Search for resonant production of HH decaying to the bbZZ final state at CMS

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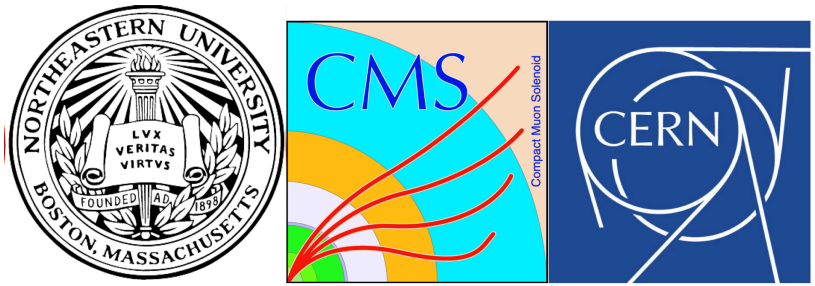
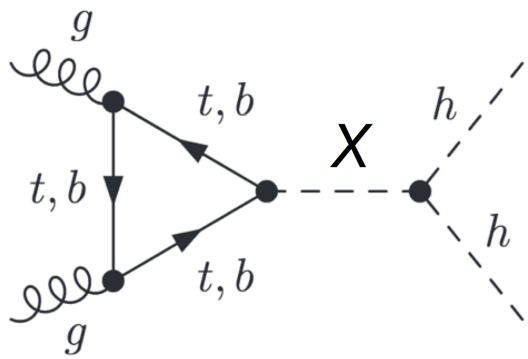


HH in BSM: Resonant Production

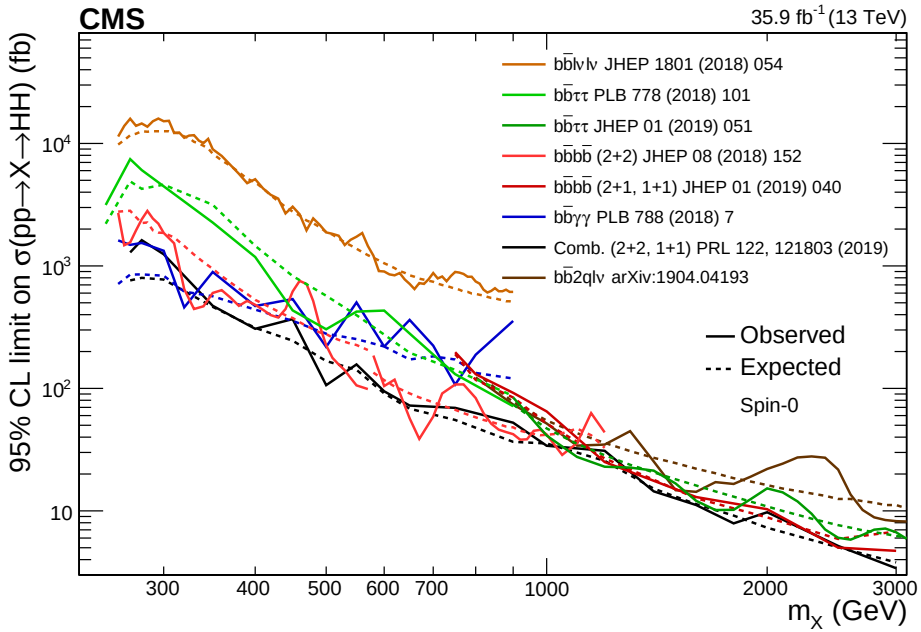
Predicted by several SM extensions:

- MSSM/2HDM
- Warped Extra Dimensions
  - spin-0 radion
  - spin-2 graviton

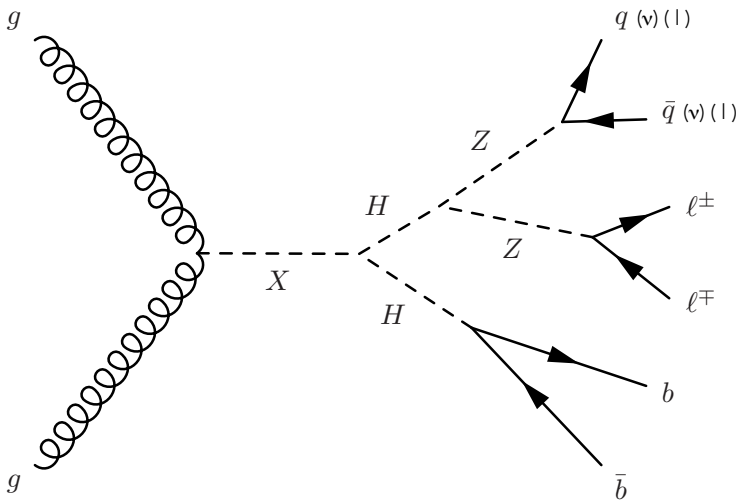


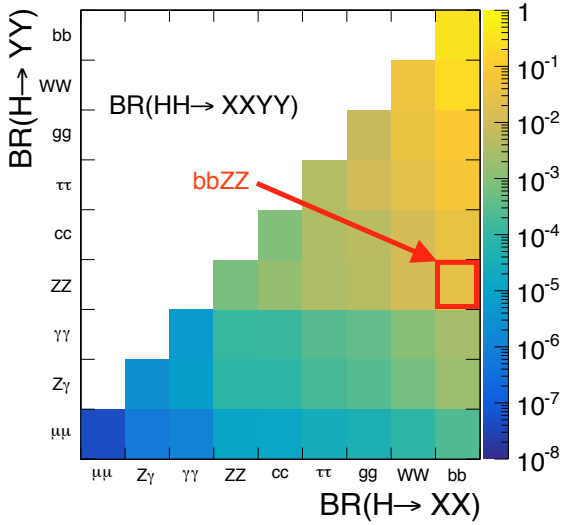
CMS Experimental Searches:

- H $\rightarrow$ bb: chosen for one H boson to keep BR high enough
- Four decay channels for the other H published thus far:
  - H $\rightarrow$ bb, WW, $\tau\tau$, $\gamma\gamma$
- Mass range covered in the searches:
  - 250 - 3000 GeV
- This talk: the first searches in the bbZZ channel



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, using 2016 data ($\sqrt{s}$=13TeV, 35.9 fb^{-1})
- Search for a narrow width resonance:
  - spin-0 radion [PhysRevD.62.045015]
  - spin-2 KK graviton [PhysRevLett.84.2080]
  - cover mass range 250-1000 GeV
- Two final states are considered (where $\ell\ell = \mu\mu$, ee):
  - bbZ($\ell\ell$)Z($\nu\nu$) :CMS-PAS-HIG-17-032
  - bbZ($\ell\ell$)Z(jj) :CMS-PAS-HIG-18-013 **[NEW]**
  - upper limits calculated for each individual channel and then combined.

HH $\to$ bb$\ell\ell\nu\nu$: Signature and Backgrounds

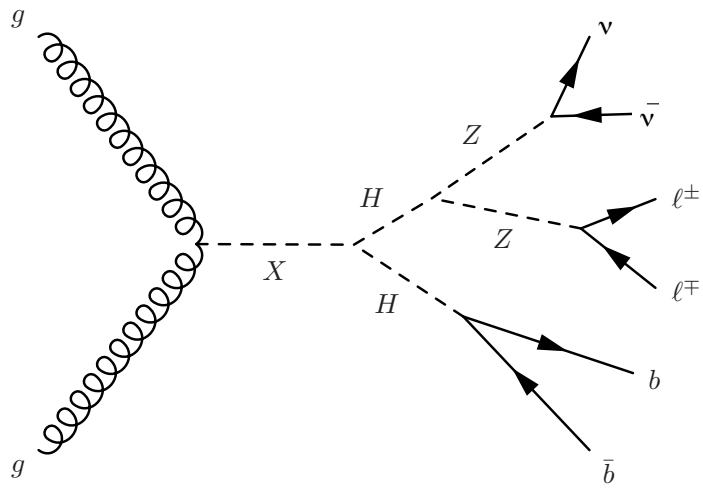
- 2 b jets from H$\to$bb, 2 leptons from Z, and MET from the other Z.
- HH $\to$ bbWW $\to$ bb$\ell\ell\nu\nu$ also enters selections but orthogonality to bbWW analysis is maintained by the requirement that $M_{\ell\ell} > 76$ GeV.

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:

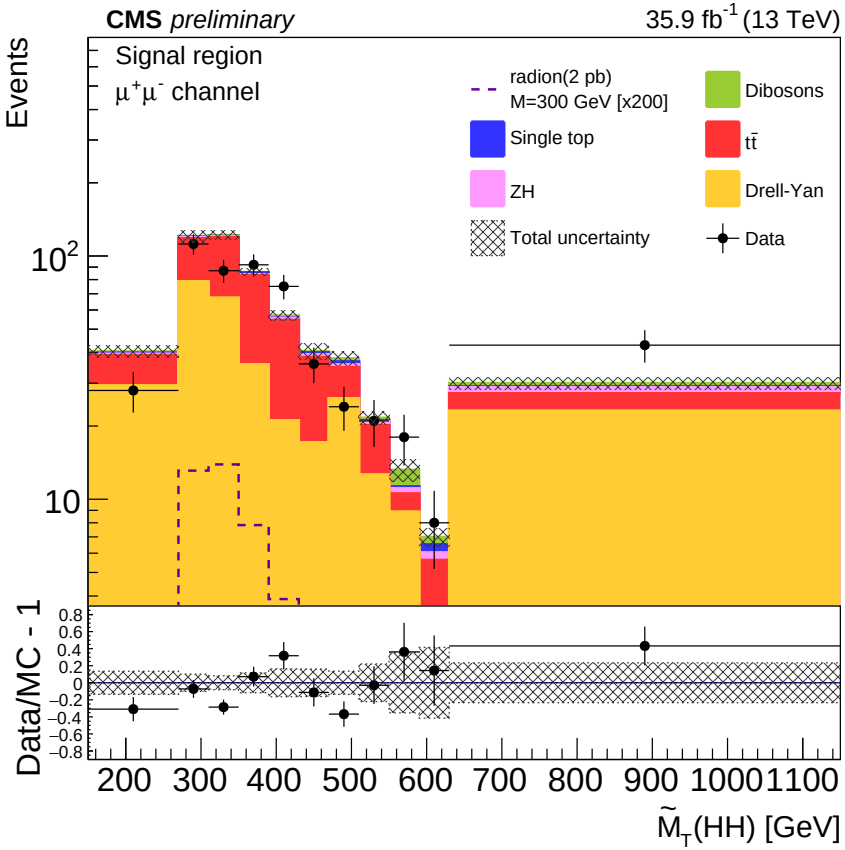
- single top quark productions
- diboson+jets
- ZH production



$HH \to bb\ell\ell\nu\nu$: 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 medium working point.
  - $90 < M_{bb}^{H} < 150$ GeV, $76 < M_{\ell\ell} < 106$ GeV (leptonic Z on-shell)
  - $M_T^{HH} > 100$ GeV
  - E_T^{miss} cuts which vary with M_X, orthogonal with $bb\ell\ell jj$ analysis
- DY and $t\bar{t}$ nomalization
  - simultaneously fit of SR and CRs (defined by $M_{\ell\ell}^{Z}$ and M_{bb}^{H})
  - other minor backgrounds taken directly from MC
- BDTs are trained on bbZZ signal vs DY and $t\bar{t}$ events
  - 2 BDTs are used: low ($M_X \leq$450 GeV) and high mass regions
  - 9 variables are used: $M_{\ell\ell}^{Z}$, M^{ZZ}, M_{bb}^{H}, $\Delta R_{\ell\ell}$, ΔR_{bb}^{H}, $p_T^{H_{bb}}$, $p_T^{Z_{\ell\ell}}$, p_T^{ZZ}, E_T^{miss}
  - BDT cuts are optimized for each mass hypothesis and each channel (ee/$\mu\mu$) separately
- M_T^{HH} distribution is used in the fits to extract limits (binned shape analysis)

HH → bb$\ell\ell\nu\nu$: M_T^{HH}



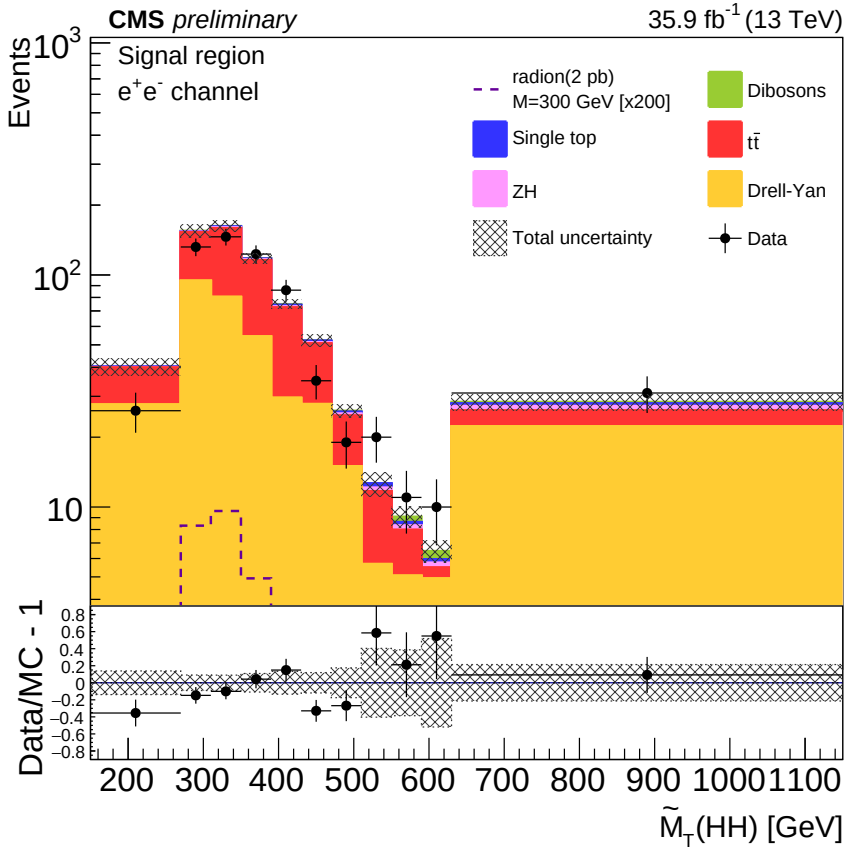
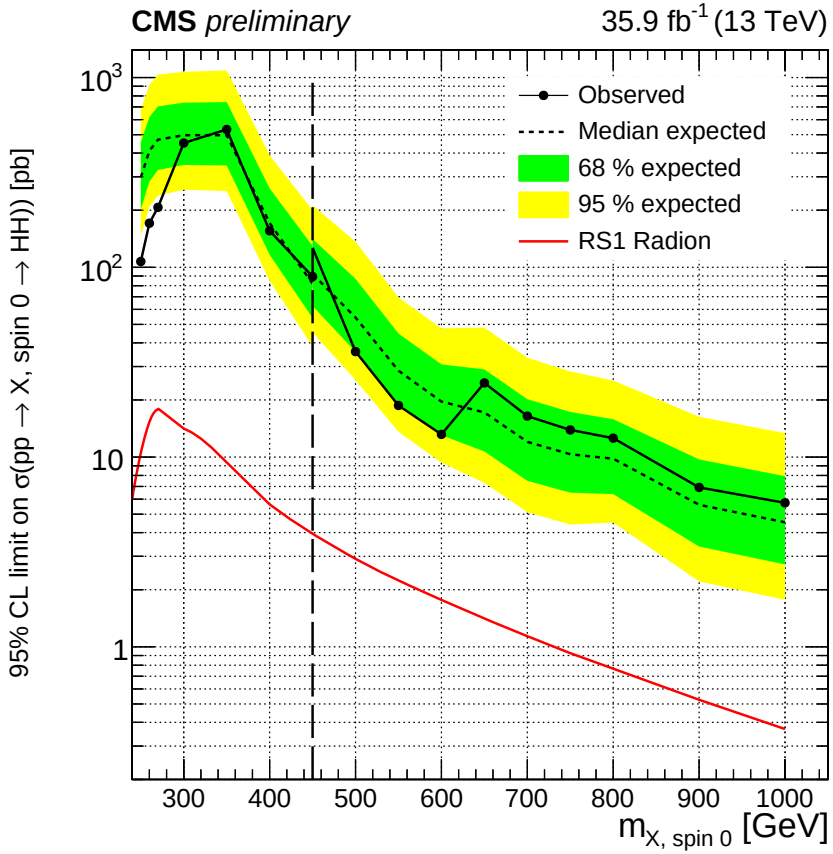


Figure: M_T^{HH} distribution in the muon channel (left) and in the electron channel (right) where the signal is spin-0 radion for the 300 GeV mass hypothesis and is normalized to 2 pb for the pp→X→HH process.

HH $\to$ bb$\ell\ell\nu\nu$: Upper limits



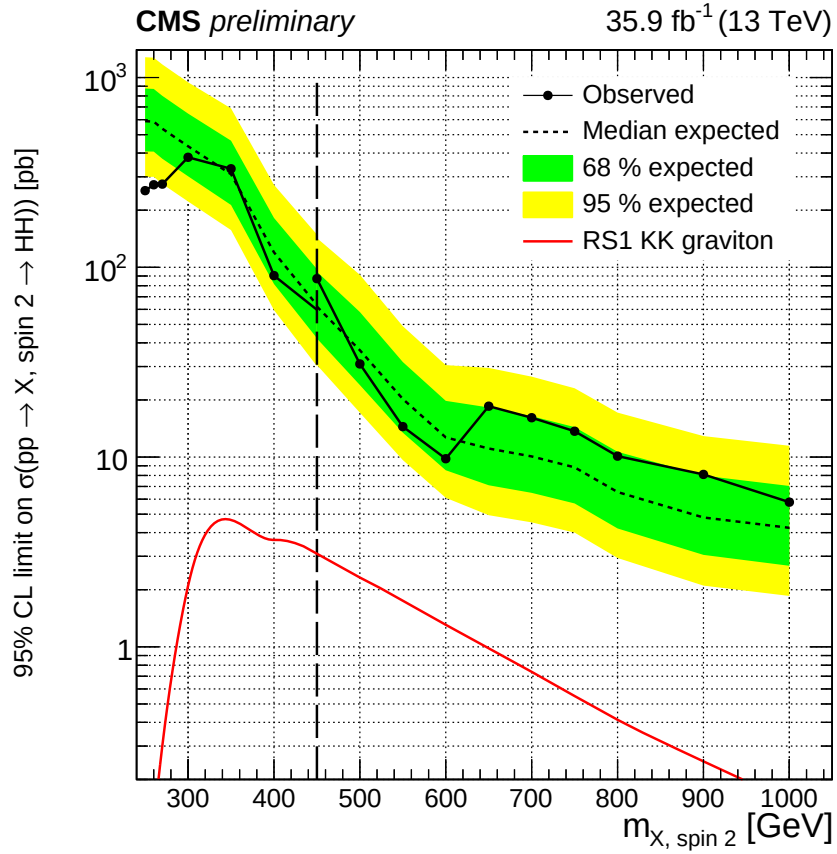


Figure: Expected (black dashed line) and observed (black solid line) limits on the cross section of resonant HH production as a function of the mass of the resonance for the bb$\ell\ell\nu\nu$ channel.

HH $\to$ bb$\ell\ell$jj: Signature and Backgrounds

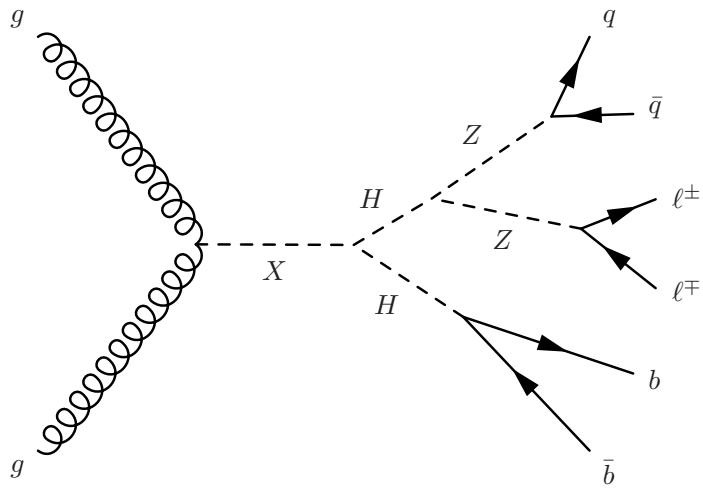
- 2 b jets from H$\to$bb, 2 leptons from Z, and 2 jets from the other Z

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



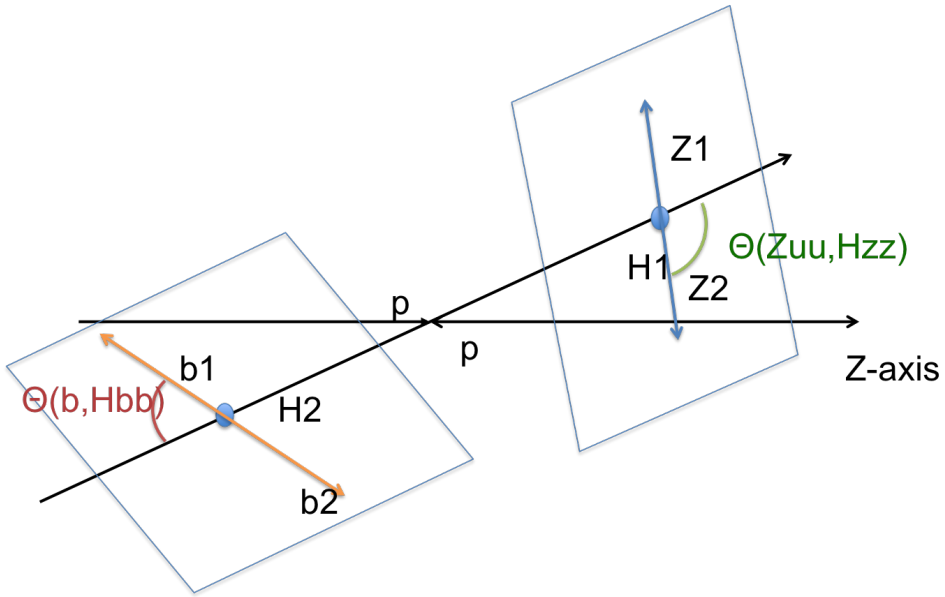
$HH \to bb\ell\ell jj$: Analysis Strategy

- Combine $\mu\mu$ and ee channels
- Assign 4 jets as H(bb) and Z(jj) using b-tag and kinematic information.
- Baseline selections
  - 2 opposite sign leptons, $M_{\ell\ell}$ >15 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, $t\bar{t}$) 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
  - E_T^{miss} cuts which vary with M_X, orthogonal with $bb\ell\ell\nu\nu$ analysis
  - train BDT discriminant for each signal mass point
- BDT distributions are used in the fits to extract limits (binned shape analysis)

HH $\to$ bb$\ell\ell$jj: BDT Training

- Construct BDT for each of the resonance mass hypotheses.
- Trained with 22 variables:

- M^H_{bb}, M^Z_{jj}, $M_{\ell\ell}$, $\Delta\Phi_{\ell 1, p_T^{miss}}$,
- $\Delta R_{\ell\ell}$, ΔR^H_{bb}, ΔR^Z_{jj}, $\Delta R_{\ell\ell, bb^H}$,
- $\Delta R_{\ell\ell, jj^Z}$, $\Delta R_{\ell 1 b 1}$, $\Delta R_{\ell 1 b 2}$, $\Delta R_{\ell 2 b 1}$,
- $\Delta R_{\ell 2 b 2}$, $\Delta R_{\ell 1 j 1}$, $\Delta R_{\ell 1 j 2}$, $\Delta R_{\ell 2 j 1}$, and $\Delta R_{\ell 2 j 2}$,
- $|cos(\theta^*_{CS})|$, $|cos(\theta^*_{b,Hbb})|$, and $|cos(\theta^*_{Z\ell\ell,Hzz})|$,
- $|\phi_1|$, $|\phi_{1,Zjj}|$



Samples used for training:

- Signal and background samples described earlier, QCD multijet is ignored.
- Signal events include samples from the targeted resonance mass and its two neighboring mass points.

HH → bb$\ell\ell$jj: BDT Discriminant

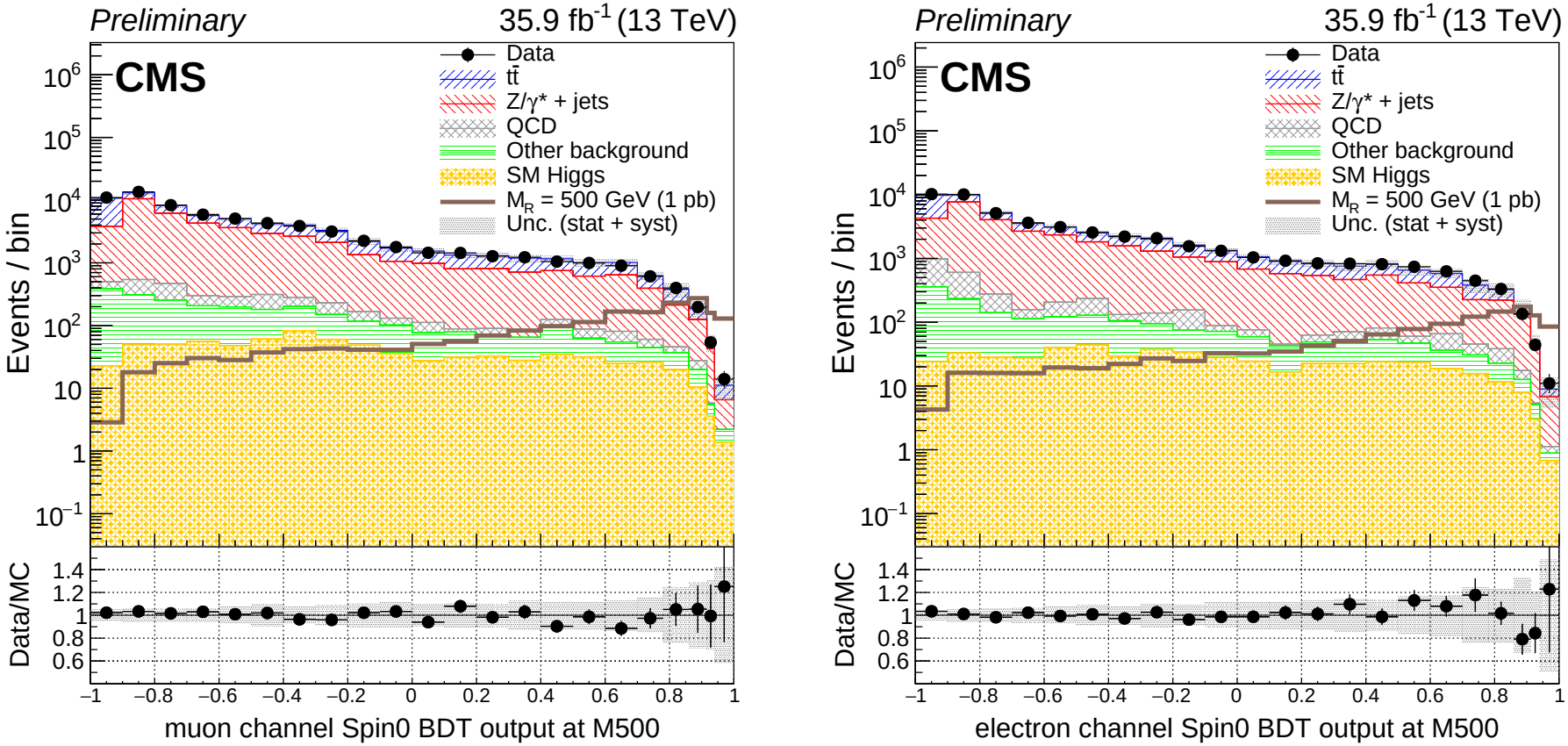
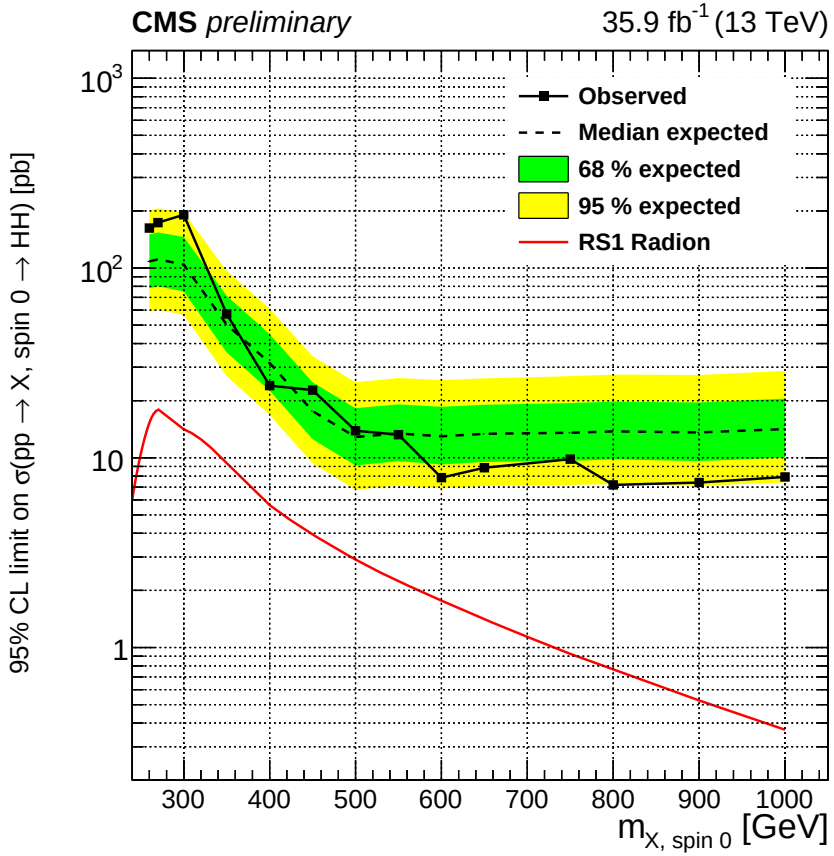


Figure: BDT discriminant in the muon channel (left) and in the electron channel (right) where the signal is spin-0 radion for the 500 GeV mass hypothesis and is normalized to 1 pb for the HH→bbZZ→ bb$\ell\ell$jj process.

HH $\to$ bb$\ell\ell$jj: Upper limits

[NEW]



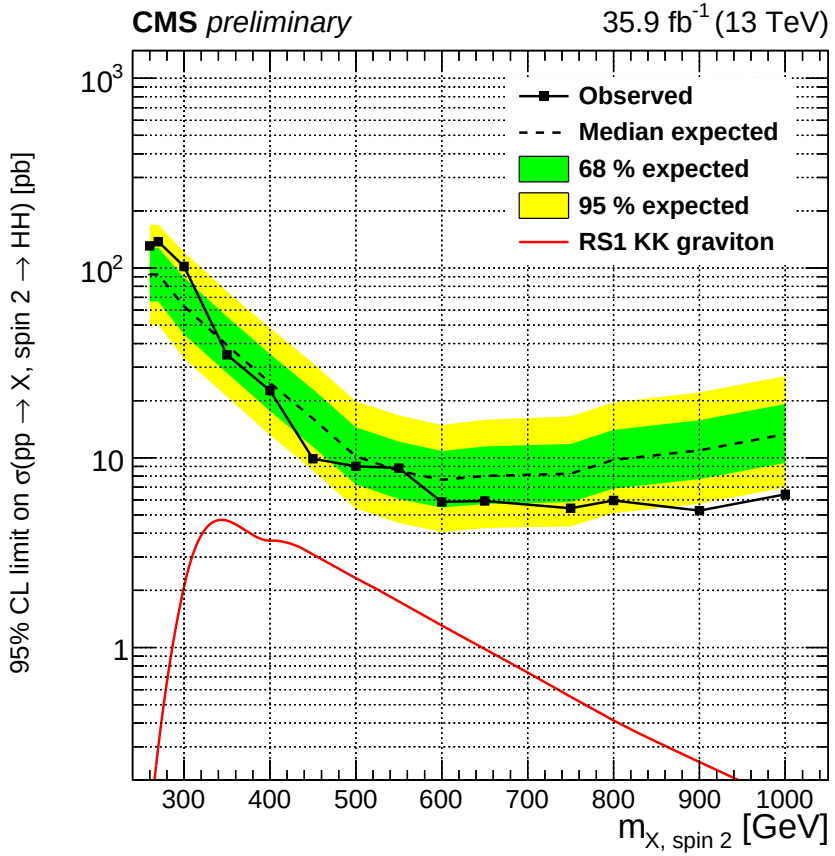
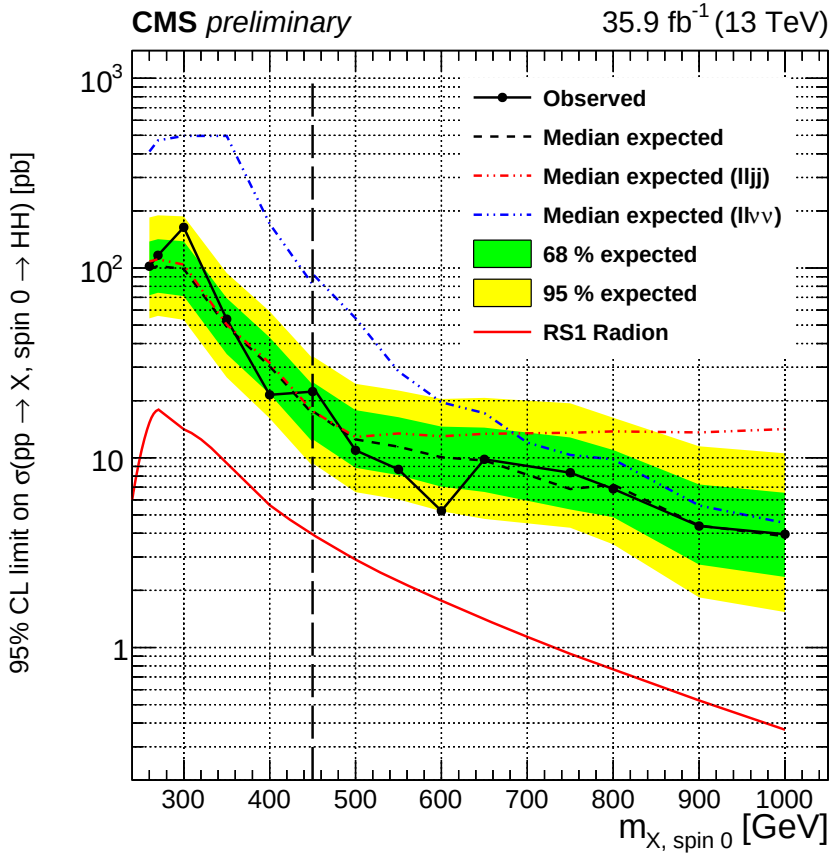


Figure: Expected (black dashed line) and observed (black solid line) limits on the cross section of resonant HH production as a function of the mass of the resonance for the bb$\ell\ell$jj channel.

Final Limits: Combined $bb\ell\ell jj$ and $bb\ell\ell\nu\nu$ channel

[NEW]



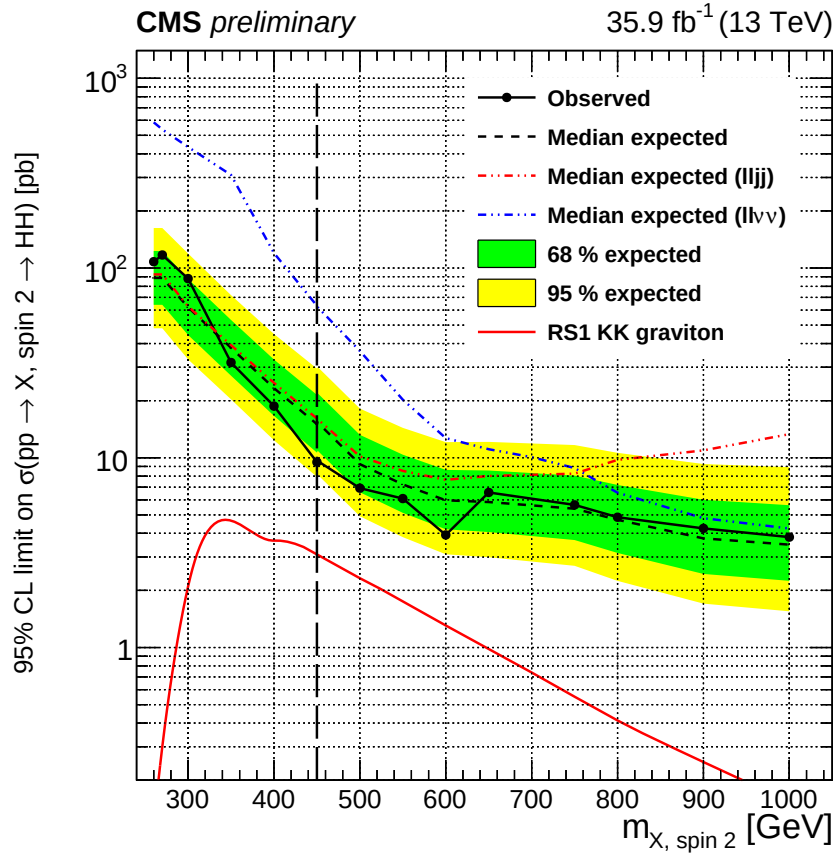


Figure: Expected (black dashed line) and observed (black solid line) limits on the cross section of resonant HH production as a function of the mass of the resonance for the the combination of the $bb\ell\ell jj$ and $bb\ell\ell\nu\nu$ channels.

Summary: X→HH→bbZZ

- First searches for resonant HH in the bbZZ decay channels at CMS presented here:
  - HH → bbZ($\ell\ell$)Z($\nu\nu$)
  - HH → bbZ($\ell\ell$)Z(jj) **[NEW]**
- The new channels contribute to the diverse CMS HH program and will be added to the full combination.

Backup

$HH \to bb\ell\ell jj$: 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(ℓ_1+ℓ_2+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%

$HH \to bb\ell\ell jj$: 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, $M_{\mu\mu}$ >15 GeV
    - ★ electrons with p_T >25(15) GeV, M_{ee} >15 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
  - E_T^{miss} cuts which vary with mass (in agreement with $bb\ell\ell\nu\nu$ analysis, to keep the two channels orthogonal):
    - ★ $E_T^{miss} < 40$ GeV for $M_X = 260$-300 GeV
    - ★ $E_T^{miss} < 75$ GeV for $M_X = 350$-600 GeV
    - ★ $E_T^{miss} < 100$ GeV for $M_X = 650$-1000 GeV

$HH \to bb\ell\ell jj$: 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.
- Φ_1, angle between z′-z plane and h→zz decay plane, where z′ is the higgs momentum direction.
- $\Phi_{1,Zjj}$, angle between z'_2-z plane and Z→jj decay plane, where z'_2 is the Z (decaying to jj) momentum direction.