Search for resonant di-Higgs production with bbZZ decays

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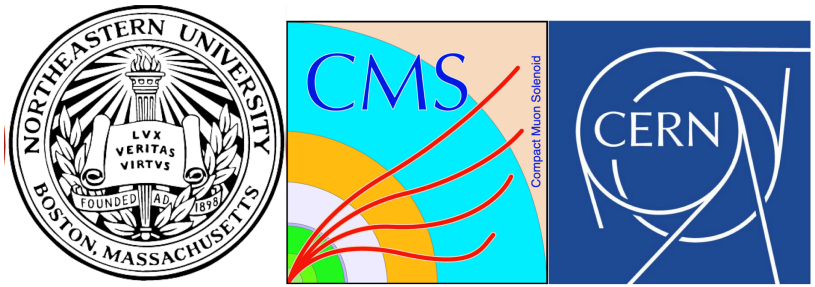
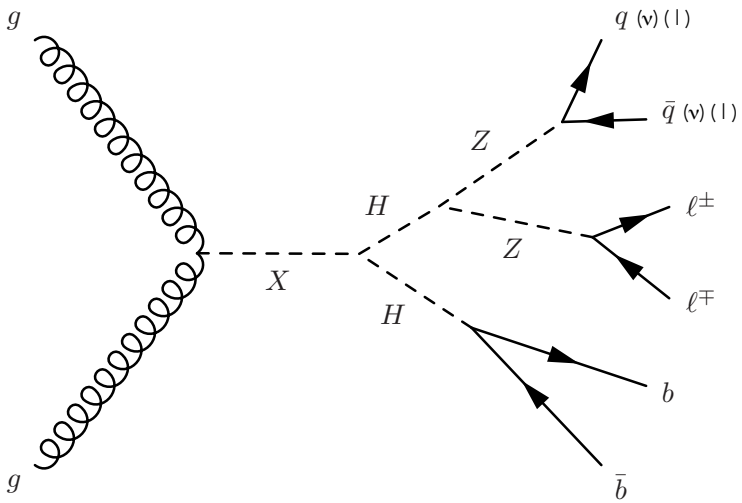
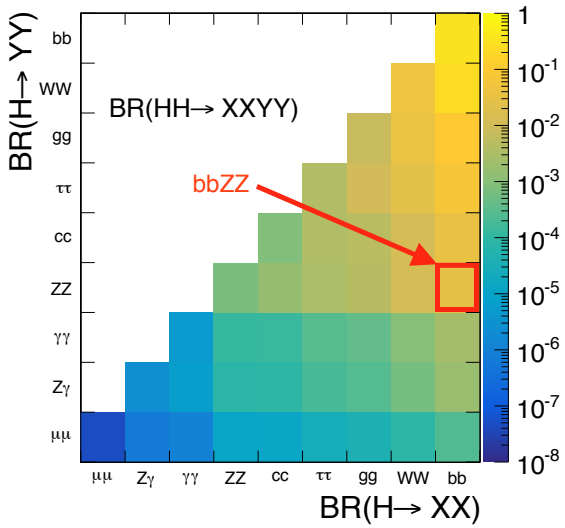


Resonant HH production in bbZZ decay channel





decay channel	BR
$b\bar{b}b\bar{b}$	33%
$b\bar{b}WW^*$	25%
$b\bar{b}\tau^+\tau^-$	7.3%
$ZZb\bar{b}$	3.1%
$WW^*\tau^+\tau^-$	2.7%
$ZZWW^*$	1.1%
$b\bar{b}\gamma\gamma$	0.26%

- X $\rightarrow$ HH $\rightarrow$ bbZZ.
- Currently looking at narrow width Radion (spin-0) [PhysRevD.62.045015] and Graviton (spin-2) [PhysRevLett.84.2080] models.
- Various final states can be considered (ll = $\mu\mu$, ee):
  - bbZ(ll)Z($\nu\nu$)
  - bbZ(ll)Z(qq)
  - bbZ(ll)Z(ll)
- Analyses being reviewed, no public results available.

$HH \to bb2l2\nu$: Signature and Backgrounds

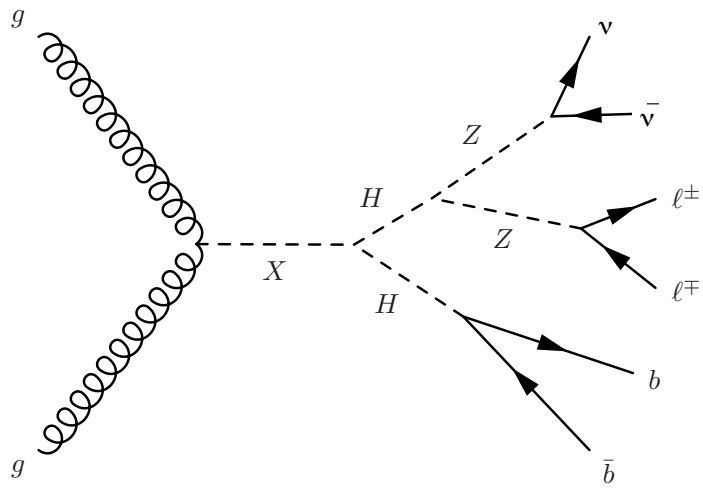
- 2 b jets from H→bb, 2 leptons from Z, and MET from the other Z.
- $HH \to bbWW \to bb2l2\nu$ also enters selections but orthogonality to bbWW analysis is maintained by the requirement that $M_{ll} > 76$ GeV.

The main backgrounds in this channel are:

- $t\bar{t}$ + jets
- DY+ jets
- $t\bar{t}$ is the most dominant one while DY is more signal-like background.

Other backgrounds are:

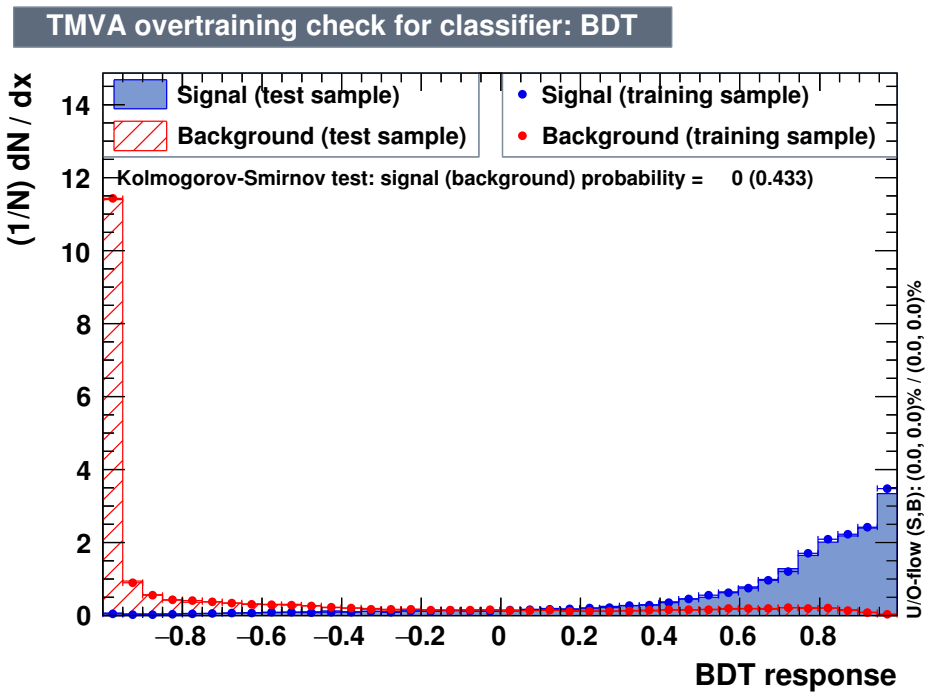
- single top quark productions
- diboson+jets
- ZH production



$HH \to bb2l2\nu$: Analysis Strategy

- Combine $\mu\mu$ and ee channels
- Baseline selections
  - 2 opposite sign leptons
  - a pair of b-jets with the highest MVA based b-tagging discriminant value and passing loose working point.
  - $90 < M^{H}_{bb} < 150$ GeV
  - $76 < M_{ll} < 106$ GeV (leptonic Z on-shell)
  - $M^{HH}_{T} > 100$ GeV
  - MET cuts which vary with M_X, orthogonal with bb2l2q analysis
- DY and TT SFs, simultaneously fit of SR and CRs (defined by M^{Z}_{ll} and M^{H}_{bb})
  - other minor backgrounds taken directly from MC
- BDTs are trained on bbZZ signal vs DY&TT events
  - 2 BDTs are used: low ($M_X \leq$450 GeV) and high mass regions
  - 9 variables are used: M^{Z}_{ll}, M^{ZZ}, M^{H}_{bb}, ΔR_{ll}, ΔR^{H}_{bb}, $p_T^{H_{bb}}$, $p_T^{Z_{ll}}$, p_T^{ZZ}, E_T^{miss}
  - BDT cuts are optimized for each mass hypothesis and each channel (ee/$\mu\mu$) separately
- M^{HH}_{T} distribution is used in the fits to extract limits (binned shape analysis)

HH $\to$ bb2l2ν: BDT Discriminant and M_T^{HH}



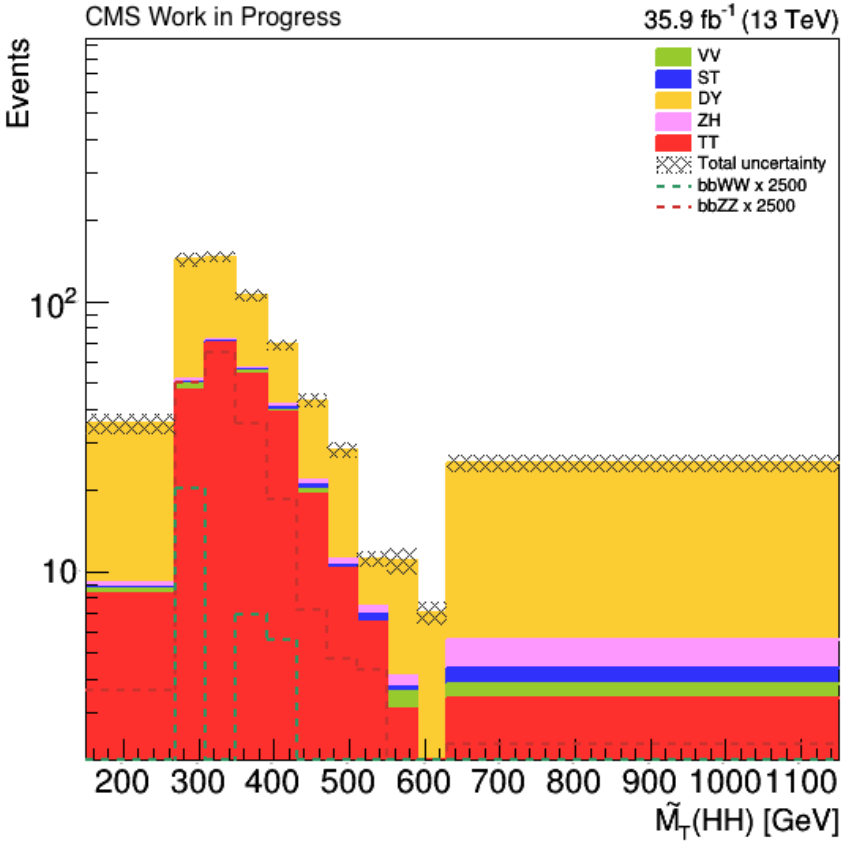


Figure: Output distribution for the BDT trained for low M_X mass in the electron channel (left) where the signal is KK-graviton, and the M_T^{HH} distribution (right).

HH $\rightarrow$ bb2l2q: Signature and Backgrounds

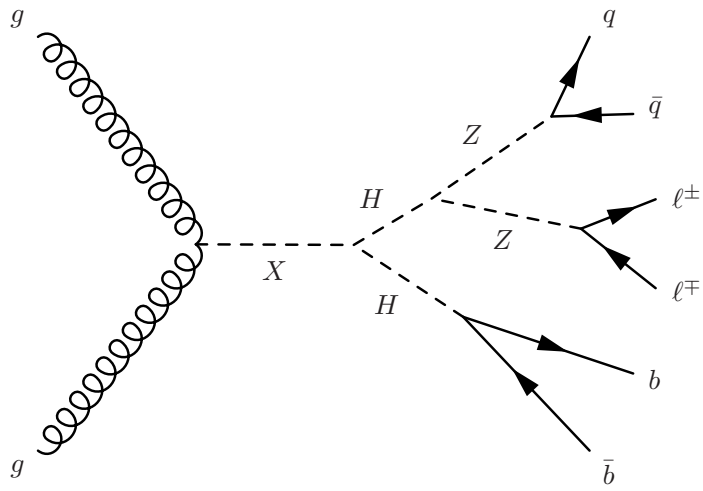
- 2 b jets from H$\rightarrow$bb, 2 leptons from Z, and 2 jets from the other Z.

The main backgrounds in this channel are:

- $t\bar{t}$ + jets
- DY+ jets
- DY is the larger background, but $t\bar{t}$ is closer kinematically to signal.

Other backgrounds are:

- W+jets
- single top quark productions
- diboson+jets
- SM Higgs production
- QCD multijet production

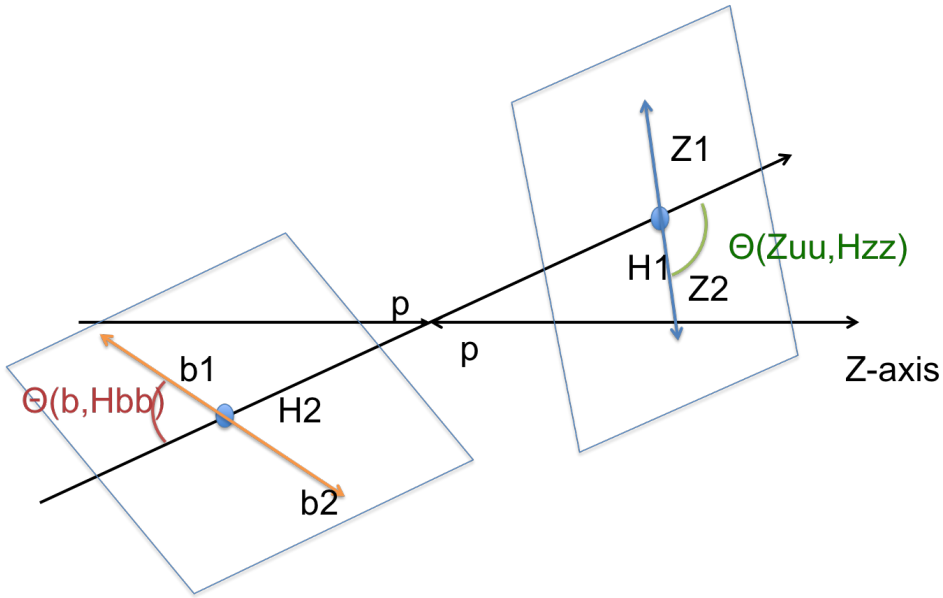


HH $\rightarrow$ bb2l2q: Analysis Strategy

- Combine $\mu\mu$ and ee channels
- Assign 4 jets as H(bb) and Z(jj) using b-tag and kinematic information (see backup slide).
- Baseline selections
  - 2 opposite sign leptons, M_{ll} >12 GeV
  - 4 jets assigned to H(bb) and Z(jj), at least 1 loose btag jet among the 4 H/Z jets
- Background estimation
  - normalize major backgrounds (DY, tt) to data in control regions
  - QCD multijets background from data driven approach
  - other minor backgrounds taken directly from MC
- Signal extraction
  - at least 1 medium btag jet among the 4 H/Z jets
  - MET cuts which vary with M_X, orthogonal with bb2l2ν analysis
  - train BDT discriminant for each signal mass point
- BDT distributions are used in the fits to extract limits (binned shape analysis)

HH $\rightarrow$ bb2l2q: BDT Training

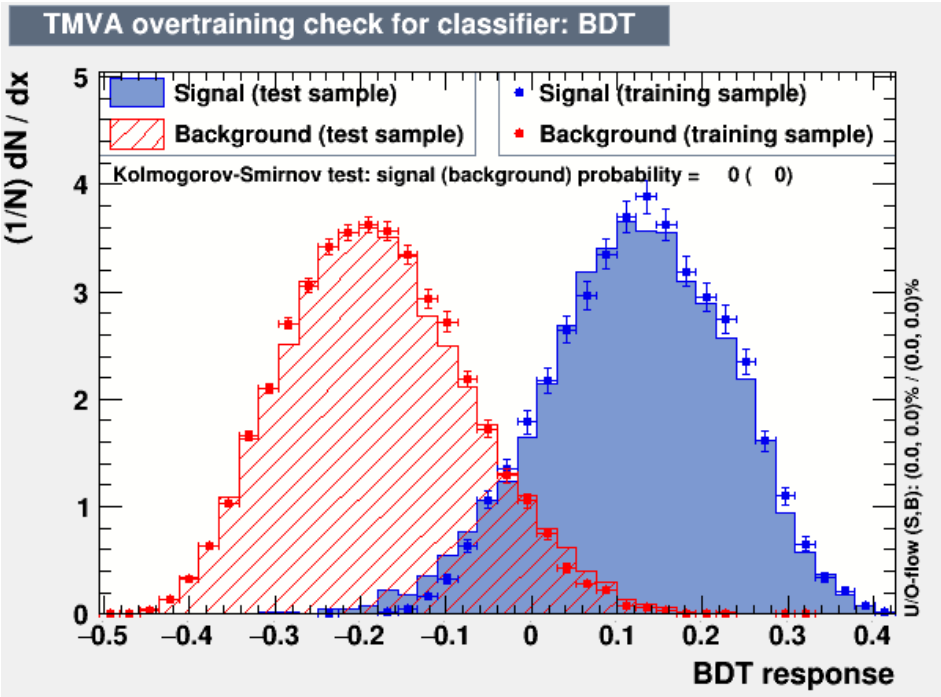
- Construct BDT for each of the resonance mass hypotheses.
- Trained with 25 variables:
  - M_{ll}^{Z}, M_{bb}^{H}, M_{jj}^{Z}, $\Delta\phi_{l1,p_T^{miss}}$
  - p_T^{b1}, p_T^{l1}, p_T^{l2}, $p_T^{Z_{ll}}$, $p_T^{H_{bb}}$
  - ΔR_{ll}, ΔR_{bb}^{H}, ΔR_{jj}^{Z}, $\Delta R_{ll,bb^H}$, $\Delta R_{ll,jj^Z}$, ΔR_{l1b1}, ΔR_{l1b2}, ΔR_{l2b1}, ΔR_{l2b2}, ΔR_{l1j1}, ΔR_{l1j2}, ΔR_{l2j1}, ΔR_{l2j2}
  - $|cos(\theta^*_{CS})|$, $|cos(\theta^*_{b,Hbb})|$, and $|cos(\theta^*_{Zll,Hzz})|$



Samples used for training:

- Signal and background samples described earlier, QCD multijet is negligible

HH → bb2l2q: BDT Discriminant and M_{HH}



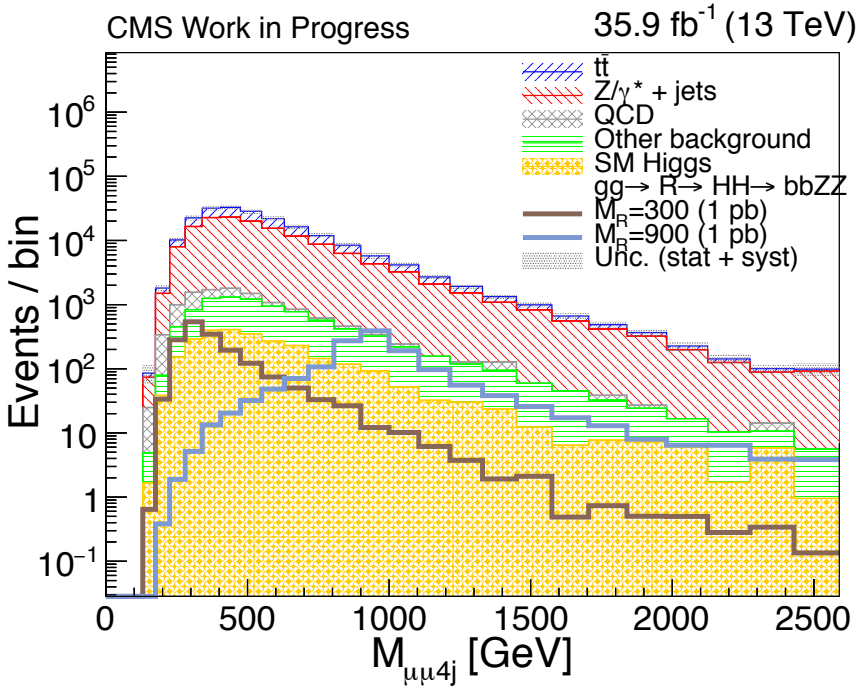


Figure: Output distribution for the BDT trained at $M_X = 650$ GeV in the muon channel (left) where the signal is Radion, and the M_{HH} distribution (right).

HH $\rightarrow$ bb4l

- Signature: 2 b jets from H$\rightarrow$bb, 4 leptons from ZZ.
- Combine 4μ, 4e, and 2μ2e channels
- Backgrounds: ZZ and ggH
  - others: ttZ, SM Higgs production, ...
- Baseline selections
  - 4 leptons, $|M_{4l} - M_H| \leq 10$
  - 2 jets with the highest MVA based b-tagging discriminant value and at least 1 jet passing medium working point.
- Bayesian Neural Network for signal extraction.

Summary

- Review of ongoing efforts for HH $\rightarrow$ bbZZ including
  - HH $\rightarrow$ bb2l2ν
  - HH $\rightarrow$ bb2l2q
  - HH $\rightarrow$ bb4l
- The works are being carried out both on RunII data and for the HL-LHC projections.

Backup

HH → bb2l2q: H(bb) and Z(jj) Jets Assignment

H(bb):

- Find the 2 highest CMVA score jets passing loose WP.
  - If 2 jets are found, done.
  - If only 1 jet is found, find another jet (without b-score requirement) which give closest invariant mass to M(j1+j2)=125 GeV.
- If not found, pick 2 jets which give closest invariant mass to M(j1+j2)=125 GeV.

Z(jj):

- Pick 2 jets (from the rest) which give closest invariant mass to M(mu1+mu2+j1+j2)=125 GeV as Z(jj).

Table: Efficiency of jet assignment, considering events with 4 reco jets (with generated jet matched).

Mass (GeV)	300	550	900
2 H(bb) jets are correctly assigned	60%	59%	57%
2 Z(jj) jets are correctly assigned	30%	29%	30%

HH $\rightarrow$ bb2l2q: Preselection and Final Selection

- Preselection: (BG-dominated preselection for background determination and validation of control region.
  - 2 opposite sign leptons
    - ★ muons with p_T >20(10) GeV, $M_{\mu\mu}$ >12 GeV
    - ★ electrons with p_T >25(15) GeV, M_{ee} >12 GeV
  - 4 jets assigned to H(bb) and Z(jj) with $p_T > 20$ GeV
    - ★ jets defined as H(bb) have b-jet regression applied, as provided by bb$\gamma\gamma$ group
  - at least 1 loose btag jet among the 4 H/Z jets
- Final Selection: (applied for BDT training, also when calculating limits)
  - at least 1 medium btag jet among the 4 H/Z jets
  - MET cuts which vary with mass (in agreement with bbll$\nu\nu$ analysis):
    - ★ MET $<$ 40 GeV for M_X = 260-300 GeV
    - ★ MET $<$ 75 GeV for M_X = 350-600 GeV
    - ★ MET $<$ 100 GeV for M_X = 650-1000 GeV

HH $\rightarrow$ bb2l2q: HH Angular Variables

- $cos(\theta^*_{CS})$, θ^*_{CS} is the angle between the higgs momentum and the CS-axis (an axis that bisects the angle between the proton and the opposite of the another proton direction).
- $cos(\theta^*_{b,Hbb})$, $\theta^*_{b,Hbb}$ is the angle between the leading b-jet and the higgs momentum.
- $cos(\theta^*_{Zuu,Hzz})$, $\theta^*_{Zuu,Hzz}$ is the angle between the Z boson decaying to muons and the higgs momentum.