

Study of di-Higgs production in the $ZZbb$ channel with the ATLAS experiment

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December 12, 2018

Motivation

- 1 Search for SM di-Higgs production to study the Higgs boson self-interaction
- 2 Search for new particles through di-Higgs production

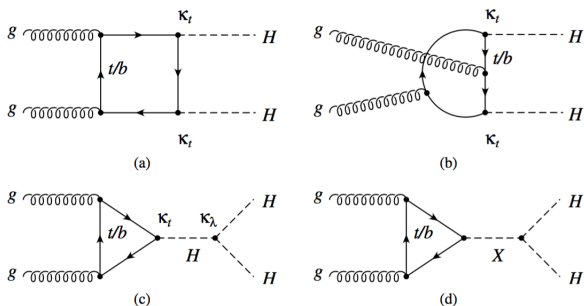
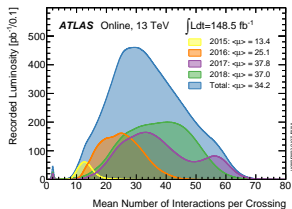


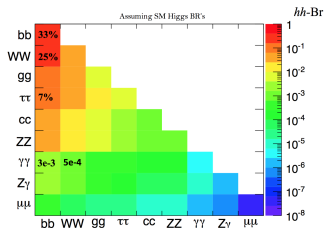
Figure: SM di-Higgs production diagrams (a, b, c), and BSM di-Higgs production through new particle production (d)

Advantage and Challenge of ZZ Production Channel Search

- Comparatively low background ($4l + b\bar{b}$)
- Less dependence on high pile-up
- Statistical uncertainty dominates the measurement
- Develop the analysis strategy and study the expected significance using large data-set (3000 fb^{-1}) with LHC high luminosity operations



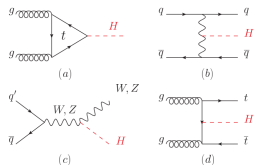
(a) Mean Interactions per Crossing



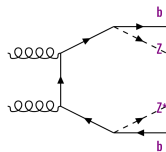
(b) di-Higgs final states

Major Background

- Single Higgs production background
- SM production of ZZbb (VBS, triboson, loop-induced...)



(a) selected single Higgs background processes.



(b) example of SM ZZbb background processes.

Current Study Objective and Methods

- 1 Produce signal and background MC samples at $\sqrt{s} = 13$ TeV from pp collisions
- 2 Study signal and background kinematic distributions and select sensitive discriminant variables
- 3 Design the event selection cuts based on kinematic distributions, and cut events where background dominates
- 4 Study two categories, 2b jets and 1b1j, where the latter accounts for b jet mis-tagging and increases statistics amount for future studies with multi-variable methods

- NLO SM di-Higgs production (non-resonant + self-coupling)
- Higgs and SM ZZbb background sample

| | NLO Signal | ggF | VBFH | ZH | WH | ttH-semi | ttH-all |
|--------------------------|------------|------------|----------|----------|----------|----------|----------|
| luminosity (fb^{-1}) | 3000 | 3000 | 3000 | 3000 | 3000 | 3000 | 3000 |
| cross section (fb) | 33.4 | 48580 | 3782 | 883.9 | 1373 | 507.1 | 507.1 |
| branching ratio | 0.0000722 | 0.00015987 | 0.000275 | 0.000275 | 0.000275 | 0.00012 | 0.000126 |

Table: Signal xs and BR ratio: the generator. Background xs and BR ratio: CERN Yellow Report, PDG.

- SM ZZbb background xs \times BR from MadGraph calculation: $66.7 fb^{-1}$. The imprecision in MG calculation can be constrained by sideband mJJ.

Two b jets Category

- lepton kinematics: $P_t > 7\text{GeV}$, $\eta < 2.5$
- jet kinematics: if $\eta < 2.4$, $P_t > 30\text{GeV}$. if η is between 2.4 to 4.5, $P_t > 40\text{GeV}$
- 4 or more leptons, 2 or more b jets
- minimum lepton separation $\delta R > 0.1$
- One on-shell Z boson mass: 66 GeV to 116 GeV

Signal and background mass and p_T distributions after pre-selection

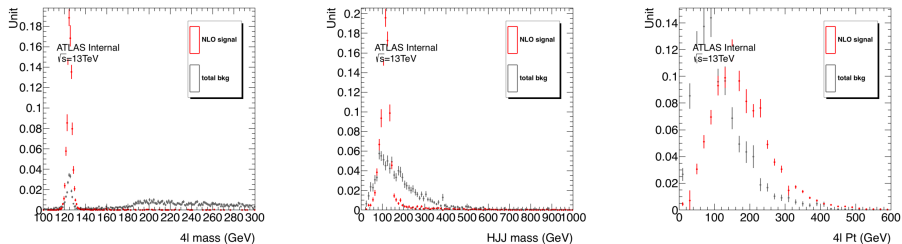


Figure: left: 4l mass distribution after preliminary cuts on p_8 . middle: H_{JJ} mass distribution after 4l mass cut. right: 4l Pt distributions after H_{JJ} mass cut.

Event Selection Optimization

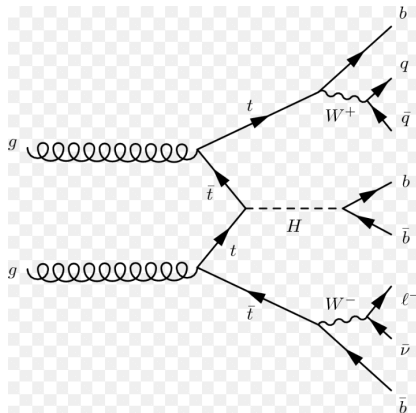
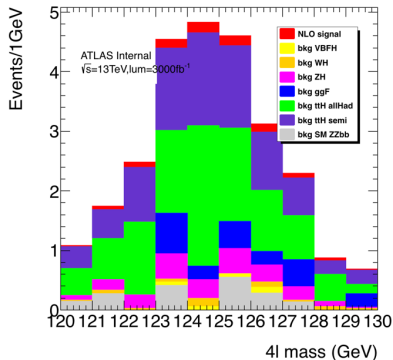


Figure: left: Four lepton mass graph after 4l Pt cut. right: ttH process semi-lepton channel Feynman diagram.

Event Selection Optimization

- ttH processes produces more jets and leptons due to additional W bosons from top quark decay.

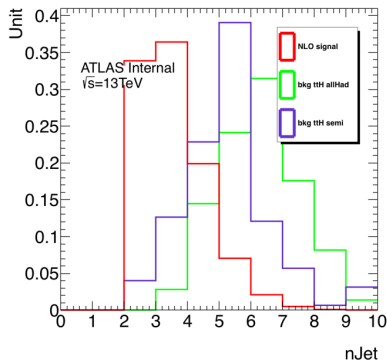
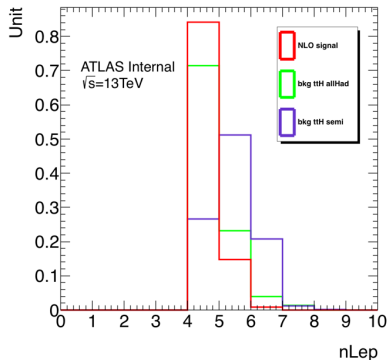


Figure: left: lepton number distribution of NLO signal and major ttH processes (allhad, semi-lepton). right: jet number distribution of above processes.

Final Event Selections

- 4 or more leptons, 2 or more b jets
- lepton kinematics: $P_t > 7\text{GeV}$, $\eta < 2.5$
- jet kinematics: if $\eta < 2.4$, $P_t > 30\text{GeV}$. if η is between 2.4 to 4.5, $P_t > 40\text{GeV}$
- minimum lepton δR : minimum δR among all lepton > 0.1
- on-shell Z boson mass: 66 GeV to 116 GeV
- four lepton mass: 120 GeV to 130 GeV
- Higgs mass (reco from jets): $< 160\text{ GeV}$
- transverse momentum of 4 lepton: $> 100\text{ GeV}$
- number of lepton equals 4
- jet number < 4

Cutflow Table

| | NLO signal | SM ZZbb | ttHdilept | ttHdilept | ggH |
|------------|-------------|---------|-------------|-------------|--------------|
| two b jets | 1.3 | 769.5 | 46.6 | 42.9 | 6.3 |
| 4l mass | 1.23 | 13.72 | 40.1 | 34.3 | 6.1 |
| JJ mass | 1.13 | 7.52 | 18.6 | 16.1 | 4.3 |
| 4l Pt | 0.95 | 1.81 | 10.1 | 8.16 | 2.3 |
| 4Lep | 0.80 | 1.67 | 7.2 | 2.17 | 2.3 |
| nJet<4 | 0.56 | 0.68 | 0.20 | 0.36 | 1.34 |
| | ZH | WH | VBFH | total bkg | significance |
| two b jets | 5.06 | 1.18 | 1.91 | 874.8 | 0.044 |
| 4l mass | 4.41 | 1.0 | 1.68 | 102.5 | 0.121 |
| JJ mass | 4.1 | 0.7 | 0.95 | 53.4 | 0.156 |
| 4l Pt | 2.26 | 0.50 | 0.28 | 26.3 | 0.184 |
| 4 Lep | 1.87 | 0.50 | 0.16 | 16.6 | 0.195 |
| nJets<4 | 1.51 | 0.41 | 0.16 | 4.67 | 0.259 |

Table: Cutflow of expected number of events; normalize to 3000 fb^{-1}

Signal and background four-lepton mass distribution with final selection with adjustment

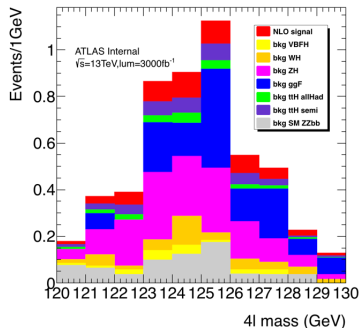


Figure: 4l mass after all cuts using 4l mass shape after mJJ selection

Signal and background four-lepton mass distribution with final selection

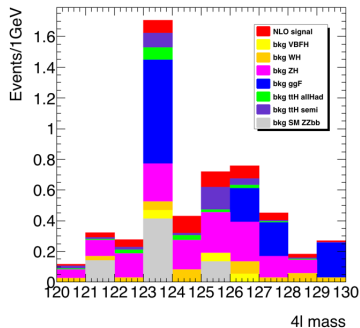


Figure: 4l mass after all cuts

1b1j Category

Event Selection

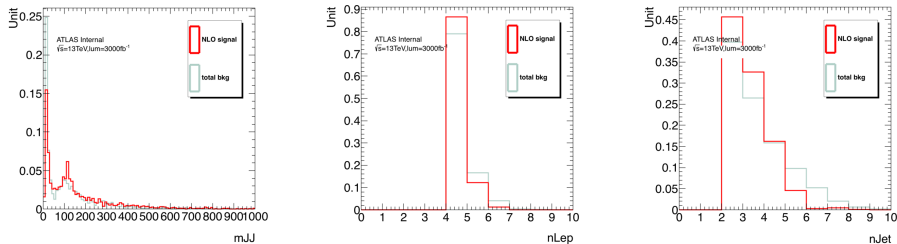


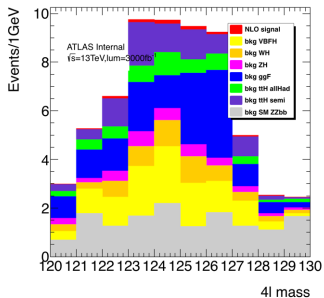
Figure: left: H_{JJ} mass distribution after 4l mass cut. middle: n_{Lep} distribution after previous cuts. right: n_{Jet} distribution after previous cuts.

Final Event Selections

- 4 or more leptons, 1 b jet and 1 non-b jet
- lepton kinematics: $P_t > 7\text{GeV}$, $\eta < 2.5$
- jet kinematics: if $\eta < 2.4$, $P_t > 30\text{GeV}$. if η is between 2.4 to 4.5, $P_t > 40\text{GeV}$
- minimum lepton δR : minimum δR among all lepton > 0.1
- on-shell Z boson mass: 66 GeV to 116 GeV
- four lepton mass: 120 GeV to 130 GeV
- Higgs mass (reco from jets): $> 15\text{GeV}$
- transverse momentum of 4 lepton: $> 100\text{GeV}$
- number of lepton < 6
- jet number < 5

Results on 1 bjet tagging category

| | NLO signal | SM ZZbb | ggH | VBFH | ZH |
|------------|------------|------------|-------------|-----------|--------------|
| final cuts | 0.82 | 4.55 | 7.83 | 11.5 | 3.3 |
| | WH | ttH allhad | ttH semilep | total bkg | significance |
| final cuts | 5.5 | 4.55 | 7.83 | 62.2 | 0.10 |



Conclusions

Current study observations and result

- SM ZZbb (non-resonant background) is a sizable component of the final background
- Leptons from signal and Higgs background are clustered together
- With our current cuts, we achieve a significance of 0.26, with 0.56 signal and 4.67 total background in 2b jets category, and a significance of 0.10 with 0.82 signal and 62.2 total background in 1b1j category.

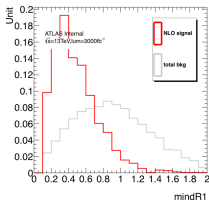


Figure: minimum δR among all leptons distribution after preliminary cuts

Prospect in further studies

- 1 Study $HH \rightarrow llqq + b\bar{b}$ and $HH \rightarrow ll\nu\nu + b\bar{b}$ channels
 - 2 Multivariable methods (e.g. BDT) to improve event selections cannot be applied due to low MC sample size at final stage
 - 3 Higgs to 4l spin correlation (generated by MadSpin) is not included in the current signal sample
-
- 1 Create 3 categories with no b jet, 1 b jet and 2 b jets

Acknowledgements

I would like to acknowledge Professor Bing Zhou from the University of Michigan and Dr. Bing Li for guiding my research. I would also like to acknowledge the University of Michigan Department of Physics, specifically Professor Jean Krisch, Tom Schwarz and Steven Goldfarb for organizing the program.

Appendix 1: Spin Correlation

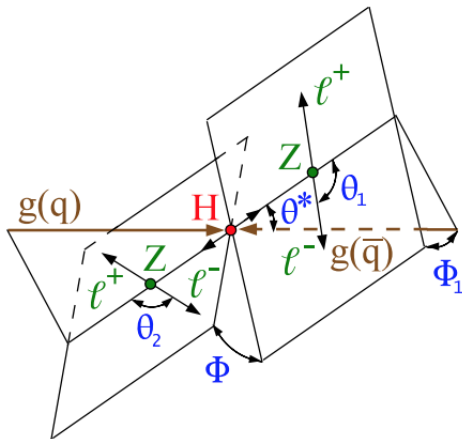


Figure: 4 lepton angular correlation due to Higgs spin properties

Appendix 2: CMS results

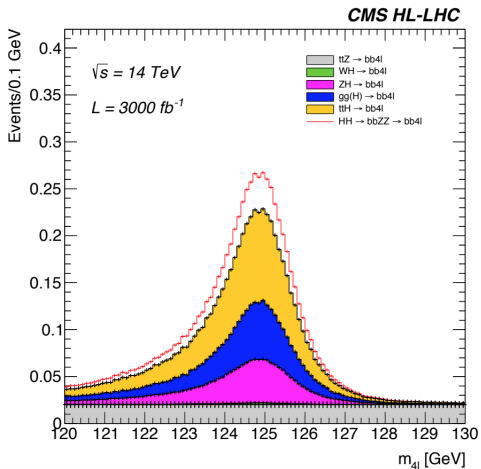


Figure: CMS di-Higgs analysis result, significance 0.4