

Diboson resonance searches including HH in ATLAS and CMS in Run2

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On behalf of the ATLAS and CMS collaborations

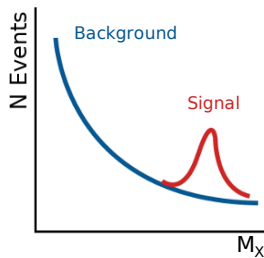
16-23 March 2019

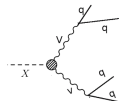
Overview

- General strategy
- $VV \rightarrow JJ$ ($V=W,Z$)
- $HH \rightarrow bbbb$
- $VV \rightarrow \text{leptons} + \text{jets}$
- $VH \rightarrow \text{leptons} + bb$
- $HH \rightarrow WW + bb$
- $HH \rightarrow \tau\tau bb$
- $VV \rightarrow \text{leptons}$
- $HH \rightarrow bb\gamma\gamma$
- Combinations of results

Motivation and General Strategy

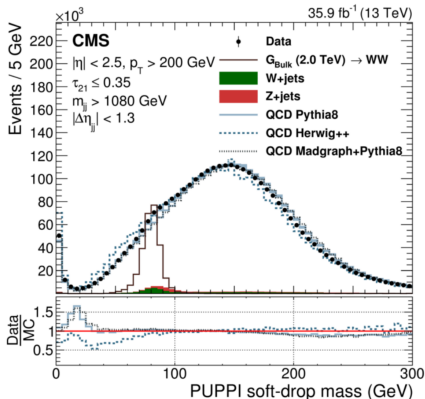
- Heavy resonances of vector bosons or Higgs bosons would be a sign of new physics at LHC
 - Many different models predicted, often motivated by hierarchy or naturalness arguments
 - Examples: extended Higgs sector (2HDM), heavy vector triplets (HVT - W' , Z'), Kaluza-Klein graviton from bulk Randall-Sundrum model
- Search Strategy:
 - Select events based on final state of interest (leptons, missing E_T , jets, etc)
 - Categorise events based on signal purity (based on (di-)jet mass, jet substructure, b-tagging, number of leptons, etc)
 - Look at invariant mass of dibosons or output from multivariate analysis to search for resonant signal
 - Perform statistical analysis



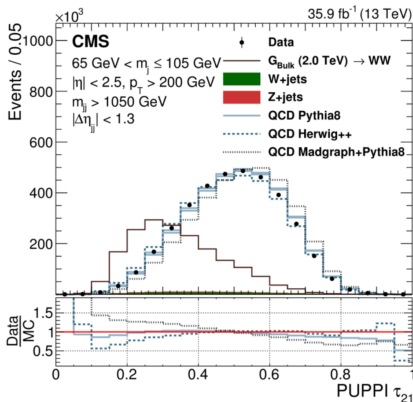


Final state: 2 high pT large-R anti-kT jets
(R=1.0 ATLAS, R=0.8 CMS)

Boson tagging used to distinguish
signal from multijet background

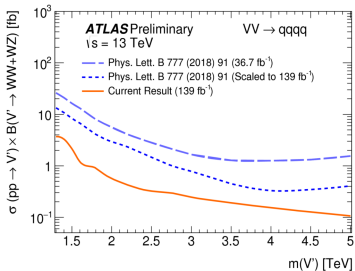


Jet mass consistent with W/Z mass



τ_{21} : ratio of how well jet can be
divided into 2 sub-jets vs 1 sub-jet

New ATLAS result on full Run 2 dataset
Improvements in boson tagging leads to better sensitivity than increase in luminosity alone (see Sofia's talk for more info)

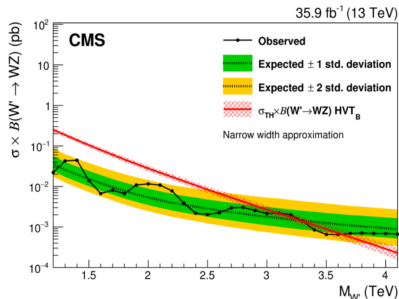
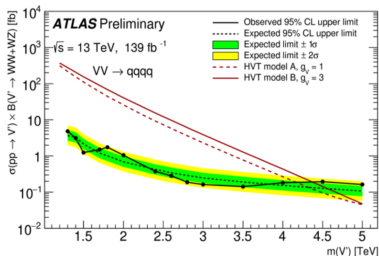


Exclusion regions:

HVT: 1.3-4.4 TeV (ATLAS)
1.2-3.8 TeV (CMS)

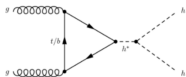
Graviton: 1.3-2.8 TeV (ATLAS, $k/M_{\text{Pl}}=1$)
0.6-36 fb (CMS, $k/M_{\text{Pl}}=0.5$)

Signal models: HVT (W', Z'), Graviton



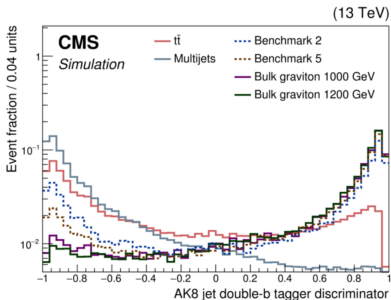
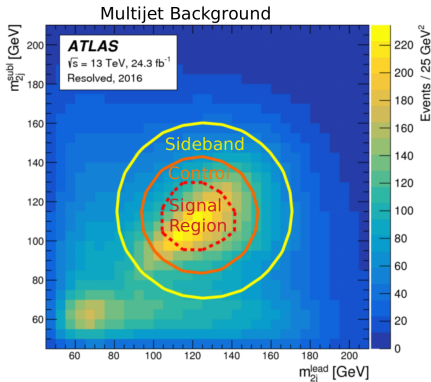
HH \rightarrow 4b

ATLAS-EXOT-2016-31, CMS-B2G-017-019



Final state: 4 small-R ($R=0.4$) or 2 large-R jets (ATLAS)
2 small-R and 1 large-R, or 2 large-R jets (CMS)

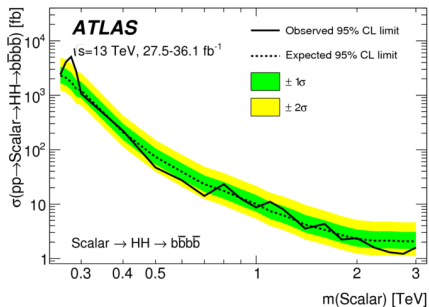
Signal models:
KK graviton
Radion
2HDM



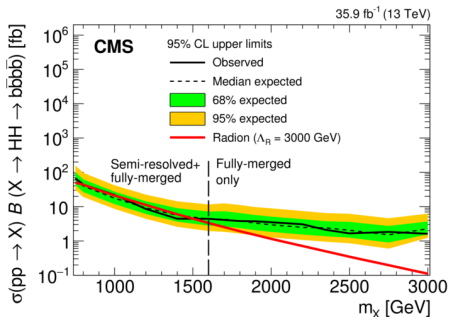
Estimate of dominant multijet background (ATLAS):
Templates with fewer b-tags used to reweight events
Weights derived based on comparison of kinematics in sideband region

Multivariate techniques used to identify b-jets
CMS double b-tagger:
Uses information about b-hadron lifetime and mass to determine probability of large-R jet to contain bb pair

HH → 4b



Local significance, $m=280 \text{ GeV}$: 3.6 σ
 Global significance: 2.5 σ

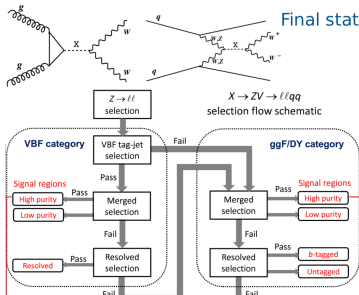


Exclusion regions:
 Scalar: ~1-5000 fb (ATLAS)
 Radion: 1.6-67 fb (CMS)

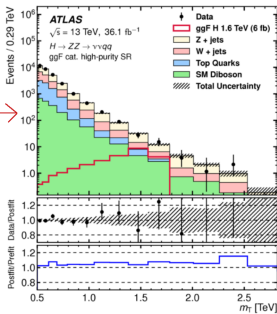
Graviton: 1.4-43.9 fb (CMS, $k/\text{Mpl}=0.5$)
 313-1362 GeV (ATLAS, $k/\text{Mpl}=1$)

VV → leptons+jets

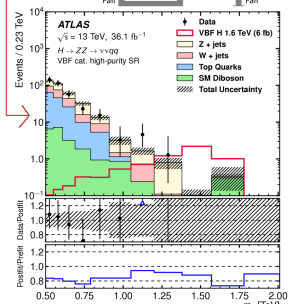
ATLAS-EXOT-2016-28, ATLAS-EXOT-2016-29, CMS-B2G-017-013, CMS-B2G-16-029, CMS-B2G-17-005



Final state: 2 leptons (e, mu) + 2 small-R or 1 large-R jet,
1 lepton + missing ET + 2 small-R or 1 large-R jet,
missing ET + 1 large-R jet



Signal models:
HVT (W' , Z')
RSG

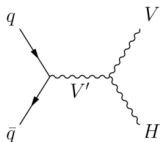


HVT signals excluded up to
 $M(W')$, $M(Z')$ ~3-3.5 TeV

Graviton signals excluded up to
 $M(G)$ ~1-1.5 TeV

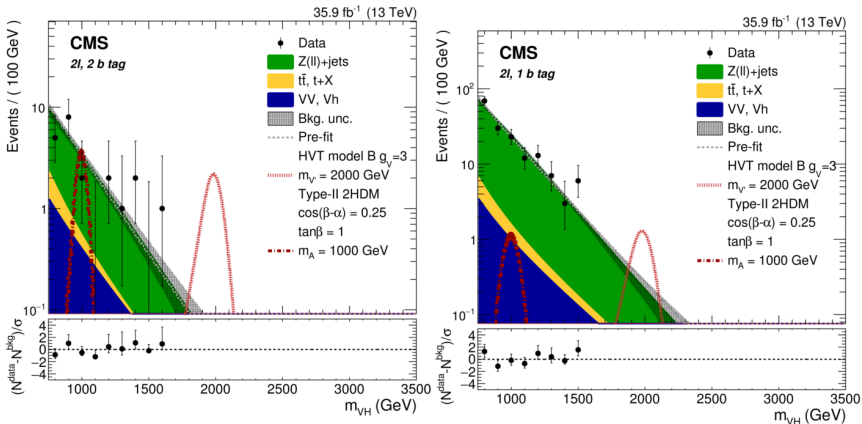
VH \rightarrow leptons + bb

ATLAS-EXOT-2016-10, CMS-B2G-17-004, CMS-HIG-18-005

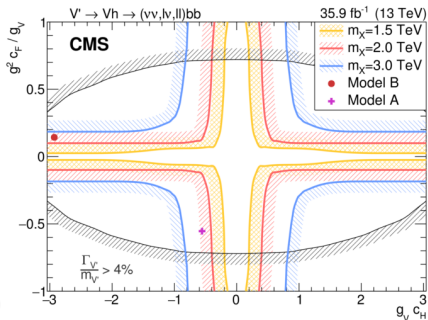
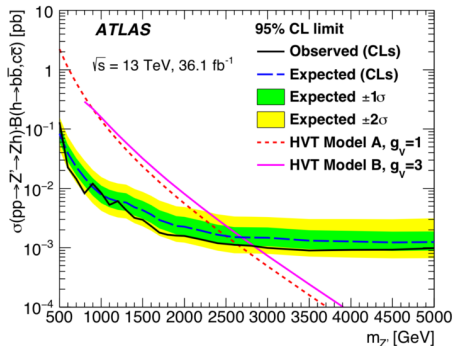


Similar to VV searches, but with H decaying to bb

Events categorised based on number and flavour of leptons, and number of b-tagged jets.



VH \rightarrow leptons+bb



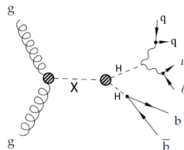
Exclusion regions:

HVT: 0.8-60 fb (CMS)
 0.9-280 fb (ATLAS)

Scalar: 0.01-1pb (CMS, $M < 1 \text{ TeV}$ only)
 0.002-0.8 pb (ATLAS, 500 GeV $M < 5 \text{ TeV}$)

HH \rightarrow bb + WW

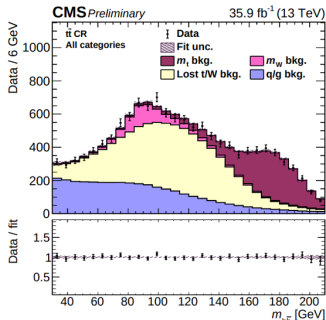
ATLAS-HIGG-2016-27, CMS-PAS-B2G-18-008



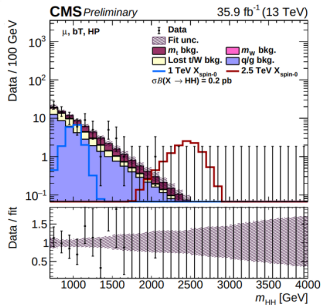
Final state: ATLAS: 1 lepton + MET + 4 small-R jets (2 b-jets)
or 1 large-R b-jet + 2 small-R jets

CMS: 1 lepton + MET + 1 large-R b-jet + 1 large-R jet

New result from CMS

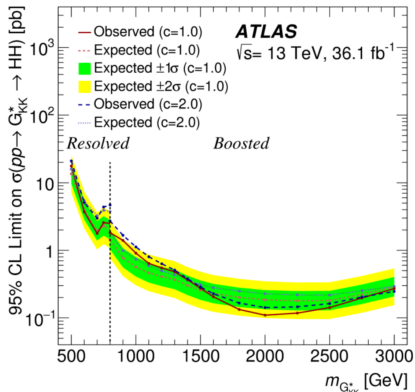
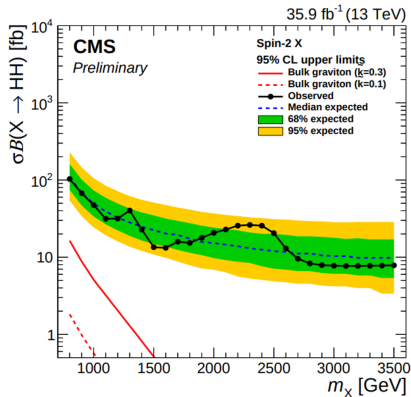


Backgrounds defined in 4 generator level categories with distinct $m(bb)$ shapes. Templates of $m(bb)$ modelled as a function of $m(HH)$.



Likelihood fit done in 2D plane of $m(bb)$ and $m(HH)$

HH \rightarrow bb + WW



Exclusion regions ($\sigma \cdot BR$):

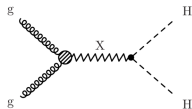
Graviton: 14-170 fb (ATLAS*)
7.8-103 fb (CMS)

*ATLAS numbers multiplied
by BR (HH \rightarrow bblvqq)

Scalar: 25-280 fb (ATLAS*)
8.3-123 fb (CMS)

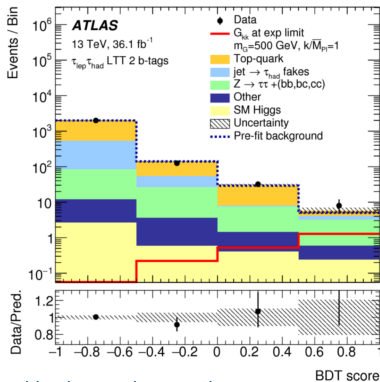
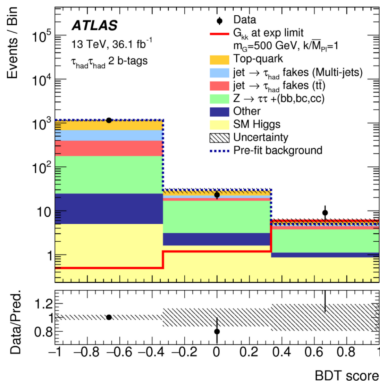
HH \rightarrow $\tau\tau b\bar{b}$

ATLAS-HIGG-2016-16, CMS-B2G-17-006



Final state: 2 taus (at least one hadronic decay)
+ 2 small-R or 1 large-R b-jet

Signal models:
Radion
KK graviton
hMSSM scalar

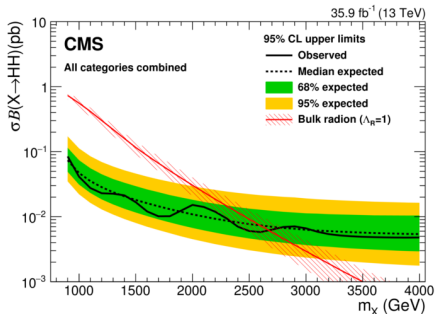
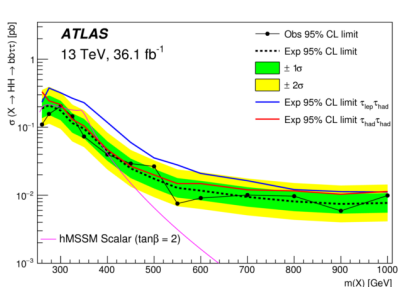


Boosted decision tree used to improve signal-background separation.

BDT trained separately for each mass point.

Includes masses from neighbouring points in signal model to keep sensitivity between simulated points

HH \rightarrow $\tau\tau b\bar{b}$



Exclusion regions:

hMSSM: 305 < M(X) < 402 GeV (ATLAS)

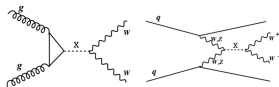
Radion: M < 2.7 TeV (CMS)

KK Graviton: 325 < M(G) < 885 GeV (ATLAS, k/Mpl=1)

5-80 fb (CMS, k/Mpl=0.5)

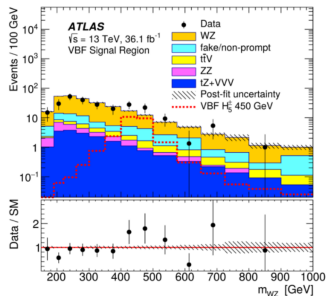
VV \rightarrow leptons

ATLAS-EXOT-2016-11, CMS-B2G-17-023



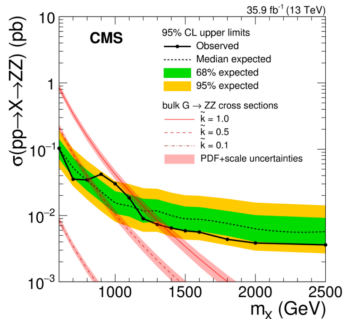
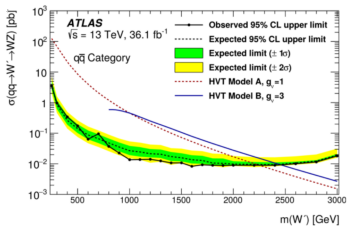
Final states: 2 or 3 leptons + missing ET (+2 VBF jets)

Signal models:
KK graviton
HVT (W')



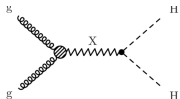
Neutrino z-momentum estimated using W-mass constraint

Exclusion regions:
 $M(W') < 2.3$ TeV (ATLAS)
 $M(G) < 800$ GeV

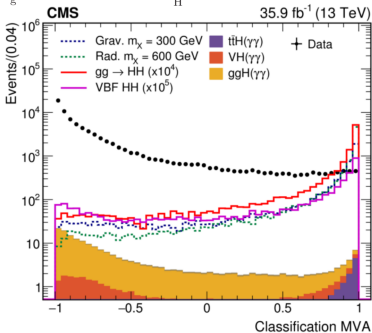


HH → bbγγ

ATLAS-HIGG-2016-15, CMS-HIG-17-008

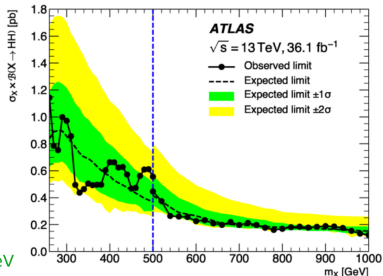
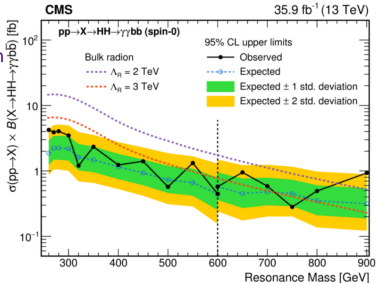


Final state: 2 photons + 2 small-R jets
 Signal models: 2HDM
 Radion
 Graviton



Boosted decision tree trained using b-tagging and helicity variables.
 Trained separately for $m(X) < 600$ GeV and $m(X) > 600$ GeV

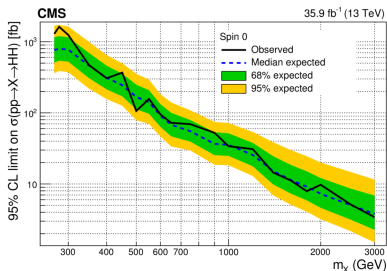
Exclusion regions:
 ATLAS $\sigma \times BR(X \rightarrow HH)$: 0.12-1.1 pb
 CMS Radion: $m(X) < 540$ GeV
 Graviton: $290 < m(X) < 810$ GeV



Combinations

ATLAS-CONF-2018-043, CMS-HIG-17-030, ATLAS-EXOT-2017-31, CMS-PAS-B2G-18-006

Combinations of HH with bbbb, bb $\tau\tau$, bb $\gamma\gamma$, and bbVV (*) final states
and VV+VH with qq $\bar{q}\bar{q}$, vv $\bar{q}\bar{q}$, lv $\bar{q}\bar{q}$, lvll, llll (**), qqbb, vvbb, lvbb, llbb, qq $\tau\tau$ (*)
(*) CMS only, (**) ATLAS only



Exclusion regions HH:

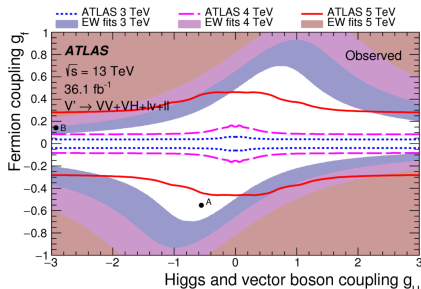
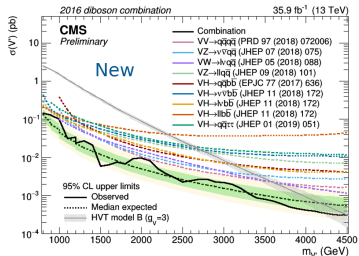
Scalar: 0.02-0.83 pb (ATLAS)
0.003-1 pb (CMS)

Graviton: 0.02-1.89 pb (ATLAS, $k/M_{\text{Pl}}=1$)
0.004-1 pb (CMS, $k/M_{\text{Pl}}=0.5$)

Exclusion regions VV/VH:

HVT: $M < 5.5$ TeV (ATLAS)
 $M < 5$ TeV (CMS)

Graviton: $M < 2.4$ TeV (ATLAS, $k/M_{\text{Pl}}=1$)
 $M < 850$ GeV (CMS, $k/M_{\text{Pl}}=0.5$)



Summary

- Many results for searches for diboson resonances performed in a wide variety of final states
- No indication of resonances so far

Extra Information

Backup

References

- $VV \rightarrow JJ$ ($V=W,Z$): [ATLAS-CONF-2019-003](#), [CMS-B2G-017-001](#)
- $HH \rightarrow bbbb$: [ATLAS-EXOT-2016-31](#), [CMS-B2G-017-019](#)
- $VV \rightarrow \text{leptons} + \text{jets}$: [ATLAS-EXOT-2016-28](#), [ATLAS-EXOT-2016-29](#), [CMS-B2G-017-013](#), [CMS-B2G-16-029](#), [CMS-B2G-17-005](#)
- $VH \rightarrow \text{leptons} + bb$: [ATLAS-EXOT-2016-10](#), [CMS-B2G-17-004](#), [CMS-HIG-18-005](#)
- $HH \rightarrow \text{leptons (incl. taus)} + \text{jets}$: [ATLAS-HIGG-2016-27](#), [ATLAS-HIGG-2016-16](#), [CMS-HIG-17-006](#), [CMS-B2G-17-006](#), [CMS-PAS-B2G-18-008](#)
- $VV \rightarrow \text{leptons}$: [ATLAS-EXOT-2016-11](#), [CMS-B2G-17-023](#)
- $HH \rightarrow bb\gamma\gamma$: [ATLAS-HIGG-2016-15](#), [CMS-HIG-17-008](#)
- HH combination: [ATLAS-CONF-2018-043](#), [CMS-HIG-17-030](#)
- VV/VH combination: [ATLAS-EXOT-2017-31](#), [CMS-PAS-B2G-18-006](#)
- $HH \rightarrow WW\gamma\gamma$: [ATLAS-HIGG-2016-20](#), [CMS-HIG-17-006](#)
- $HH \rightarrow WWWW$: [ATLAS-HIGG-2016-24](#)