Invisible Decays in Higgs Pair Production

Shankha Banerjee

LAPTh, Annecy-le-Vieux

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Plan of my talk

- Motivation
- Higgs invisible decays
- $b\bar{b} + \not{E}_T$ final state
- SM production
- Results
- Other exotic Higgs decays
- Summary and Conclusions

Motivation

- Di-Higgs provides means to directly probe Higgs cubic coupling
- LHC or 100 TeV colliders : self-coupling at 10-50% precision measurement possible $\rightarrow$ size of dataset, beam energy, control over systematics
- Enhancement of σ_{hh} $\rightarrow$ s-channel resonance [xSM models *etc.*], new coloured particles in loops or HD operators [Mühlleitner *et. al.*, 2015; Ramsey-Musolf *et. al.*, 2016 *etc.*] $\rightarrow$ kinematics altered $\rightarrow$ requires different experimental search strategies

Motivation

- Till date → major focus on BSM di-Higgs sector → enhancement in production
- New physics can affect Higgs *decays* → exotic Higgs decays now actively studied [Curtin *et. al.*, 2015]
- $\sigma_{pp\to h} \gg \sigma_{pp\to hh}$ → 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 → present bounds on variety of Higgs decays : BR very weak (10-50%)

Invisible Higgs decays

- Here we will discuss the scenario where one Higgs decays invisibly ($h \to \not{E}_T$)
- Motivations $\to$ DM connection, decay to long-lived sterile neutrinos, PNGBs like axions or Majorons, LSP in SUSY, KK-states in extra-dimensional theories
- $\mathrm{BR}_{\mathrm{inv}}$ 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

$b\bar{b} + \not{E}_T$ final state

- We focus on the $b\bar{b} + \not{E}_T$ channel and explore HL-LHC prospects for SM and resonance augmented production
- Important to study such channels $\rightarrow$ realisation of invisible Higgs decays must be confirmed from di-Higgs production and if $\mathrm{BR}_{\mathrm{inv}}$ sizable $\rightarrow$ channel needs to be studied to probe scalar potential
- $\sigma^{hh}_{\mathrm{NNLO}} = 37.52^{+5.2\%}_{-7.6\%}$ fb @ 14 TeV [Florian *et. al.*, 2016]
- 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 fully leptonic will give additional $\not{E}_T$ (reconstruction of both Higgs extremely challenging) and fully hadronic will have large SM backgrounds. Similarly for $\tau\tau + \not{E}_T$

$b\bar{b} + \not{E}_T$ final state

- Combining with the aforementioned channels might yield a larger sensitivity $\rightarrow$ future work
- Proposed signature similar to *mono-Higgs*, studied as a probe of certain DM scenarios [See Shin-Shan Eiko Yu's talk] $\rightarrow$ little overlap, cuts for mono-Higgs searches not optimised for di-Higgs especially the hard $\not{E}_T$ cut [Carpenter *et. al.*, 2013 *etc.*]
- Events generated with MadGraph5 aMC@NLO, showered through Pythia 6/8, detector analysis with Delphes 3, cross-checked with Herwig 7
- Higgs BRs are now scaled by $(1 - Br_{\mathrm{inv}})$ $\rightarrow$ rates diluted by $(1 - Br_{\mathrm{inv}})^2$

$b\bar{b} + \not{E}_T$ 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

$b\bar{b} + \not{E}_T$ final state

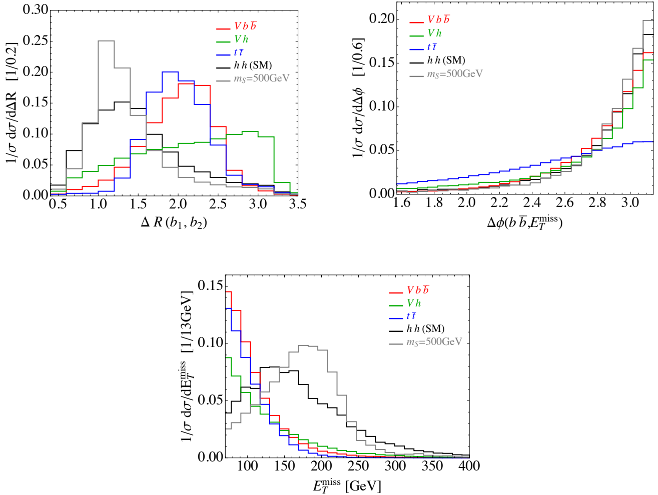

Figure : Kinematic distributions for the variables $\Delta R(b_1, b_2)$, $\Delta\phi(b\bar{b}, \not{E}_T)$, and $\not{E}_T$ after the first selection of two b-jets. Here we have fixed $\mathrm{Br}_{\mathrm{inv}} = 0.2$.

$b\bar{b} + \not{E}_T$ final state

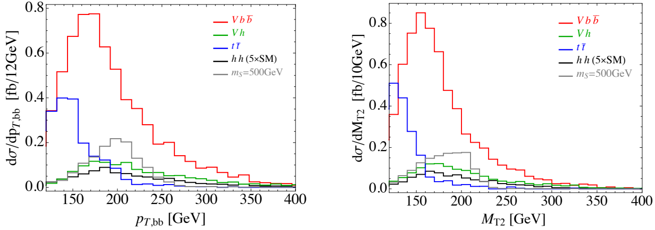

Figure : Kinematic distributions for the variables $p_T(b\bar{b})$ and M_{T2} before the final event selection. Here we have fixed $\mathrm{Br}_{\mathrm{inv}} = 0.2$.

SM production

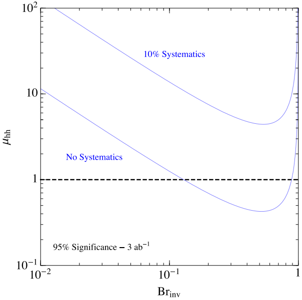

Figure : Reach of the $b\bar{b} + \not{E}_T$ search to di-Higgs production at LHC $\sqrt{s} = 14$ TeV with 3 ab^{-1} integrated luminosity. Here we display the 95% significance in the $\mathrm{Br_{inv}}$ - μ_{hh} plane for two assumptions on background systematics: 1) statistics dominated, $\gamma_B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

Results

- For SM production : Cut based analysis $\rightarrow S/B = 0.026$, $S/\sqrt{B} = 2.82$
- 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, $\not{E}_T$
- MVA does not improve results significantly $\rightarrow S/B = 0.033$, $S\sqrt{B} = 4.44$
- If systematic uncertainties are controlled using data-driven techniques, then only the SM production mode can be tackled
- We choose a heavy resonance with mass $m_S \gg 2m_h \rightarrow$ highly boosted Higgs $\rightarrow$ highly boosted bottom jets and large $\not{E}_T \rightarrow$ easier separation from backgrounds

Results

- Model-independent constraints for di-Higgs resonances (from $4b, 2b2\gamma, 2b2\tau$ *etc.* searches) $\rightarrow$ scaling 8 TeV results using gluon luminosities at 14 TeV yield $\sigma(pp \rightarrow S \rightarrow hh)_{14 \text{ TeV}}$ between 25 pb - 200 fb for masses 200 GeV - 1 TeV
- Recent results at 13 TeV, 13.3 fb^{-1} in $hh \rightarrow 4b$ channel constrains the cross-section from 1 pb - 50 fb at 14 TeV in the same mass range [ATLAS 1606.04782]
- For $m_S = 500$ GeV, $\sigma_{hh} < 450$ fb $\rightarrow$ these assume SM BRs and hence for us results will be larger by $(1 - BR_{\text{inv}})^{-2}$
- Benchmark chosen : $m_S = 500$ GeV, $\sigma(pp \rightarrow S \rightarrow hh)_{14 \text{ TeV}} = 5\sigma_{SM}^{hh}$, $\Gamma_S/m_S = 0.01$
- $p_{T,bb} > 200$ GeV and $M_{T2} > 200$ GeV
- Cut based analysis : $S/B = 0.13, S/\sqrt{B} = 12$ and MVA : $S/B = 0.22, S/\sqrt{B} = 24$ for $Br_{\text{inv}} = 0.1$

Other exotic Higgs decays

- $\gamma\gamma + \not{E}_T$: good potential for a resonance scenario
- 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 $(WW^*, ZZ^*, \tau\tau)$
- 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 bb or leptonically
- Another potential channel : $h \to aa \to 2\gamma 2j$ and a final signature of $2b2\gamma 2j$
- 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
- New search strategy proposed $pp \to hh \to b\bar{b} + \not{E}_T$ with a non-SM decay mode
- Persistent backgrounds like $Zb\bar{b}$ make it a challenging task to see di-Higgs with an SM production mode
- On introducing a resonance, the prospects of observing this channel improve significantly
- 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

	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)
$\not{E}_T$ 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	$\mu_{hh}\,\mathrm{Br}_{\mathrm{inv}}$ (1-$\mathrm{Br}_{\mathrm{inv}}$)	1	1	(1-$\mathrm{Br}_{\mathrm{inv}}$)	(1-$\mathrm{Br}_{\mathrm{inv}}$)	$\mathrm{Br}_{\mathrm{inv}}$	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 $\mathrm{Br}_{\mathrm{inv}}$.

Backup

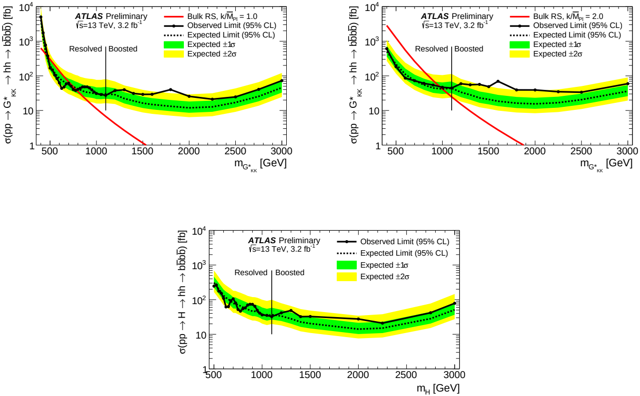

Figure : The combined expected and observed upper limit for $pp \rightarrow G^*_{KK} \rightarrow hh \rightarrow bbbb$ in the bulk RS model with (a) $k/MPI = 1$ and (b) $k/MPI = 2$, as well as (c) $pp \rightarrow H \rightarrow hh \rightarrow bbbb$ with fixed $_H = 1$ GeV, at the 95% confidence level. The results of the resolved analysis are used up to a mass of 1100 GeV and those of the boosted analysis are used at higher mass where its expected sensitivity is higher. The red curves show the predicted cross sections as a function of resonance mass for the models considered. Limits are computed within the asymptotic approximation.

Backup

- Mühlleitner *et. al.* mentions in their whitepaper that using an xSM model, one can get a di-Higgs enhancement of ~ 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