Searches for the Higgs pair production at the HL-LHC and beyond

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April 24, 2018

Based on

arXiv: 1712.05346 (with A. Adhikary, R. K. Barman, B. Bhattacherjee and S. Niyogi)
arXiv: 1608.08601 (Phys. Rev. D 95, 035009) (with B. Batell and M. Spannowsky)
arXiv: 1802.01607 (Eur. Phys. J. C (2018) 78: 322) (with C. Englert, M. Mangano, M. Selvaggi and M. Spannowsky)

Plan of my talk

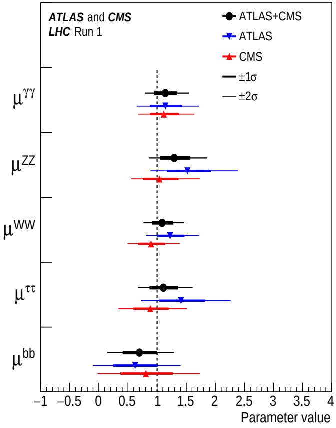
- Motivation
- Status of the di-Higgs searches
- Non resonant di-Higgs production at the HL-LHC
- Higgs invisible decays in the Higgs pair productions
- Contaminations to the Higgs pair producing channels
- Di-Higgs + jet at a 100 TeV collider
- Other exotic di-Higgs final states
- Summary and Conclusions

The story so far

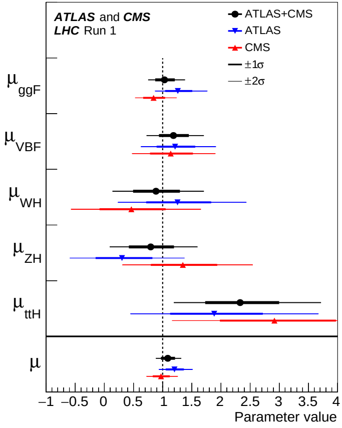
- The nature of the discovered boson is more or less consistent with the *SM* Higgs
- Its combined (CMS + ATLAS) mass, from run-I data, is measured to be $M_h = 125.09 \pm 0.21$ (stat.) ± 0.11 (syst.) GeV in the $h \to \gamma\gamma$ and the $h \to ZZ^* \to 4\ell$ channels
- A *CP*-even spin zero hypothesis is favoured
- If it is "the Higgs", then its mass has fixed the *SM*
- Still to be measured: $h \to Z\gamma$, $h \to \mu^+\mu^-$, y_t, λ_{hhh}
- Till a reliable measurement of self-coupling is available it is best to consider the available final states that reflect the Higgs couplings

Signal strengths (7 + 8 TeV @ 25 fb^{-1}) !!!

Final states



Production modes



[arXiv:1606.02266]

Motivation

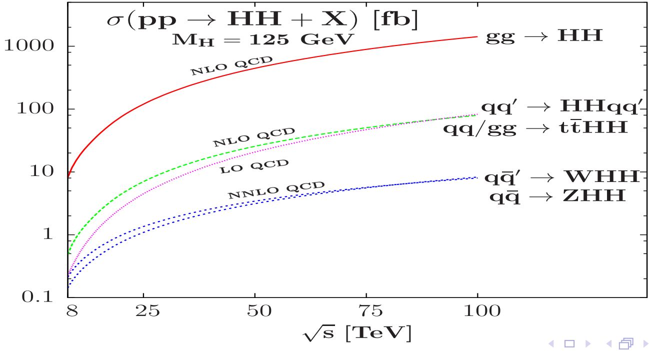
- Di-Higgs provides means to directly probe Higgs self coupling
- Indirect probe: Through radiative corrections of single Higgs productions [Goertz *et. al.*, 2013, McCullough, 2013, Degrassi *et. al.*, 2016]
- Challenging task : small di-Higgs cross-section in SM ($39.56^{+7.32\%}_{-8.38\%}$ fb at NNLO + NNLL at 14 TeV with the exact top-quark mass dependence at NLO [deFlorian *et. al.*, 2013, Borowka *et. al.*, 2016]) $\leftarrow$ partial cancellation of triangle and box diagram contributions
- LHC or 100 TeV colliders : self-coupling measurement at 10-50% precision possible $\rightarrow$ size of dataset, beam energy, control over systematics
- Assuming SM couplings, HL-LHC prediction: $-0.8 < \frac{\lambda}{\lambda_{\rm SM}} < 7.7$ at 95% C.L. [ATL-PHYS-PUB-2017-001]

Motivation

- Enhancement of σ_{hh} $\rightarrow$ s-channel heavy di-Higgs resonance [xSM models *etc.*] [Mühlleitner *et. al.*, 2015; Ramsey-Musolf *et. al.*, 2016 *etc.*], new coloured particles in loops [Kribs *et. al.*, 2012, Nakamura *et. al.*, 2017] or HD operators [Nishiwaki *et. al.*, 2013] $\rightarrow$ kinematics altered $\rightarrow$ requires different experimental search strategies
- Till date $\rightarrow$ major focus on BSM di-Higgs sector $\rightarrow$ enhancement in production
- New physics can affect Higgs *decays* $\rightarrow$ exotic Higgs decays now actively studied [Curtin *et. al.*, 2015]
- $\sigma_{pp\rightarrow h} \gg \sigma_{pp\rightarrow hh}$ $\rightarrow$ expect exotic Higgs decays to show up in single Higgs channels first unless di-Higgs is enhanced considerably
- Worthwhile to consider exotic decays for di-Higgs $\rightarrow$ present bounds on variety of Higgs decays : BR very weak (10-50%)

Di-Higgs production cross-sections at 14 TeV

- Di-Higgs cross-section largest in the *ggF* mode
- In *VBF* @ NLO : $2.01^{+7.6\%}_{-5.1\%}$ fb
- In *Whh* @ NNLO : $0.57^{+3.7\%}_{-3.3\%}$ fb
- In *Zhh* @ NNLO : $0.42^{+7.0\%}_{-5.5\%}$ fb
- In $qq'(gg) \to t\bar{t}hh$ @ LO : 1.02 fb [Baglio *et. al.*, 2012]



Status of the di-Higgs searches

Channel	CMS (NR) ($\times$SM)	CMS (R) [fb, (GeV)]	ATLAS (NR) ($\times$SM)	ATLAS (R) [fb, (GeV)]
$b\bar{b}b\bar{b}$	342	1511-47 (260-1200)	13	2000-2 (260-3000)
$b\bar{b}\gamma\gamma$	19.2	232-325 (250-900)	117	7000-4000 (275-400)
$b\bar{b}\tau^+\tau^-$	30	3120-73 (250-900)		
$\gamma\gamma WW^*$ ($\gamma\gamma\ell\nu jj$)			747	47700-24300 (260-500)
$b\bar{b}\ell\nu\ell\nu$	79	20499-803 (300-900)		

NR: Non-resonant, R: Resonant, $\sim$ 36 fb^{-1}, $\sim$ 13.3 fb^{-1} and $\sim$ 2.3-3.2 fb^{-1}

Non resonant di-Higgs production at the HL-LHC

- We choose channels based on the rate and cleanliness
- Focus on final states with leptons and/or photons
- Focus on 11 channels, *viz.*
  - $b\bar{b}\gamma\gamma$
  - $b\bar{b}\tau^+\tau^- \to b\bar{b}\ell\ell + \not{E}_T,\ b\bar{b}\ell\tau_h + \not{E}_T,\ b\bar{b}\tau_h\tau_h + \not{E}_T$
  - $b\bar{b}WW^* \to b\bar{b}\ell\ell + \not{E}_T,\ b\bar{b}\ell jj + \not{E}_T$
  - $WW^*\gamma\gamma \to \ell\ell\gamma\gamma + \not{E}_T,\ \ell jj\gamma\gamma + \not{E}_T$
  - $WW^*WW^* \to \ell^\pm\ell^\pm jjjj + \not{E}_T,\ \ell\ell\ell jj + \not{E}_T,\ \ell\ell\ell\ell + \not{E}_T$
- $4\tau,\ WW^*\tau^+\tau^-,\ ZZ^*\tau^+\tau^-,\ 4\gamma,\ ZZ^*\gamma\gamma,\ 4Z$ may be important at 100 TeV colliders
- Follow CMS and ATLAS analyses (when available) and optimise upon them

Non resonant di-Higgs production at the HL-LHC: $b\bar{b}\gamma\gamma$

- Cleanest channel in spite of the low rate
- Major backgrounds: QCD-QED $b\bar{b}\gamma\gamma$, $hb\bar{b}$, $t\bar{t}h$, Zh
- Dominant fakes: $c\bar{c}\gamma\gamma, jj\gamma\gamma, b\bar{b}j\gamma, c\bar{c}j\gamma, b\bar{b}jj$

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

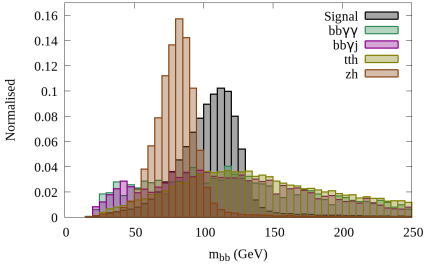
- significance: $S/B = 0.17$ and $S/\sqrt{B} = 1.46$
- With additional $\not{E}_T < 50$ GeV, $S/B = 0.19$ and $S/\sqrt{B} = 1.51$
- Changing to: 90 GeV $< m_{bb} <$ 130 GeV: $S/B = 0.19$ and $S/\sqrt{B} = 1.64$

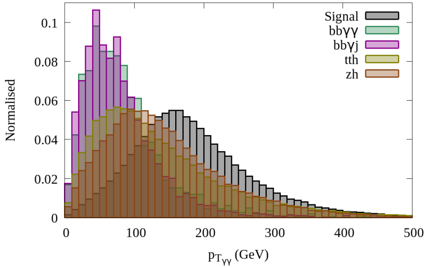
- Multivariate technique employed to further optimise search
- Boosted decision tree (BDT) algorithms chosen
- Overtaining checked using the Kolmogorov-Smirnov test
- Variables chosen:

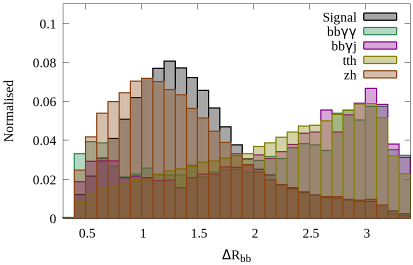
$$m_{bb},\ p_{T,\gamma\gamma},\ \Delta R_{\gamma\gamma},\ p_{T,bb},\ \Delta R_{b_1\gamma_1},\ p_{T,\gamma_1},\ \Delta R_{bb},$$
$$p_{T,\gamma_2},\ \Delta R_{b_2\gamma_1},\ \Delta R_{b_2\gamma_2},\ p_{T,b_1},\ \Delta R_{b_1\gamma_2},\ p_{T,b_2},\not{E}_T$$

- $S/B = 0.19$ and $S/\sqrt{B} = 1.76\sigma$ CMS (ATLAS) projection: 1.6σ (1.05σ)

Non resonant di-Higgs production at the HL-LHC: $b\bar{b}\gamma\gamma$







Non resonant di-Higgs production at the HL-LHC: $b\bar{b}\tau^+\tau^-$

- Major backgrounds: $t\bar{t}$ (hadronic, semi-leptonic and leptonic), $\ell\ell b\bar{b}$, $hb\bar{b}$, Zh, $t\bar{t}X$, $b\bar{b}jj$
- Variables for $\tau_h\tau_h$, $\tau_h\tau_\ell$ and $\tau_\ell\tau_\ell$:

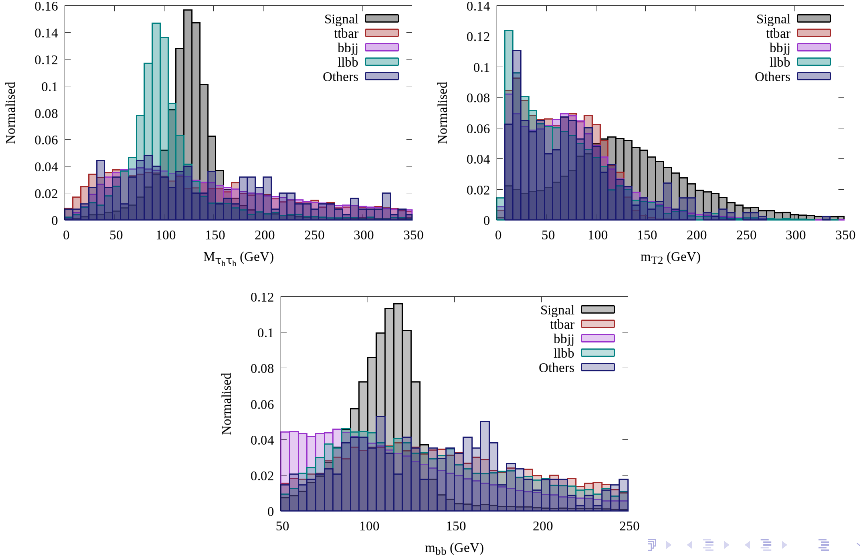
$$p_{T,bb},\ m_{bb},\ \Delta R_{bb},\ M_{\tau_h\tau_h},\ m_{T2},\ \Delta\phi_{\tau_{h_1}\not{E}_T},\ m_{hh}^{\mathrm{vis}},\ p_{T,hh}^{\mathrm{vis}},\ \Delta R_{hh}^{\mathrm{vis}}$$

$$p_{T,bb},\ m_{bb},\ \Delta R_{bb},\ M_{\tau_h\tau_l},\ m_{T2},\ \Delta\phi_{\tau_h\not{E}_T},\ \Delta\phi_{\tau_\ell\not{E}_T},\ m_{hh}^{\mathrm{vis}},\ \Delta R_{hh}^{\mathrm{vis}}$$

$$p_{T,bb},\ m_{bb},\ \Delta R_{bb},\ M_{\tau_l\tau_l},\ m_{T2},\ \Delta\phi_{\tau_{\ell_1}\not{E}_T},\ \Delta\phi_{\tau_{\ell_2}\not{E}_T},\ m_{hh}^{\mathrm{vis}}$$

- $\tau_h\tau_h$: $S/B = 0.013$, $S/\sqrt{B} = 0.74$; $\tau_h\tau_\ell$: $S/\sqrt{B} = 0.49$; $\tau_\ell\tau_\ell$: $S/\sqrt{B} = 0.08$

Non resonant di-Higgs production at the HL-LHC: $b\bar{b}\tau^+\tau^-$



Non resonant di-Higgs production at the HL-LHC: $b\bar{b}WW^*$

- Two scenarios considered: leptonic: $b\bar{b}\ell\ell + \not{E}_T$ and semi-leptonic: $b\bar{b}\ell jj + \not{E}_T$
- Major backgrounds: $t\bar{t}$: leptonic and semi-leptonic, $Wb\bar{b}+$ jets: semi-leptonic, $\ell\ell bb$: leptonic and semi-leptonic
- Subdominant backgrounds: $b\bar{b}h$, $t\bar{t}h$, $t\bar{t}V$, Vh, $Vb\bar{b}$, VVV: leptonic and semi-leptonic
- Variables for $b\bar{b}\ell\ell + \not{E}_T$

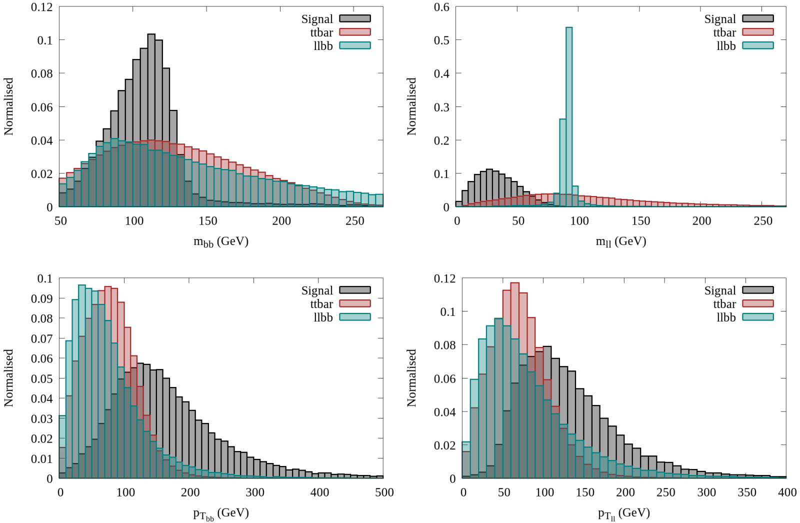
$$p_{T,\ell_{1/2}},\ \not{E}_T,\ m_{\ell\ell},\ m_{bb},\ \Delta R_{\ell\ell},\ \Delta R_{bb},\ p_{T,bb},\ p_{T,\ell\ell},\ \Delta\phi_{bb\,\ell\ell},$$

- Variables for $b\bar{b}\ell jj + \not{E}_T$

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

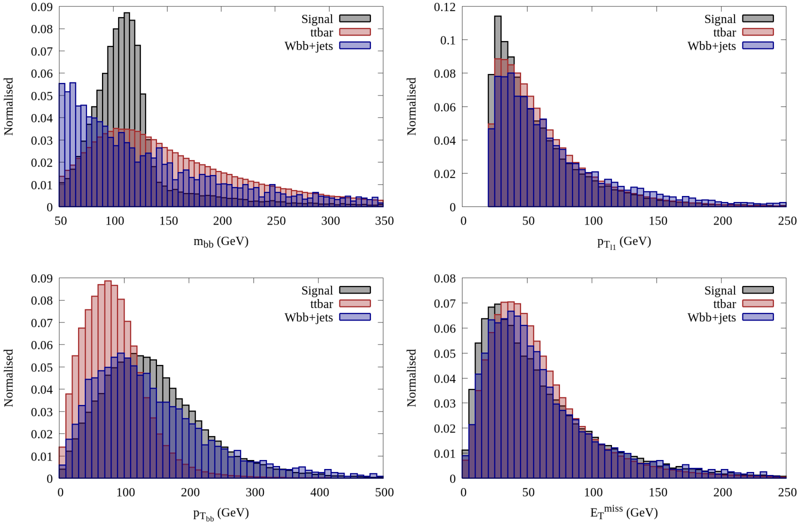
Non resonant di-Higgs production at the HL-LHC: $b\bar{b}WW^*$

- Leptonic: $S/B = 0.01$ and $S/\sqrt{B} = 0.62$; CMS projection: $S/B = 0.009$ and $S/\sqrt{B} = 0.59$



Non resonant di-Higgs production at the HL-LHC: $b\bar{b}WW^*$

- Semi-leptonic: $S/B = 1.2 \times 10^{-4}$ and $S/\sqrt{B} = 0.13$



Non resonant di-Higgs production at the HL-LHC: $\gamma\gamma WW^*$

- We study fully leptonic: $\ell^+\ell^-\gamma\gamma + \not{E}_T$ and semi-leptonic: $\ell jj\gamma\gamma + \not{E}_T$ states
- Fully hadronic case entails an enormous background
- Backgrounds: $t\bar{t}h$, $Zh+$ jets, $\ell\ell\gamma\gamma+$ jets (leptonic) and $Wh+$ jets, $\ell\nu\gamma\gamma+$ jets (in addition for semi-leptonic case)
- In addition demand b-jet veto to control the $t\bar{t}h$ backgrounds
- Variables for $\ell^+\ell^-\gamma\gamma + \not{E}_T$

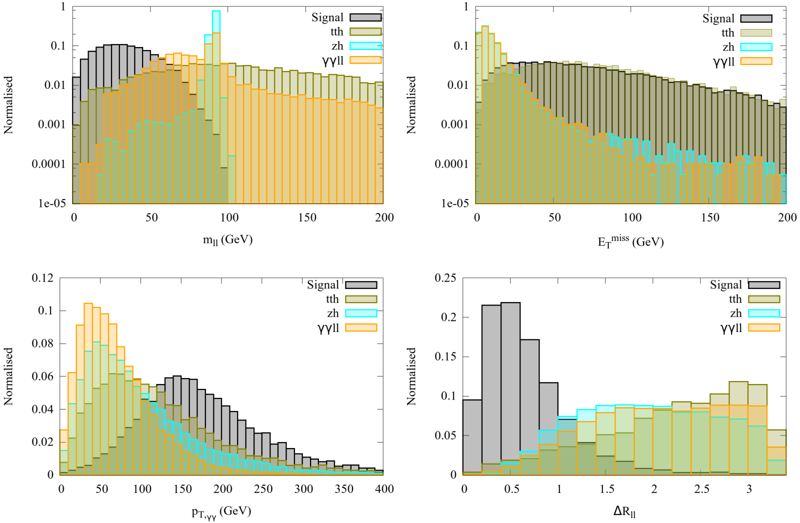
$$p_{T,\ell_{(1,2)}},\ \not{E}_T,\ m_{\ell\ell},\ m_{\gamma\gamma},\ \Delta R_{\gamma\gamma(\ell\ell)},\ p_{T,\ell\ell},\ p_{T,\gamma\gamma},\ \Delta\phi_{\ell\ell\ \gamma\gamma}$$

- Variables for $\ell jj\gamma\gamma + \not{E}_T$

$$p_{T,\ell_1},\ \not{E}_T,\ m_{\gamma\gamma},\ \Delta R_{\gamma\gamma},\ p_{T,\gamma\gamma},\ p_{T,\ell j},\ \Delta\phi_{\ell j\ \gamma\gamma},\ \Delta R_{\ell j},\ m_T$$

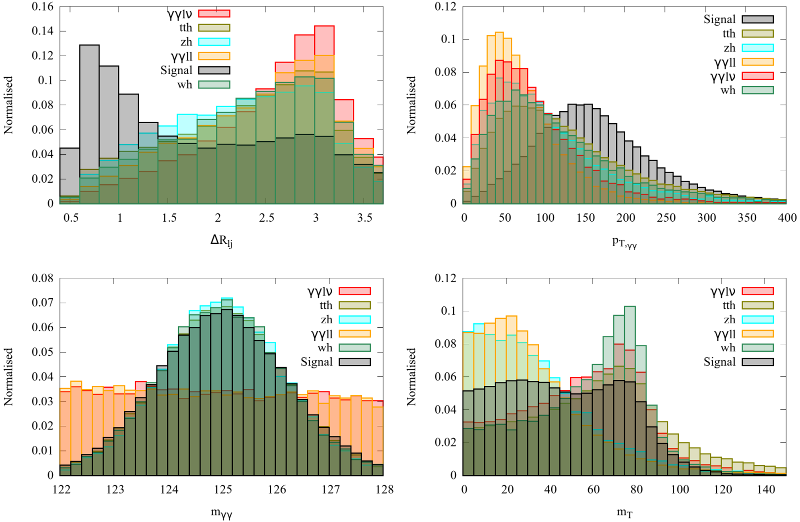
Non resonant di-Higgs production at the HL-LHC: $\gamma\gamma WW^*$

- Leptonic: $S/B = 0.40$; Less than 1 signal event; Higher luminosity/energy



Non resonant di-Higgs production at the HL-LHC: $\gamma\gamma WW^*$

- Semi-leptonic: $S/B = 0.11$; Less than 5 signal events; Higher luminosity/energy: Perfect channel at 100 TeV colliders



Non resonant di-Higgs production at the HL-LHC: $4W$

- We consider $\ell^\pm\ell^\pm + 4j + \not{E}_T$ ($SS2\ell$), $3\ell + 2j + \not{E}_T$ (3ℓ) and $4\ell + \not{E}_T$ (4ℓ)
- Lose cleanliness (rate) upon including more jets (leptons)
- Major backgrounds for $SS2\ell$: WZ, $t\bar{t}$, $W^\pm W^\pm$, Vh, $t\bar{t}X$, VVV, 4ℓ
- For $SS2\ell$, demand two same-sign leptons with $p_T > 25$ GeV and at least two jets with $p_T > 30$ GeV
- Major backgrounds for 3ℓ: Same as before save for $W^\pm W^\pm$
- For 3ℓ, $p_{T,\ell_{1/2/3}} > 25, 20, 15$ GeV and $|m_Z - m_{\ell\ell}| > 20$ GeV
- Variables for $SS2\ell$

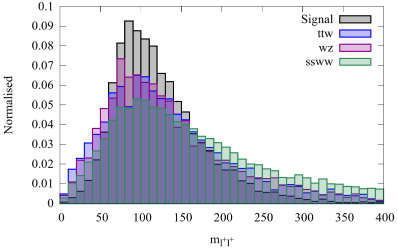
$$m_{\ell^\pm\ell^\pm},\ \Delta R_{\ell_i j_k},\ m_{jj}$$

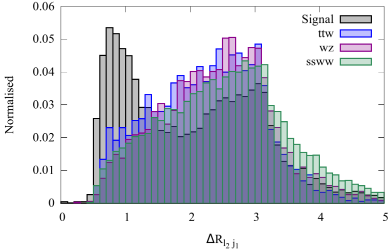
- Variables for 3ℓ

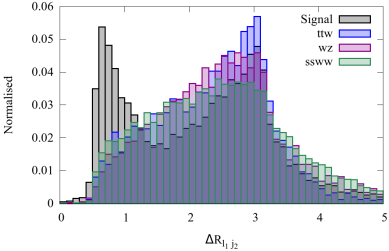
$$m_{\ell_i\ell_j},\ \Delta R_{\ell_i\ell_j},\ m_{\ell\ell\ell},\ m_{\rm eff},\ \not{E}_T,\ p_{T,\ell_i},\ n_{\rm jet}$$

Non resonant di-Higgs production at the HL-LHC: $4W$

- $SS2\ell$: $S/B = 1 \times 10^{-3}$, $S/\sqrt{B} = 0.11$

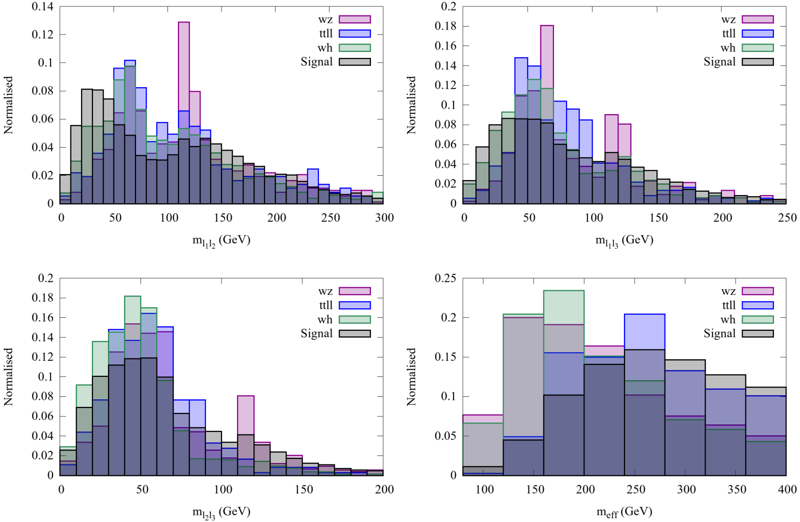






Non resonant di-Higgs production at the HL-LHC: $4W$

- 3ℓ: $S/B = 3 \times 10^{-3}$, $S/\sqrt{B} = 0.20$



Non resonant di-Higgs production at the HL-LHC: Summary

- Bleak prospects for discovering SM non-resonant di-Higgs channel at HL-LHC with 3 ab^{-1} data
- $b\bar{b}\gamma\gamma$ is the cleanest ($S/B \sim 0.19$) but suffers from small rate
- Combined significance $\sim 2.1\sigma$ from the aforementioned channels
- Combination to other (hadronic) channels will not drastically improve this: Still to be optimised and seen
- Purely leptonic case for $b\bar{b}WW^*$ shows promise but needs better handle over backgrounds $\rightarrow$ data driven backgrounds
- Both semi-leptonic and leptonic channels for $\gamma\gamma WW^*$ show excellent $S/B \rightarrow$ need larger luminosity (considering CMS and ATLAS datasets separately to form 6 ab^{-1}) or higher energy colliders

Higgs invisible decays in the Higgs pair productions: Motivation

- Here we will discuss the scenario where one Higgs decays invisibly ($h \to \not{E}_T$)
- $\mathrm{BR}_{\mathrm{inv}}$ constrained from global fits of Higgs data or from direct searches like mono-jet (hj), VBF (hjj) and Vh channels $\to$ $BR_{\mathrm{inv}} \lesssim 25-50\%$ $\to$ potential to bound $Br_{\mathrm{inv}} \lesssim 5\%$ at HL-LHC
- Current limit $\to$ $\mathrm{BR}_{\mathrm{inv}} < 0.28\ (0.31)$ from ATLAS @ 8 TeV and $< 0.24\ (0.23)$ from CMS at 7+8+13 TeV at 95% CL [CMS-PAS-HIG-16-016]
- If any new light particles couple to Higgs even with a coupling strength comparable to b-quark Yukawa ($\sim 1/60$) $\to$ sizeable exotic BR
- Motivations $\to$ DM connection, decay to long-lived sterile neutrinos, PNGBs like axions or Majorons, LSP in SUSY, KK-states in extra-dimensional theories

Higgs invisible decays in the Higgs pair productions: $b\bar{b} + \not{E}_T$ final state

- Several other interesting channels like $2\gamma + \not{E}_T, 4\ell + \not{E}_T$ $\rightarrow$ tiny cross-section due to small BR, important for resonance scenario
- $WW^* + \not{E}_T$ has larger BR but a fully leptonic channel will give additional $\not{E}_T$ (reconstruction of both Higgs extremely challenging) and fully hadronic will have large SM backgrounds. Similarly for $\tau\tau + \not{E}_T$. However, even without being able to reconstruct either Higgs, a counting of events for such channels can be useful

Higgs invisible decays in the Higgs pair productions: $b\bar{b} + \not{E}_T$ final state

- We will thus consider the scenario : $pp \to hh + X \to (b\bar{b})(\not{E}_T) + X \to$ largest possible signal rate
- Combining with the aforementioned channels might yield a larger sensitivity $\to$ future work
- Proposed signature similar to *mono-Higgs*, studied as a probe of certain DM scenarios $\to$ little overlap, cuts for mono-Higgs searches not optimised for di-Higgs especially the hard $\not{E}_T$ cut [Carpenter *et. al.*, 2013 *etc.*]
- Each visible Higgs BR is now scaled by $(1 - BR_{\rm inv}) \to$ rates diluted by $(1 - BR_{\rm inv})^2$ per visible Higgs decay

Higgs invisible decays in the Higgs pair productions: $b\bar{b} + \not{E}_T$ final state

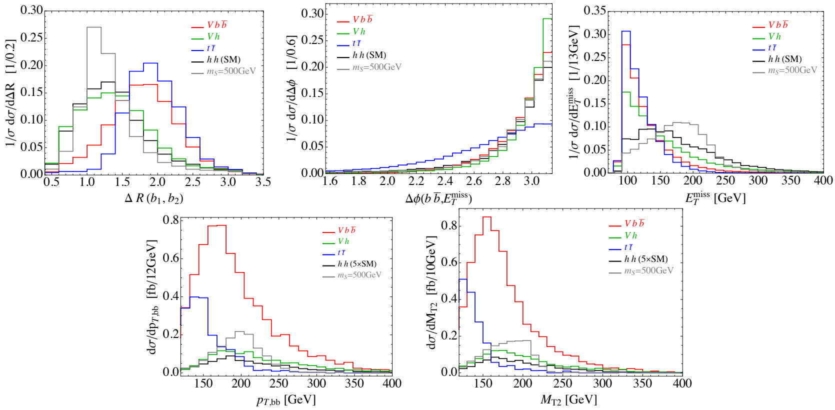
- Fake backgrounds : $b\bar{b}$ (completely removed by large $\not{E}_T$ cut), Vjj, Vjb ($V = W, Z$) ($j \to b$ fake rate $\mathcal{O}(10^{-2})$) $\to$ subdominant to Vbb)
- Dominant backgrounds : $Wb\bar{b}, Zb\bar{b}, t\bar{t}, Wh, Zh$. Subdominant background: single top
- MET trigger of 90 GeV used [CMS-PAS-EXO-16-012]
- Selection cuts :
    - 2 b-jets with $p_T > 55$ (35) GeV, at most one additional jet with $p_T > 35$ GeV
    - 0 leptons with $p_T > 10$ GeV and $|\eta| < 2.5$
    - 115 GeV $< m_{bb} <$ 135 GeV, $0.4 < \Delta R(b_1, b_2) < 2.0$, $\Delta\phi(bb, \not{E}_T) > 2.5$
    - $\not{E}_T > 160$ GeV, $p_{T,bb} > 180$ GeV and $m_{T2} > 160$ GeV

Higgs invisible decays in the Higgs pair productions: m_{T2}

- Dominant $t\bar{t}$ background can be greatly tackled with this variable
- Designed for the case where a pair of equal mass particles (A and A') decay : $A \to B + C$, $A' \to B' + C'$
- B and B' are visible particles and C and C' are not observed
- m_{T2} gives the maximal possible mass of parent particle A; provides greatest lower bound on $m_A = m_{A'}$
- $m_{T2}(m_B, m_{B'}, \mathbf{b}_T, \mathbf{b}_{T'}, \mathbf{p_T}^{\Sigma}, m_C, m_{C'}) \equiv \min_{\mathbf{c}_T + \mathbf{c}_{T'} = \mathbf{p}_T^{\Sigma}} \{max(m_T, m_{T'})\}$
- $m_T^2(\mathbf{b}_T, \mathbf{c}_T, m_b, m_c) \equiv m_b^2 + m_c^2 + 2(e_b e_c - \mathbf{b}_T \cdot \mathbf{c}_T)$, with $e^2 = m^2 + \mathbf{p}_T^2$
- Bounded above by top mass but unbounded below for the di-Higgs process

Higgs invisible decays in the Higgs pair productions: $b\bar{b} + \not{E}_T$ final state

- Cut-based analysis: after selection of 2 b-jets: $S/B = 0.026$, $S/\sqrt{B} = 2.82$ (Non-resonant)
- Cut-based analysis: before the final event selection ($\mathrm{BR}_{\mathrm{inv}} = 0.2$)



Higgs invisible decays in the Higgs pair productions: Non-resonant

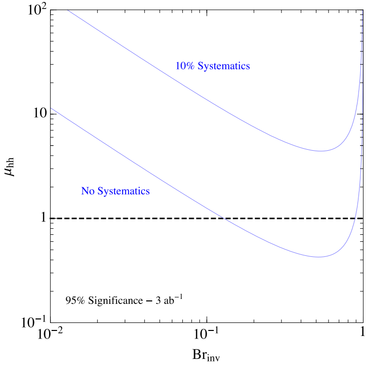


Figure : Reach of the $b\bar{b} + \not{E}_T$ search to di-Higgs production at LHC $\sqrt{s} = 14$ TeV with 3 ab^{-1} integrated luminosity. Here we display the 95% significance in the $\mathrm{BR_{inv}}$ - μ_{hh} plane for two assumptions on background systematics: 1) statistics dominated, $\gamma_B = \gamma_S = 0$, and 2) 10% systematic uncertainty on both signal and background, $\gamma_B = \gamma_S = 0.1$.

Higgs invisible decays in the Higgs pair productions: BDT

- BDT with 13 kinematic variables, *viz.* $M_{b_1 b_2}$, $\Delta R(b_1, b_2)$, $p_T^{b_1}$, $p_T^{b_2}$, η^{b_1}, η^{b_2}, ϕ^{b_1}, ϕ^{b_2}, $\Delta\phi(\not{E}_T, b_1 b_2)$, $p_T^{b_1 b_2}$, M_{T2}, M_T, $\not{E}_T$
- Non-resonant: $S/B = 0.033$, $S\sqrt{B} = 4.44$
- If systematic uncertainties are controlled using data-driven techniques, then only the SM production mode can be a useful channel
- For $m_S = 500$ GeV, $\sigma_{hh} < 450$ fb $\rightarrow$ these assume SM BRs and hence for us results will be larger by $(1 - BR_{\rm inv})^{-2}$ $\rightarrow$ Boosted b-jets and larger $\not{E}_T$
- Benchmark chosen : $m_S = 500$ GeV, $\sigma(pp \rightarrow S \rightarrow hh)_{14 \text{ TeV}} = 5\sigma_{SM}^{hh}$, $\Gamma_S = 5.47$ GeV
- Cut-based analysis: $S/B = 0.13$, $S/\sqrt{B} = 12$ and BDT: $S/B = 0.20$, $S/\sqrt{B} = 21.60$ for $\text{BR}_{\rm inv} = 0.1$

Higgs invisible decays in the Higgs pair productions: Complementing VBF

- We demand 90% exclusion for $\mathrm{BR_{inv}} = 5\%$, with a heavy scalar of $m_H = 500$ GeV
- Assuming zero systematics, after BDT cut, we have 27 (58) signal (background) events. We need $\mathcal{L} = 54\ \mathrm{fb}^{-1}$
- Assuming 5% systematics, after BDT cut, we have 237 (513) signal (background) events. We require $\mathcal{L} = 120\ \mathrm{fb}^{-1}$
- This channel has the potential to give a stiff competition to the VBF channel having the potential to exclude invisible BR of 5% at 90% CL and at the same time also has potential to study di-Higgs signatures
- With a BDT multi-variate analysis @ 13 TeV with $\mathcal{L} = 10\ \mathrm{fb}^{-1}$, reach on $\mathrm{BR_{inv}}$ improves from 47% to 28% at 95% CL. For the HL-LHC at 3 ab^{-1}, one can have a final reach of $\mathrm{BR_{inv}} = 3.5\%$ [Bernaciak *et. al.*, 2014]

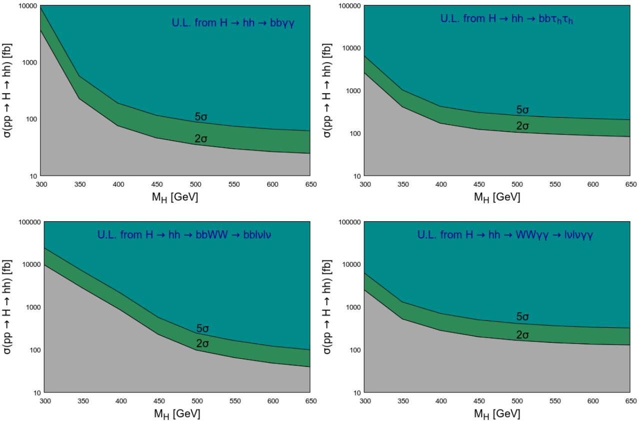
Contaminations to the Higgs pair producing channels

- SM di-Higgs signal events are rather small for most final states
- BSM physics may distort or contaminate the signal $\rightarrow$ if statistically significant $\rightarrow$ new physics
- May be due to y_t or λ_{hhh}
- May be some totally different new physics scenarios mimicking some or all SM di-Higgs final states
- Q: How much contamination possible once BDT performed to maximise SM di-Higgs?
- A: If new physics kinematic variables overlap with SM counterpart or If overlap is not significant but overall rate is large
- Correlations possible: Some non-resonant channels will incur contamination from more new physics scenarios than others

Contaminations to the Higgs pair producing channels: $hh(+X)$

- Extended Higgs sectors like 2HDM, complex scalar extension, MSSM allow for a heavy resonant Higgs decaying to an SM-like Higgs pair
- Requirement: alignment limit and low $\tan\beta$ for large di-Higgs cross-section for $m_{H(A)} \sim$ few 100 GeV
- Require narrow width assumption (GeV range)
- Cross-section upper limit defined as: $S_{\rm NP}^{\rm UL}/\sqrt{B_{\rm SM}} > N\sigma$
- Green (blue) region indicate upper limit on cross-section to contaminate SM yield at $2\sigma(5\sigma)$: $B_{\rm SM}$ contains SM di-Higgs

Contaminations to the Higgs pair producing channels: $hh(+X)$



- Order 100 fb cross-section for resonant Higgs mass $\gtrsim$ 400 GeV $\longrightarrow$ Contaminates SM di-Higgs expectation to at least 2σ

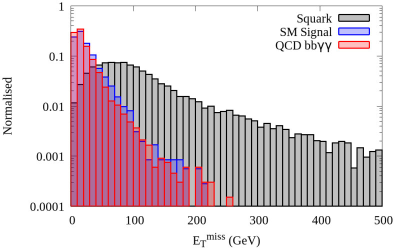
Contaminations to the Higgs pair producing channels: BPs

$M_A = 1000$ GeV, $\tan\beta = 10$, $A_t = 2500$ GeV, $m_{\tilde{Q}_{3\ell}} = m_{\tilde{b}_R} = 3000$ GeV, $A_b = A_\tau = 0$, $M_3 = 3000$ GeV

Benchmark Points	Parameters (GeV)	Mass (GeV)	Processes	Branching Fraction
BP1 $pp \to \tilde{q}_L^{(*)}\tilde{q}_L^{(*)}$ (Cross-section: 128.5 fb) $\tilde{q}_L = \tilde{u}_L, \tilde{d}_L, \tilde{c}_L, \tilde{s}_L$	$M_1 = 700, M_2 = 840$ $\mu = 3000, m_{\tilde{t}_R} = 3000$	$m_{\tilde{u}_L} = 850.1$ $m_{\tilde{d}_L} = 850.1$ $m_{\tilde{c}_L} = 850.1$ $m_{\tilde{s}_L} = 850.1$ $m_H = 1000.0$ $m_{H^\pm} = 1003.0$ $m_{\chi_2^0} = 836.0$ $m_{\chi_1^0} = 700.0$	$\tilde{u}_L \to \chi_2^0 u_L$ $\tilde{d}_L \to \chi_2^0 d_L$ $\tilde{c}_L \to \chi_2^0 c_L$ $\tilde{s}_L \to \chi_2^0 s_L$ $\chi_2^0 \to \chi_1^0 h$	13.8% 15.4% 13.8% 15.4% 98.7%
BP2 $pp \to \chi_1^\pm \chi_2^0$ (Cross-section: 420 fb)	$M_1 = 150, M_2 = 300$ $\mu = 1000, m_{\tilde{t}_R} = 3000$	$m_{\chi_2^0} = 296.7$ $m_{\chi_1^\pm} = 296.7$ $m_{\chi_1^0} = 149.3$ $m_h = 125.0$ $m_{H^\pm} = 1003.0$ $m_H = 1000.0$	$\chi_1^\pm \to \chi_1^0 W^\pm$ $\chi_2^0 \to \chi_1^0 h$	100% 93.5%
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%

Contamination to the Higgs pair producing channels: $hh(+X)$

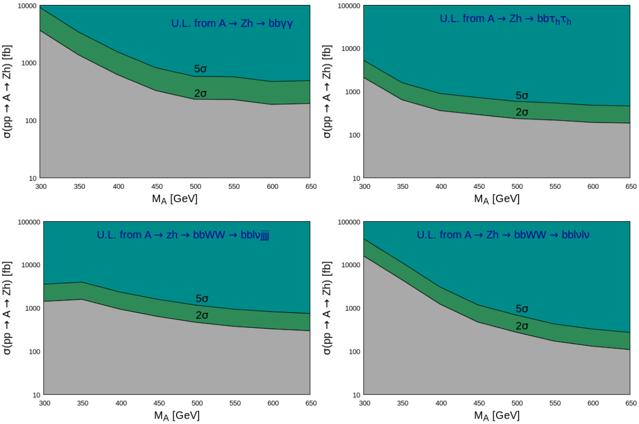
- LHC already imposed strong constraints on first and second generation squark masses ($\gtrsim \mathcal{O}(\mathrm{TeV})$)
- Squark pair production $\tilde{q}_L\tilde{q}_L$, $\tilde{q}_L\tilde{q}_L^*$, $\tilde{q}_L^*\tilde{q}_L^*$ (BP1)
- Final state: $hh + \not{E}_T + \text{ jets}$; From BP1, cross-section $\sim$ 10.8 fb $\rightarrow$ one-third of SM-expectation; Large $\not{E}_T$; Only 0.60 events $\rightarrow$ not significant



Contaminations to the Higgs pair producing channels: $h(+X)$

- The $hh(+X)$ modes may contaminate all SM non-resonant di-Higgs channels
- The $h(+X)$ modes may contaminate some (or all) the SM non-resonant di-Higgs channels
- Looking at excesses in some channels and not others may help us narrow down on the new physics searches
- In 2HDMs, we have $pp \to A \to Zh$ and this may contaminate when $M_A < 2M_t$ and $\tan\beta$ is small
- Upper limits on cross-sections contaminating the SM non-resonant di-Higgs signals are weaker

Contaminations to the Higgs pair producing channels: $h(+X)$



- $A \longrightarrow Zh$ contaminates the SM signals to a lesser degree; Possible reason: Reconstructed Z-peak is shifted from the reconstructed Higgs peak and m_{bb} is an important discriminatory variable for all such searches involving a b-jet pair

Contaminations to the Higgs pair producing channels: $h(+X)$

- Observation of SUSY will depend on its electroweak sector ($\chi_i^\pm$ and χ_j^0s)
- With decoupled Higgs sector, chargino-neutralino production mediated through W propagator
- $W^\pm \chi^\mp \chi_1^0$ coupling contains both wino and higgsino components $\rightarrow$ wino components dominate
- CMS and ATLAS searched in the $3\ell + \not{E}_T$ and SFOS $2\ell + \not{E}_T$ for non-generic scenarios with $\chi_1^\pm$, χ_2^0 dominantly wino-like and degenerate
- Choose BP2 with $M_2 \ll \mu \rightarrow \chi_1^\pm$ and χ_2^0 wino-like $\rightarrow$ $\sigma(pp \rightarrow \chi_1^\pm \chi_2^0) \gg \sigma(pp \rightarrow \chi_2^0 \chi_2^0)$
- BP2 marginally outside projected exclusion from ATLAS HL-LHC study

Contamination to the Higgs pair producing channels: $h(+X)$

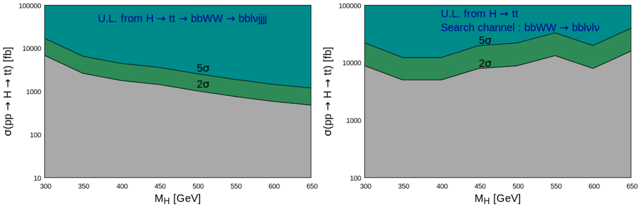
- We get a $Wh + \not{E}_T$ final state with cross-section ~ 400 fb
- Contaminations possible to: $b\bar{b}WW^* \to b\bar{b}\ell jj + \not{E}_T$, $\gamma\gamma WW^* \to \gamma\gamma\ell jj + \not{E}_T$, $4W \to \ell^\pm\ell^\pm jjjj + \not{E}_T$, $3\ell jj + \not{E}_T$

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

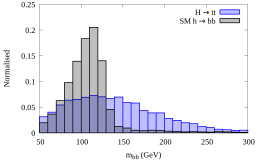
- Large contaminations $\to$ calling for carefully treating these channels in the future in case of observance of large number of events $\to$ potential new physics contributions

Contaminations to the Higgs pair producing channels: Null Higgs

- $H(A) \to t\bar{t}$ for $m_{H(A)} > 2m_t$ may contaminate $b\bar{b}\tau^+\tau^-$ and $b\bar{b}WW^*$

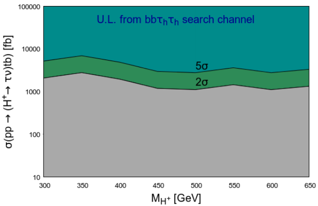


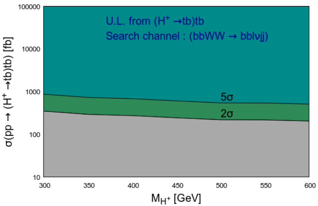
- Weaker bounds because m_{bb} is different for $t\bar{t}$; Require a large production cross-section for heavy resonant scalar in order to contaminate appreciably

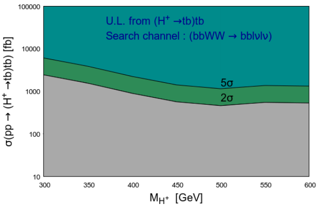


Contaminations to the Higgs pair producing channels: Null Higgs

- Charged Higgs production: $\bar{t}bH^+ / t\bar{b}H^-$ with charged Higgs decaying to $\tau\nu$ or $t\bar{b}$ depending on mass of m_{H^+} (Affects low tan β regions)







Contaminations to the Higgs pair producing channels: Null Higgs

- For stop masses of $\mathcal{O}$(several hundreds of GeVs), $pp \to \tilde{t}_1 \tilde{t}_1^*$ may be large
- From BP3, BR($\tilde{t}_1 \to b\chi_1^+ \to bW^+\chi_1^0$ may be dominant $\to 2b + 2W + \not{E}_T$
- Potentially contaminate $b\bar{b}\tau^+\tau^-$ and $b\bar{b}WW^*$ channels

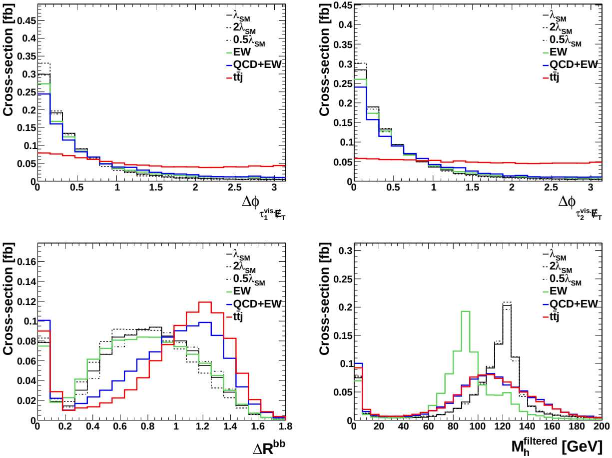
SM background	SM *hh* production	BP3 contamination
1103017.13	134.34	101.83

Di-Higgs + jet at a 100 TeV collider

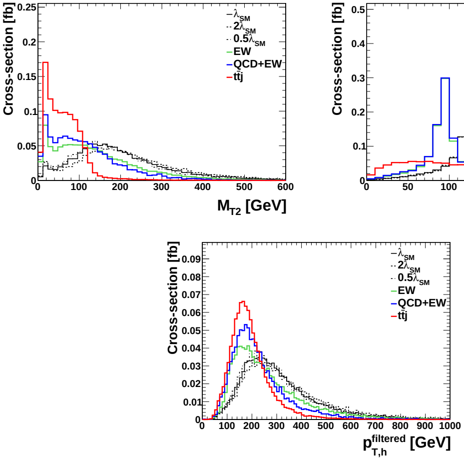
- Observing the Higgs self-coupling at the HL-LHC seem far fetched
- Di-Higgs cross-section increases by 39 times going from 14 TeV $\to$ 100 TeV
- Extra jet emission becomes significantly less suppressed: 77 times enhancement from 14 TeV $\to$ 100 TeV collider $\to$ extra handle
- Recoiling a collimated Higgs pair against a jet exhibits more sensitivity to λ_{hhh} as compared to $pp \to hh$ $\to$ statistically limited at the LHC
- Study $hhj \to b\bar{b}\tau^+\tau^- j \to b\bar{b}\tau_h(\tau_\ell)\tau_\ell j$ and $hhj \to b\bar{b}b\bar{b}j$
- Use substructure technique: BDRS [Butterworth, *et. al.*, 2008] with mass drop and filtering

Di-Higgs + jet at a 100 TeV collider ($jb\bar{b}\tau^+\tau^-$)

- $R = 1.5$, $p_T^j > 110$ GeV, τ-tag efficiency 70%, b-tag efficiency 70%, b-mistag rate 2%; Combined $\tau_h\tau_h$ and $\tau_h\tau_\ell$



Di-Higgs + jet at a 100 TeV collider ($jb\bar{b}\tau^+\tau^-$)



Di-Higgs + jet at a 100 TeV collider ($jb\bar{b}\tau^+\tau^-$)

observable	reconstructed object
p_T	2 hardest filtered subjets 2 visible τ objects (τ_ℓ or τ_h) hardest non b, τ-tagged jet reconstructed Higgs from filtered jets reconstructed Higgs from visible τ final states
p_T ratios	2 hardest filtered jets 2 visible τ final state objects
m_{T2}	described before
ΔR	two hardest filtered subjets two visible τ objects ($\tau_\ell \tau_\ell$ or $\tau_\ell \tau_h$) b-tagged jets and lepton or τ_h b-tagged jets and jet j_1 lepton or τ_h with jet j_1
$M_{\tau\tau}^{\text{col}}$	collinear approximation of $h \to \tau\tau$ mass
M^{filt}	filtered j_1 and j_2 (and j_3 if present)
$M_{hh}^{vis.}$	filtered jets and leptons (or lepton and τ_h)
$\not{E}_T$	reduce sub-leading backgrounds
$\Delta\phi$	between visible τ final state objects and $\not{E}_T$ between filtered jets system and $\ell\ell$ (or ℓ τ_h) systems
N_{jets}	number of anti-k_T jets with $R = 0.4$

Di-Higgs + jet at a 100 TeV collider ($jb\bar{b}\tau^+\tau^-$)

	signal	QCD+QED	QED	$t\bar{t}j$	tot. background	S/B	$S/\sqrt{B}$, 3/ab
$\kappa_\lambda = 0.5$	0.444					0.126	12.47
$\kappa_\lambda = 1$	0.363	0.949	0.270	2.311	3.530	0.103	10.57
$\kappa_\lambda = 2$	0.264					0.075	7.69

$$0.76 < \kappa_\lambda < 1.28 \quad 3/\text{ab}$$

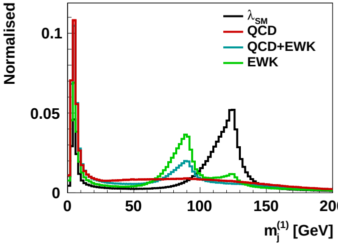
$$0.92 < \kappa_\lambda < 1.08 \quad 30/\text{ab}$$

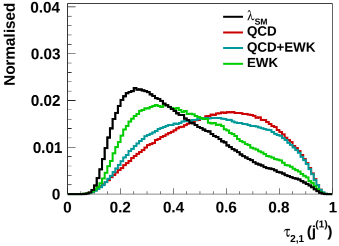
at 68% confidence level using the CLs method.

Di-Higgs + jet at a 100 TeV collider ($jb\bar{b}b\bar{b}$)

- Major background: pure QCD: $g \to b\bar{b}$ (soft and collinear splittings $\to$ Resulting fat jets (R = 0.8) are one-pronged.
- Signal: $H \to b\bar{b}$; clear two prongs
- Requre: $\tau_{2,1} < 0.35$ and $100\ \mathrm{GeV} < m_{SD} < 130\ \mathrm{GeV}$

	signal	QCD	QCD+EW	EW	tot. background	$S/B \times 10^3$	$S/\sqrt{B}$, 30/ab
$\kappa_\lambda = 0.5$	0.094					20.8	7.67
$\kappa_\lambda = 1$	0.085	4.3	0.1	0.003	4.4	19.1	6.61
$\kappa_\lambda = 2$	0.071					16.2	5.85





Other exotic Higgs decays

- $\gamma\gamma + \not{E}_T$: good potential for a resonance scenario $\rightarrow$ clean channel, expect ~ 135 events before selection cuts at $\mathcal{L} = 3$ ab^{-1} for the aforementioned benchmark scenario
- Focus on scenarios where the Higgs decays to a pair of light (pseudo)scalars which in turn decay to fermions or gluons/photons
- Such signatures can be seen in models like 2HDM+S [Peccei, Quinn, 1977], extensions of SM with hidden light gauge bosons [Gopalakrishna *et. al.*, 2008], R-symmetry limit of NMSSM [Cao *et. al.*, 2013], Little Higgs models [Surujon *et. al.*, 2010] to name a few

Other exotic Higgs decays

- Following [Curtin *et. al.*] some interesting exotic decay modes like $h \to XX \to 4b$: potential final state $4b + 2\ell + \not{E}_T$ with the other Higgs decaying leptonically $(WW^*, ZZ^*, \tau\tau) \to \mathcal{O}(100)$ events before selection cuts (but including a b-tagging efficiency of 0.7) for $\text{BR}(h \to XX \to 4b) = 0.1$
- Decays like $h \to aa \to 2b2\tau$ and the other Higgs decaying to $b\bar{b}$: interesting $4b2\tau$ final state
- Decays like $h \to aa \to 4j$: both jet pairs reconstructable. The other Higgs may decay to $b\bar{b}$ or leptonically
- Another potential channel : $h \to aa \to 2\gamma 2j$ and a final signature of $2b2\gamma 2j$

Other exotic Higgs decays

- With $\text{BR}_{h\to 2\gamma+\not{E}_T} = 4\%$, one can expect $\mathcal{O}(1000)$ events before the selection cuts (with 70% b-tagging efficiency) in the $2b2\gamma + \not{E}_T$ final state at $\mathcal{L} = 3$ ab^{-1}
- There are other interesting exotic decay modes which might face strong backgrounds from single Higgs production but may have very less background in di-Higgs
- We leave these for a comprehensive future work

Summary and Conclusions

- Search for Higgs pair production is an important enterprise to understand the Higgs cubic coupling
- Non-resonant di-Higgs searches at the HL-LHC yields a significance of $\sim 2.1\sigma$
- New search strategy proposed $pp \to hh \to b\bar{b} + \not{E}_T$ with a non-SM decay mode $\to$ promising: may compete with VBF to constrain $h \to$ invisible BR
- Contaminations to SM non-resonant di-Higgs channels from resonance Higgs, squark pair production, $A \to Zh$, chargino-neutralino pair production, $H \to t\bar{t}$, charged Higgs production, stop pair production etc. possible
- 100 TeV collider studies show promise for di-Higgs + jet
- Systematic uncertainties need to be understood better in the future in order to make strong claims about these channels
- Other exotic decay modes like $\gamma\gamma + \not{E}_T$, $4b + 2\ell + \not{E}_T$ etc. need to be studied

Backup: Machinery in a nutshell

- Di-Higgs samples and backgrounds generated at LO with `MG5_aMC@NLO`
- Signal samples decayed using `Pythia-6`
- NN23LO parton distribution function employed
- Default factorisation and renormalisation scales used
- Shower + hadronisation using `Pythia-6`
- `Delphes-3.4.1` used for detector simulation
- Jets: anti-kT algorithm, $p_T > 20$ GeV, $R = 0.4$ (`FastJet`)
- Total energy around e, μ, γ required to be $< 12\%, 25\%, 12\%$ within $\Delta R = 0.5$
- b-tag efficiency: 70%, $j \to b$: 1%, $c \to b$: 30%

Higgs invisible decays in the Higgs pair productions: Backup

- ATLAS : Bound on Higgs width from measurement of off-shell signal strengths in $ZZ \to 4\ell, 2\ell 2\nu$ and $WW \to e\nu\mu\nu$ gives 95% observed (expected) upper limit of 22.7 MeV (33.0 MeV) [arXiv : 1503.01060]
- CMS : Bound on Higgs width from off-shell production in *ggF* and *VBF* channels in $WW \to$ leptonic final states and combing with ZZ channel, yield 95% upper limit of 13 MeV (26 MeV) [arXiv : 1605.02329]

Higgs invisible decays in the Higgs pair productions: cut-flow: backup

	Signal	$Wb\bar{b}$ (no h) ($2b\ell\nu$)	$Zb\bar{b}$ (no h) ($2b2\nu/2b2\ell$)	Wh ($2b\ell\nu$)	$Zh(1)$ $((2\nu/2\ell)(2b))$	$Zh(2)$ $((2b)(\not{E}_T))$	$t\bar{t}$ (lep+semi-lep)
flat k-factor	-	1.79	1.13	1.28	1.50	1.50	1.88
$\not{E}_T$ trigger + $2b$+0,1j	0.135	2.81×10^{-2}	5.63×10^{-2}	1.72×10^{-2}	5.21×10^{-2}	8.60×10^{-2}	7.92×10^{-3}
$p_T(b)$	0.131	2.64×10^{-2}	5.12×10^{-2}	1.65×10^{-2}	4.99×10^{-2}	8.10×10^{-2}	7.37×10^{-3}
m_{bb}	0.0484	7.54×10^{-3}	1.50×10^{-2}	7.16×10^{-3}	2.01×10^{-2}	1.73×10^{-3}	2.31×10^{-3}
$\Delta R(b_1, b_2)$	0.0438	5.29×10^{-3}	9.95×10^{-3}	5.97×10^{-3}	1.67×10^{-2}	1.32×10^{-3}	1.41×10^{-3}
$\Delta\phi(bb, \not{E}_T)$	0.0382	5.14×10^{-3}	9.56×10^{-3}	5.78×10^{-3}	1.58×10^{-2}	1.24×10^{-3}	1.07×10^{-3}
$\not{E}_T$	0.0235	9.79×10^{-4}	2.29×10^{-3}	1.62×10^{-3}	7.18×10^{-3}	6.51×10^{-4}	9.50×10^{-5}
$p_T(bb)$, M_{T2}	0.0144	4.87×10^{-4}	8.82×10^{-4}	1.21×10^{-3}	4.54×10^{-3}	3.95×10^{-4}	5.73×10^{-6}
Scaling	μ_{hh} $\mathrm{BR_{inv}}$ $(1\text{-}\mathrm{BR_{inv}})$	1	1	$(1\text{-}\mathrm{Br_{inv}})$	$(1\text{-}\mathrm{Br_{inv}})$	$\mathrm{Br_{inv}}$	1

Table : Cut-flow table for the $b\bar{b} + \not{E}_T$ search. Listed in each cell are the efficiencies after the associated cut. The final row displays the scaling of each channel with $\mathrm{BR_{inv}}$.

Backup

- Mühlleitner *et. al.* mentions in their whitepaper that using an xSM model, one can get a di-Higgs enhancement of $\sim$ 920 fb with a heavy Higgs mass of 279.65 GeV
- Similar benchmarks from Ramsey-Musolf *et. al.*, 2016 but for a 100 TeV collider

BDRS

2

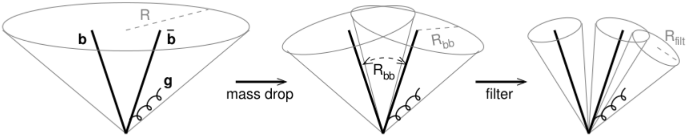


FIG. 1: The three stages of our jet analysis: starting from a hard massive jet on angular scale R, one identifies the Higgs neighbourhood within it by undoing the clustering (effectively shrinking the jet radius) until the jet splits into two subjets each with a significantly lower mass; within this region one then further reduces the radius to R_{filt} and takes the three hardest subjets, so as to filter away UE contamination while retaining hard perturbative radiation from the Higgs decay products.

Given a hard jet j, obtained with some radius R, we then use the following new iterative decomposition procedure to search for a generic boosted heavy-particle decay. It involves two dimensionless parameters, μ and y_{cut}:

1. Break the jet j into two subjets by undoing its last stage of clustering. Label the two subjets j_1, j_2 such that $m_{j_1} > m_{j_2}$.
2. If there was a significant mass drop (MD), $m_{j_1} < \mu m_j$, and the splitting is not too asymmetric, $y = \frac{\min(p_{tj_1}^2, p_{tj_2}^2)}{m_j^2} \Delta R_{j_1,j_2}^2 > y_{\text{cut}}$, then deem j to be the heavy-particle neighbourhood and exit the loop. Note that $y \simeq \min(p_{tj_1}, p_{tj_2})/\max(p_{tj_1}, p_{tj_2})$.[1]
3. Otherwise redefine j to be equal to j_1 and go back to step 1.

The final jet j is to be considered as the candidate Higgs boson if both j_1 and j_2 have b tags. One can then identify $R_{b\bar{b}}$ with $\Delta R_{j_1 j_2}$. The effective size of jet j will thus be just sufficient to contain the QCD radiation from the

In practice the above procedure is not yet optimal for LHC at the transverse momenta of interest, $p_T \sim 200 - 300\,\text{GeV}$ because, from eq. (1), $R_{b\bar{b}} \gtrsim 2m_H/p_T$ is still quite large and the resulting Higgs mass peak is subject to significant degradation from the underlying event (UE), which scales as $R_{b\bar{b}}^4$ [15]. A second novel element of our analysis is to *filter* the Higgs neighbourhood. This involves resolving it on a finer angular scale, $R_{\text{filt}} < R_{b\bar{b}}$, and taking the three hardest objects (subjets) that appear — thus one captures the dominant $\mathcal{O}(\alpha_s)$ radiation from the Higgs decay, while eliminating much of the UE contamination. We find $R_{\text{filt}} = \min(0.3, R_{b\bar{b}}/2)$ to be rather effective. We also require the two hardest of the subjets to have the b tags.

N-Subjettines

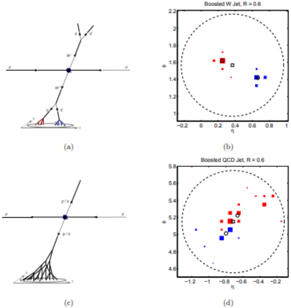


Figure 1: Left: Schematic of the fully hadronic decay sequences in (a) W^+W^- and (c) dijet QCD events. Whereas a W jet is typically composed of two distinct lobes of energy, a QCD jet acquires invariant mass through multiple splittings. Right: Typical event displays for (b) W jets and (d) QCD jets with invariant mass near m_W. The jets are clustered with the anti-k_T jet algorithm [31] using $R = 0.6$, with the dashed line giving the approximate boundary of the jet. The marker size for each calorimeter cell is proportional to the logarithm of the particle energies in the cell. The cells are colored according to how the exclusive k_T algorithm divides the cells into two candidate subjets. The open square indicates the total jet direction and the open circles indicate the two subjet directions. The discriminating variable τ_2/τ_1 measures the relative alignment of the jet energy along the open circles compared to the open square.