
# Searches for heavy diboson resonances with ATLAS

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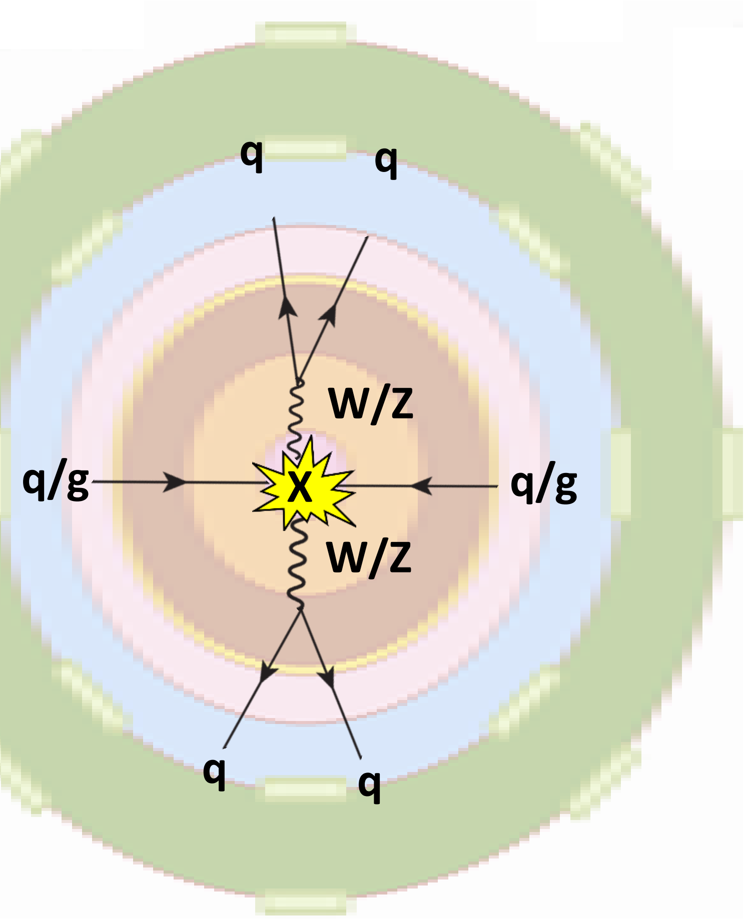
# Outline

Recent Results on

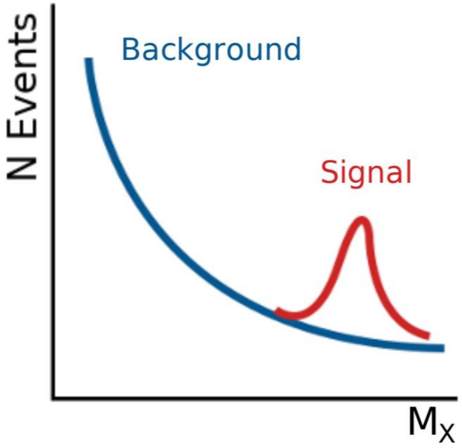
- VV $\rightarrow$ JJ
- VH $\rightarrow$ $\nu\nu bb$ / $\ell\ell bb$ / $\ell\nu bb$
- Diboson resonance combination
- Di-Higgs $\rightarrow$ $bb\tau\tau$ & Combination

- Will expand on novel techniques

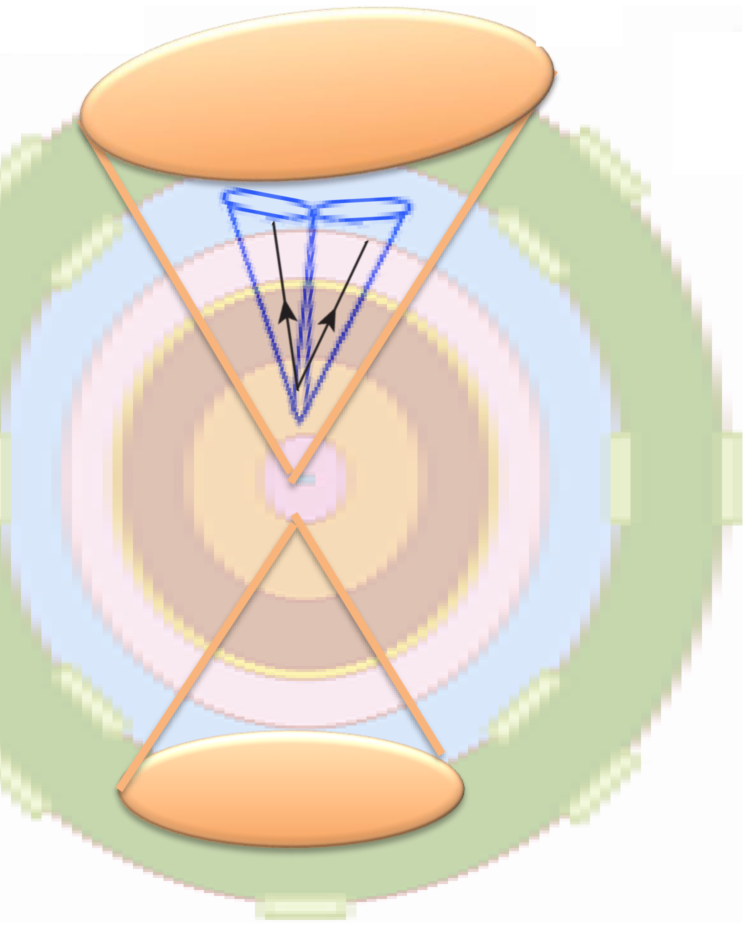
# VV to JJ




- X = spin-0 radion, spin-1 Heavy Vector Triplet Model (HVT) W'/Z', spin-2 Randall–Sundrum (RS) graviton
- Hadronic decay modes have high BR (67% for W and 70% for Z bosons), but high multi-jet background
- Multi-jet (poorly modeled in MC ) - model it by parametric function fit to the smoothly falling dijet invariant mass in data



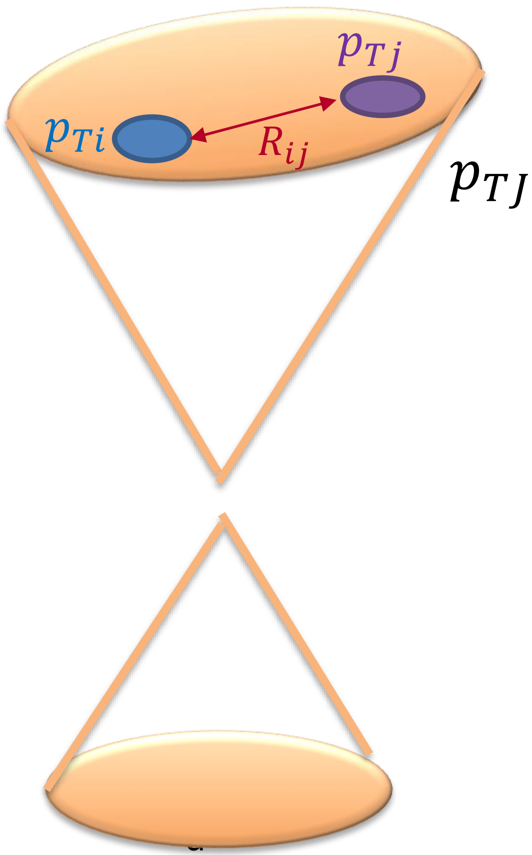
# VV to JJ



- At high momentum, the hadronic decays of the W/Z are very collimated – use large R = 1 fat jets
  - Remove soft components from pileup (trimming)
- Close to granularity limits of calorimeter – use angular track information to improve spatial resolution
- Track-CaloClusters (TCC): TCC 4-vector is combination of $p_T^{calo}, E^{calo}, \eta^{track}, \phi^{track}$

# VV to JJ

- New W/Z boson taggers to separate from multi-jet background use jet substructure (mass, $D_2$ and $n_{track}$)




$$e_2 = \frac{1}{p_{TJ}J} \sum p_{Ti}\, p_{Tj}\, R_{ij}$$

# VV to JJ

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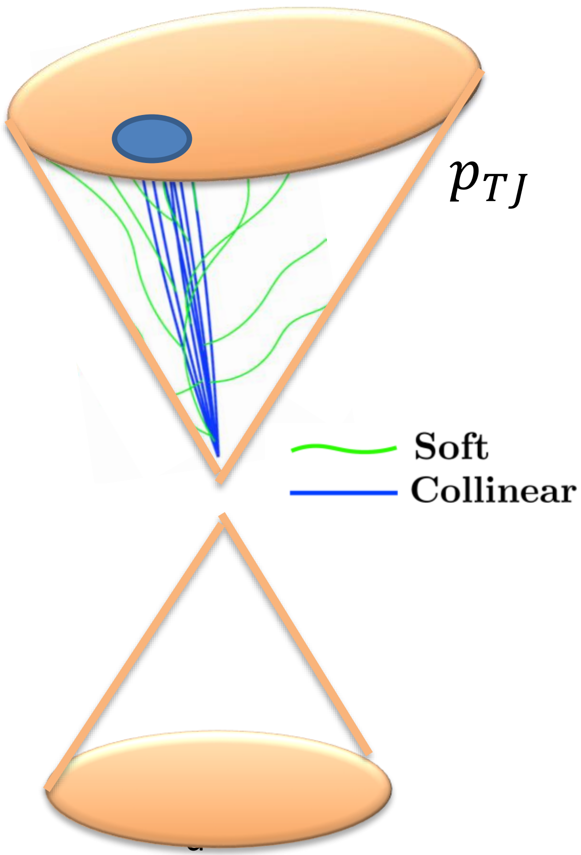
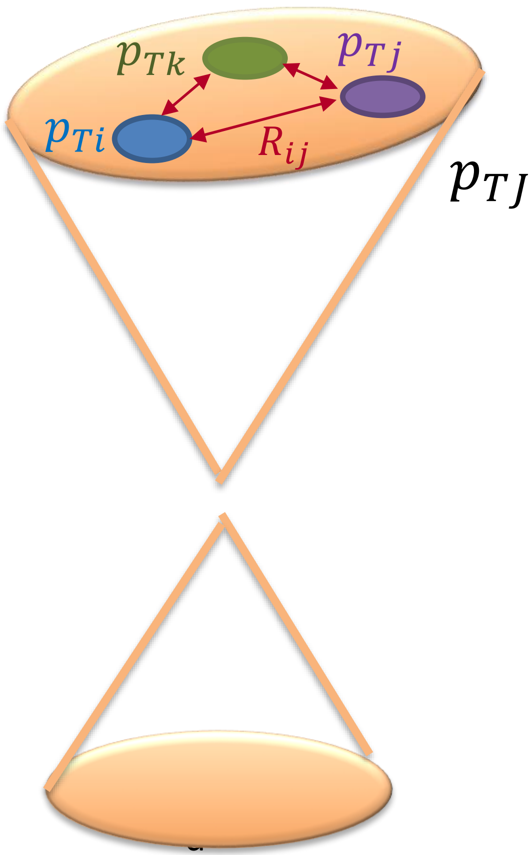



$$e_2 = \frac{1}{p_{TJ}J} \sum p_{Ti}\, p_{Tj}\, R_{ij}$$

1-prong jet identification (quark-gluon)

# VV to JJ

- New W/Z boson taggers to separate from multi-jet background use jet substructure (mass, $D_2$ and $n_{track}$)

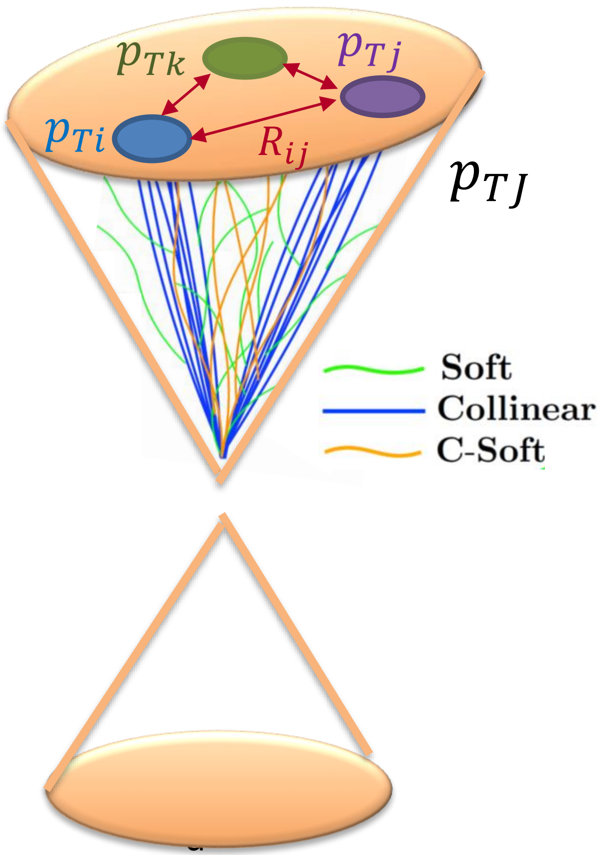



$$e_2 = \frac{1}{p_{TJ}J} \sum p_{Ti}\, p_{Tj}\, R_{ij}$$

$$e_3 = \frac{1}{p_{TJ}J} \sum p_{Ti}\, p_{Tj}\, p_{Tk} R_{ij}\, R_{ik}\, R_{jk}$$

# VV to JJ

- New W/Z boson taggers to separate from multi-jet background use jet substructure (mass, $D_2$ and $n_{track}$)



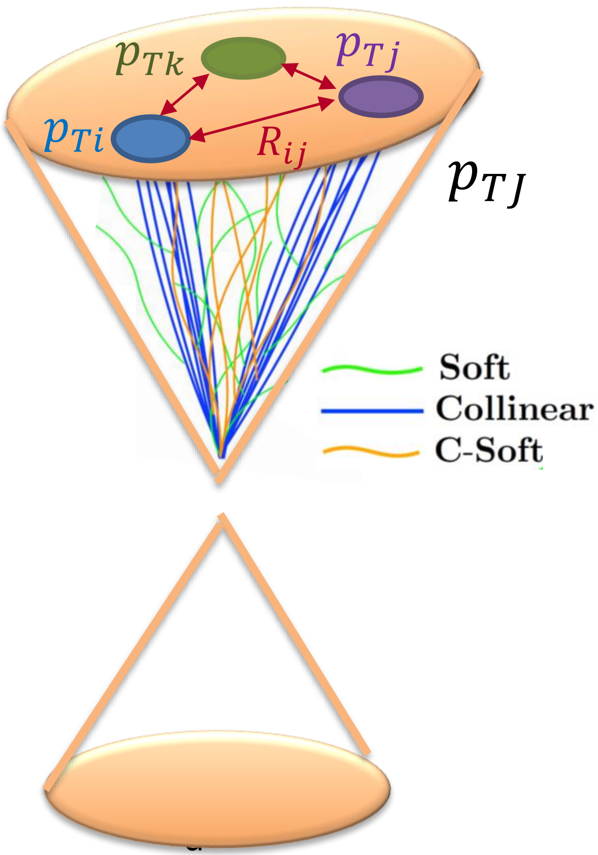

$$e_2 = \frac{1}{p_{TJ}J} \sum p_{Ti}\, p_{Tj}\, R_{ij}$$

$$e_3 = \frac{1}{p_{TJ}J} \sum p_{Ti}\, p_{Tj}\, p_{Tk} R_{ij}\, R_{ik}\, R_{jk}$$

2-, 3-prong jet identification
(W/Z/H bosons)

# VV to JJ

- New W/Z boson taggers to separate from multi-jet background use jet substructure (mass, $D_2$ and $n_{track}$)




$$e_2 = \frac{1}{p_{TJ}J} \sum p_{Ti}\, p_{Tj}\, R_{ij}$$

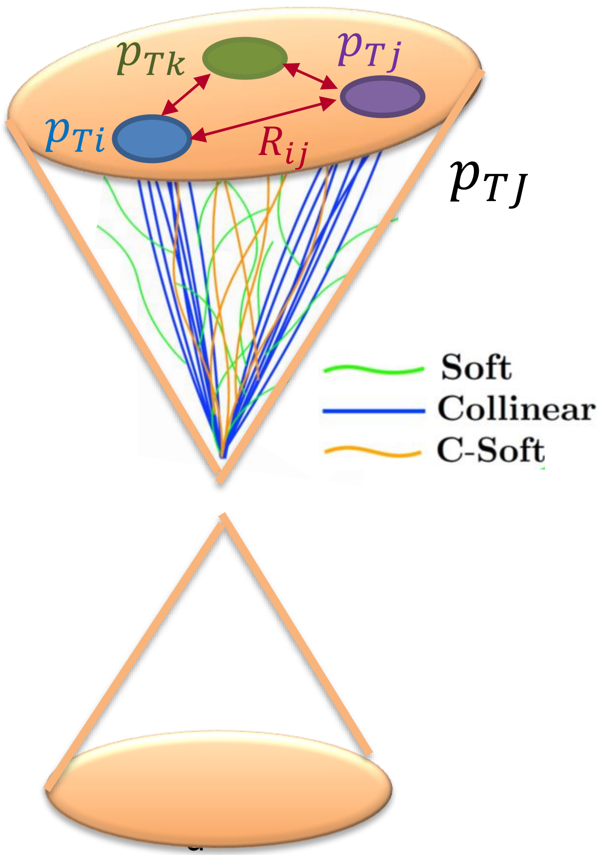
$$e_3 = \frac{1}{p_{TJ}J} \sum p_{Ti}\, p_{Tj}\, p_{Tk} R_{ij}\, R_{ik}\, R_{jk}$$

$$\boldsymbol{D_2 = \frac{e_3}{(e_2)^3}}$$

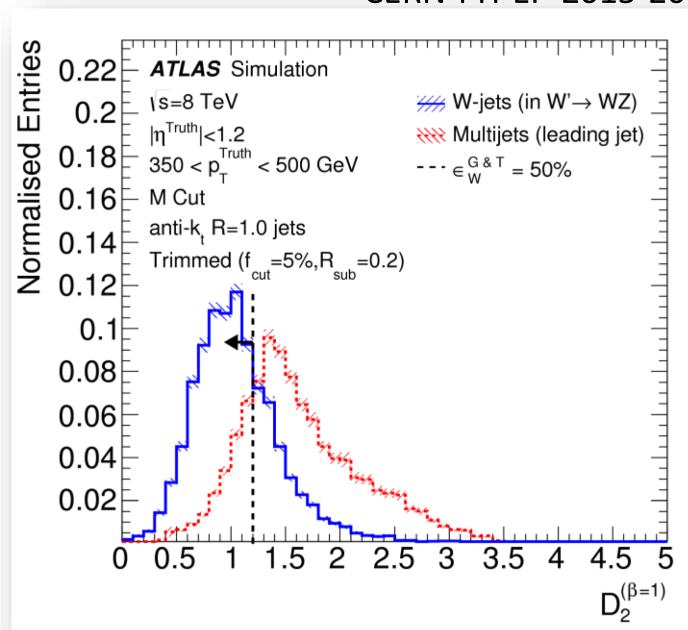
# VV to JJ

- New W/Z boson taggers to separate from multi-jet background use jet substructure (mass, $D_2$ and $n_{track}$)

*charged hadron multiplicity to reduce multi-jet background with radiated gluon that can mimic 2 prong structure*



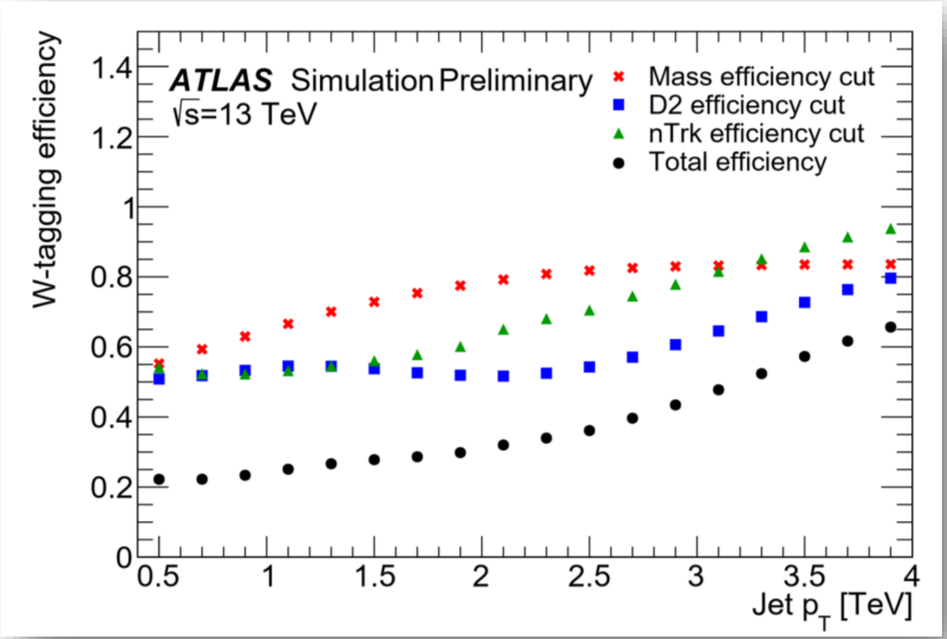

CERN-PH-EP-2015-204



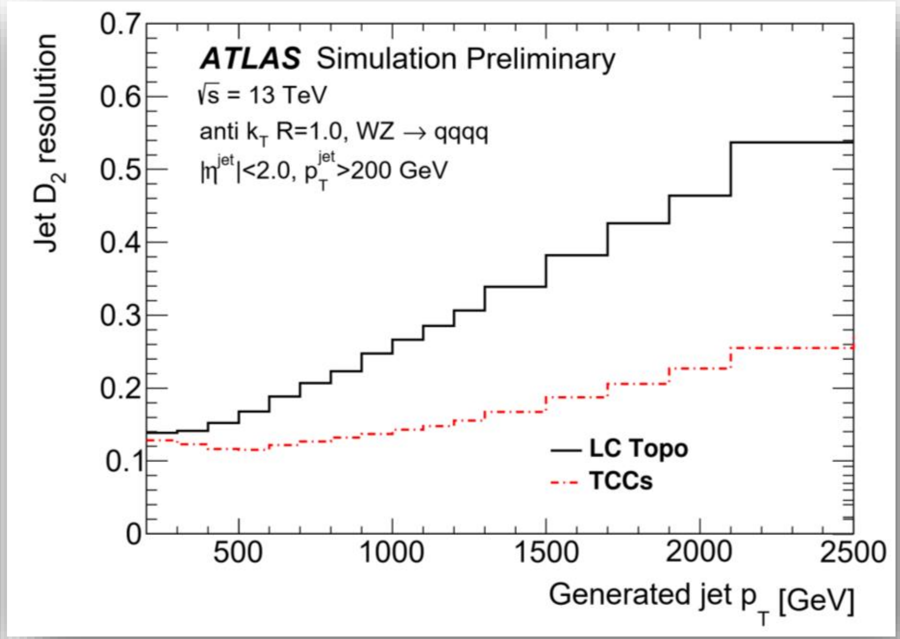

$$D_2 = \frac{e_3}{(e_2)^3}$$

# VV to JJ

ATLAS-CONF-2019-003




ATLAS-CONF-2019-003



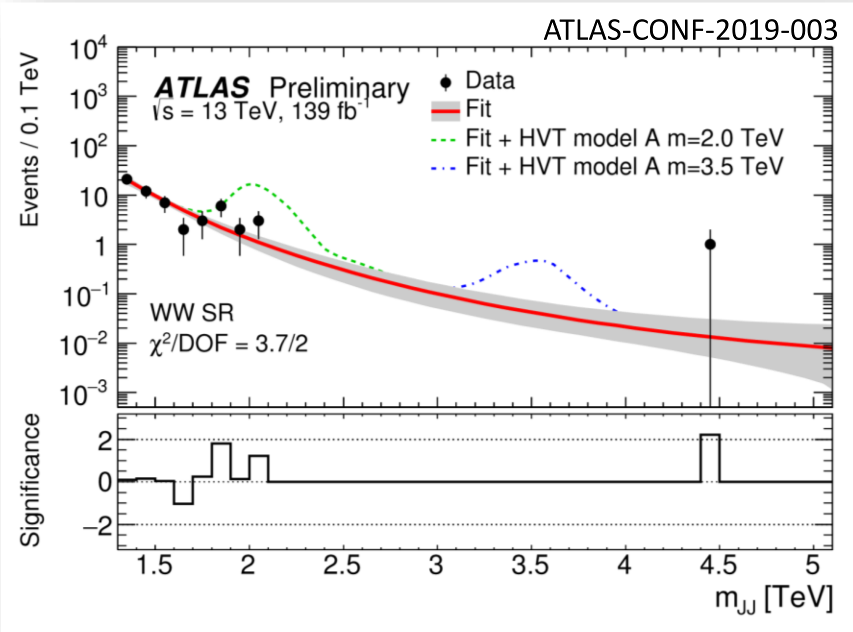

Use combination of cuts that leads to the highest significance

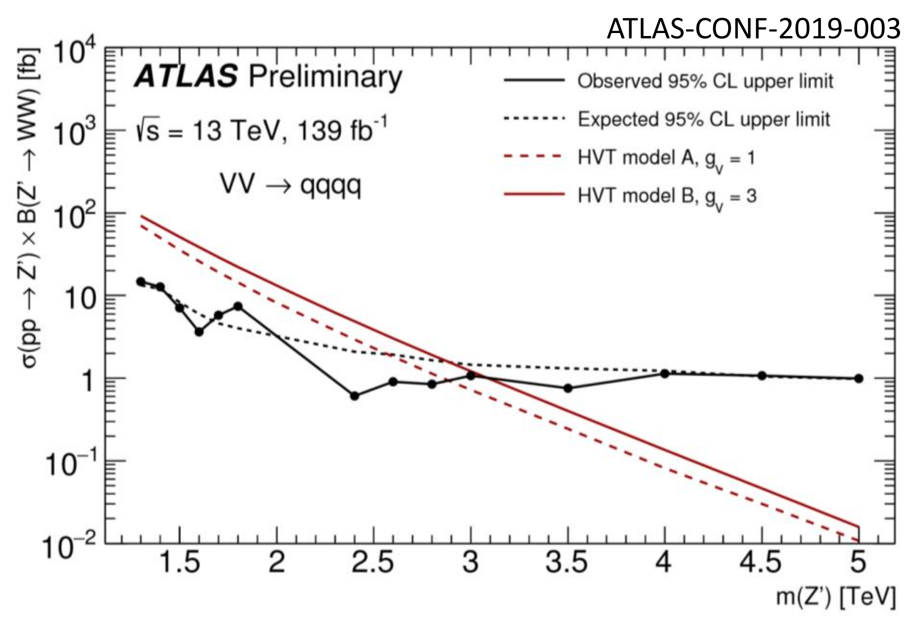
$$D_2 = \frac{e_3}{(e_2)^3}$$

# VV to JJ

139 fb$^{-1}$

WW SR



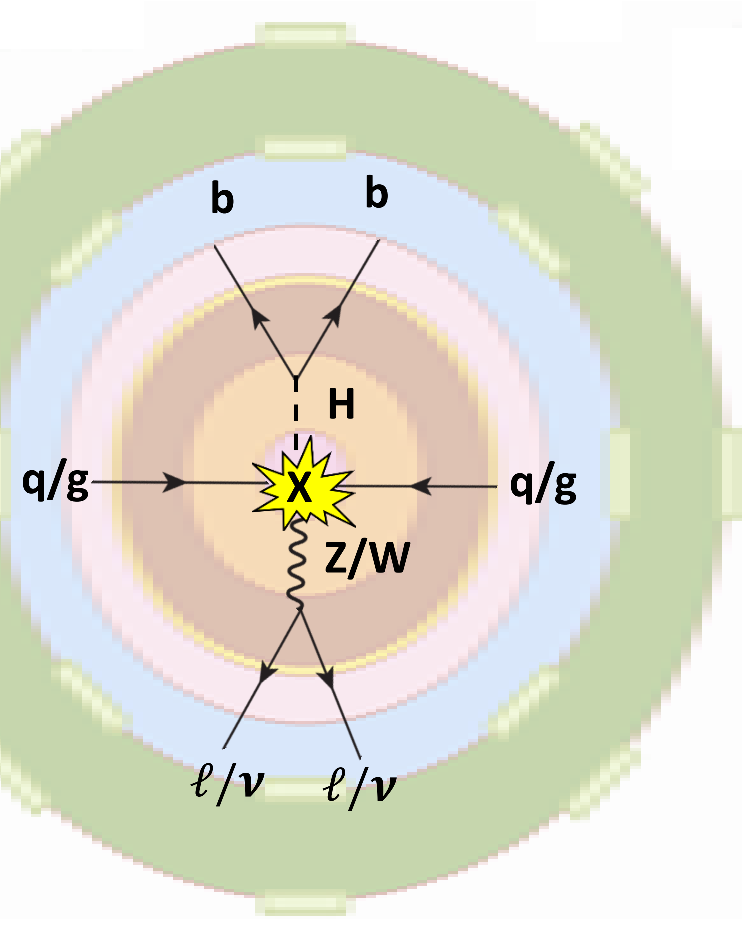




| Model | Signal Region | Excluded Mass (TeV) |
|---|---|---|
| HVT model A | WW / WZ | 1.3-2.9 / 1.3-3.4 |
| HVT model B | WW / WZ | 1.3-3.1 / 1.3 – 3.6 |
| Graviton | WW | 1.3 – 1.6 |

Model A : W’/Z’ branching fractions to fermions and gauge bosons comparable

Model B: fermionic couplings suppressed

# VH → $\nu\nu bb$ / $\ell\ell bb$ / $\ell\nu bb$




- X = W'/Z' in HVT, CP-odd scalar boson A in 2HDM

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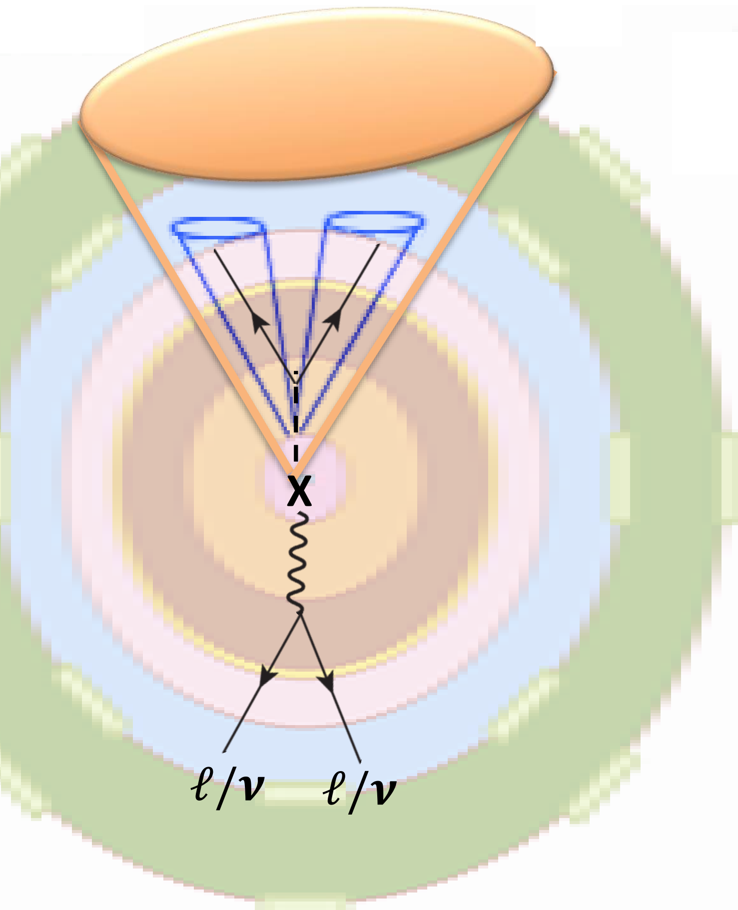
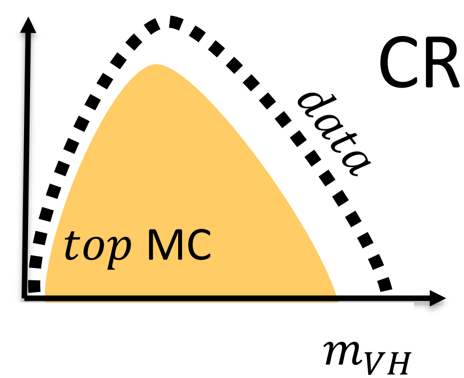



- X = W'/Z' in HVT, CP-odd scalar boson A in 2HDM
- 0, 1 and 2 lepton signal regions with:
  - R = 0.4 b-tagged jets (low-$p_T$ H)
  - R = 1 fat jets (high - $p_T$ H)
    - match b-tagged track jets to fat jet
- Background: top, W+jets taken from background-rich control region (CR)



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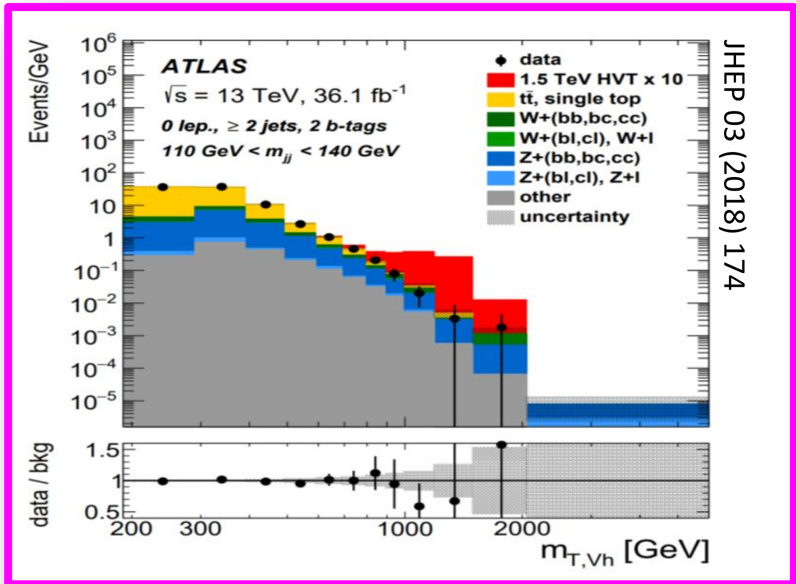


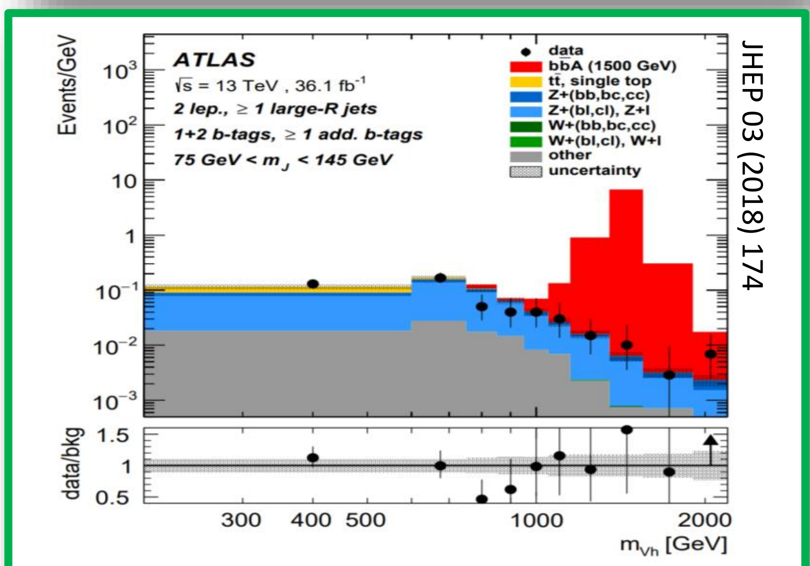


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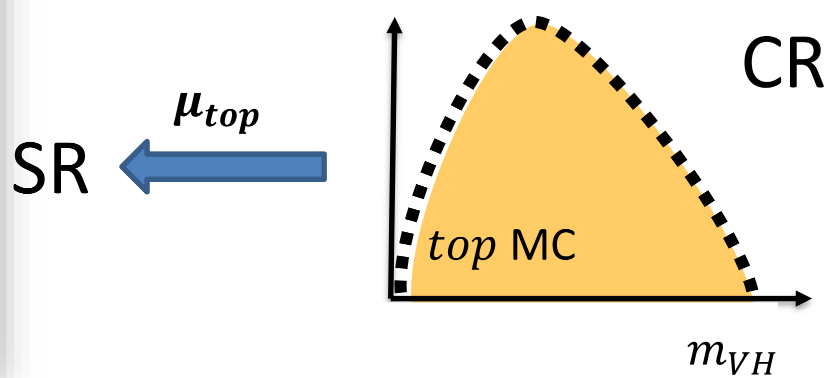
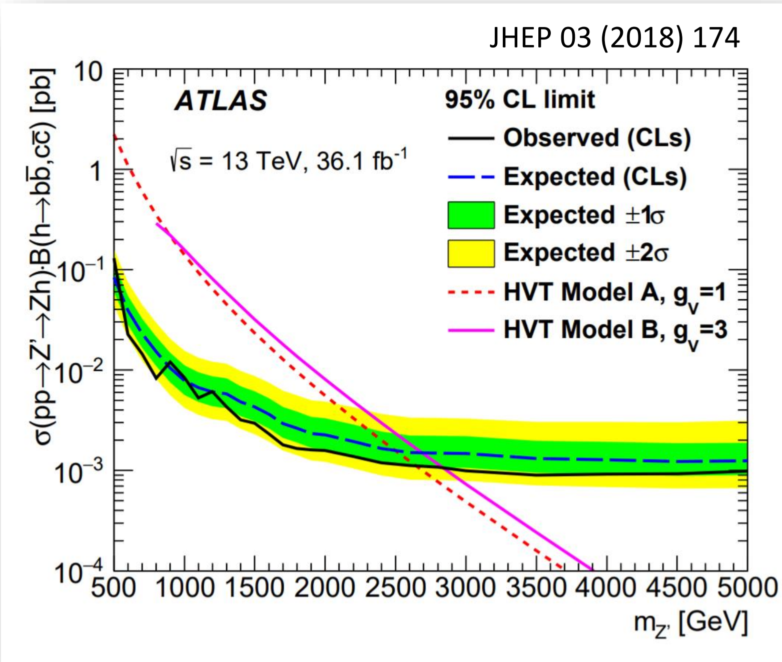
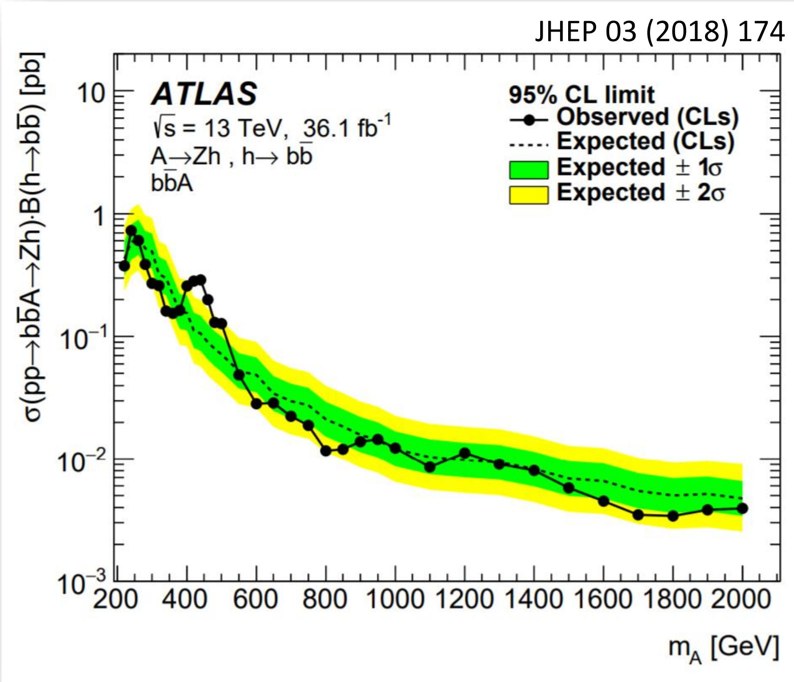


# VH → $\nu\nu bb$ / $\ell\ell bb$ / $\ell\nu bb$

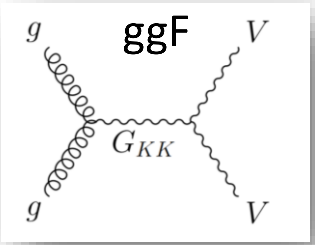


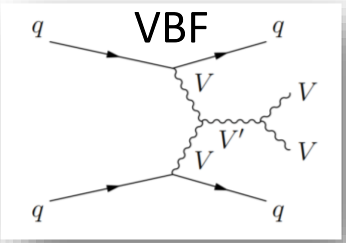



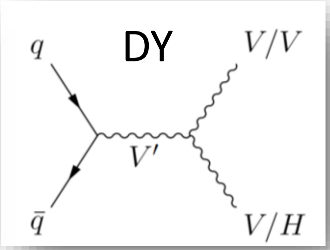

HVT: $m_{W'}$< 2.67 TeV (2.82 TeV) and $m_{Z'}$ < 2.65 TeV (2.83 TeV) in Model A (Model B)

2HDM: $m_A$ = 440 GeV - 3.6 (2.4) σ local (global) excess in associated b production channel

# Diboson Resonance Combination

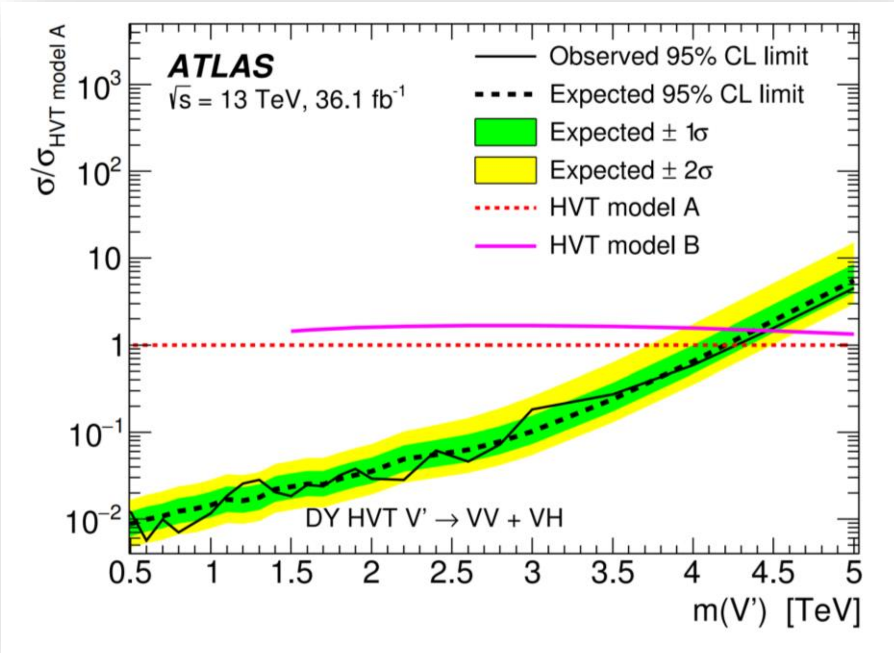



Phys. Rev. D 98 (2018) 052008

- Models: W'/Z' in HVT, RS Graviton, new heavy scalar singlet
- VV/H→ $qqqq, \ell\nu qq, \ell\nu\ell\ell, \ell\nu qq,$ $\ell\nu\ell\nu, \nu\nu qq, \ell\ell qq, \ell\ell\nu\nu,$ $\ell\ell\ell\ell, qqbb, \ell\nu bb, qqbb, \ell\ell bb$
- Regions orthogonal (selections on number of leptons, jets, $E_T^{miss}$)
- Discriminating variable $m_{VH}$ or $m_{T,VH}$

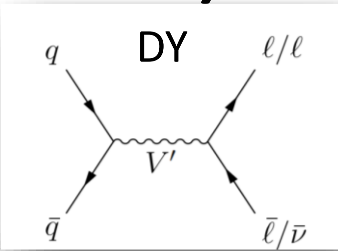



Excluded: $m_{V'} < 5.5$ TeV (4.5) HVT Model A (B)
$m_G < 2.3$ TeV (Graviton)

No big excesses

# Combination (Diboson & Dilepton)

+

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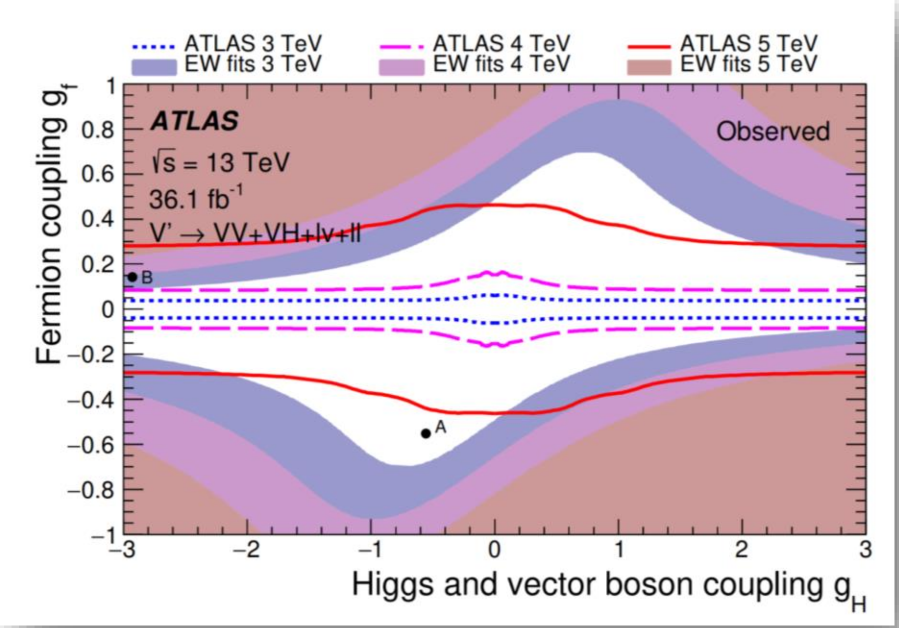
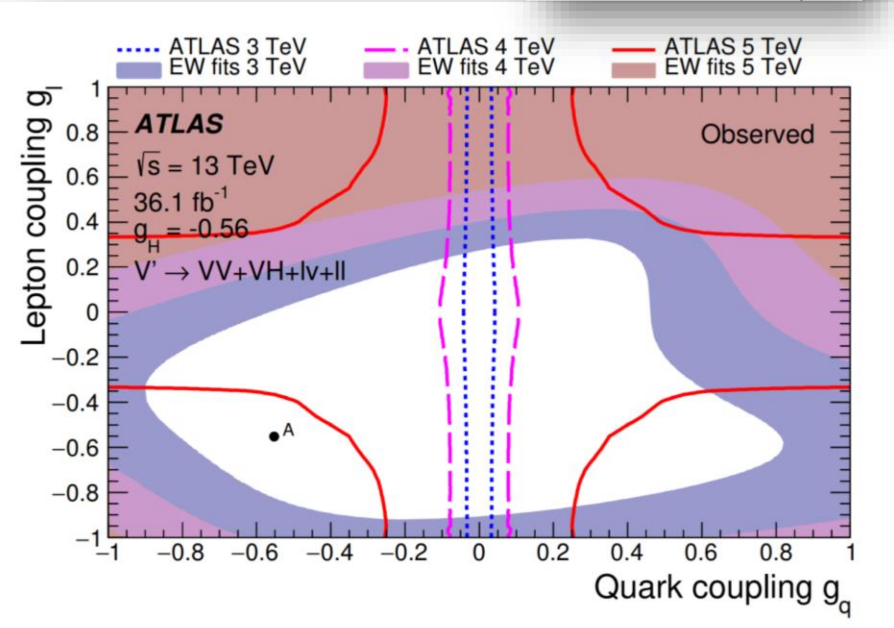
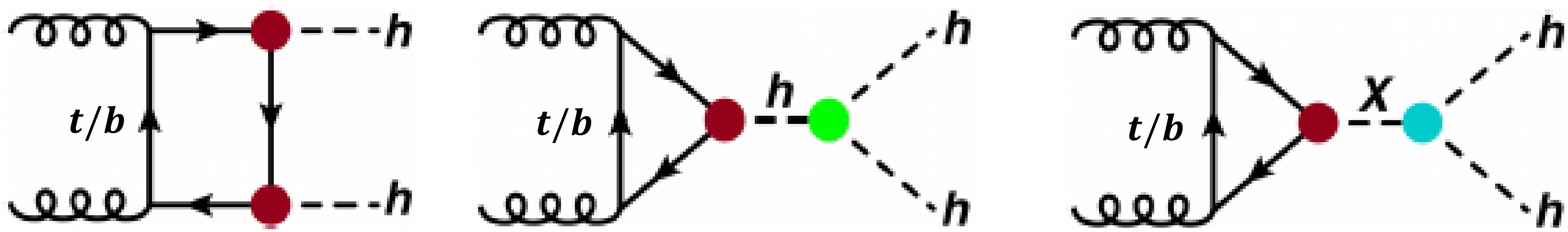



- Limits improved with respect to current constraints from precision EW measurements
  - except at low $g_q$ values because EW measurements are asymmetric due to interference affects
- Constraints on HVT A stronger than B due to small fermion couplings in B

# Di-Higgs

SM Di-Higgs production much lower than single Higgs production




Di-Higgs production enhanced in BSM models

- Non resonant production: modified h coupling
- Resonant production: 2HDM, RS graviton, heavy scaler particle S

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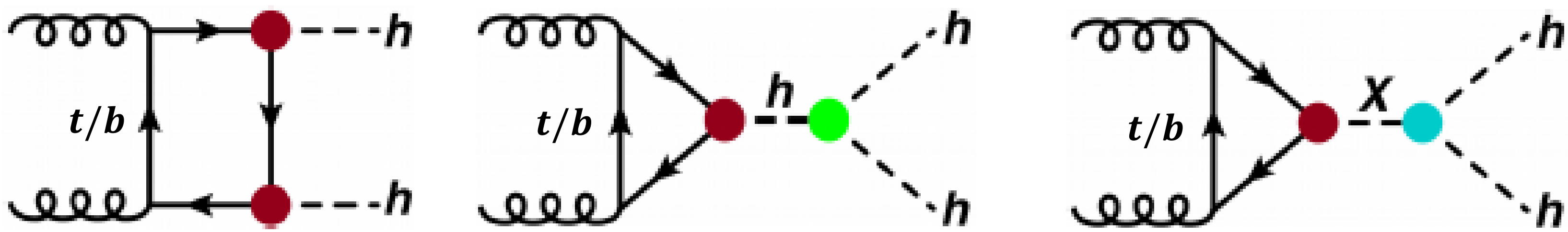



Di-Higgs production enhanced in BSM models

- Non resonant production: modified h coupling
- Resonant production: 2HDM, RS graviton, heavy scaler particle S

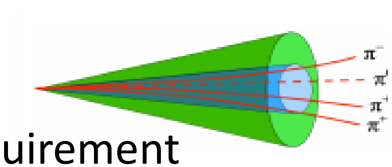
| BR | bb | WW |
|---|---|---|
| bb | 33% | |
| WW | 25% | 4.6% |
| $\tau\tau$ | **7.4%** | 2.5% |
| ZZ | 3.1% | 1.2% |
| $\gamma\gamma$ | 0.26% | 0.10% |

Combination
(ATLAS-CONF-2018-043)
After Combination
JHEP 04 (2019) 092, CERN-EP-2018-227

# Di-Higgs → $bb\tau\tau$

- Background: jets/leptons misidentified as $\tau$ estimated using Fake Factors

SR – real $\tau_h$



Medium BDT requirement

To identify τ

- Find jet, match 1 or 3 tracks to it
- Boosted Decision Tree (BDT) - use information on hadronic activity to separate τ from jets
- Likely-hood based veto separates τ from e

# Di-Higgs → $bb\tau\tau$

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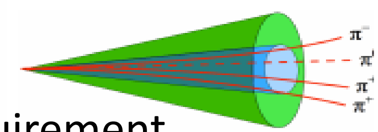
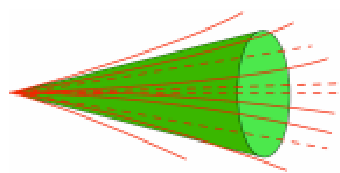


Medium BDT requirement

$\boldsymbol{F}$ = **probability of jet faking** $\boldsymbol{\tau}$

Region with jets that resemble (anti-$\tau_h$)



Loose BDT requirement

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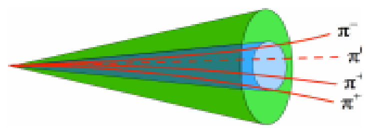
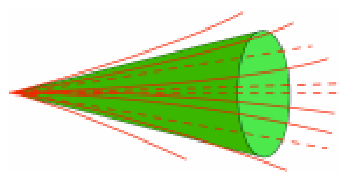


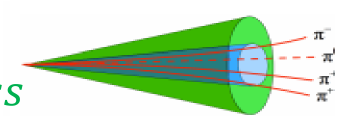
Region with jets that resemble (anti-$\tau_h$)

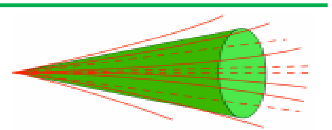


$$\boldsymbol{F} = F_{multi-j} + F_{W+j/t\bar{t}}$$

Multi-jet region (g-initiated)

$$F_{multi-j} = \frac{N_{pass}}{N_{fail}}$$





W+jets (q-initiated)

$F_{W+j/t\bar{t}}$

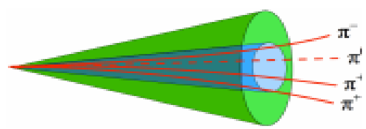
$t\bar{t}$ region

$F_{W+j/t\bar{t}}$

# Di-Higgs → $bb\tau\tau$

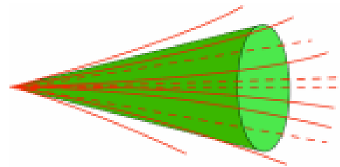
- Background: jets/leptons misidentified as $\tau$ estimated using Fake Factors

SR – real $\tau_h$



$$F = \alpha_{multi-j}\, F_{multi-j} + (1\text{-}\alpha_{multi-j})\, F_{W+j/t\bar{t}}$$

Region with jets that resemble (anti-$\tau_h$)



$\alpha_{multi-j} F_{multi-j} + (1\text{-}\alpha_{multi-j}) F_{W+j/t\bar{t}}$

Multi-jet region (g-initiated)

$F_{multi-j}$

W+jets (q-initiated)

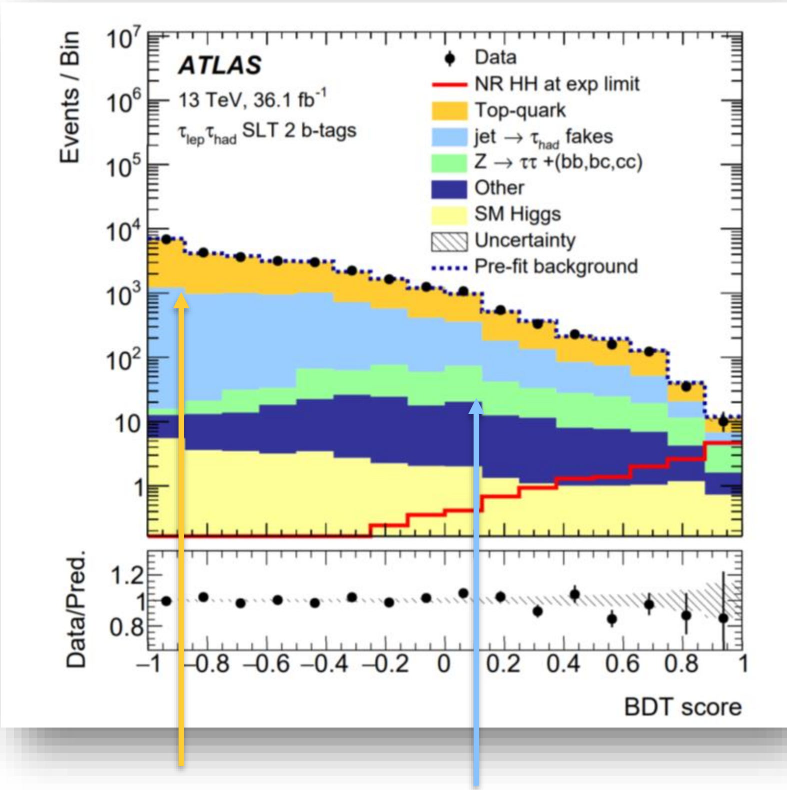
$F_{W+j/t\bar{t}}$

$t\bar{t}$ region

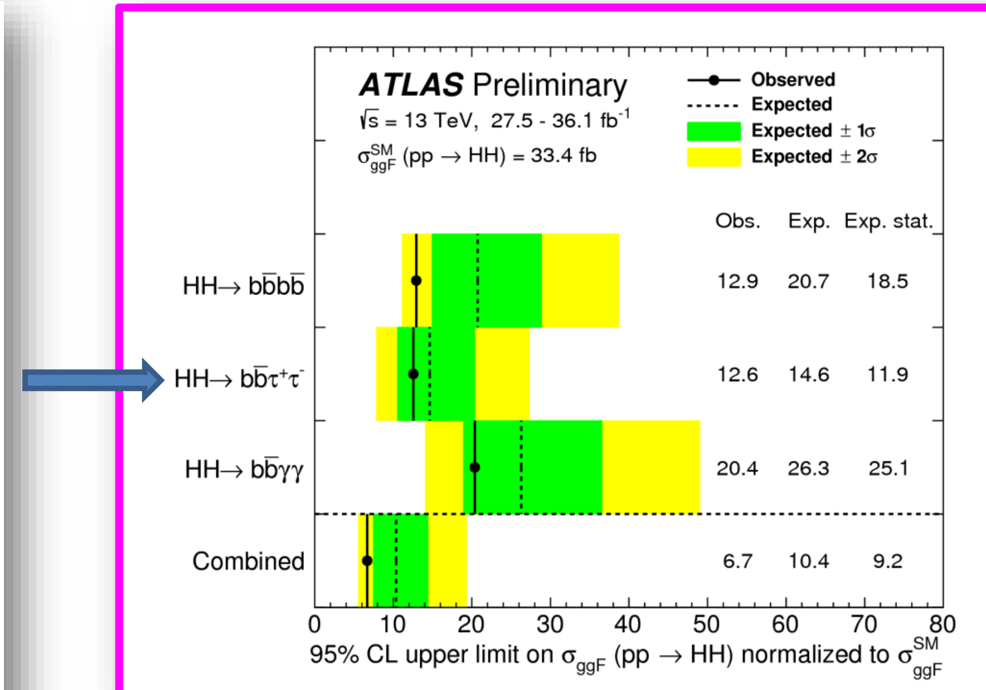
$F_{W+j/t\bar{t}}$

# Di-Higgs → $bb\tau\tau$ & Combination

PhysRevLett.121.191801




ATLAS-CONF-2018-043




MC normalized from CR, Fake-factor method
BDT is discriminating variable

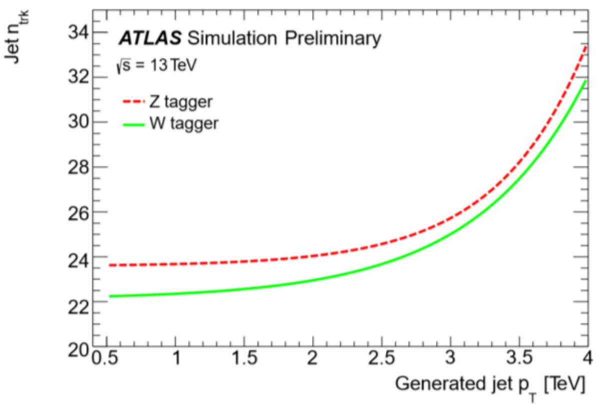
a deficit of data with respect to the background-only prediction

# Summary

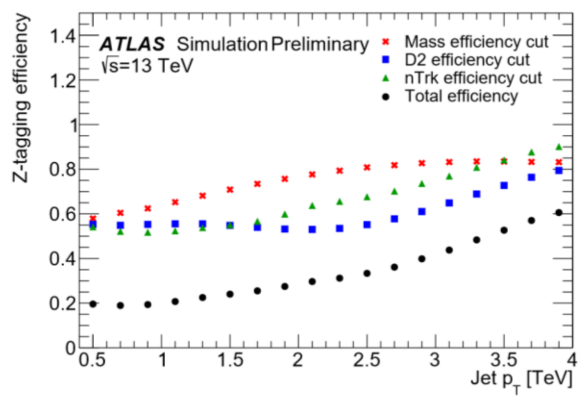
- VV, VH and Di-Higgs searches presented, with focus on novel techniques
- No significant excesses, limits set on cross sections times branching fractions
- Many more results coming with Full Run 2 data

# Backup

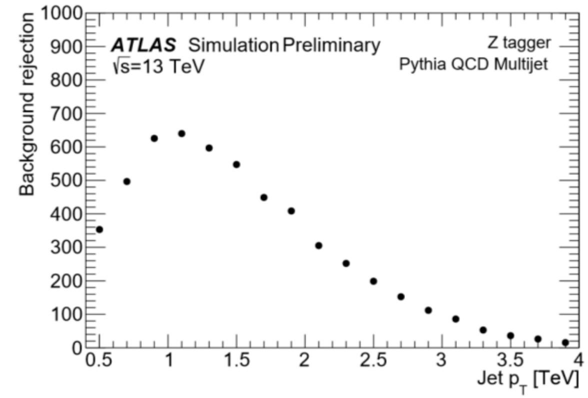
# VV to JJ



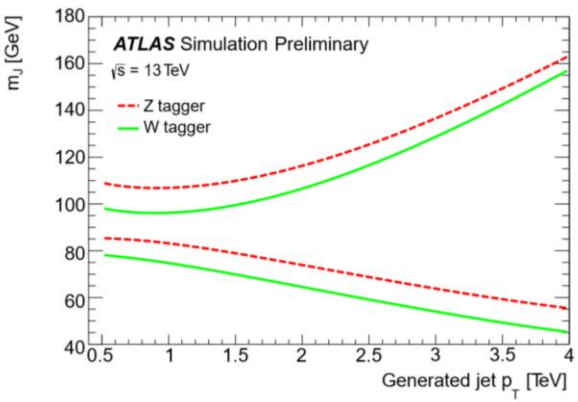
ATLAS Simulation Preliminary
√s = 13 TeV
Z tagger
W tagger
Jet $n_{trk}$
20
22
24
26
28
30
32
34
0.5
1
1.5
2
2.5
3
3.5
4
Generated jet $p_T$ [TeV]

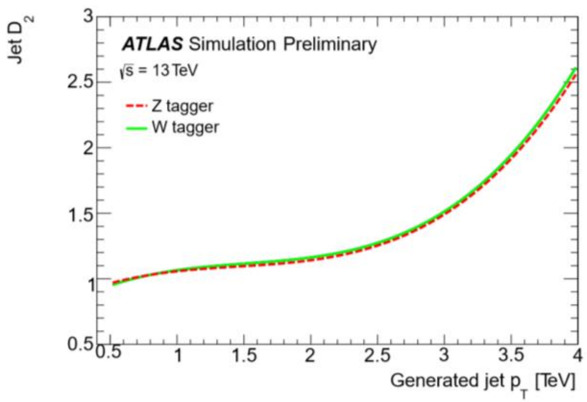
ATLAS Simulation Preliminary
√s=13 TeV
Mass efficiency cut
D2 efficiency cut
nTrk efficiency cut
Total efficiency
Z-tagging efficiency
0
0.2
0.4
0.6
0.8
1
1.2
1.4
0.5
1
1.5
2
2.5
3
3.5
4
Jet $p_T$ [TeV]

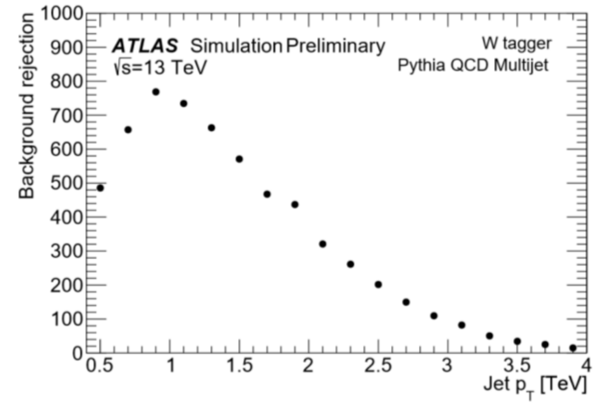
ATLAS Simulation Preliminary
√s=13 TeV
Z tagger
Pythia QCD Multijet
Background rejection
0
100
200
300
400
500
600
700
800
900
1000
0.5
1
1.5
2
2.5
3
3.5
4
Jet $p_T$ [TeV]

ATLAS Simulation Preliminary
√s = 13 TeV
Z tagger
W tagger
$m_J$ [GeV]
40
60
80
100
120
140
160
180
0.5
1
1.5
2
2.5
3
3.5
4
Generated jet $p_T$ [TeV]

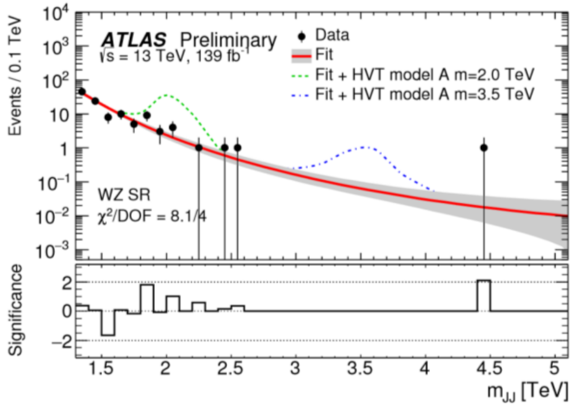



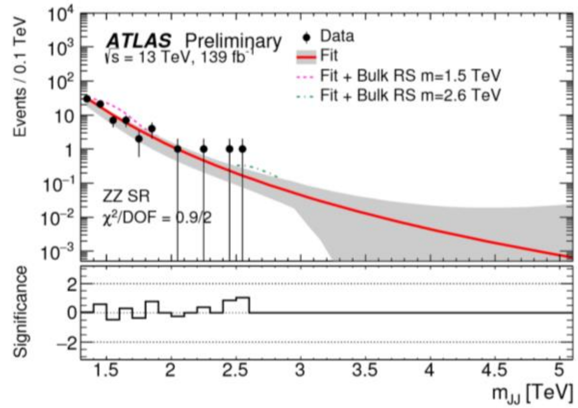
ATLAS Simulation Preliminary
√s = 13 TeV
Z tagger
W tagger
Jet $D_2$
0.5
1
1.5
2
2.5
3
0.5
1
1.5
2
2.5
3
3.5
4
Generated jet $p_T$ [TeV]

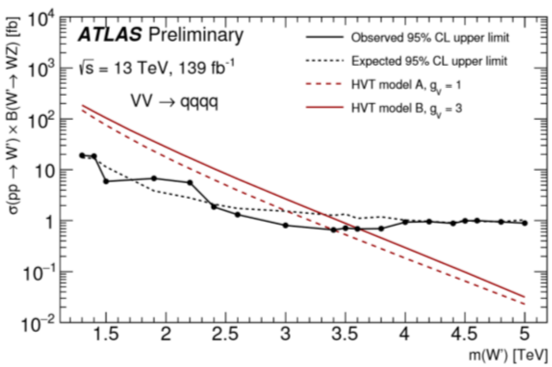



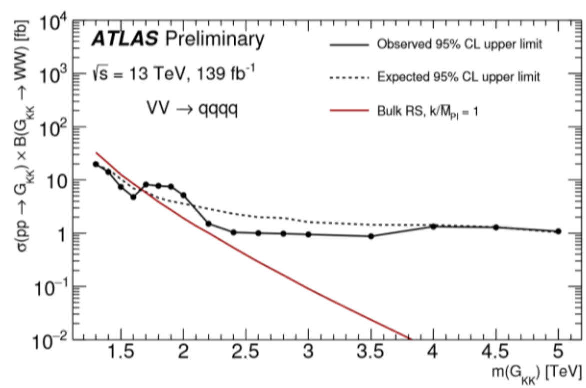
ATLAS Simulation Preliminary
√s=13 TeV
W tagger
Pythia QCD Multijet
Background rejection
0
100
200
300
400
500
600
700
800
900
1000
0.5
1
1.5
2
2.5
3
3.5
4
Jet $p_T$ [TeV]

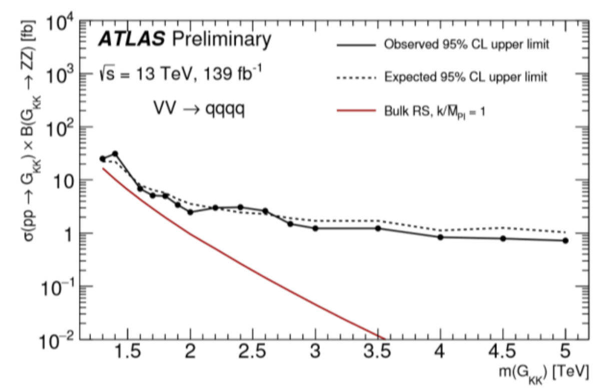
# VV to JJ




| Mass [TeV] | Observed Limit [fb] | Expected Limit [fb] | Prediction [fb] |
|---|---|---|---|
| WW SR | | | |
| 2.0 | 5.35 | 3.60 | 2.755 |
| 3.0 | 1.46 | 2.20 | 0.267 |
| 4.0 | 1.61 | 1.91 | 0.026 |
| 5.0 | 1.58 | 1.69 | 0.004 |
| ZZ SR | | | |
| 2.0 | 2.32 | 3.00 | 1.532 |
| 3.0 | 1.17 | 1.74 | 0.148 |
| 4.0 | 0.99 | 0.98 | 0.014 |
| 5.0 | 0.87 | 0.98 | 0.002 |

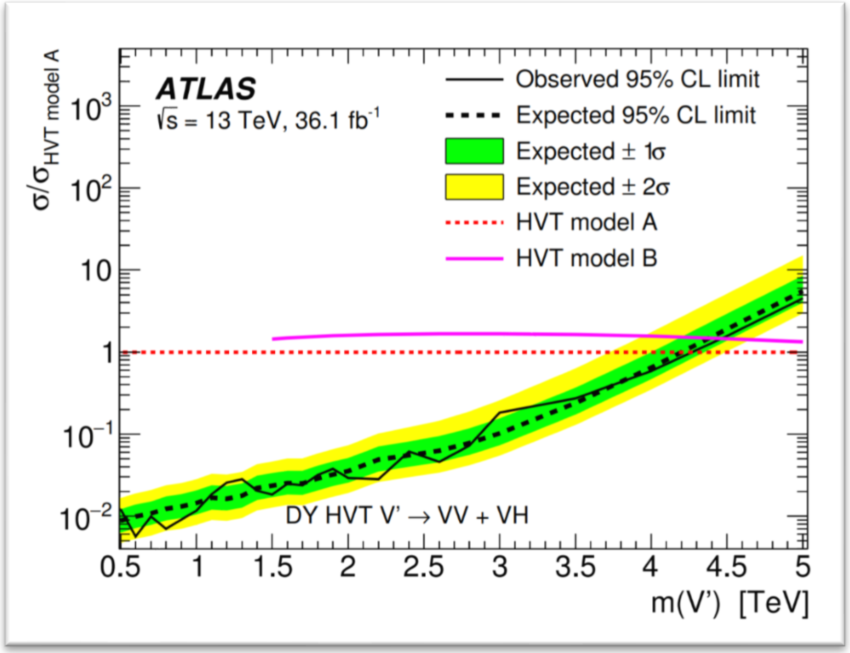
| Model | Signal Region | Excluded mass range [TeV] |
|---|---|---|
| Radion | $WW$ | none |
| | $ZZ$ | none |
| HVT model A, $g_V = 1$ | $WW$ | 1.3–2.9 |
| | $WZ$ | 1.3–3.4 |
| HVT model B, $g_V = 3$ | $WW$ | 1.3–3.1 |
| | $WZ$ | 1.3–3.6 |
| Bulk RS, $k/\overline{M}_{\mathrm{Pl}} = 1$ | $WW$ | 1.3–1.6 |
| | $ZZ$ | none |

# VV to JJ

| | |
|---|---|
| Signal region | Veto events with leptons: |
| | No $e$ or $\mu$ with $p_T > 25$ GeV and $\|\eta\| < 2.5$ |
| | Event preselection: |
| | $\geq 2$ large-$R$ jets with $\|\eta\| < 2.0$ and mass $> 50$ GeV |
| | $p_{T1} > 500$ GeV and $p_{T2} > 200$ GeV |
| | $m_{JJ} > 1.2$ TeV |
| | Topology and boson tag: |
| | $\|\Delta y\| = \|y_1 - y_2\| < 1.2$ |
| | $A = (p_{T1} - p_{T2}) / (p_{T1} + p_{T2}) < 0.15$ |
| | Boson tag with $D_2$ variable, $n_{trk}$ variable, and $W$ or $Z$ mass window |
| $V$+jets control region | Veto events with leptons: |
| | No $e$ or $\mu$ with $p_T > 25$ GeV and $\|\eta\| < 2.5$ |
| | $V$+jets selection: |
| | $\geq 2$ large-$R$ jets with $\|\eta\| < 2.0$ |
| | $p_{T1} > 600$ GeV and $p_{T2} > 200$ GeV |
| | Boson tag with $D_2$ and $n_{trk}$ variables on either jet |
| | Anti-boson tag with $D_2$ variable on other jet |

# Combination

| Channel | Lower limits on resonance mass [TeV] | | | | | |
|---|---|---|---|---|---|---|
| | HVT model A | | HVT model B | | Bulk RS | |
| | Obs | Exp | Obs | Exp | Obs | Exp |
| $WW$ | 2.9 | 3.1 | 3.6 | 3.5 | 1.7 | 1.9 |
| $WZ$ | 3.6 | 3.6 | 3.9 | 3.9 | - | - |
| $ZZ$ | - | - | - | - | 1.5 | 1.7 |
| $VV$ | 3.7 | 3.7 | 4.0 | 3.9 | 2.3 | 2.2 |
| $WH$ | 2.6 | 2.8 | 2.8 | 3.1 | - | - |
| $ZH$ | 2.7 | 2.5 | 2.8 | 2.8 | - | - |
| $VH$ | 2.8 | 3.1 | 3.0 | 3.4 | - | - |
| $\ell\nu$ | 4.6 | 4.6 | - | - | - | - |
| $\ell\ell$ | 4.5 | 4.4 | - | - | - | - |
| $\ell\nu/\ell\ell$ | 5.0 | 5.0 | - | - | - | - |
| $VV/VH$ | 4.3 | 4.3 | 4.5 | 4.4 | - | - |
| $VV/VH/\ell\nu/\ell\ell$ | 5.5 | 5.3 | - | - | - | - |




From paper: For most of the VV and VH analyses, MC-modeling systematic uncertainties play the dominant role in the theoretical uncertainty, while for the leptonic channels, the PDF variation and PDF choice are by far the most dominant. For the experimental systematic uncertainties, analyses selecting jets are most sensitive to systematic uncertainties in the modeling of large-R jets, while the leptonic channels are affected mostly by the uncertainty in the muon reconstruction efficiency and electron isolation efficiency

# Combination