Prospects for Di-Higgs boson searches with multilepton final states in the qqHH production mode

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Why is Di-Higgs production interesting?

- Measuring the Higgs boson self interaction
  - Trilinear self-coupling
  - Quartic self-coupling
- Determining the shape of the Higgs potential

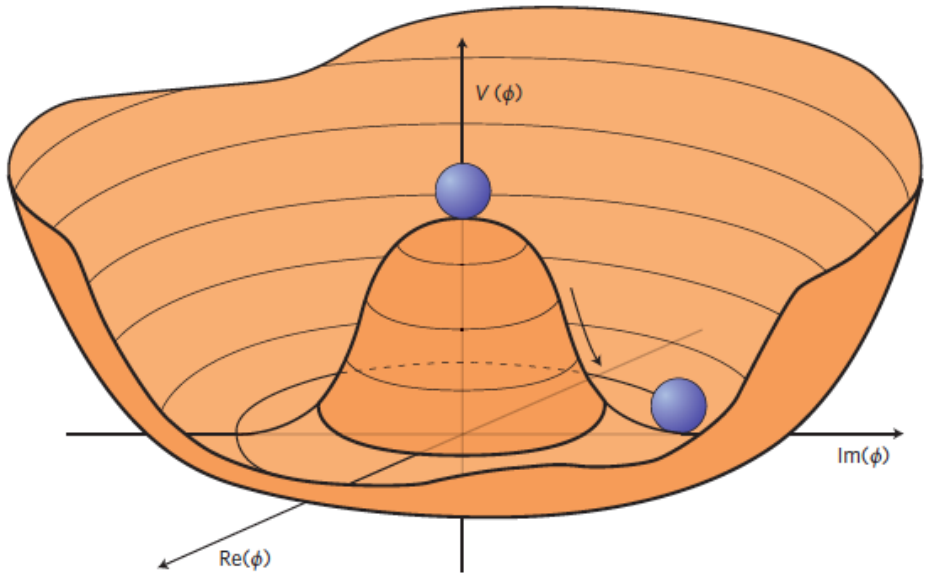


Figure: The Higgs potential [1]

Higgs production mechanisms

Gluon-Gluon Fusion (GGF)

- Dominant Higgs production mechanism at the LHC
- Gluons fusing via a top-quark loop
- Governed by λ and Y_t

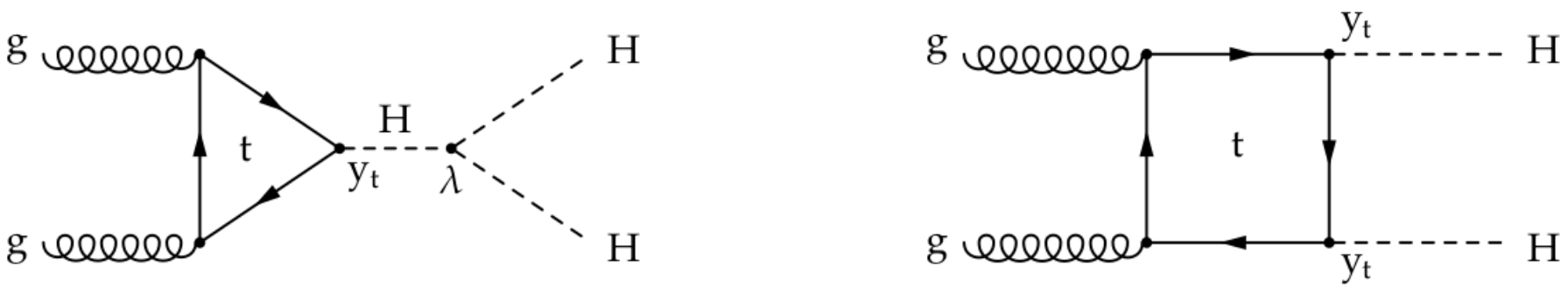


Figure: LO Feynman diagrams for SM non-resonant HH production via gluon fusion [2]

Higgs production mechanisms

Vector Boson Fusion (VBF)

- Sub-dominant Higgs production mechanism at the LHC
- Two initial-state quarks radiate off virtual electroweak gauge bosons (W or Z) that fuse together
- Characterized by two high energy jets in the detector

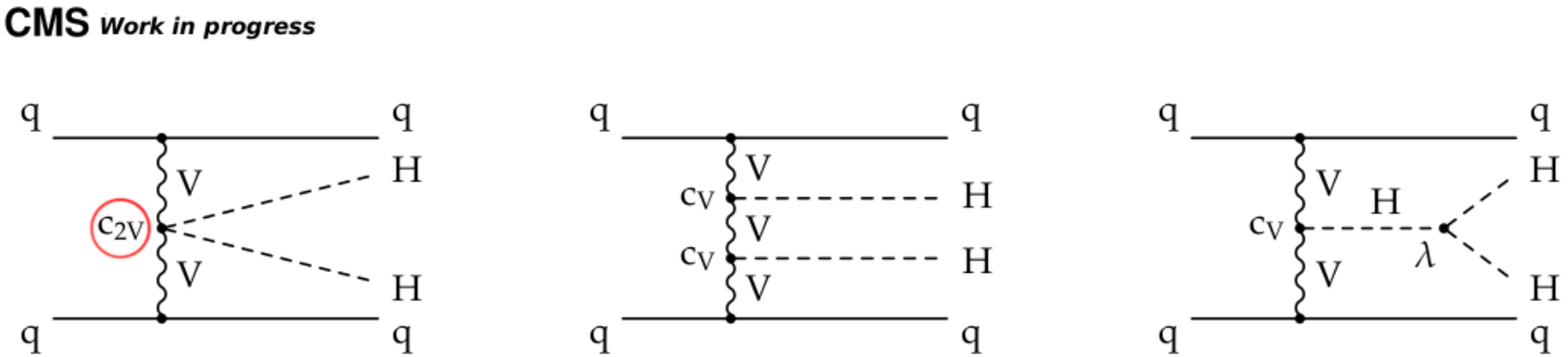


Figure: LO Feynman diagrams for SM non-resonant HH production via vector boson fusion

HH multilepton

- Search for HH production in WWWW, WW$\tau\tau$, and $\tau\tau\tau\tau$ decay modes
- Full LHC Run2 dataset, integrated luminosity of 138 fb^{-1}, center-of-mass energy of 13 TeV
- Events contain 2,3,4 reconstructed leptons (including e^{-}, μ^{-}, τ_{had})
- Includes 7 different channels
- Constraints on the trilinear Higgs self-coupling and the HH signal component in the ggHH production mode

Motivation

- Extending the HH multilepton analysis focus to the sub-dominant qqHH production mode
- Learn more about the so far unmeasured VVHH Higgs boson (H) coupling to Vector bosons (V)

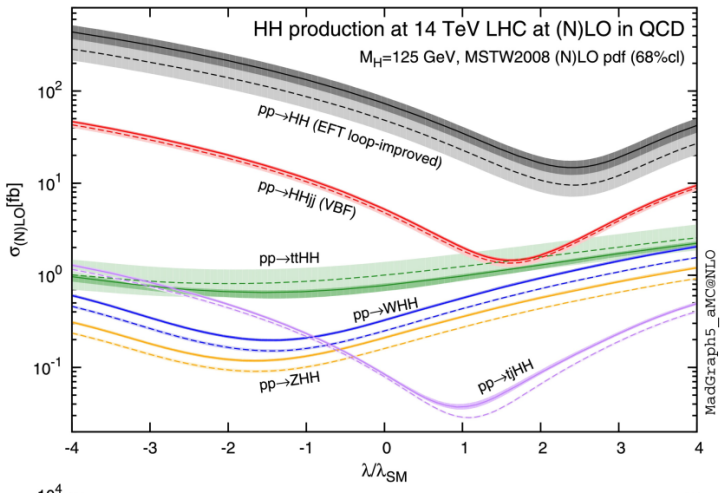


Figure: Production cross section for non-resonant Di-Higgs production at the LHC [3]

qqHH decay channel

2 same-sign leptons with 1 or less tau final state:

- 2 leptons (electron or muon) with same-sign electric charge
- 1 or less hadronic tau
- Missing transverse energy
- 2 VBF jets

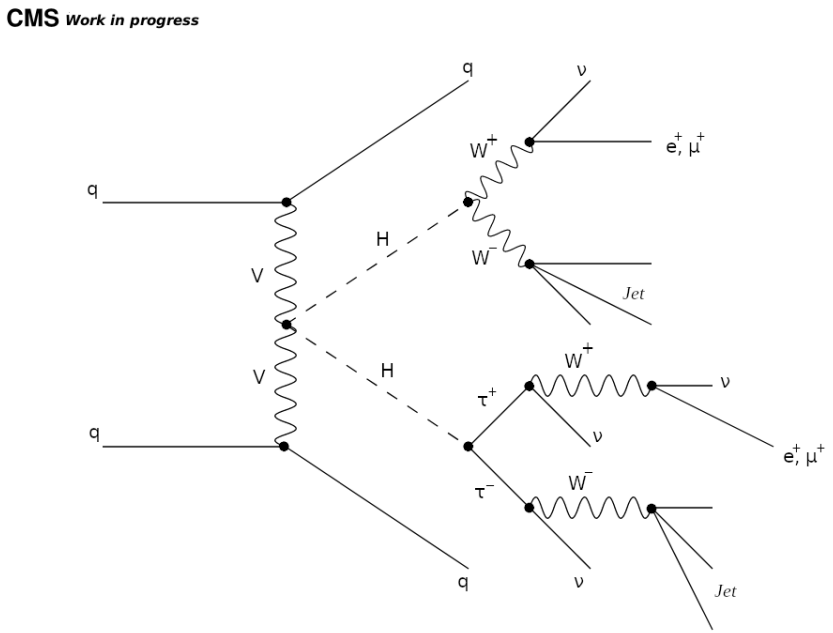


Figure: Feynman diagram for VBF 2lssleq1tau

qqHH decay channel

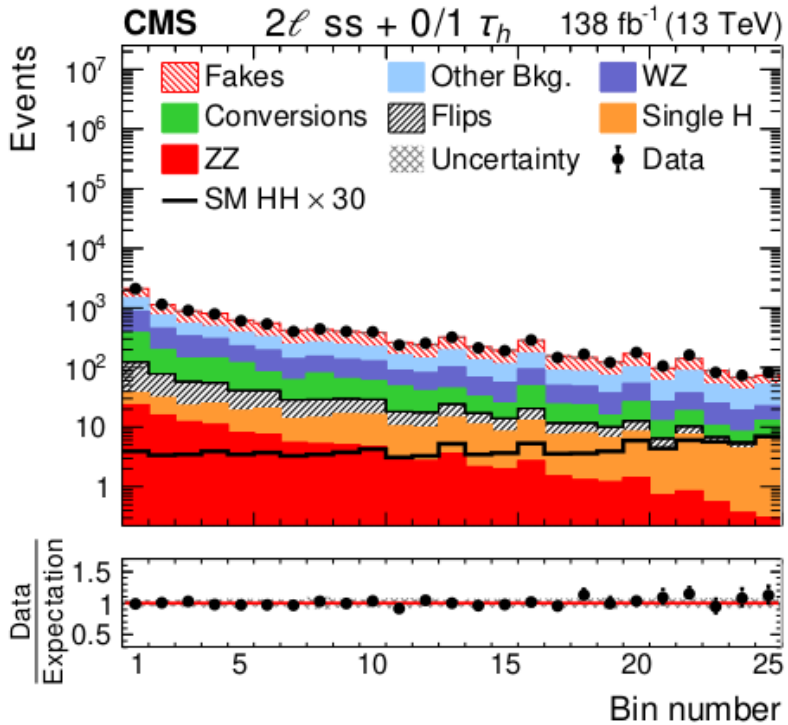


Figure: HH - multilepton analysis 2lss distribution [2]

- Fakes
- WZ, ZZ
- Other smaller backgrounds

Approach

- Separate VBF from GGF and signal from background using machine learning methods (Boosted Decision Tree)

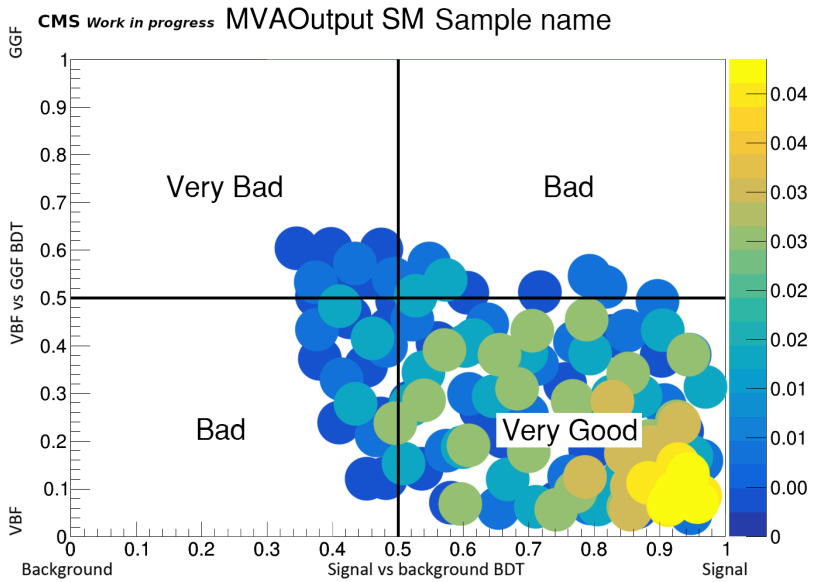


Figure: 2D histogram skematic

VBF jet selection

The following requirements are needed to classify VBF jets:

- $|\eta| < 4.7$
- $p_T > 20$ GeV
- Largest mass of 2 jets in the event

BDT input variables

We use angular separation and invariant masses between pairs of jets, leptons, hadronic taus, transverse momenta, transverse energy, reconstructed mHH, etc

For example:

- ΔR_{jj}^{VBF} - angular separation between the 2 vbf jets

$$\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$$

Nodewise predictions

The training was done on (nr of events):

- Signal: 5 340 257 (GGF)
- Background: 106 414 (VBF)

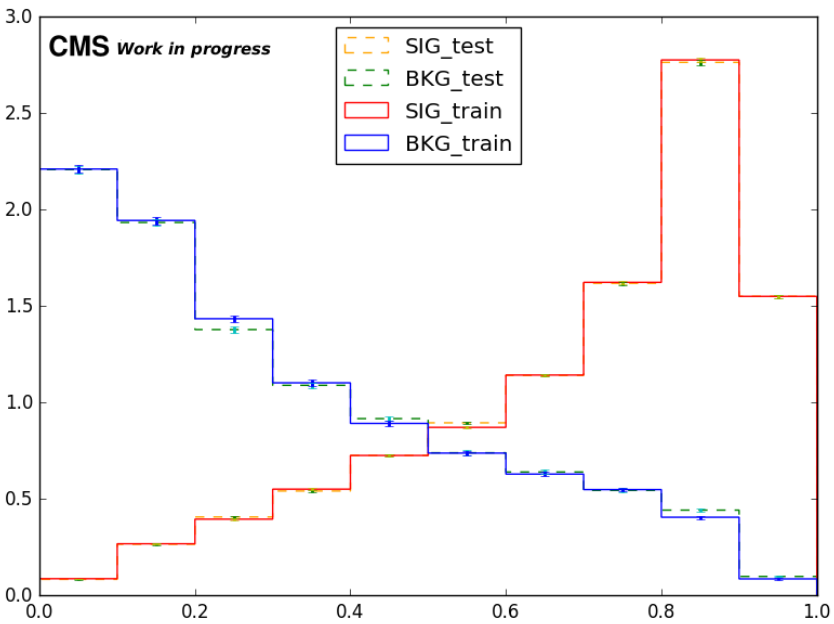


Figure: SM VBF vs GGF bdt

- Signal: 5 345 899
- Background: 486 124

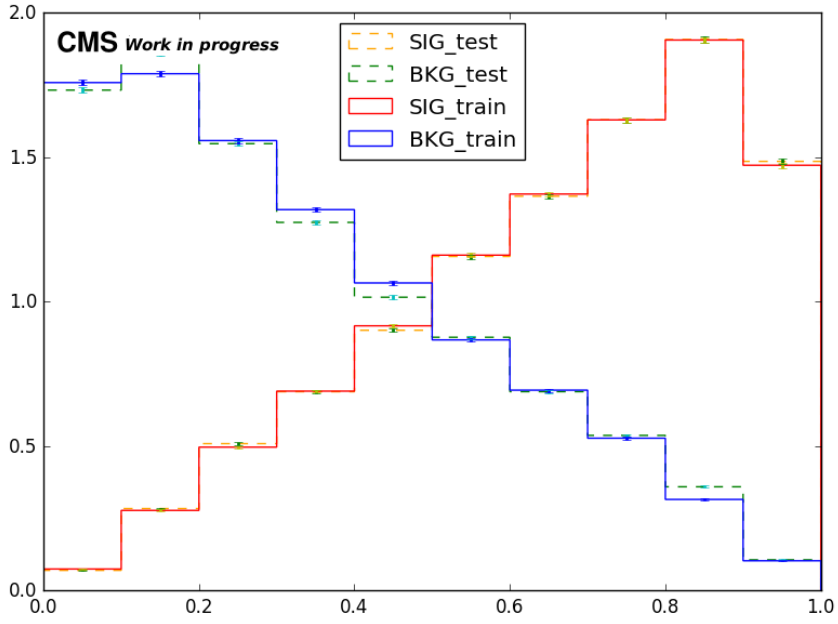
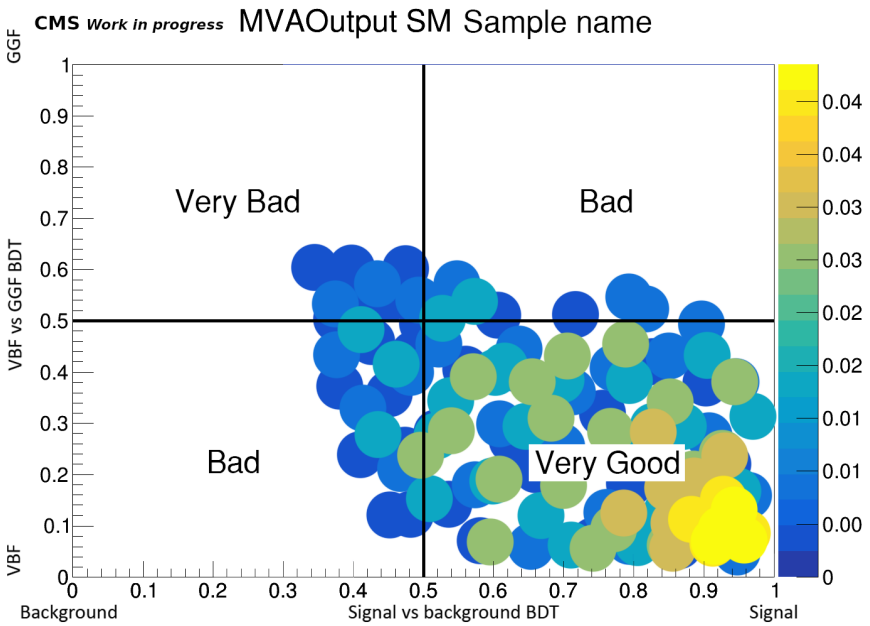


Figure: SM signal vs background bdt

2D histograms



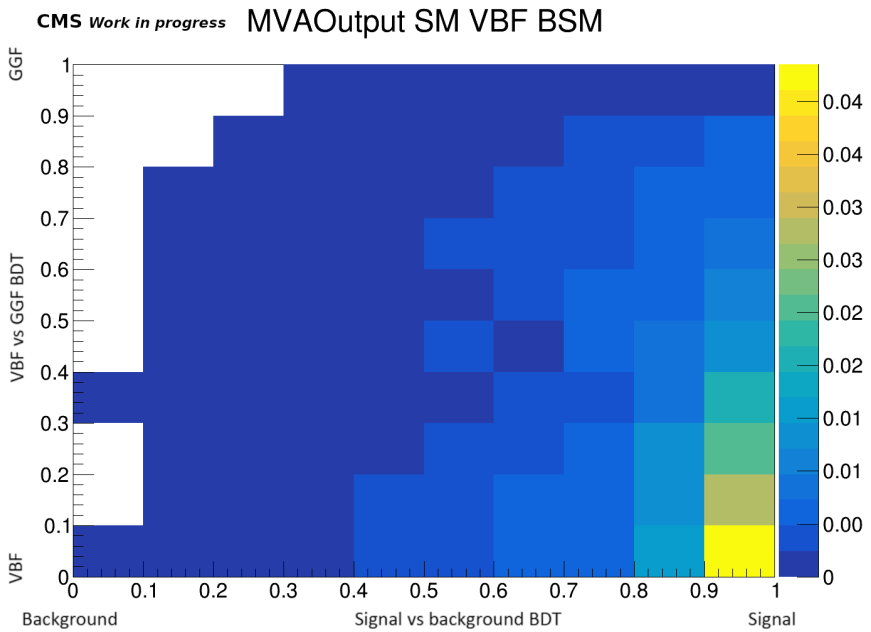
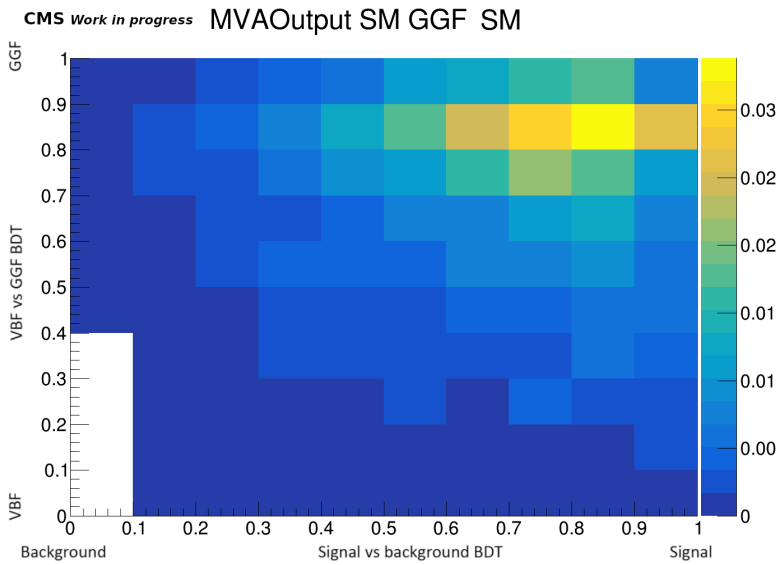
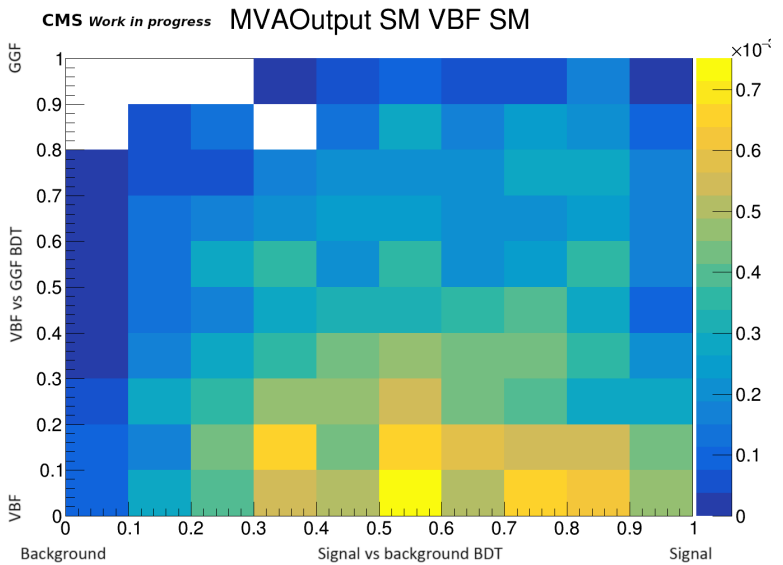
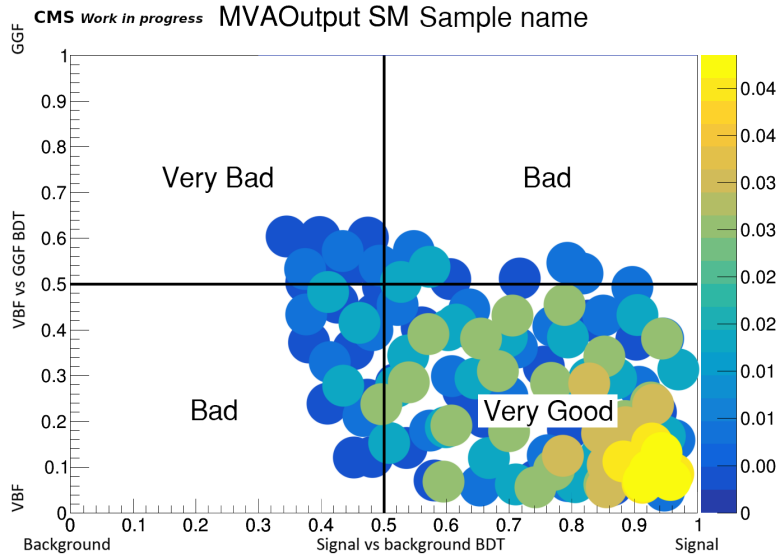


Figure: 2018 era MVAOutput 2d signal histogram for BSM VBF

2D histograms







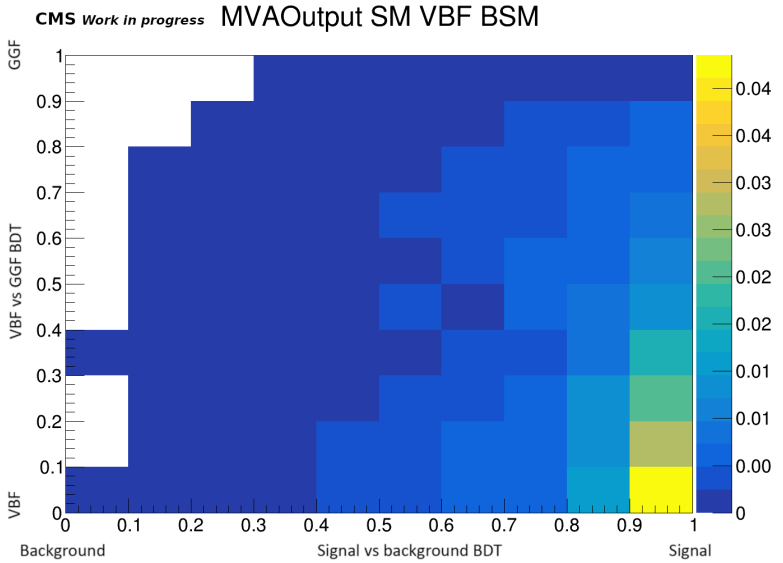
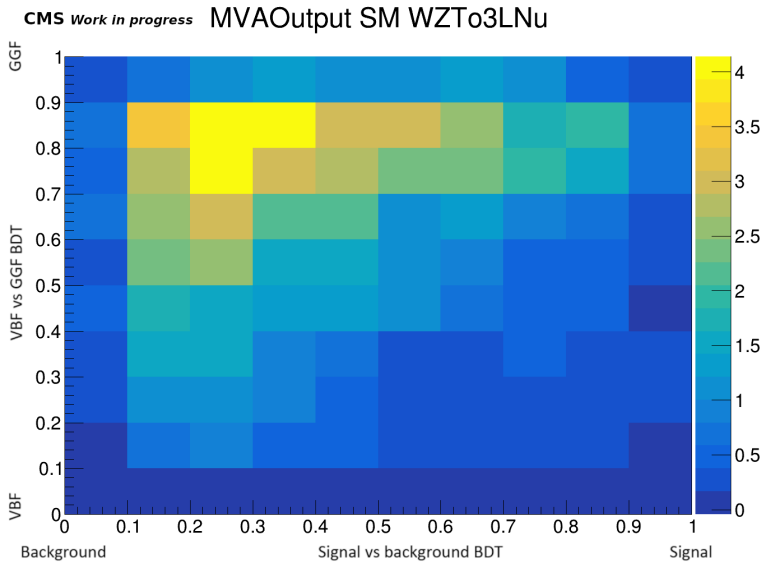
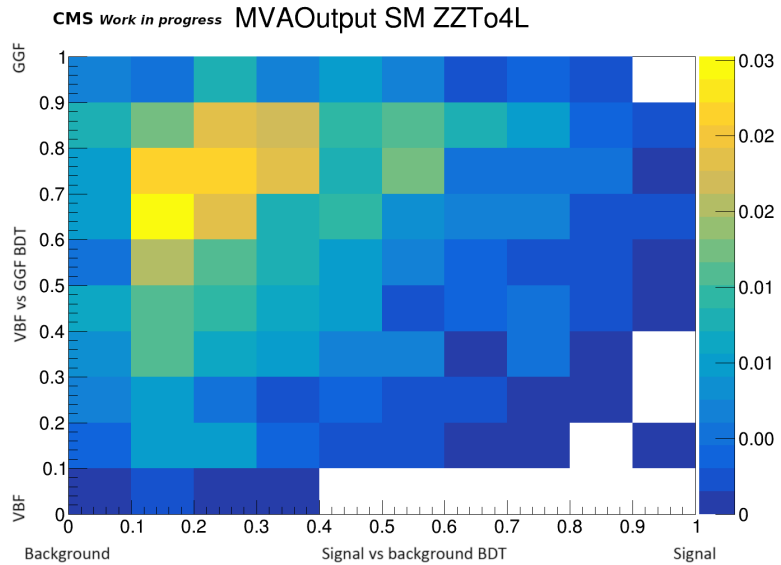


Figure: 2018 era MVAOutput 2d signal histograms

2D histograms





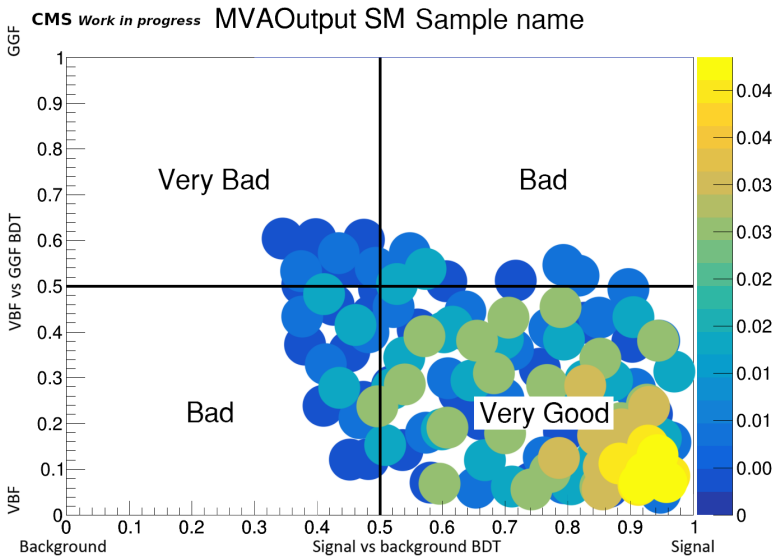


Figure: 2018 era MVAOutput 2d background histograms

Limits

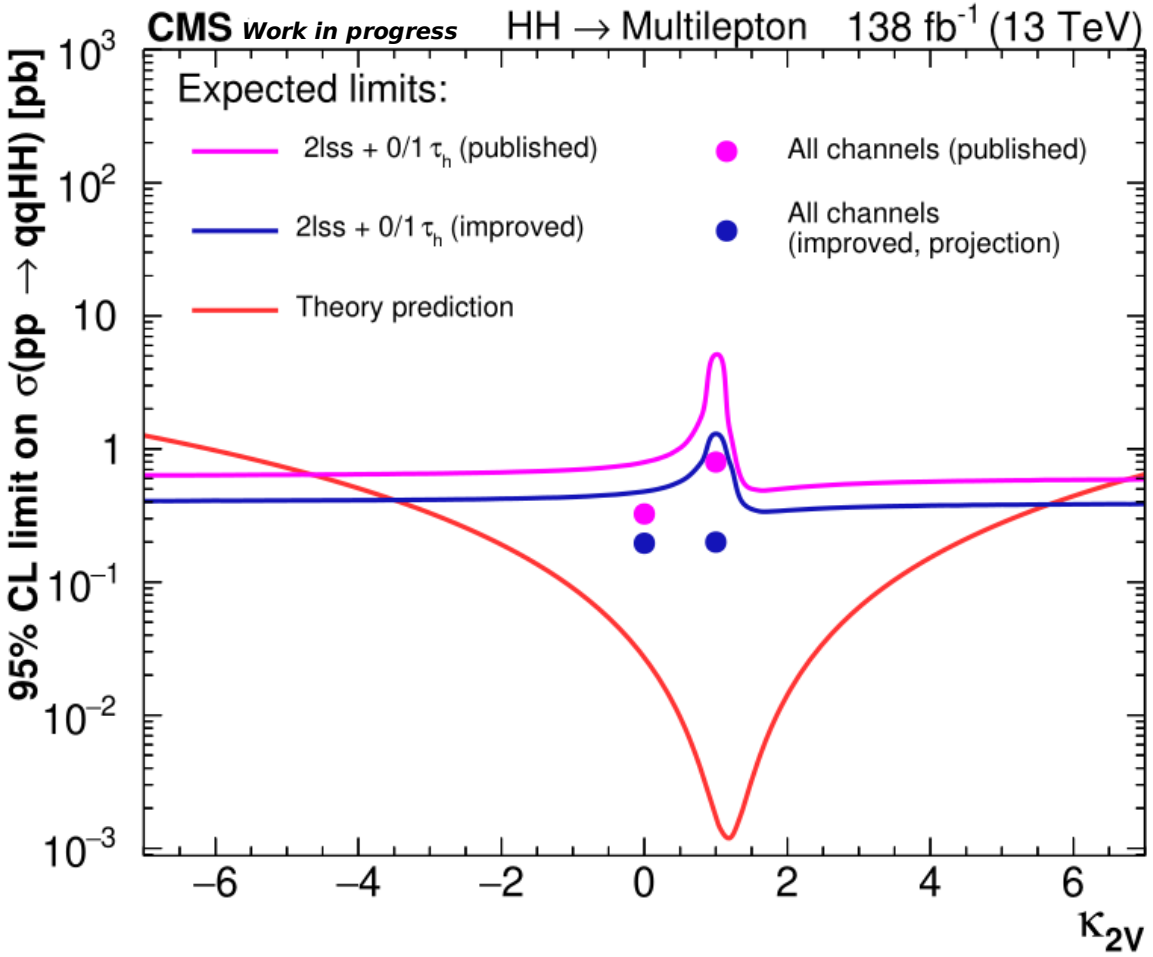


Figure: Limits on 2lss

Improved by a factor of 4.
Improvement better for SM than BSM

Limits

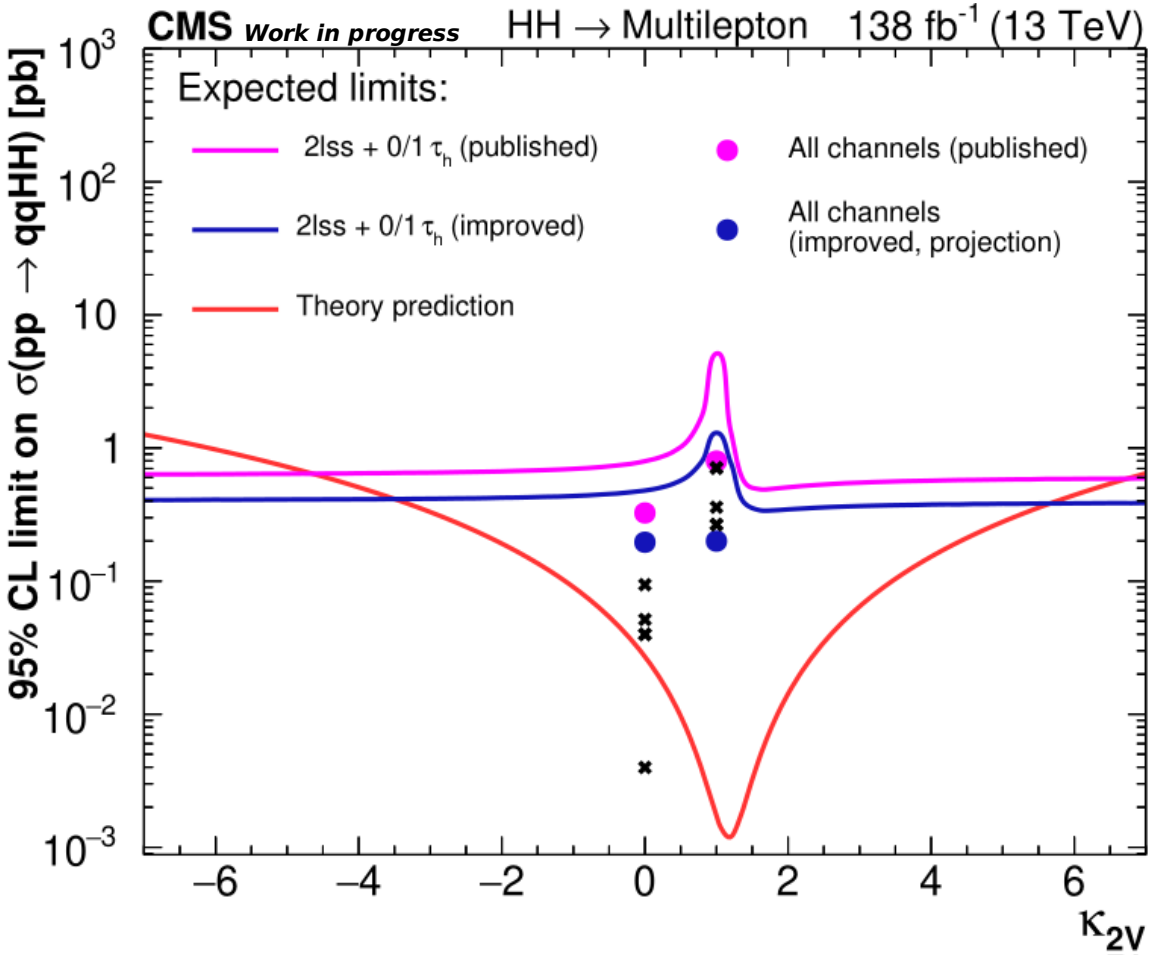


Figure: Limits on 2lss

x - other Di-Higgs analyses: bb$\gamma\gamma$, bb$\tau\tau$, bbbb.
SM potentially comparable to other Di-higgs analyses results

Summary

- We have a classifier that can distinguish between vbf and ggf
- improved our limits on qqHH by a factor of 4
- The study turned out to be feasible and can be improved
- Potentially comparable to other analyses results

Back-up slides

BDT input variables

VBF vs GGF BDT:

- vbf m_{jj}
- HT
- maxJetPt_vbf
- dihiggsMass_wMet_sel
- nJet
- m_{ll}
- max dR_vbfjet_lep
- vbf $pT_{sublead}$
- $dR_{h_1 h_2}$
- vbf dR_{jj}

Signal vs Background BDT:

- dR_l_Wjets_min
- mindr_lep1_jet
- nJet_vbf
- STMET
- mindr_lep2_jet
- dihiggsMass_wMet_sel
- dR_l_leadWjet_min
- leptonPairMass_sel
- nJet
- dR_2j_fromW1

ROC

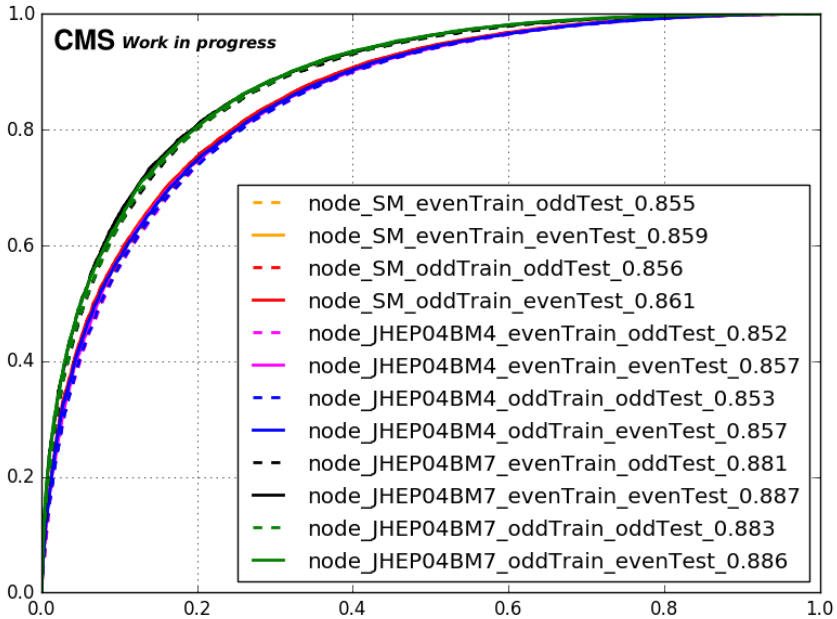


Figure: VBF vs GGF bdt nodeWise ROC performance

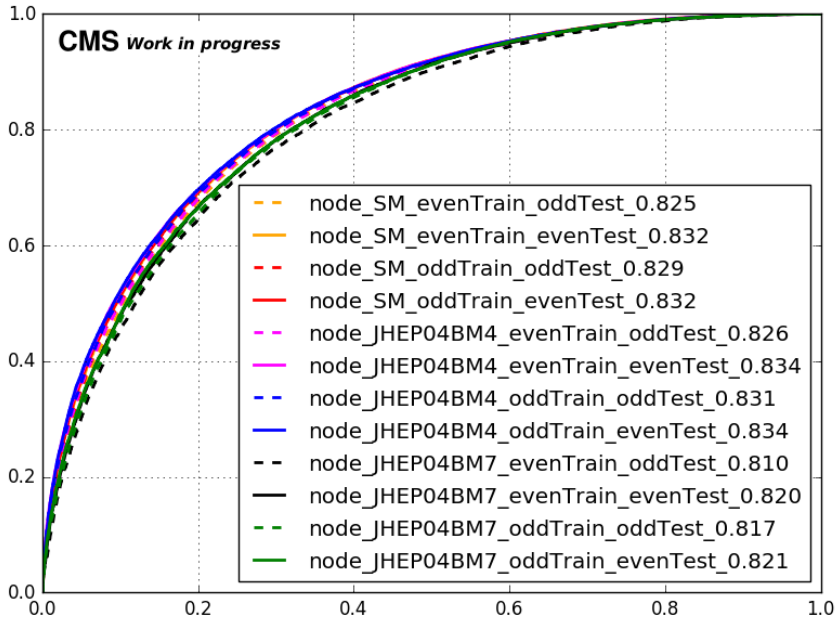


Figure: Signal vs background nodeWise ROC performance

References

[1] Ellis, John *"Higgs Physics"*, p. 05, 2013, URL: https://arxiv.org/pdf/1312.5672.pdf

[2] CMS Collaboration *"Search for Higgs boson pairs decaying to WWWW, WW$\tau\tau$, and $\tau\tau\tau\tau$ in proton-proton collisions at $\sqrt{s} = 13$ TeV"*, p. 01, 22, 2022, URL: https://arxiv.org/abs/2206.10268.pdf

[3] R. Frederix et al. *"Higgs pair production at the LHC with NLO and parton-shower effects"*, p. 06, 2014, Physics Letters B, URL: https://arxiv.org/pdf/1401.7340.pdf