell + \not{E}_T$.

Backgrounds

- SS2l :
  - Dominant backgrounds : $WZ(W \to \ell\nu, Z \to \ell\ell)$ and same-sign W-pair.
  - Other important ones : Vh, $t\bar{t}X$ $(X = W^\pm, Z, h)$, • Fakes : $t\bar{t}$.
- 3l :
  - Dominant backgrounds : Wh, WZ, • Fake backgrounds : $t\bar{t}$
  - Others : Zh $(Z \to \ell\ell, h \to W^+W^-)$, $t\bar{t}X$ $(X = W^\pm, Z, h)$ and ZZ
- 4l :
  - Fake backgrounds : $t\bar{t}$ • Other important backgrounds : Wh, $t\bar{t}h$, $t\bar{t}$, ZZ and Zh

SS2l :

		Events
Background	Total	12366.53
Signal		11.96
Significance $(S/\sqrt{B})$		0.11

3l :

		Events
Background	Total	5374.45
Signal		15.01
Significance $(S/\sqrt{B})$		0.20

4l :

		$\not{E}_T$ cut
		> 50 GeV
Background	5876.22	131.51
Signal	2.02	1.42

- Combination of results from the previous channels yield a combined signifiance of 2.1σ.
- Small di-Higgs production rate makes the prospect of discovering di-Higgs at the HL-LHC quite weak.
- The $b\bar{b}\gamma\gamma$ channel offers the highest signal significance.
- The $WW\gamma\gamma$ channel has the potential to play an important role in di-Higgs searches at higher luminosities or HE-LHC, owing to its excellent S/B value.

Ramifications of varying λ_{hhh}

- The HL-LHC study by ATLAS[a] predicts a sensitivity of $-0.8 < \lambda_{hhh}/\lambda_{SM} < 7.7$.
- Change in λ_{hhh} can alter the di-Higgs production rate as well as the kinematics.

[a] ATL-PHYS-PUB-2017-001

5 different values of $\lambda_{hhh}/\lambda_{SM}$ is considered : -1, 1, 2, 5, 7, and we do the following:

Signal production is done with the new λ_{hhh} values, and

- Case A : Passed through the cut-based analysis optimized for SM case ($\lambda_{hhh}/\lambda_{SM} = 1$).
- Case B : Passed through the BDT analysis optimized for SM case ($\lambda_{hhh}/\lambda_{SM} = 1$).
- Case C : The BDT framework is trained with an alternative $\lambda_{hhh}/\lambda_{SM} = 5$
- Case D : Training is performed for each specific value of λ_{hhh}.

Ramifications of varying λ_{hhh}

Case A : Passed through the cut-based analysis optimized for SM case $(\lambda_{hhh}/\lambda_{SM} = 1)$

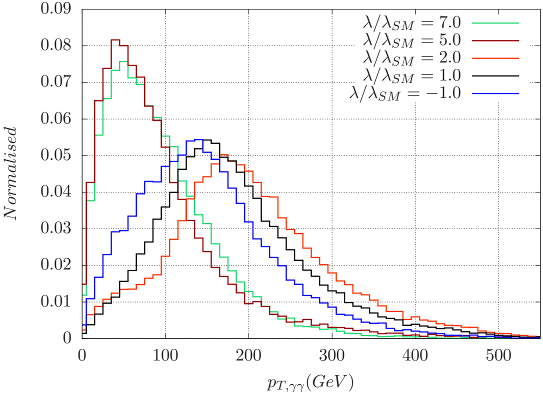
Cut Based (optimised for $\lambda_{hhh}/\lambda_{SM} = 1$)					
λ/λ_{SM}	Sigma xs (fb)	Efficiency	Signal yield	Background yield	$S/\sqrt{B}$
-1	0.40	0.027	32.40	70.81	3.85
1	0.105	0.039	12.28		1.46
2	0.05	0.046	6.90		0.82
5	0.26	0.008	6.24		0.74
7	0.70	0.010	21.00		2.49

Case B : Passed through the BDT analysis optimized for SM case $(\lambda_{hhh}/\lambda_{SM} = 1)$.

BDT (optimised for $\lambda_{hhh}/\lambda_{SM} = 1$)					
λ/λ_{SM}	Signal xs (fb)	Efficiency	Signal yield	Background yield	$S/\sqrt{B}$
-1	0.40	0.035	41.76	87.05	4.48
1	0.105	0.052	16.46		1.76
2	0.05	0.063	9.42		1.01
5	0.26	0.010	7.84		0.84
7	0.70	0.011	23.10		2.48

Ramfications of varying λ_{hhh}

Difference in kinematic distributions cropping from variation in λ_{hhh} :



Ramifications of varying λ_{hhh}

Case D

Training the BDT with corresponding λ_{hhh} samples $\rightarrow$

- the training becomes more tuned to the modified kinematic distributions.

Marks an improvement in the signal significance.

BDT (optimised for each λ_{hhh})					
λ/λ_{SM}	Signal xs (fb)	Efficiency	Signal yield	Background yield	$S/\sqrt{B}$
-1	0.40	0.049	58.80	166.13	4.55
1	0.105	0.052	16.46	87.05	1.76
2	0.05	0.068	10.20	85.54	1.10
5	0.26	0.046	35.88	455.51	1.69
7	0.70	0.049	102.90	466.97	4.76

- Changes accounting from variations in λ_{hhh} requires a careful analysis.
- Using the kinematic distributions to segregate the modifications emerging from changes in λ_{hhh} would be essential in searches for new physics.

Contaminations to non-resonant di-Higgs pair production.

- The SM signal is susceptible to contamination or distortion from small new physics effects.
- Statistically significant deviations may be considered as New Physics signatures.
- Deviations can also be solely attributed to modifications in λ_{hhh}.

The BDT was trained to maximize the SM di-Higgs yield $\rightarrow$ Do the NP signatures mimic the SM signal and render the BDT optimisation insensitive?

Contaminations can arise if :

- the discriminatory kinematics variables used to train the BDT, have a significant overlap with the SM counterparts.
- large new physics cross-section, with a smaller kinematic overlap.

We study some such imposters ensuing from various well-motivated new physics scenarios through benchmark studies.

New Physics scenarios

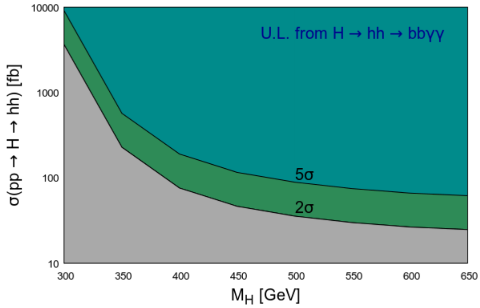
A typical example would be extensions of SM, with an extended Higgs sector. Resonant heavy Higgs production followed by decay into SM-like Higgs pair can enhance the di-Higgs cross-section.

Three possible scenarios which can contaminate :

- Double Higgs production : $pp \to hh(+X)$
- Single Higgs production : $pp \to h + X$
- Null Higgs scenario : $pp \to X$

We derive upper limits on $\sigma(pp \to H \to hh)$ as a function of M_H, in a model independent fashion, using the inequality $S_{NP}^{UL}/\sqrt{B_{SM}} \geq N\sigma$.

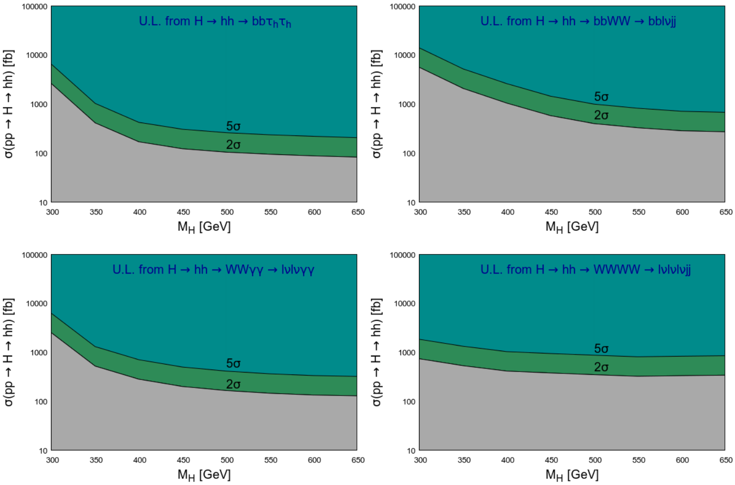
- B_{SM} includes the SM backgrounds as well as the SM di-Higgs contirbution.
- The BDT optimization derived for non-resonant SM di-Higgs has been used to quantify the amount of contamination.



- The grey region do not contaminate the SM expectation.
- The blue and green region contaminate at 5σ and 2σ.

The $hh(+X)$ channel

Upper limits corresponding to all other non-resonant di-Higgs final states considered earlier, were obtained.



The $hh(+X)$ channel

Generic features :

- Strongest upper limits are obtained for $b\bar{b}\gamma\gamma$. Around ~ 25 fb at $M_H = 650$ GeV.
- $b\bar{b}\tau\tau$ offers the second strongest bound. Cross-section varies between $170 - 80$ fb.
- $b\bar{b}WW^*$, varying between 228 fb and 40 fb for m_H varying between 450 GeV and 650 GeV.
- The 2σ upper limit plateaus between 129 fb and 282 fb for the fully leptonic case $WW\gamma\gamma$.
- Bounds from the $4W$ modes are much weaker.

The $h + X$ channels

Resonant production of pseudoscalar Higgs boson, followed by its decay into $A \to Zh$, can imitate a majority of di-Higgs final states.

Within MSSM, $A \to Zh$ can be appreciable below $t\bar{t}$ threshold.

We derive upper limits on $\sigma(pp \to A \to Zh)$ as a function of M_A.

- Weaker limits than those from resonant scalar production.
- $b\bar{b}\tau\tau$ yields the strongest upper limit : 292 *fb* to 186 *fb*.
- Upper limits from $b\bar{b}\gamma\gamma$ vary in between : $\sim$ 330 *fb* to $\sim$ 197 *fb* (at 650 GeV).
- Upper limits from di-leptonic $b\bar{b}WW$ strengthens from 1236 *fb* to 110 *fb* (at 650 GeV).
- $m_{b\bar{b}}$ serves as an important discriminator between the Zh and hh signals, thereby, weakening the contamination from $A \to Zh$.
- Hence, more cross-section required to contaminate the SM signal to the same degree as in the $H \to hh$ channel.

The $h + X$ channels

SUSY contamination to $h + X$

- Bounds on squarks and gluino have already surpassed a TeV.
- The elctroweakino sector still remains as the plausible search area.
- We choose a benchmark point marginally outside the projected exclusion obtained by ATLAS for HL-LHC.
- Pair production of wino dominated $\chi_2^0 \chi_1^\pm$ is considered (cross-section $= 420$ fb).

Parameters (GeV)	Mass (GeV)	Processes	Branching Fraction
$M_1 = 150, M_2 = 300$ $\mu = 1000, m_{\tilde{t}_R} = 3000$	$m_{\chi_2^0} = 296.7$ $m_{\chi_1^\pm} = 296.7$ $m_{\chi_1^0} = 149.3$ $m_h = 125.0$ $m_{H^\pm} = 1003.0$ $m_H = 1000.0$	$\chi_1^\pm \to \chi_1^0 W^\pm$ $\chi_2^0 \to \chi_1^0 h$	100% 93.5%

The $h + X$ channels

The $Wh + \not{E}_T$ final state has the potential to contaminate some of the di-Higgs search channels :
$b\bar{b}WW^* \to b\bar{b}\ell jj + \not{E}_T$, $\gamma\gamma WW^* \to \gamma\gamma\ell jj + \not{E}_T$, $4W \to \ell^\pm\ell^\pm jjjj + \not{E}_T, 3\ell\mathrm{jj} + \not{E}_T$

Channel	SM background	SM hh production	BP2 contamination
$bb\ell jj + \not{E}_T$	1103017.13	134.34	382.88
SS2$\ell jj + \not{E}_T$	12378.49	11.96	270.31
$3\ell jj + \not{E}_T$	5389.46	15.01	291.91

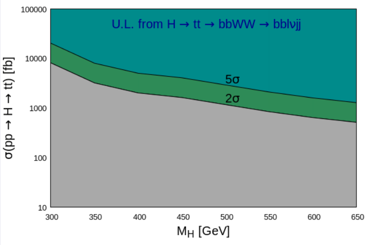
- SM di-Higgs expectations for these channels are relatively small as compared to the SUSY comtaminations.
- Observation of significant number of events in these channels over and above SM backgrounds can be a potential signature of New Physics.

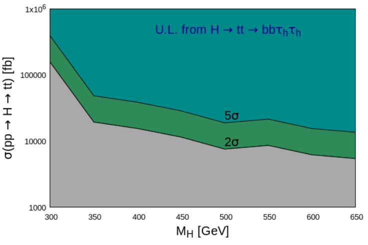
The null Higgs channels

This category of contaminant has no Higgs in the production or decay mode.

$pp \to H(A) \to t\bar{t}$ **can potentially contaminate the** $b\bar{b}\tau\tau$ **and** $b\bar{b}WW$ **final states.**

- We derive upper limits on $\sigma(pp \to H(A) \to t\bar{t})$ for both final states from $b\bar{b}WW$, and $b\bar{b}\tau\tau$.
- Relatively weaker final states are obtained $\to \sigma \times Br$ values reaching to pb values.





- Lower contamination is ensured by the BDT varibale $m_{b\bar{b}}$, owing to difference in kinematics of the final state $b\bar{b}$ pair.
- Large production cross-section of heavier Higgs will be required in order to contaminate the SM di-Higgs signal.

Null Higgs channel

SUSY contamination to null Higgs channel.

We consider stop pair production : $pp \to \tilde{t}_1 \tilde{t}_1^*$, using the following benchmark :

Benchmark Points	Parameters (GeV)	Mass (GeV)	Processes	Branching Fraction
3rd benchmark BP3 $pp \to \tilde{t}_1 \tilde{t}_1^*$ (Cross-section: 200 fb)	$M_1 = 500, M_2 = 1000$ $\mu = 1000, m_{\tilde{t}_R} = 625$	$m_{\tilde{t}_1} = 609.3$ $m_{\chi_1^0} = 498.1$ $m_h = 125.0$ $m_{H^\pm} = 1003.0$ $m_H = 1000.0$	$\tilde{t}_1 \to \chi_1^0 \, b \, W^+$	99.9%

- The benchmark point is chosen such that mass difference between $\tilde{t}_1$ and χ_1^0 is less than the top mass, ensuring the stop decays as $\tilde{t}_1 \to Wb\chi_0^1$.
- It can potentially contaminate $pp \to b\bar{b}WW$ and $pp \to b\bar{b}\tau\tau$ final states.

Contamination from stop pair production in the $b\bar{b}WW \to b\bar{b}ljj + \not{E}_T$ final state comes out to be of same order as the SM signal.

SM background	SM hh production	BP3 contamination
1103017.13	134.34	101.83

Summary till now

- A clear understanding of the Higgs self-coupling will require a precise analysis of the di-Higgs channel.
- Combination of results from multiple search channels yield a signal significance of 2.1σ.
- The effects of varying λ_{hhh} was analyzed, and it was observed that varying λ_{hhh} can significantly alter our conclusions.
- New Physics scenarios can contaminate the SM di-higgs signals. Contaminations can creep in from $H \to hh$, $A \to Zh$, $H \to t\bar{t}$, $H^{\pm} \to t\bar{b}, \tau\nu_{\tau}$.
- Contaminations from benchmark scenarios of squark pair production, electroweakino pair production and stop pair production were quantified. In most cases, the contaminations can pose a serious threat to the search analyses.

Possible future directions

- A detailed study of the less explored di-higgs final states in the context of HE-LHC. We are currently looking into the future prospect of $WW\gamma\gamma$ channel at HE-LHC.
- Moreover, a global combination of various di-Higgs signals at HE-LHC could provide interesting results concerning the projected capability of HE-LHC in probing λ.
- A detailed qualitative understanding of the alterations in the distribution of various kinematic variables emerging from different values of Higgs tri-linear coupling and aim to improve upon the robustness of the existing search strategies.
- Compilation of various allowed BSM benchmark scenarios which could possibly contaminate the di-Higgs final states.

Thank you.