# SEARCHES FOR V+H RESONANCES

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MICHIGAN STATE UNIVERSITY

FOR THE ATLAS COLLABORATION

EPS Conference on High Energy Physics
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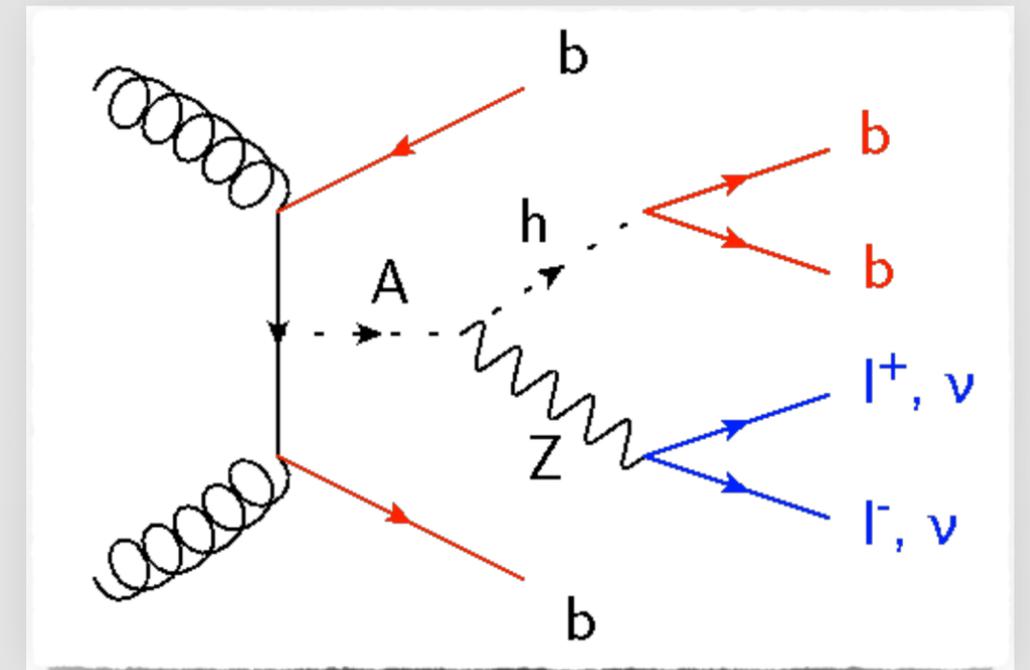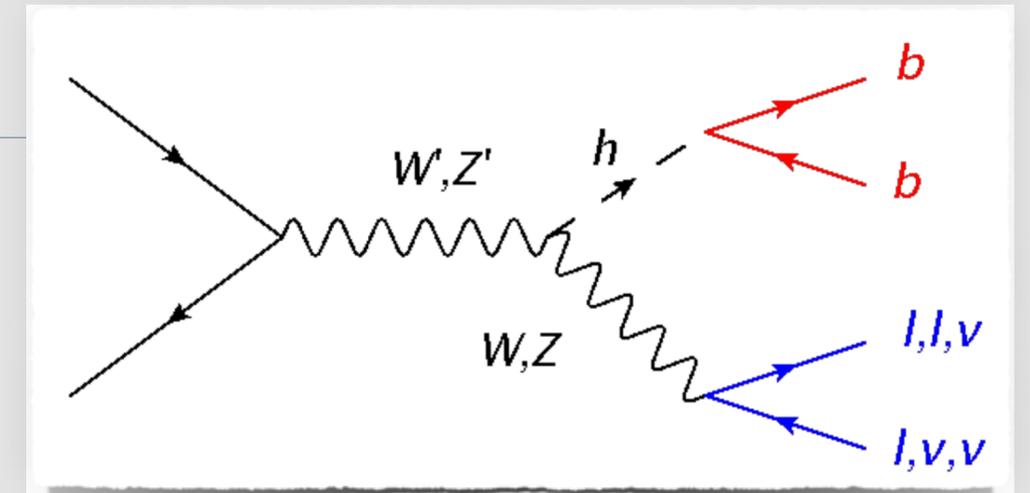
# Overview

## Higgs + Boson Resonances
- Neither exhaustive nor complete summary of ATLAS results
- Many related results in talk by Kalliopi Iordanidou today

## Vector Boson + Higgs Resonances
- Semi-leptonic searches
- Fully hadronic search
- Vector Triplet and 2HDM interpretations
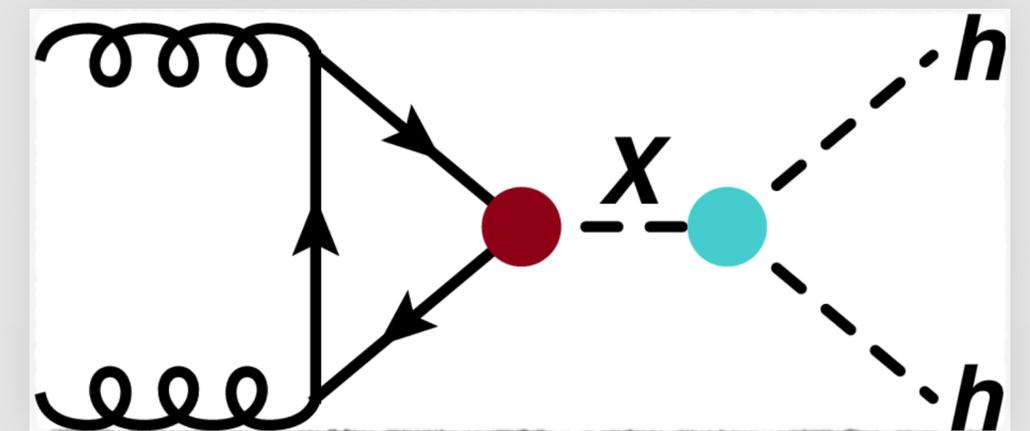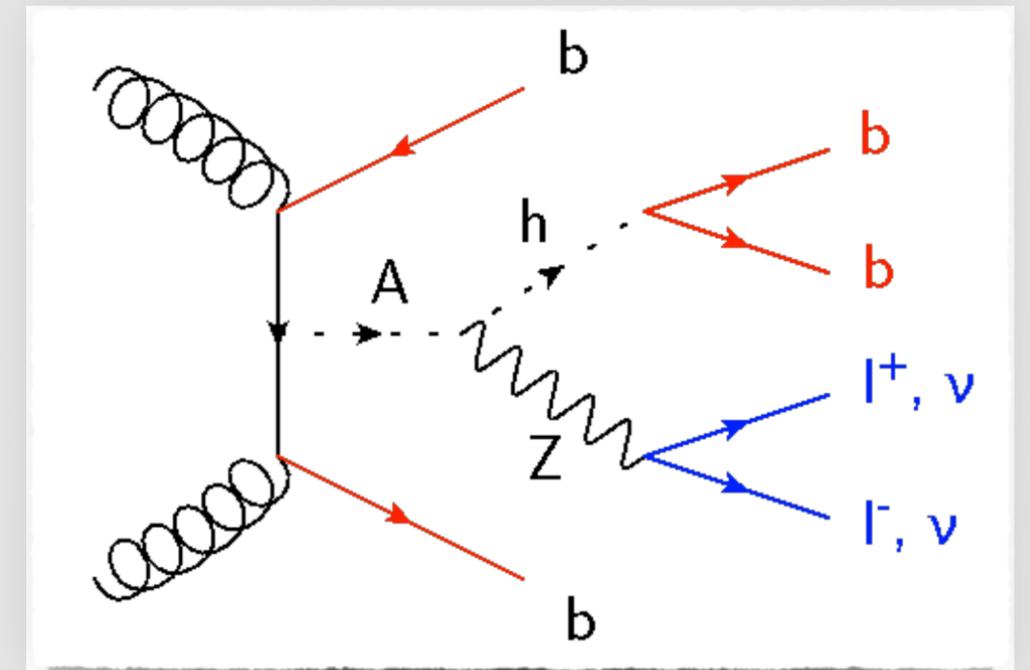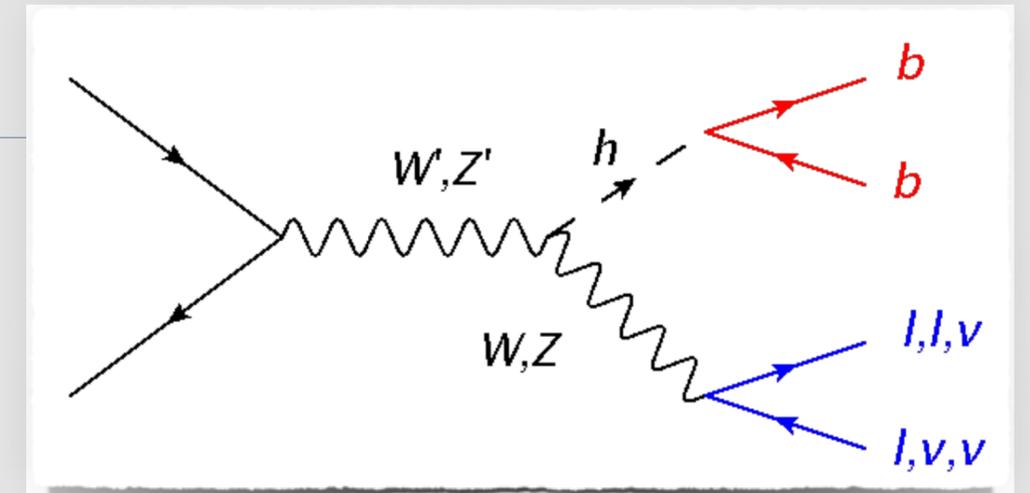
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## Vector Boson + Higgs Resonances
- Semi-leptonic searches
- Fully hadronic search
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## Di-Higgs Searches
- Covered Friday by Will Davey (talk link)
- bbbb, bbγγ and γγWW final states

# Vector Boson + Higgs Resonances

## Search for resonances decaying into Zh or Wh

### 2 Higgs Doublet Models

- Extension of SM with additional Higgs doublet ⇒ 5 Higgses: H, h, H$^+$, H$^-$, **A**

- Appear in extensions of the SM such as SUSY, axion models, baryogenesis



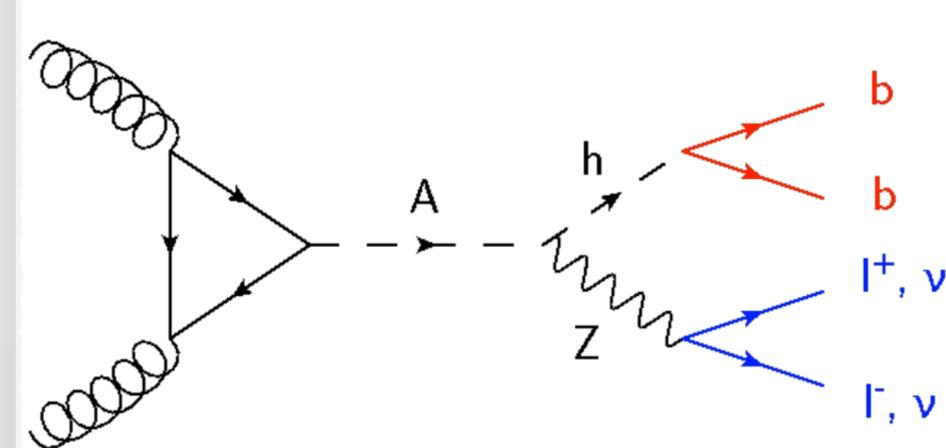gluon fusion - **A**          **bbA**

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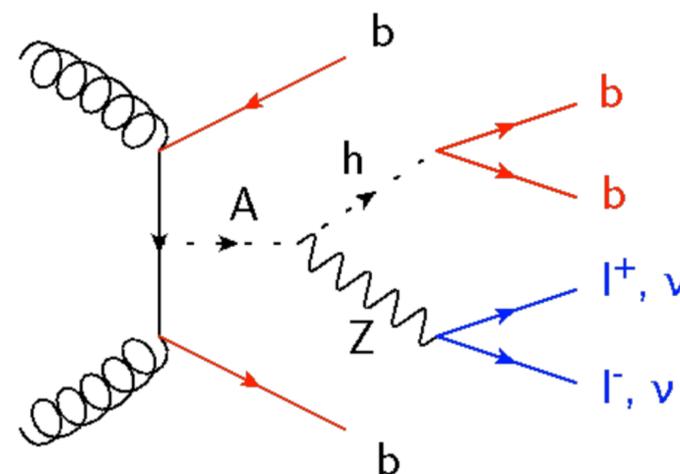
## Search for resonances decaying into Zh or Wh

### 2 Higgs Doublet Models

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### Heavy Vector Triplets

- Several SM extensions predict the existence of heavy vector bosons

- HVT: simplified model with **additional SU(2) vector triplet** ⇒ **W'$^+$, W'$^-$, Z'**

arxiv:1402.4431



gluon fusion - A
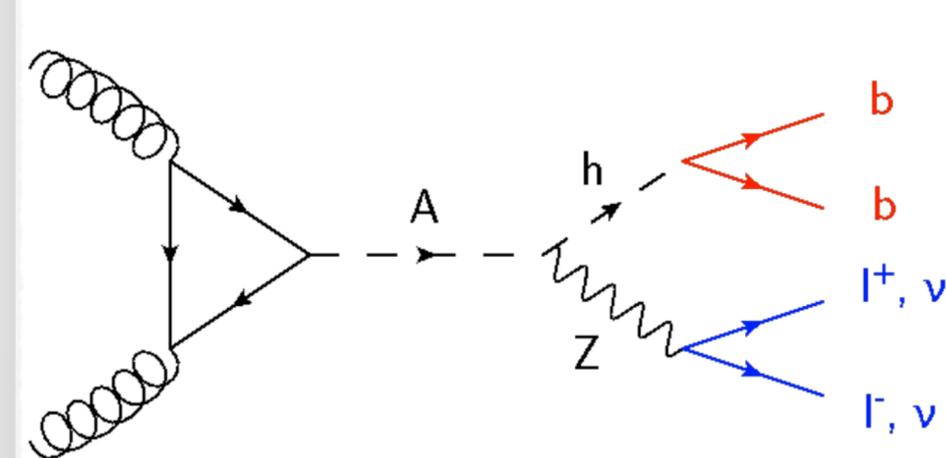
bbA
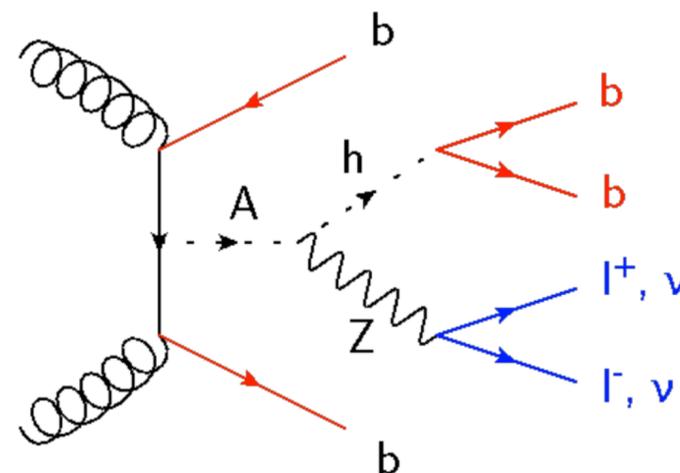
W',Z' production
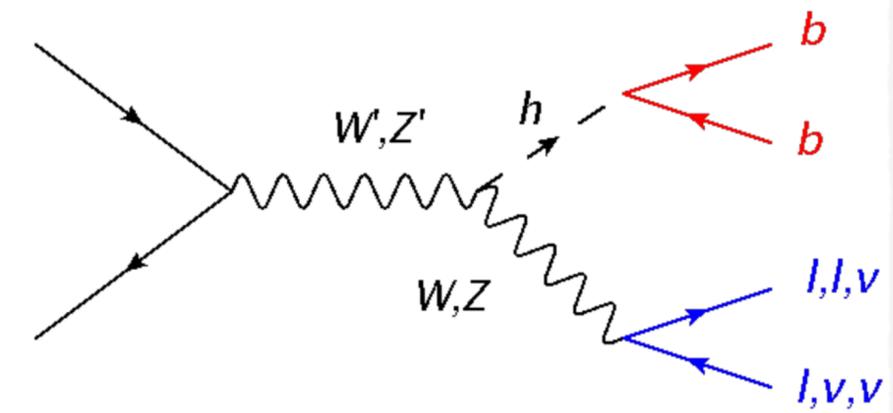
# Semi-Leptonic VH: 36 fb⁻¹

- **Resolved** & **merged** categories
- **3 channels** based on V decays
  - 0-/2-lepton (A, Z'), 1-lepton (W')
- **b-tag categories:**
  - 1-/2-tag used for A and V'
  - 3+ tag used for A (sensitive to bbA)
- **Select dijet/jet mH window to reduce bkgds**
  - Fit m(Vh) or mT(Vh) spectra
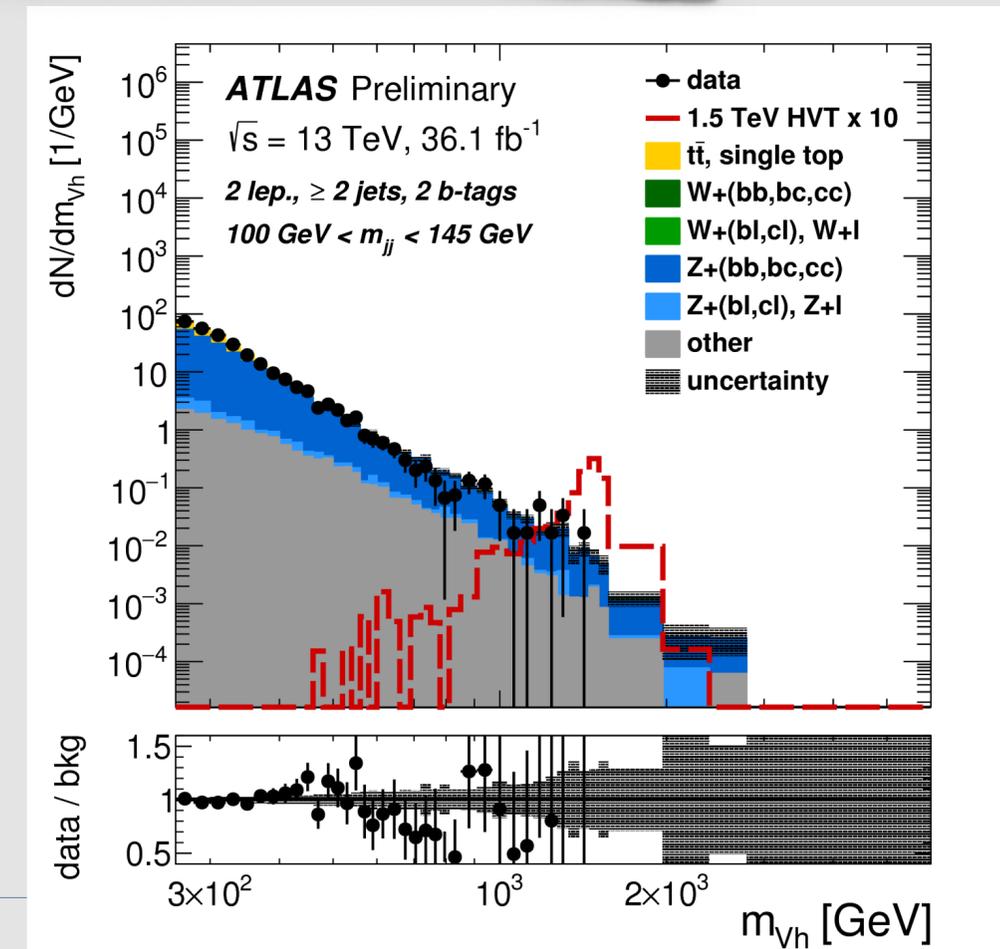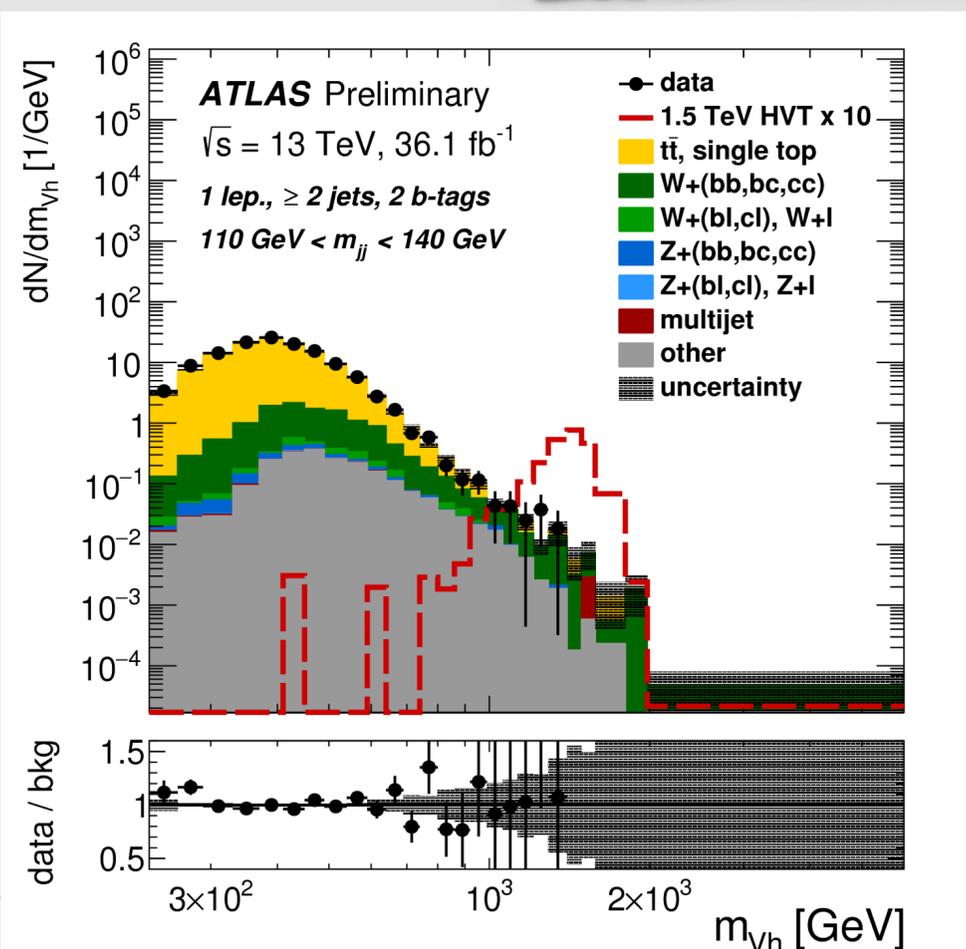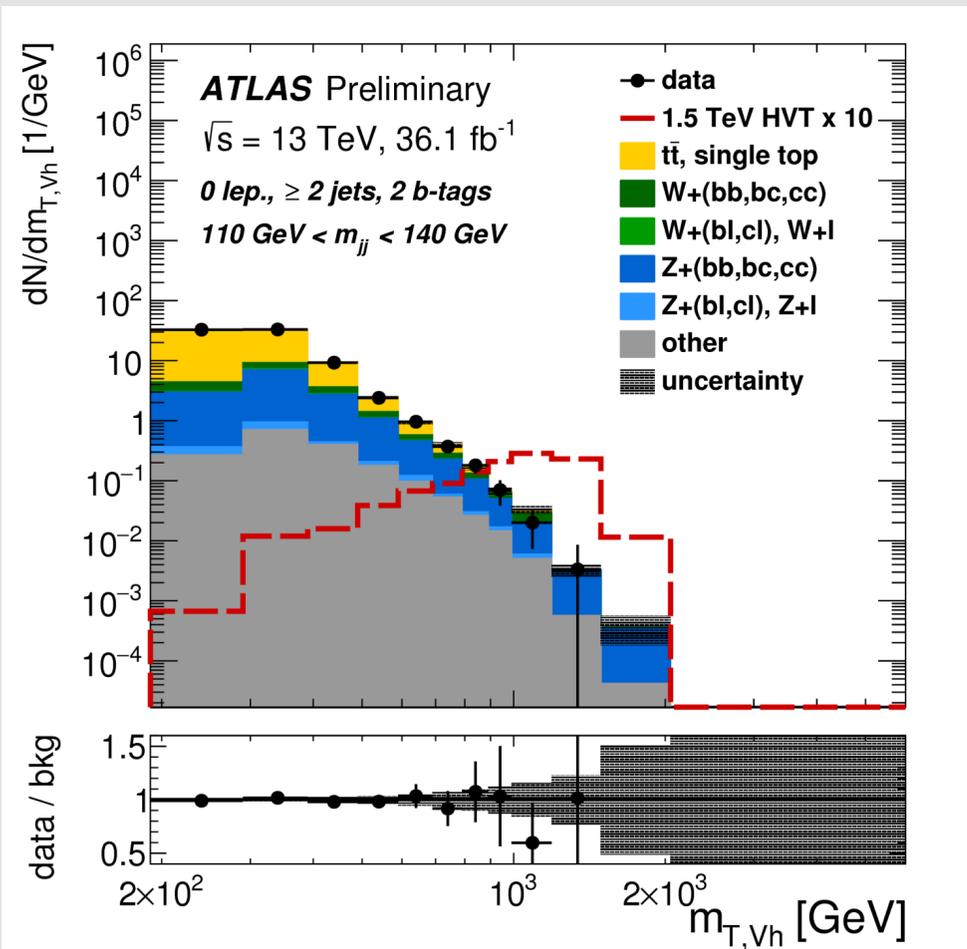
# Semi-Leptonic VH: 36 fb⁻¹

**Resolved**
R=0.4
calo-jets
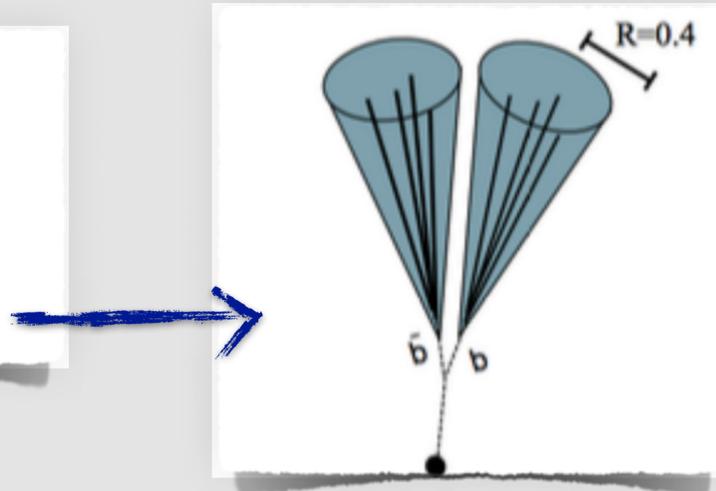
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4
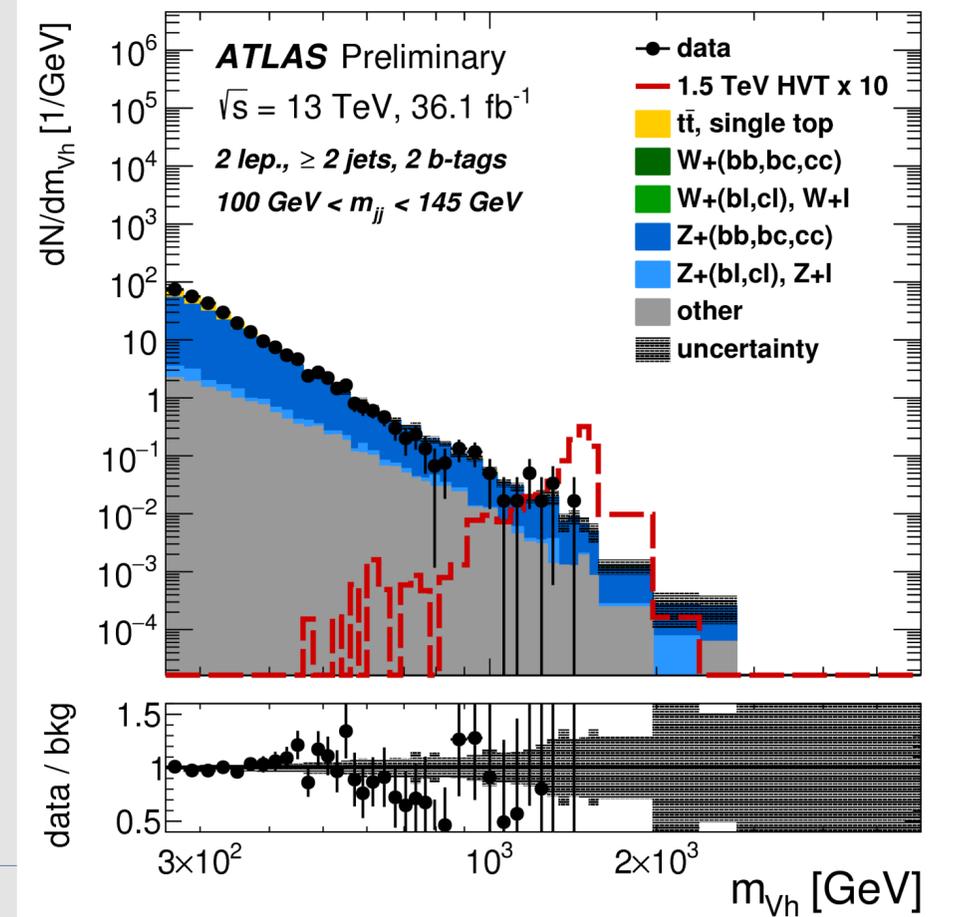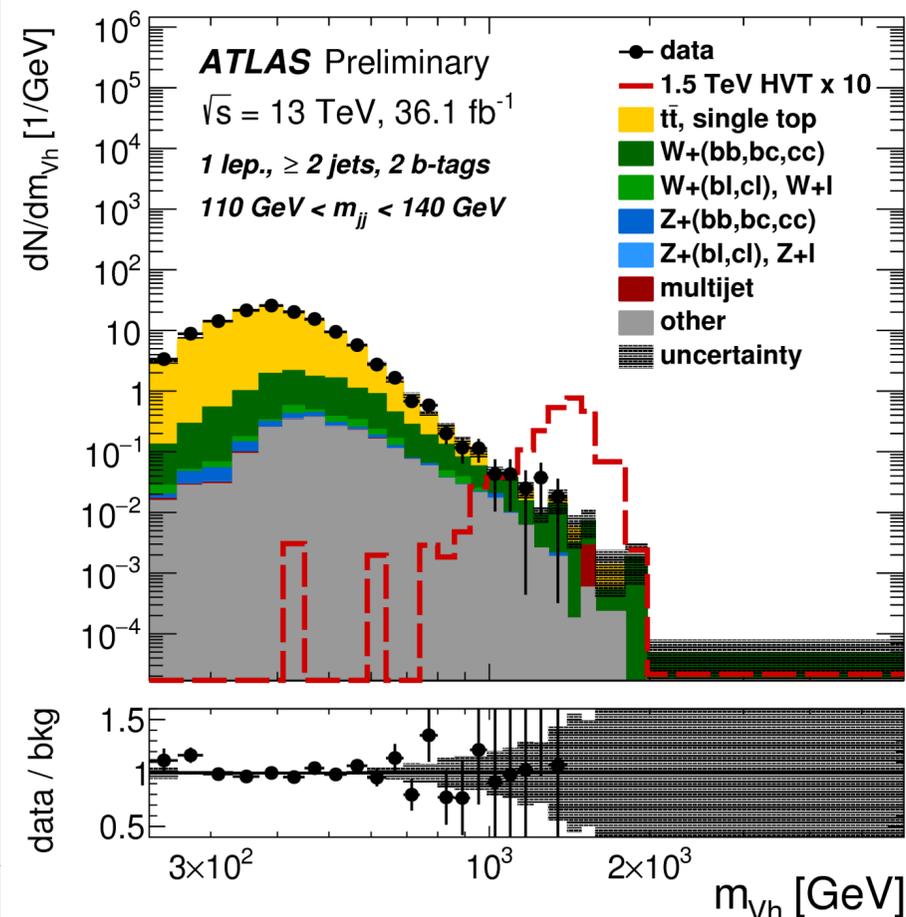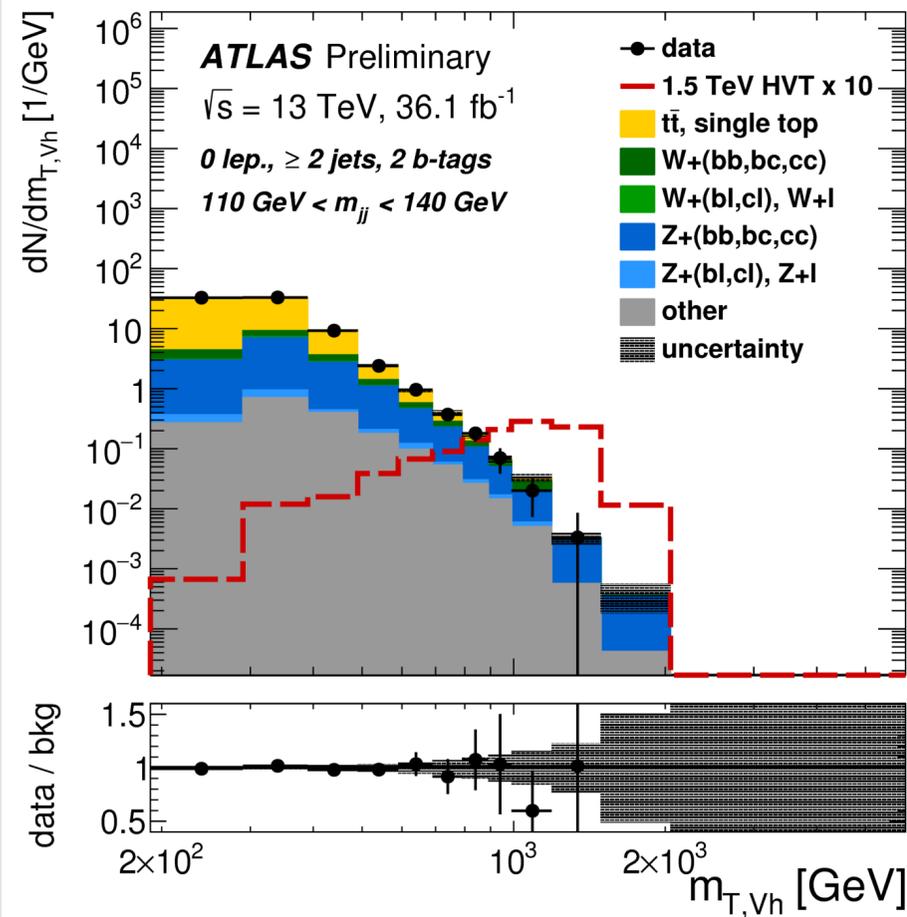
# Semi-Leptonic VH: 36 fb$^{-1}$

**Merged**

R=1 calo-jet
+ ghost associated
R=0.2 track-jets
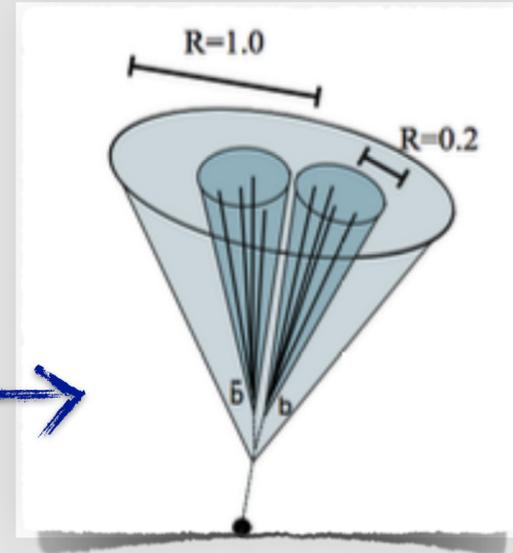
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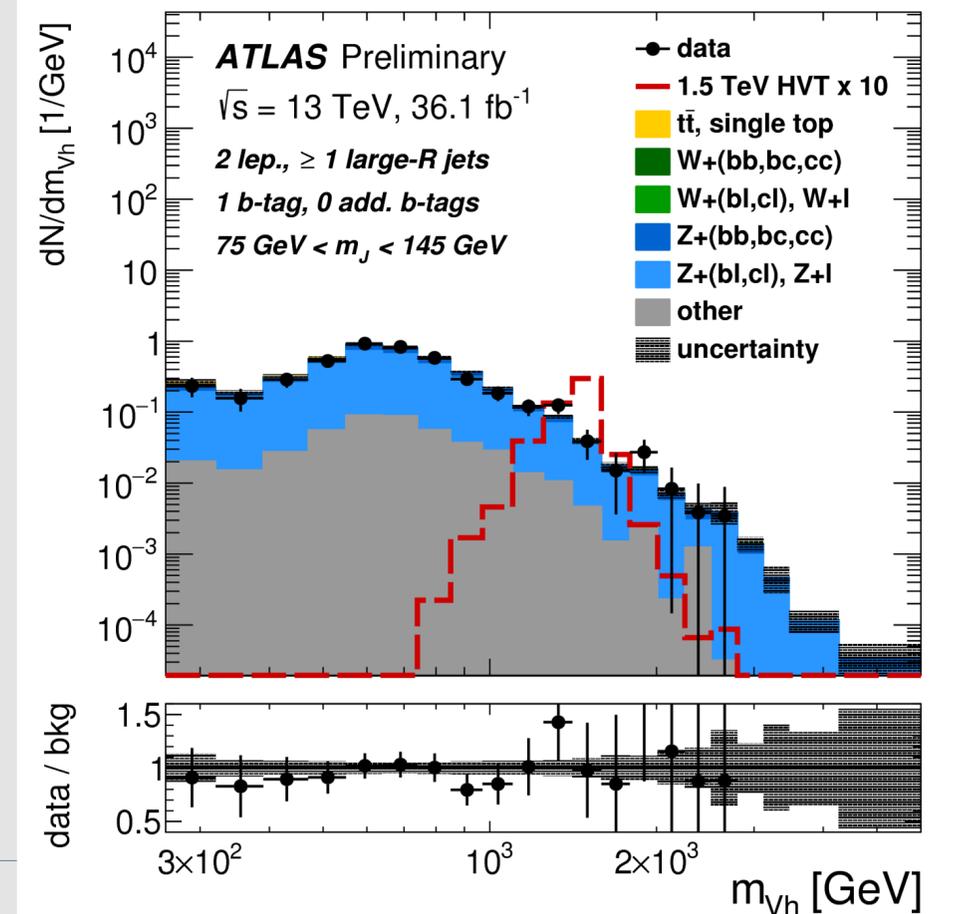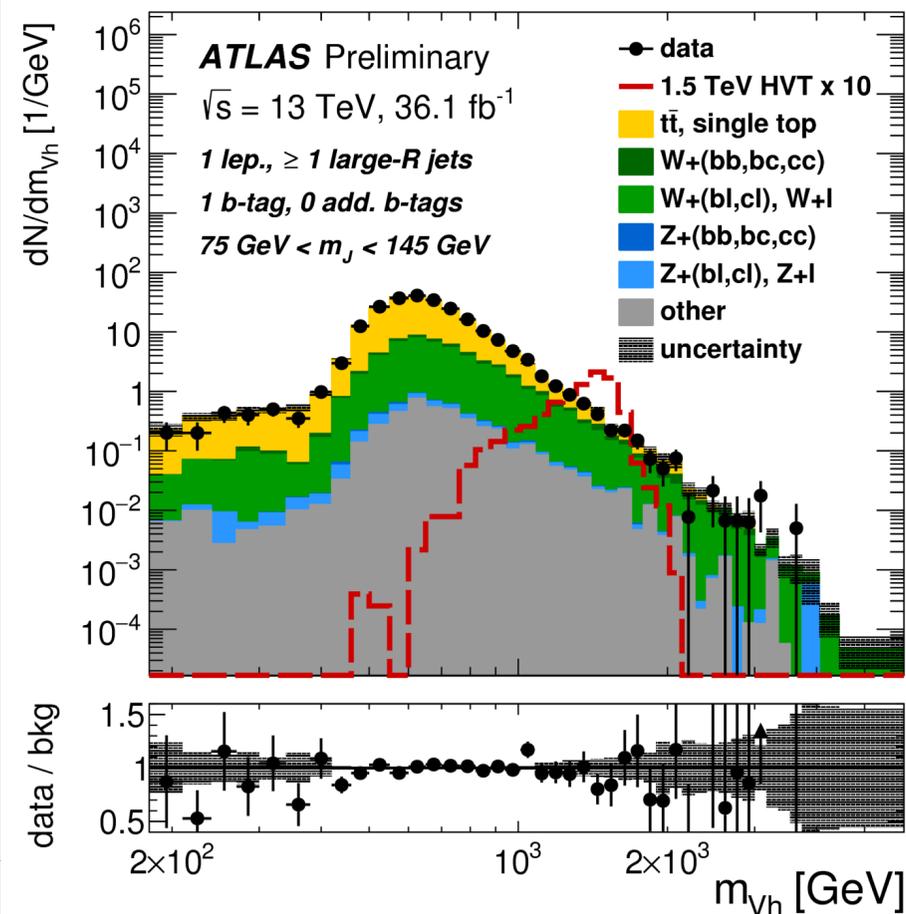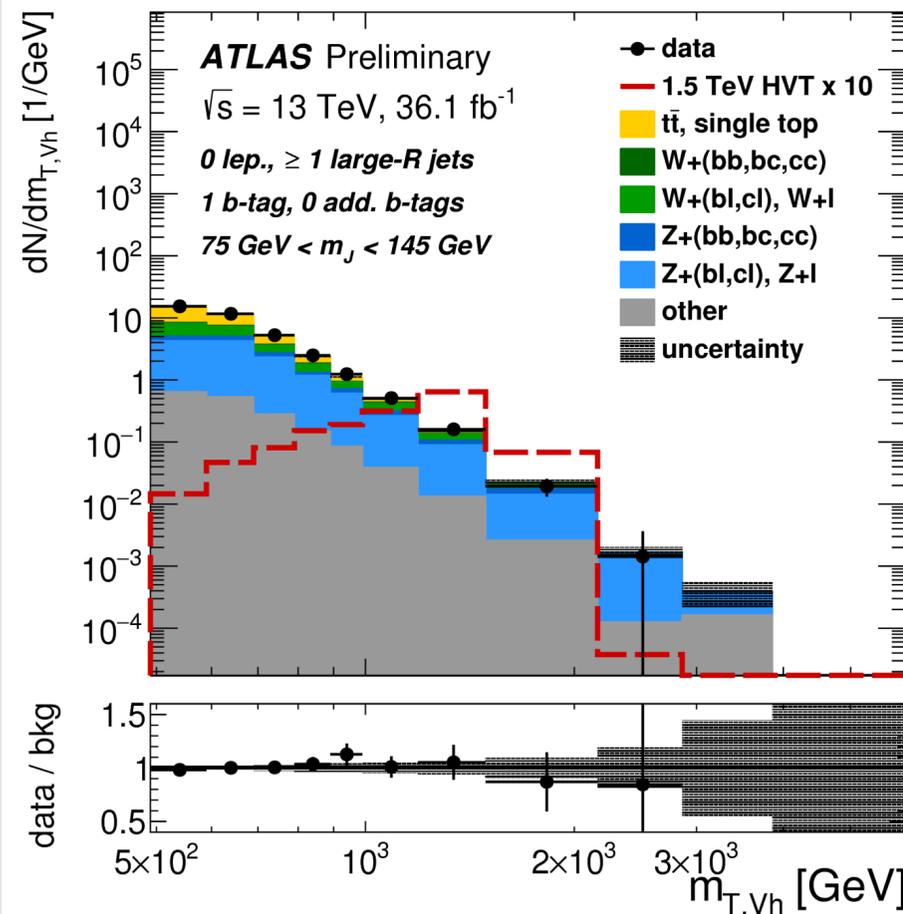
# Semi-Leptonic VH: HVT

- No significant excess observed
- Limits derived for Z' (0-/2-lepton combined) and W' (0-/1-lepton combined)
- Exclusions for HVT Model-A (B)
  - $m_{W'}$ < 2670 (2860) GeV
  - $m_{Z'}$ < 2650 (2830) GeV
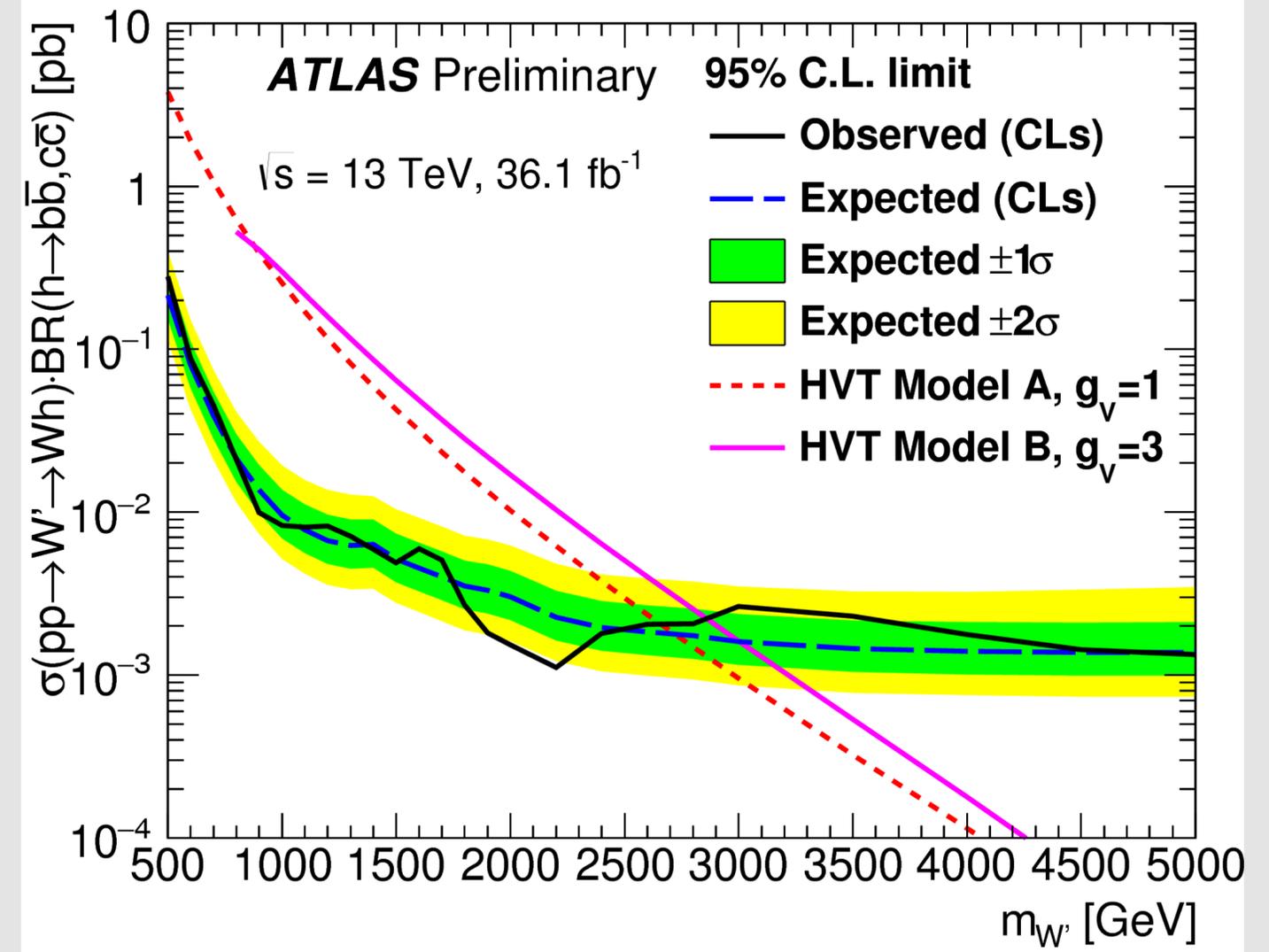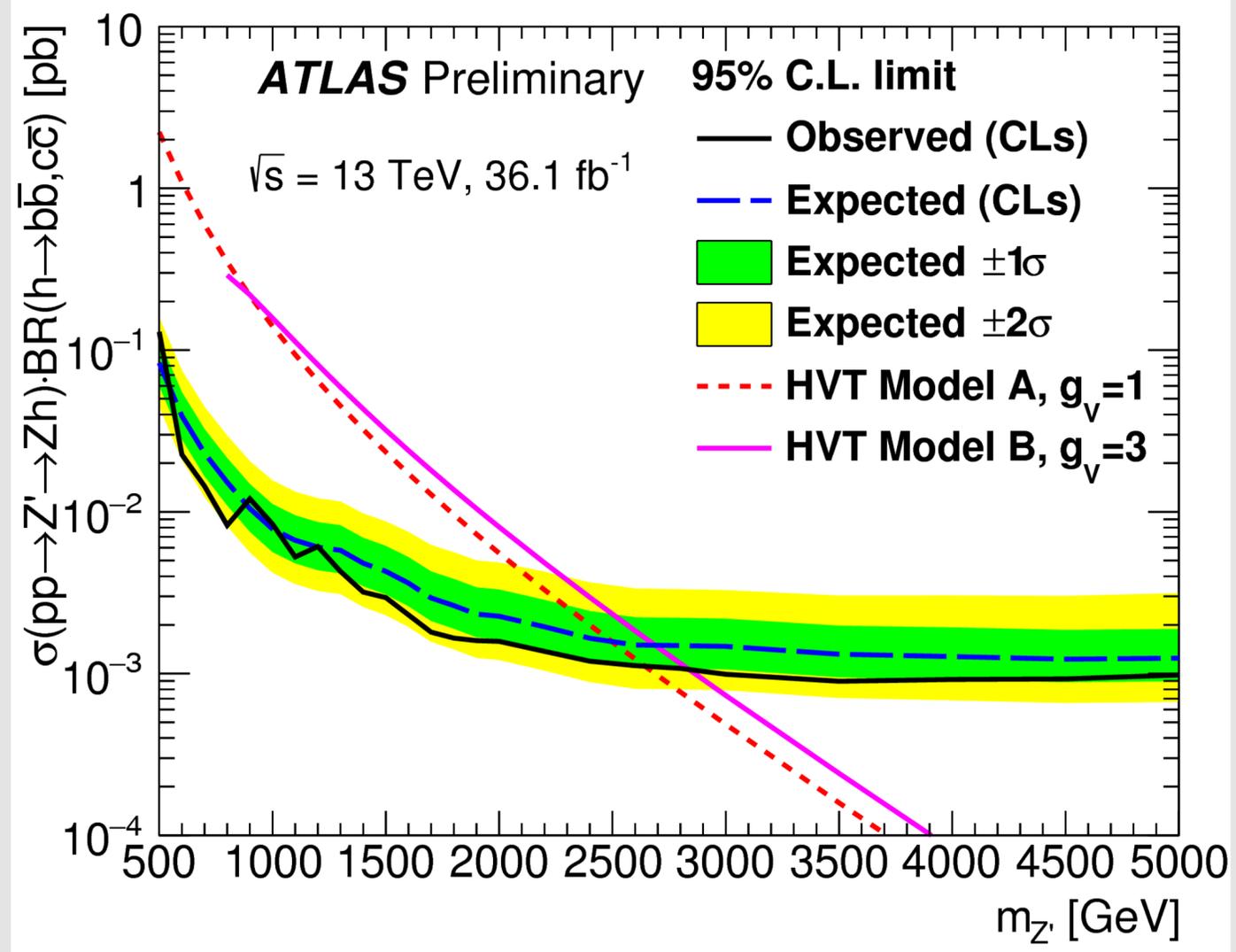
# Semi-Leptonic VH: HVT

- Left: limits on HVT model assuming simultaneous production of mass-degenerate W' and Z' bosons
- Right: limits on HVT couplings to fermions and bosons
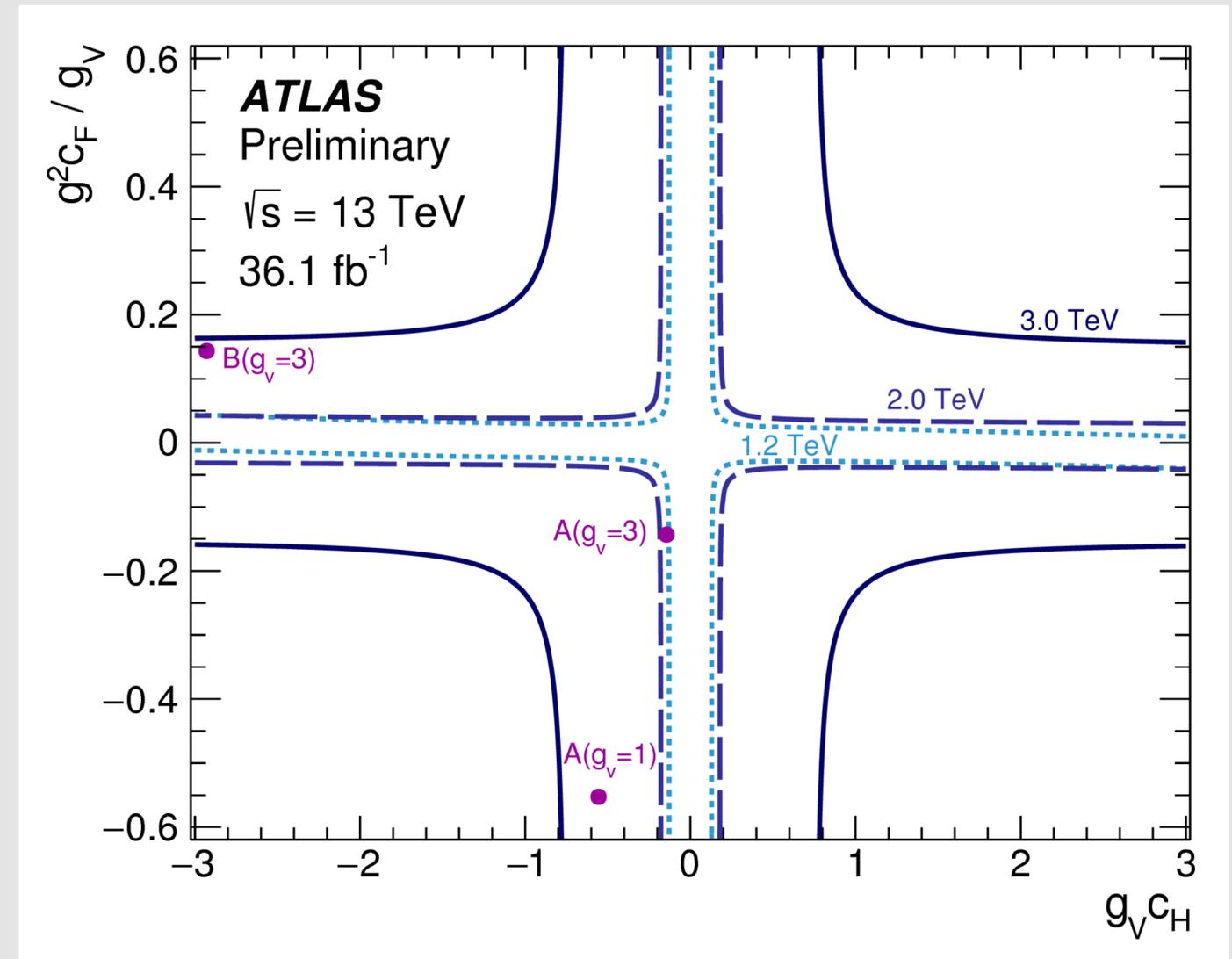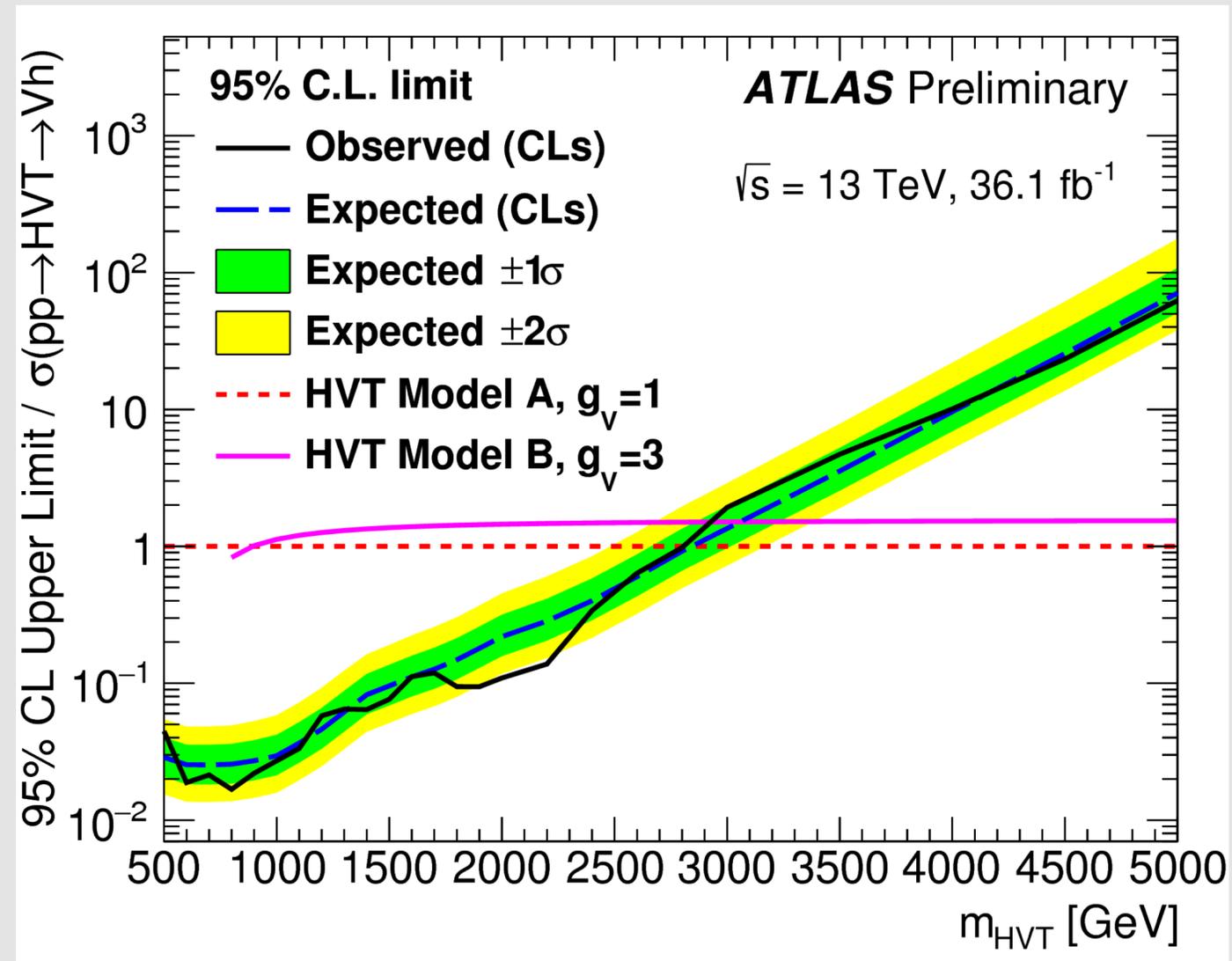
# Semi-Leptonic VH: A→Zh

- 0-/2-lepton combined limits presented separately for ggF and bbA production
- Mild excess at $m_A$=440 GeV
  - arises mostly from 3+ btag region in 2-lepton channel
  - local (global) significance: 3.6 (2.4) std. dev.
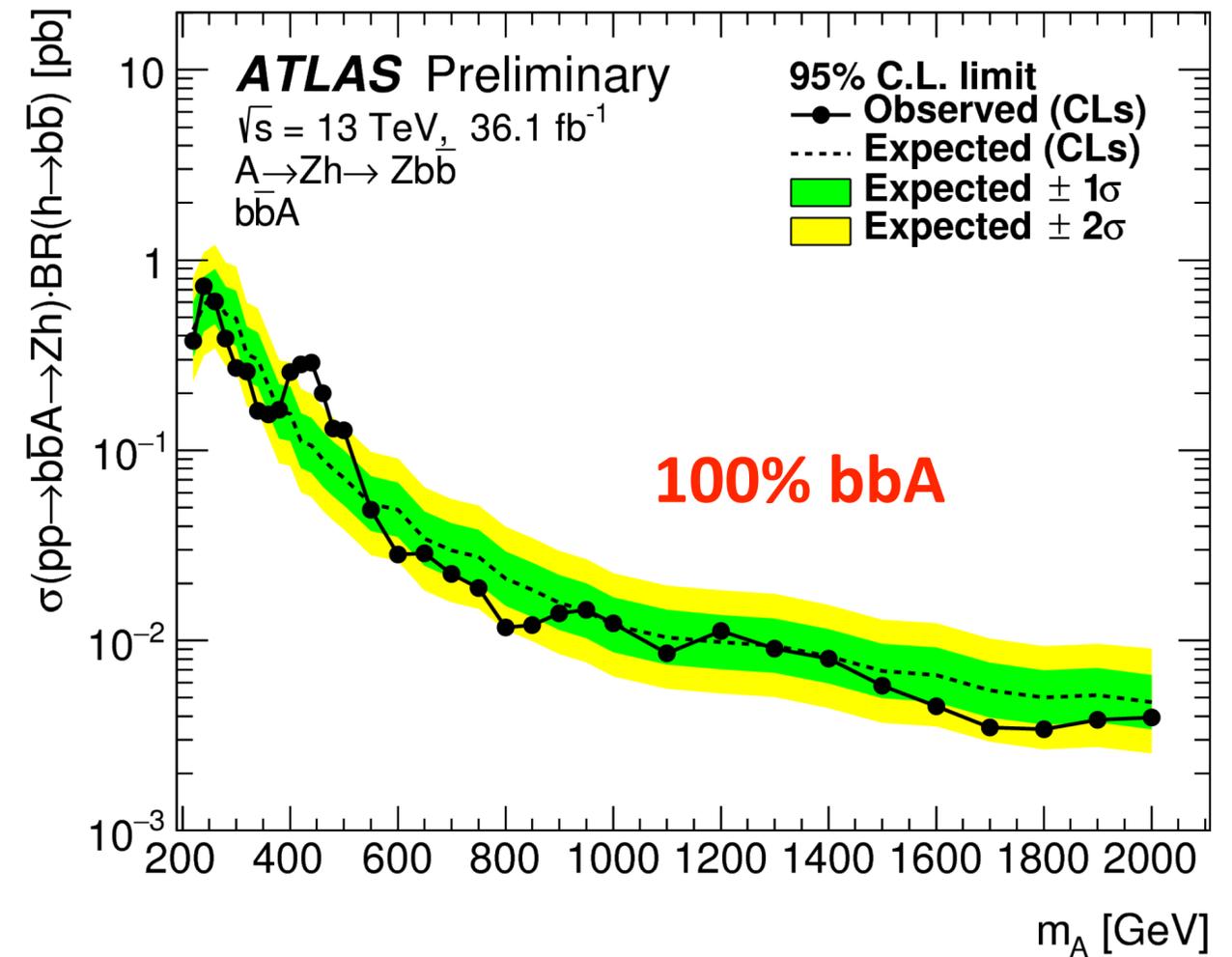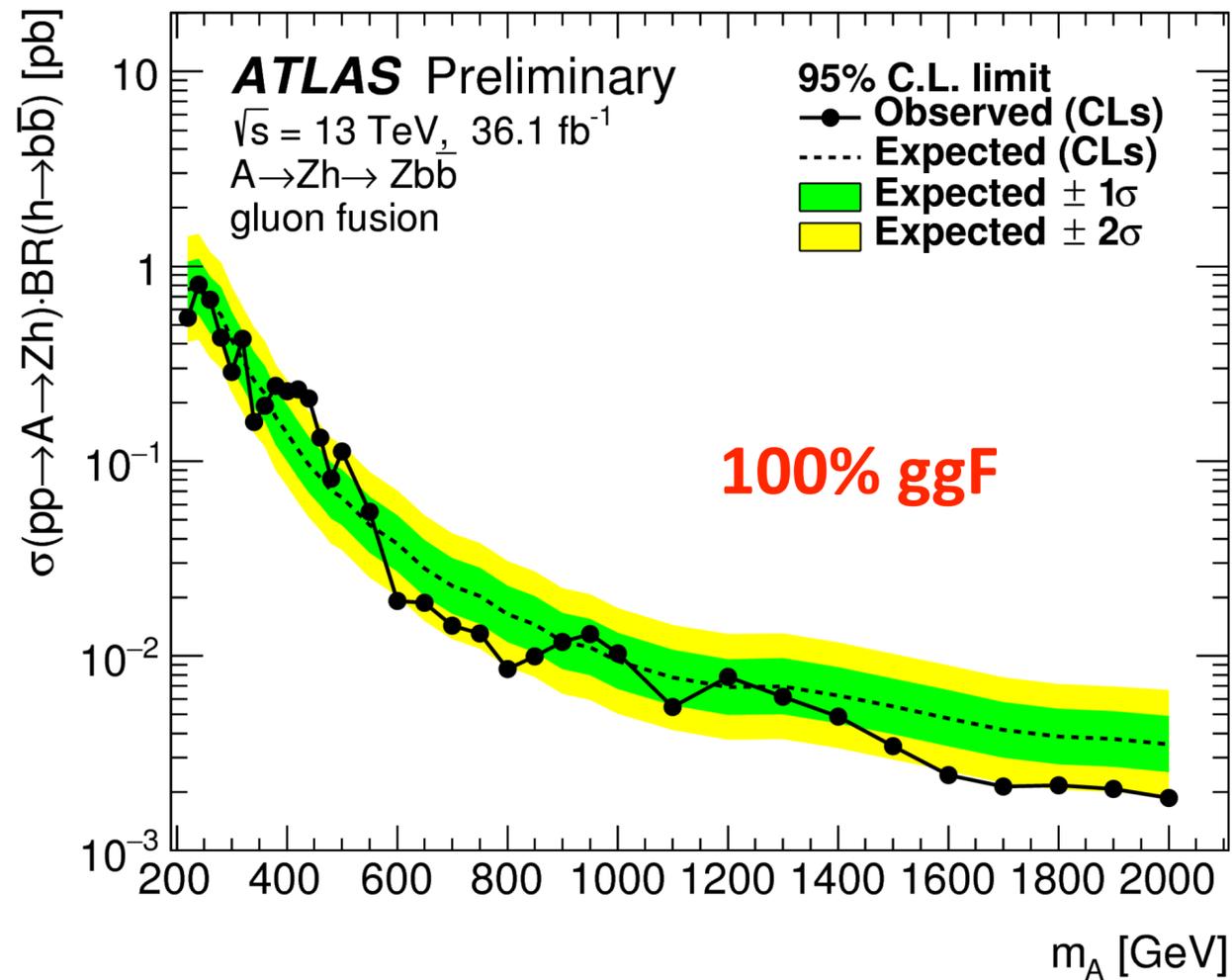
# Semi-Leptonic VH: A→Zh

- 2D limits as a function of tanβ/cos(β-α)
  - tanβ — ratio of vevs for each Higgs doublet
  - α — mixing angle between the 2 CP-even states
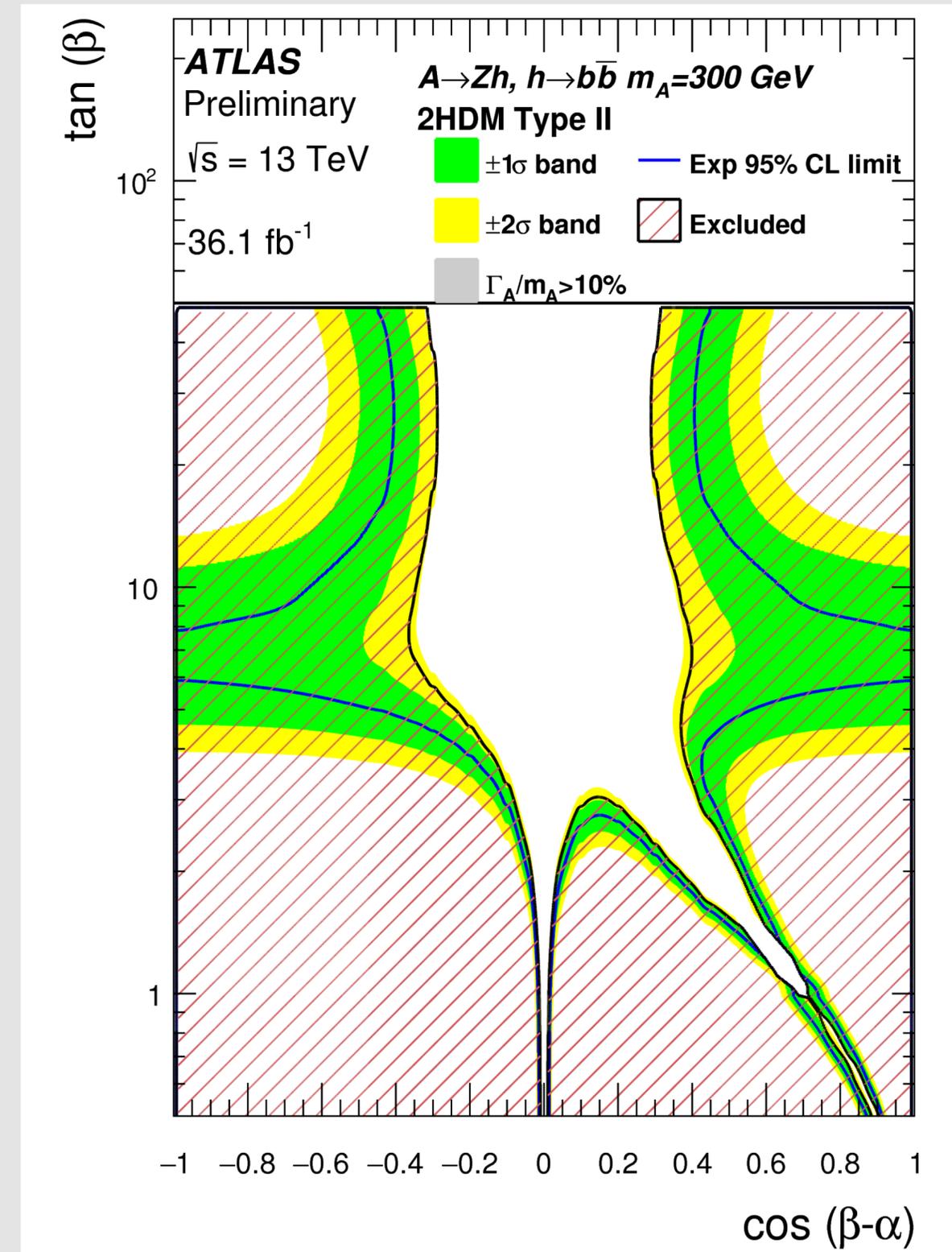
# VH Hadronic: 36 fb⁻¹

X→VH→qqbb signature:
- Vector boson and Higgs decays selected as large-R jets.
- mH and mV mass windows applied to reduce background
  - Jet substructure and b-tagging applied to further reduce backgrounds.
- Higher mass jet assigned as Higgs candidate.
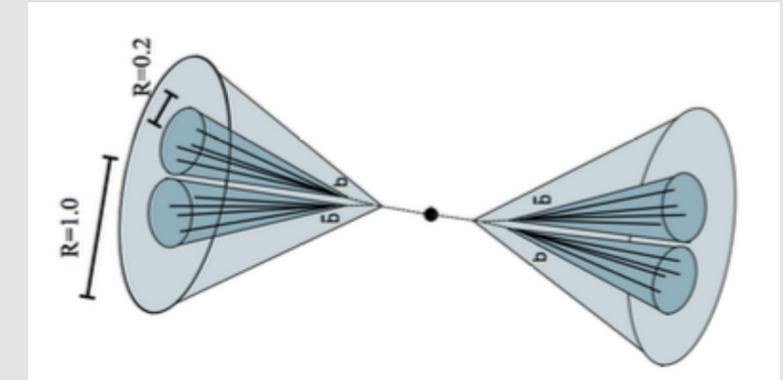
**X→ZH Selection: mZ Window**
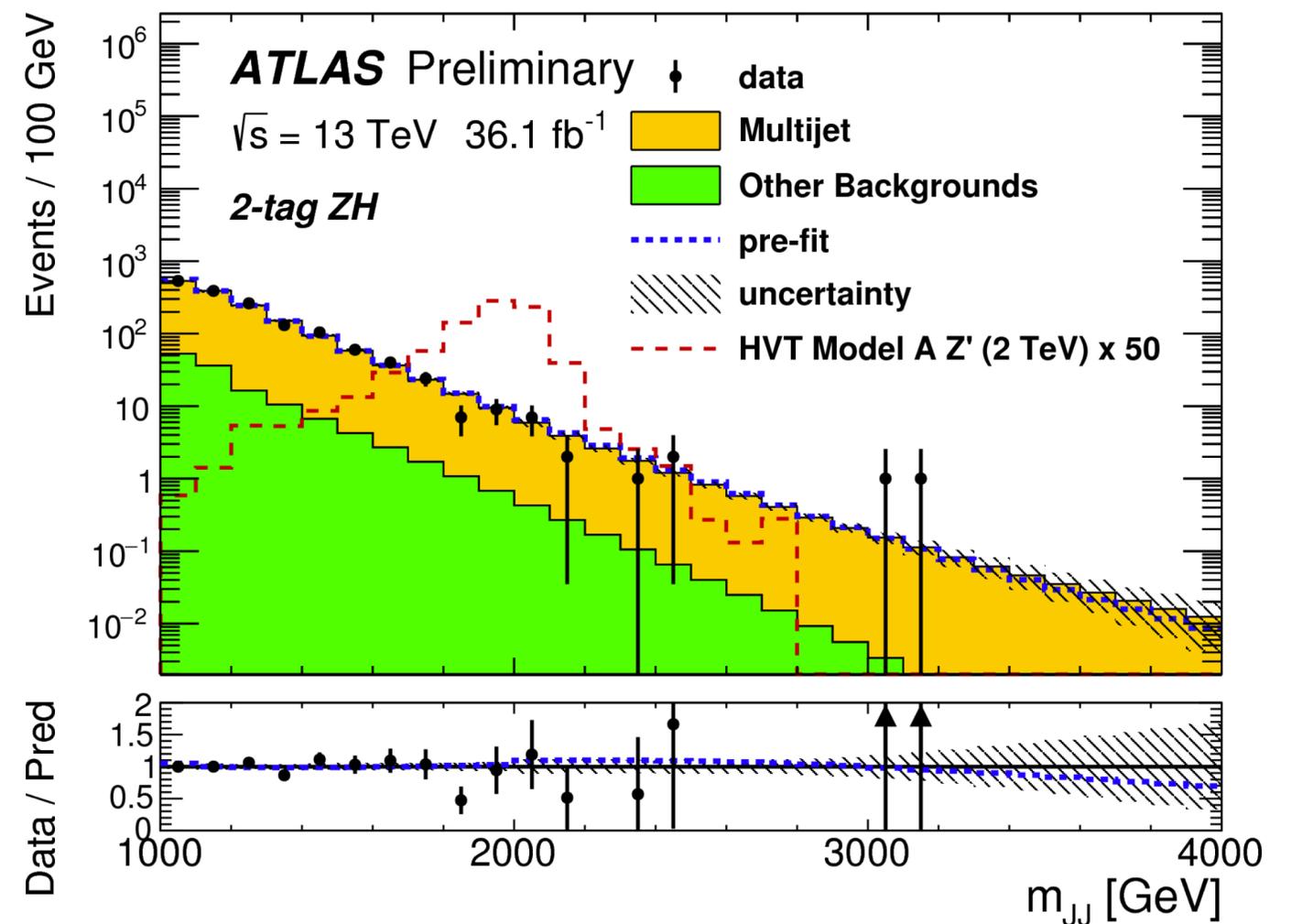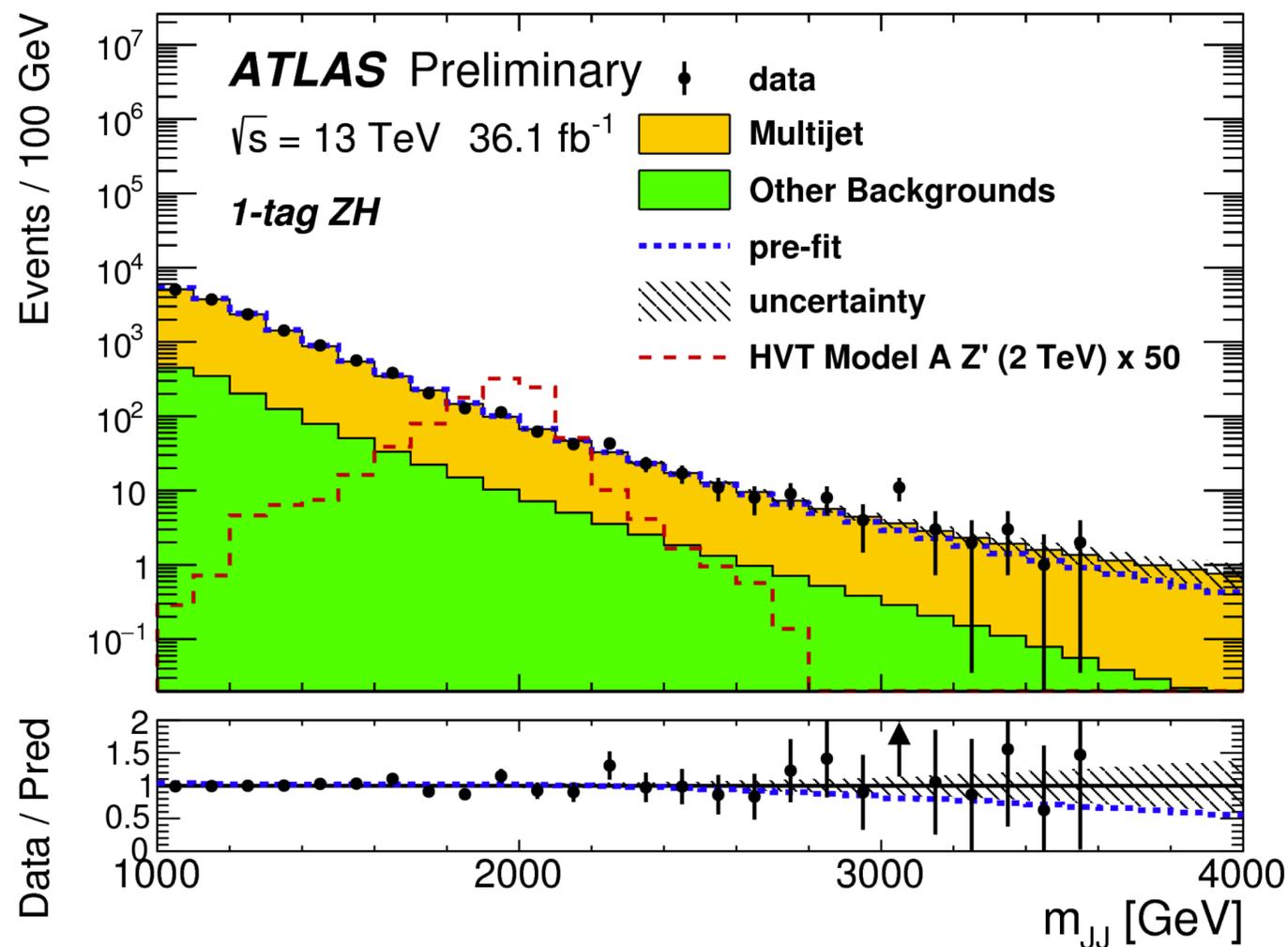
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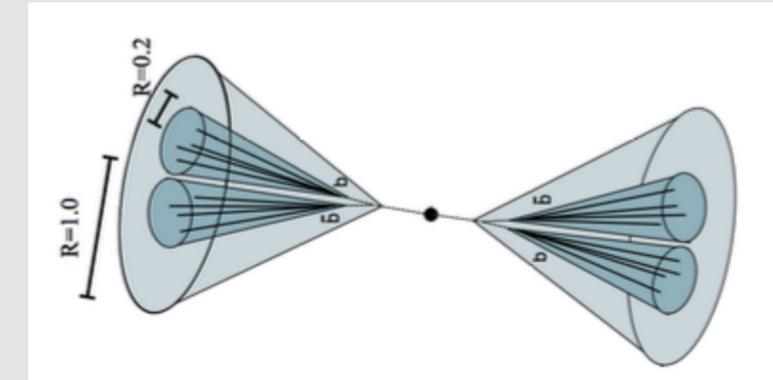


**X→WH Selection: mW Window**
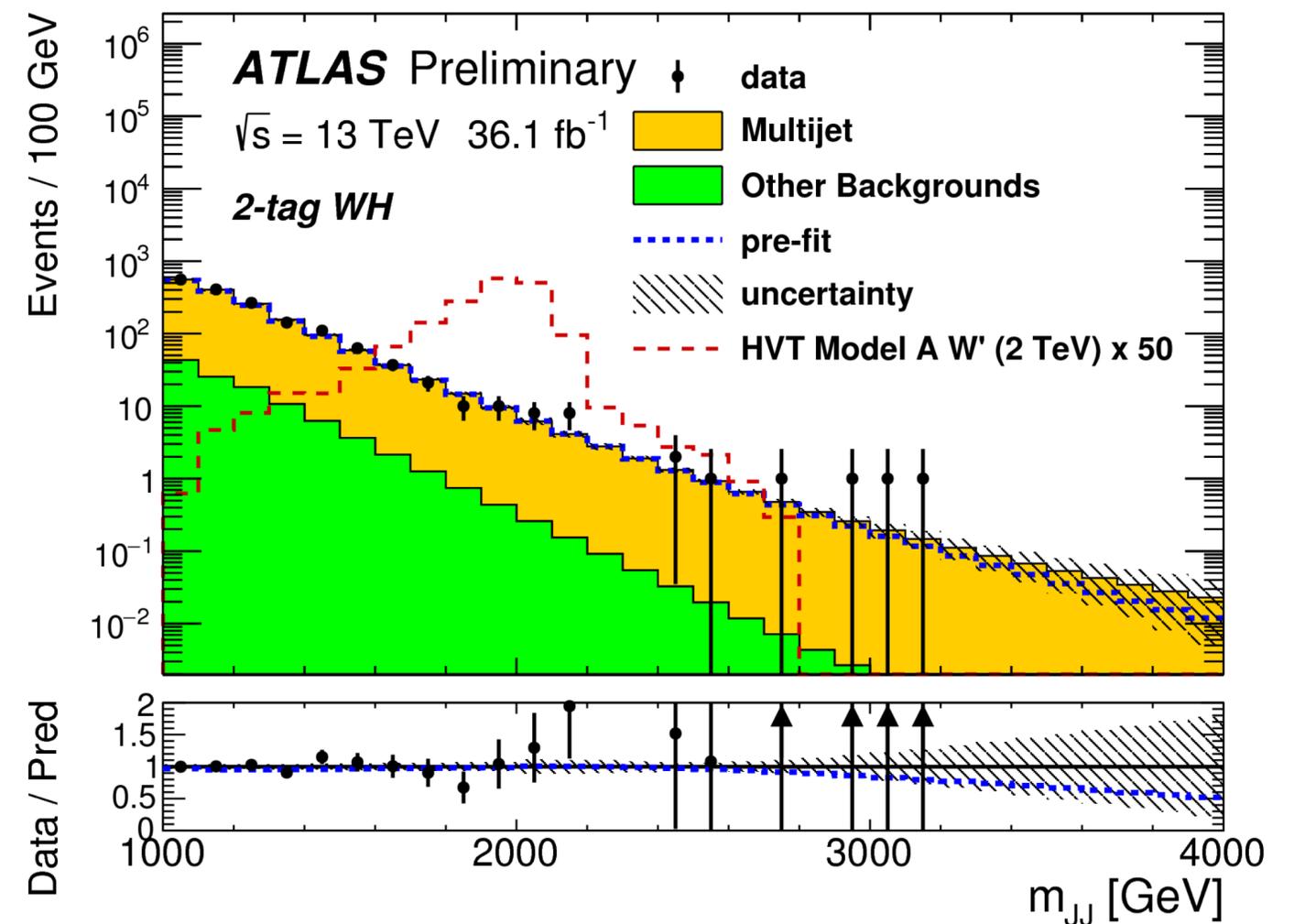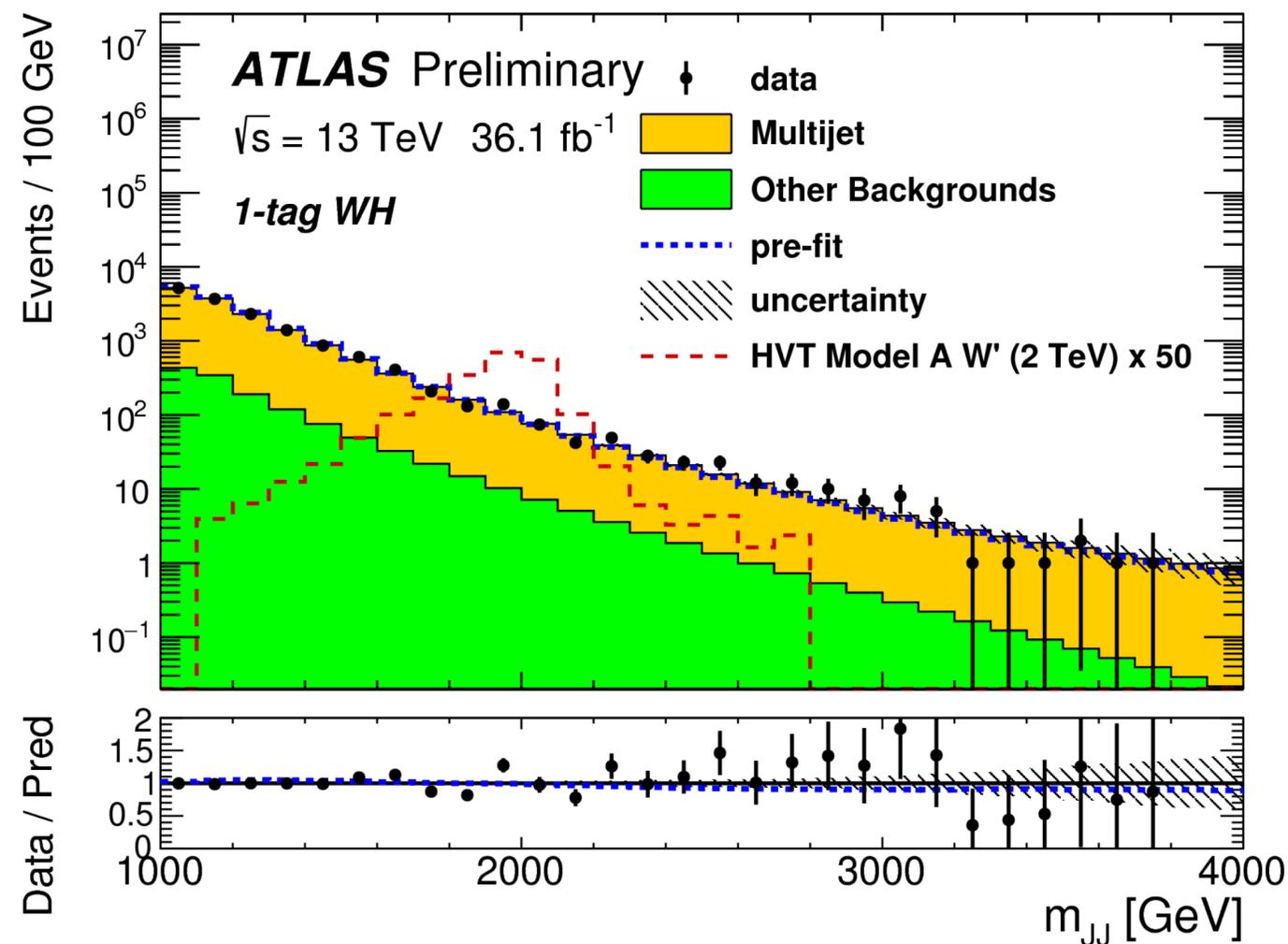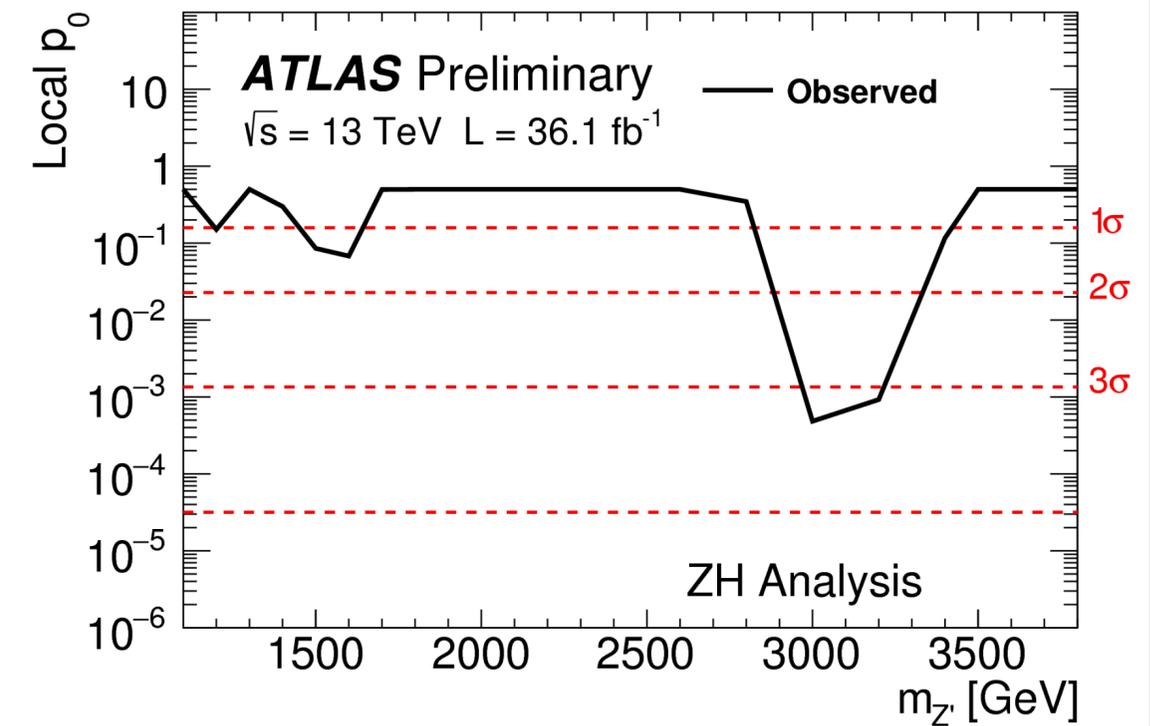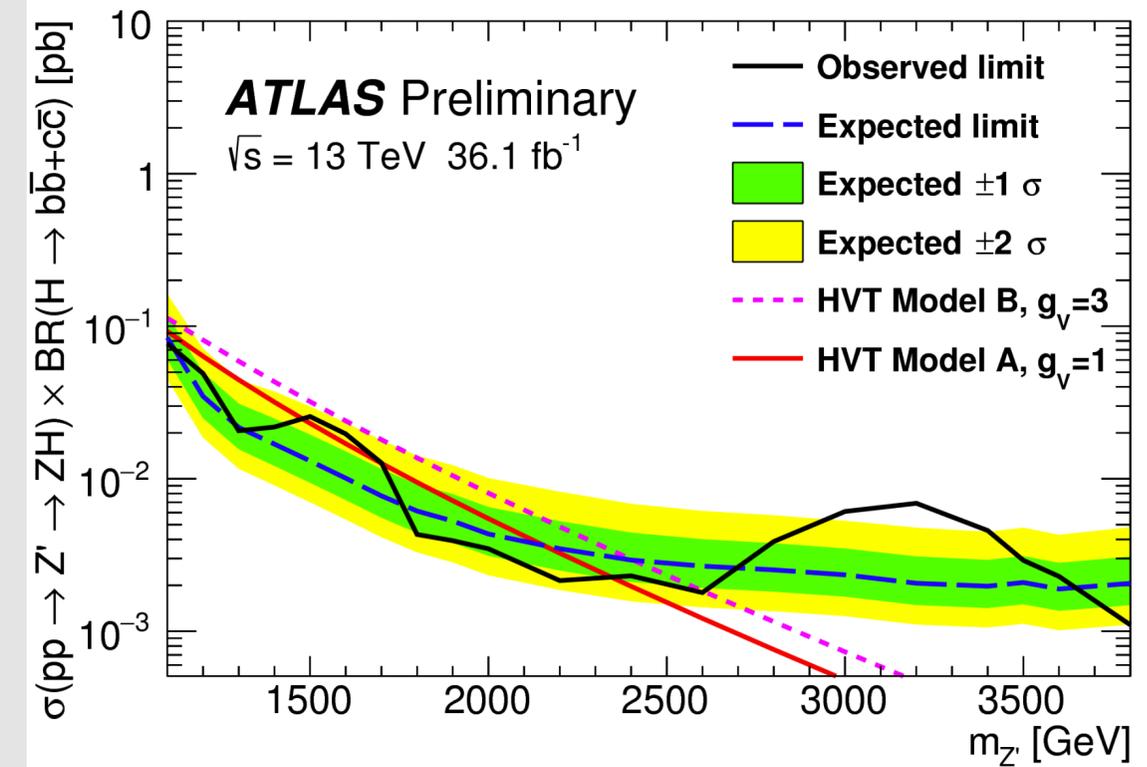
# VH Searches @ 36 fb$^{-1}$

- Comparison of limits on HVT models for VH searches
  - Semi-leptonic:  ATLAS-CONF-2017-055
  - Fully-hadronic:  ATLAS-CONF-2017-018
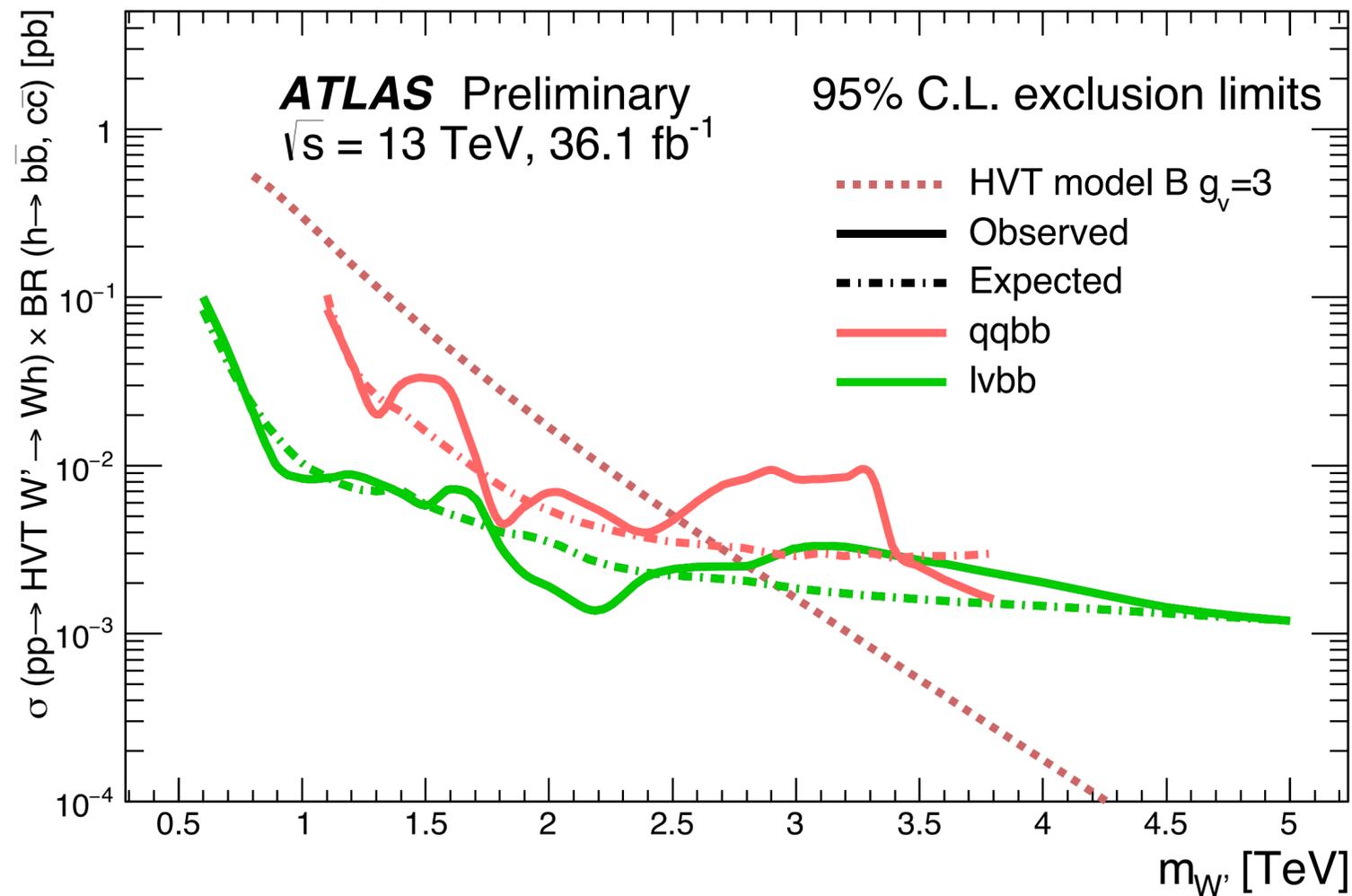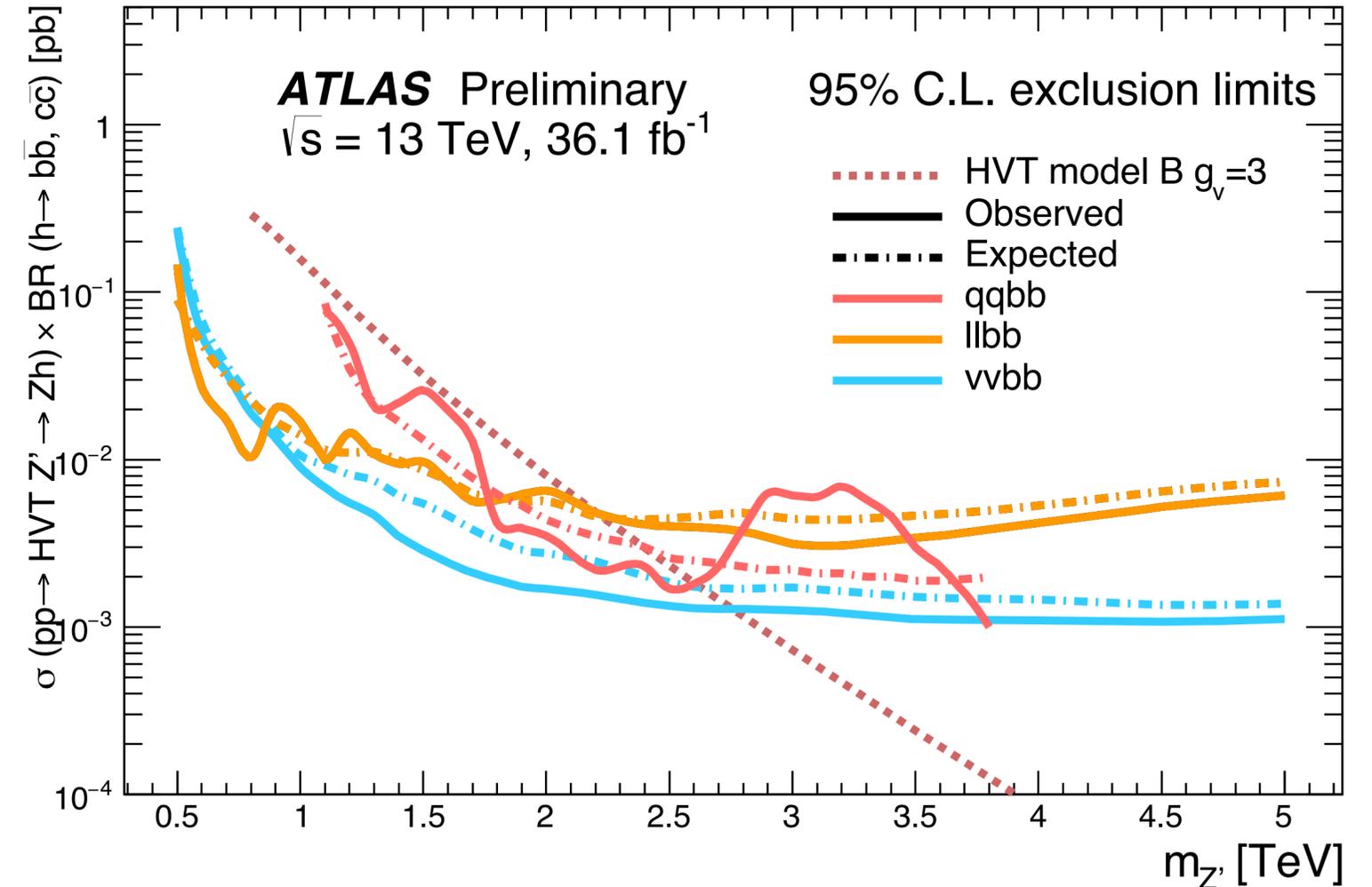
# Conclusions

**Massive Higgs + Boson Resonances @ ATLAS**

- This presentation was neither exhaustive nor complete
- See talk by Kalliopi Iordanidou today

**Vector Boson + Higgs Resonances @ 36 fb$^{-1}$**

- Vector Triplet and 2HDM interpretations

Run2:

VH semi-leptonic            (ATLAS-CONF-2017-055)

VH all-hadronic             (ATLAS-CONF-2017-018)

**Di-Higgs Searches**

- Covered Friday by Will Davey (talk link)

Run2:

hh→bbbb              (ATLAS-CONF-2016-049)

hh→γγWW*            (ATLAS-CONF-2016-071)

hh→bbγγ              (ATLAS-CONF-2016-004)

Run1:

hh→bbbb, hh→bbγγ, hh→bbττ, hh→γγWW* combined (arXiv:1509.04670v2)

# FIN

# VH Semi-Leptonic Yields

| 0-lepton | resolved | | | merged | | | |
|---|---|---|---|---|---|---|---|
| | 1 $b$-tag | 2 $b$-tag | 3+ $b$-tag | 1 $b$-tag | 2 $b$-tag | 1 $b$-tag add $b$-tag | 2 $b$-tag add $b$-tag |
| $t\bar{t}$ | 19500 ± 800 | 5760 ± 170 | 1000 ± 34 | 1300 ± 130 | 50.9 ± 9.1 | 2110 ± 73 | 105 ± 11 |
| single top | 1970 ± 260 | 448 ± 62 | 25.8 ± 5.6 | 142 ± 35 | 6.9 ± 1.7 | 136 ± 50 | 5.6 ± 2.4 |
| diboson | 299 ± 39 | 38.9 ± 5.6 | 4.5 ± 1.1 | 166 ± 26 | 32.0 ± 4.5 | 12.9 ± 2.3 | 1.59 ± 0.38 |
| $Z+l$ | 566 ± 210 | 1.3 ± 1.4 | - | 302 ± 120 | 0.24 ± 0.27 | 11.8 ± 8.2 | 0.11 ± 0.07 |
| $Z+(bl,cl)$ | 8270 ± 790 | 47 ± 17 | 5.4 ± 1.8 | 917 ± 160 | 9.9 ± 3.6 | 118 ± 27 | 0.58 ± 0.35 |
| $Z+(bb,bc,cc)$ | 1280 ± 160 | 1270 ± 140 | 41 ± 8 | 235 ± 43 | 100 ± 15 | 16.8 ± 4.2 | 8.6 ± 2.3 |
| $W+l$ | 882 ± 280 | 3.0 ± 2.1 | - | 163 ± 67 | 0.89 ± 0.53 | 5.4 ± 3.9 | 0.02 ± 0.02 |
| $W+(bl,cl)$ | 5460 ± 1000 | 48 ± 15 | 3.8 ± 2.3 | 584 ± 180 | 6.5 ± 3.2 | 65 ± 21 | 0.06 ± 0.12 |
| $W+(bb,bc,cc)$ | 499 ± 150 | 460 ± 130 | 16.5 ± 4.7 | 95 ± 37 | 35 ± 13 | 10.2 ± 5.1 | 3.0 ± 1.6 |
| SM Vh | 51 ± 20 | 95 ± 37 | 1.04 ± 0.57 | 6.6 ± 2.6 | 4.0 ± 1.6 | 0.43 ± 0.23 | 0.06 ± 0.04 |
| $t\bar{t}$ h | 8.4 ± 4.2 | 6.3 ± 3.2 | 6.4 ± 3.0 | 1.06 ± 0.54 | 0.14 ± 0.08 | 4.1 ± 2.0 | 0.64 ± 0.31 |
| $t\bar{t}$ V | 90 ± 48 | 37 ± 20 | 8.7 ± 4.5 | 15.4 ± 8.2 | 1.18 ± 0.64 | 24 ± 12 | 1.83 ± 0.97 |
| Total | 38900 ± 210 | 8210 ± 90 | 1110 ± 32 | 3930 ± 70 | 247 ± 13 | 2510 ± 50 | 127 ± 11 |
| Data | 38918 | 8212 | 1125 | 3935 | 246 | 2516 | 127 |

| 1-lepton | 1 $b$-tag | 2 $b$-tag | | 1 $b$-tag | 2 $b$-tag |
|---|---|---|---|---|---|
| $t\bar{t}$ | 16300 ± 630 | 3900 ± 120 | | 8050 ± 290 | 398 ± 45 |
| single top | 4110 ± 590 | 859 ± 130 | | 1120 ± 270 | 117 ± 27 |
| diboson | 112 ± 15 | 12.3 ± 2.0 | | 219 ± 33 | 34.1 ± 4.7 |
| $Z+l$ | 38 ± 12 | 0.09 ± 0.05 | | 14.0 ± 5.6 | 0.17 ± 0.11 |
| $Z+(bl,cl)$ | 169 ± 14 | 0.68 ± 0.50 | | 38.4 ± 5.6 | 0.43 ± 0.15 |
| $Z+(bb,bc,cc)$ | 26.0 ± 3.9 | 16.6 ± 1.7 | | 11.2 ± 1.8 | 4.48 ± 0.62 |
| $W+l$ | 532 ± 180 | 2.6 ± 2.8 | | 562 ± 220 | 0.19 ± 0.19 |
| $W+(bl,cl)$ | 5760 ± 450 | 23.5 ± 7.5 | | 1830 ± 300 | 29 ± 10 |
| $W+(bb,bc,cc)$ | 832 ± 140 | 429 ± 67 | | 356 ± 77 | 189 ± 40 |
| SM Vh | 62 ± 24 | 86 ± 34 | | 14.5 ± 5.7 | 11.5 ± 4.5 |
| multijet | 212 ± 110 | 1.71 ± 0.91 | | - | - |
| Total | 28100 ± 170 | 5330 ± 66 | | 12200 ± 120 | 781 ± 27 |
| Data | 28073 | 5348 | | 12224 | 775 |

| 2-lepton | 1 $b$-tag | 2 $b$-tag | 3+ $b$-tag | 1 $b$-tag | 2 $b$-tag | 1+2 $b$-tag add. $b$-tag |
|---|---|---|---|---|---|---|
| $t\bar{t}$ | 2570 ± 77 | 1940 ± 110 | 57.9 ± 9.4 | 5.4 ± 2.7 | 0.39 ± 0.21 | 11.2 ± 4.8 |
| single top | 186 ± 25 | 58 ± 8.6 | 1.46 ± 0.36 | 0.67 ± 0.10 | 0.20 ± 0.19 | 0.51 ± 0.33 |
| diboson | 569 ± 75 | 159 ± 24 | 5.24 ± 1.3 | 35 ± 5.2 | 8.7 ± 1.3 | 4.59 ± 0.83 |
| $Z+l$ | 2210 ± 960 | 2.3 ± 2.9 | - | 84 ± 33 | 0.95 ± 0.54 | 5.9 ± 3.5 |
| $Z+(bl,cl)$ | 37200 ± 1100 | 133 ± 50 | 11.8 ± 5.3 | 242 ± 34 | 2.32 ± 0.82 | 55 ± 11 |
| $Z+(bb,bc,cc)$ | 7790 ± 680 | 6310 ± 170 | 152 ± 18 | 73 ± 12 | 33.6 ± 4.5 | 11.5 ± 2.5 |
| $W+l$ | 1.84 ± 0.68 | - | - | 0.02 ± 0.01 | - | 0.01 ± 0.01 |
| $W+(bl,cl)$ | 37.5 ± 9.3 | 0.87 ± 0.63 | - | 0.44 ± 0.13 | - | 0.01 ± 0.01 |
| $W+(bb,bc,cc)$ | 5.5 ± 1.4 | 1.88 ± 0.33 | 0.03 ± 0.01 | 0.17 ± 0.06 | 0.02 ± 0.01 | 0.06 ± 0.05 |
| SM Vh | 106 ± 41 | 144 ± 56 | 1.28 ± 0.69 | 1.67 ± 0.65 | 0.83 ± 0.33 | 0.19 ± 0.10 |
| $t\bar{t}$ h | 0.89 ± 0.45 | 1.56 ± 0.78 | 1.1 ± 0.5 | 0.05 ± 0.02 | 0.01 ± 0.01 | 0.15 ± 0.07 |
| $t\bar{t}$ V | 143 ± 76 | 59 ± 31 | 6.2 ± 3.3 | 9.7 ± 5.1 | 0.61 ± 0.33 | 11.9 ± 6.1 |
| Total | 50900 ± 230 | 8810 ± 94 | 237 ± 15 | 452 ± 19 | 47.4 ± 4.6 | 101 ± 9 |
| Data | 50876 | 8798 | 235 | 439 | 50 | 101 |

|  | $ZH$ 2-tag | $ZH$ 1-tag |
|---|---|---|
| Multijet | 1440 $\pm$ 60 | 13770 $\pm$ 310 |
| Other Backgrounds | 135 $\pm$ 45 | 1350 $\pm$ 270 |
| Total Backgrounds | 1575 $\pm$ 40 | 15120 $\pm$ 130 |
| Data | 1574 | 15112 |
| *Model B*, M=2 TeV | 25 $\pm$ 7 | 29 $\pm$ 10 |
|  | $WH$ 2-tag | $WH$ 1-tag |
| Multijet | 1525 $\pm$ 65 | 13900 $\pm$ 290 |
| Other Backgrounds | 110 $\pm$ 45 | 1310 $\pm$ 260 |
| Total Backgrounds | 1635 $\pm$ 40 | 15220 $\pm$ 120 |
| Data | 1646 | 15212 |
| *Model B*, M=2 TeV | 51 $\pm$ 10 | 62 $\pm$ 16 |
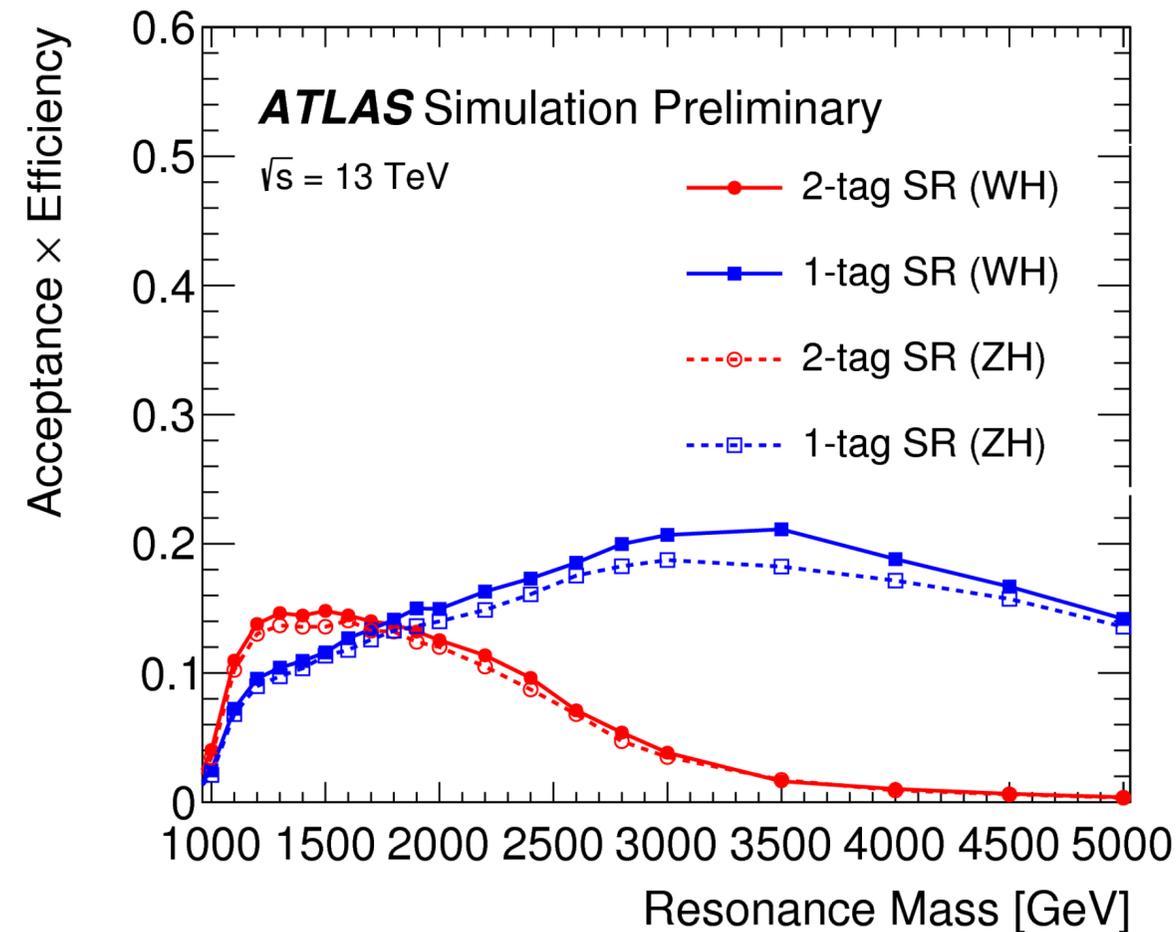
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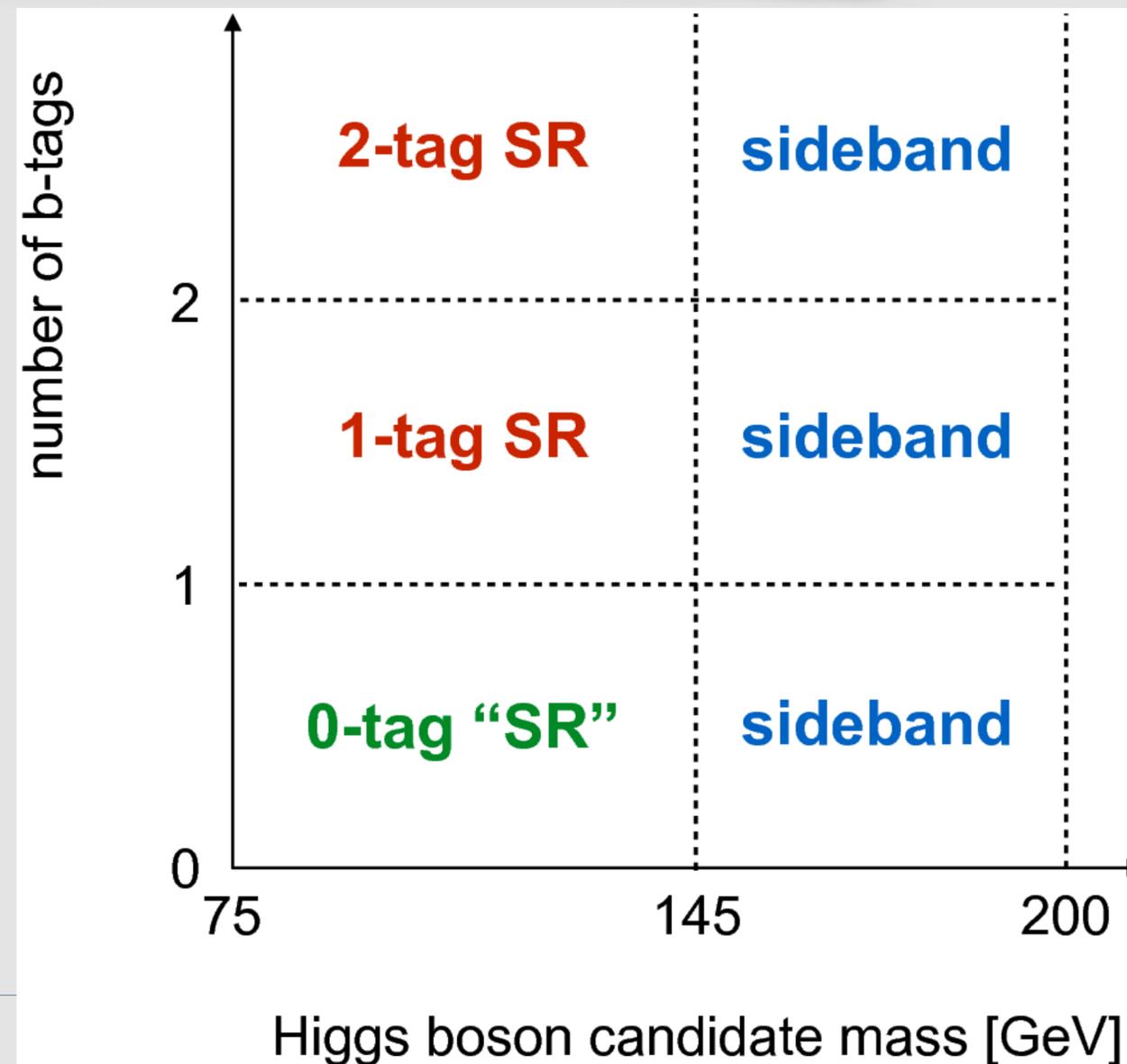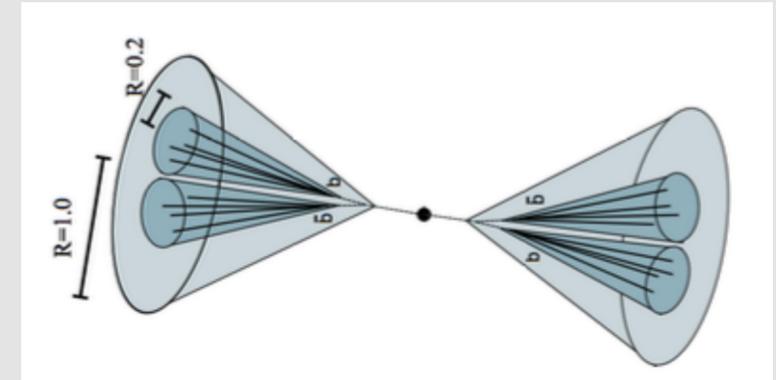
# VH Semi-Leptonic Spectra: bbA Signal
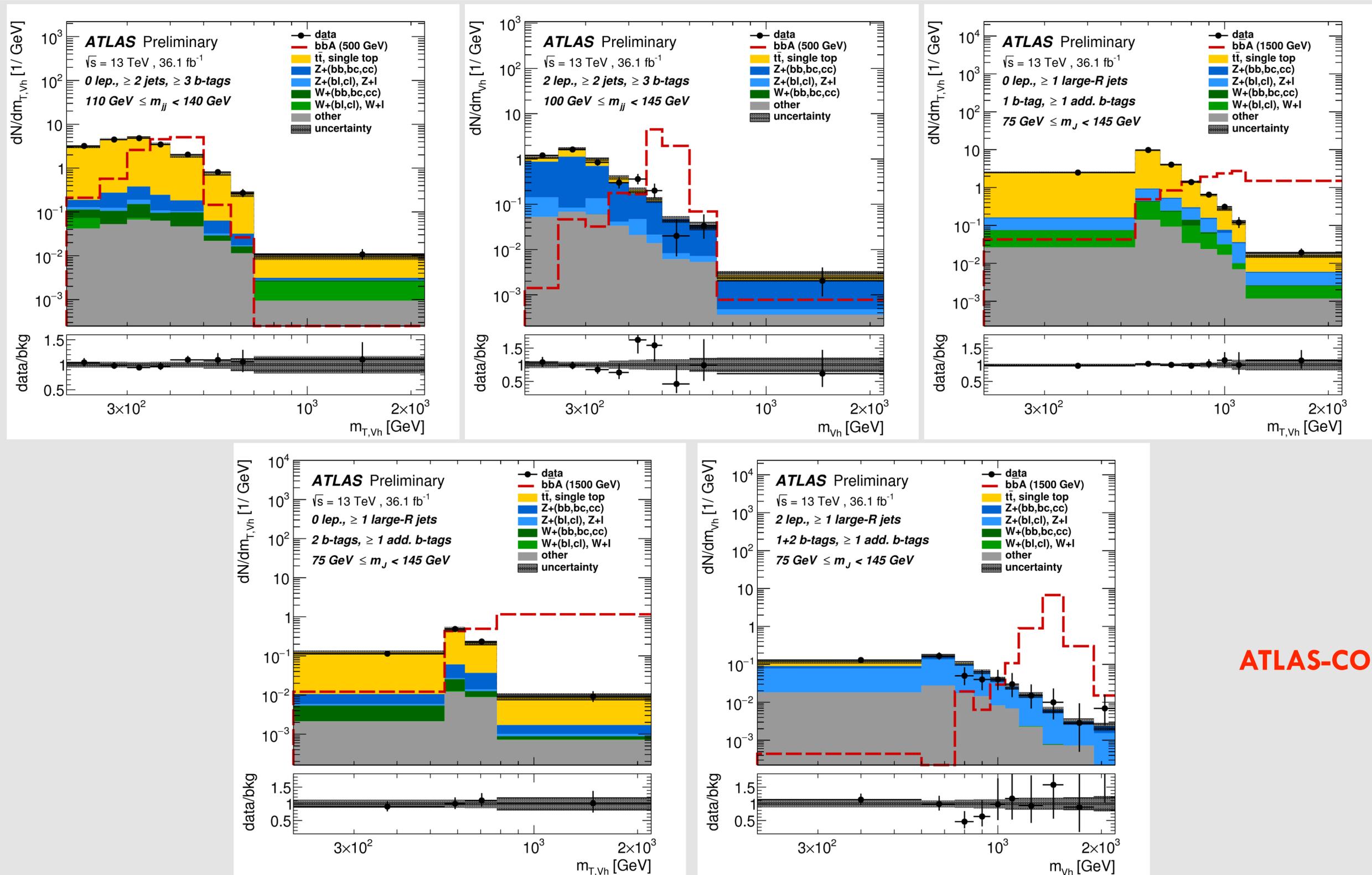


**ATLAS-CONF-2017-055**

# VH: A→Zh Interpretation

- 2D coupling limits as a function of $m_A/\tan\beta$
  - $\tan\beta$: ratio of vevs for each Higgs doublet
  - $\alpha$: mixing angle between the 2 CP-even states

# ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits

*Status: July 2017*

**ATLAS** Preliminary

$\int \mathcal{L}\, dt = (3.2 - 37.0)\ \text{fb}^{-1}$  $\sqrt{s} = 8, 13\ \text{TeV}$

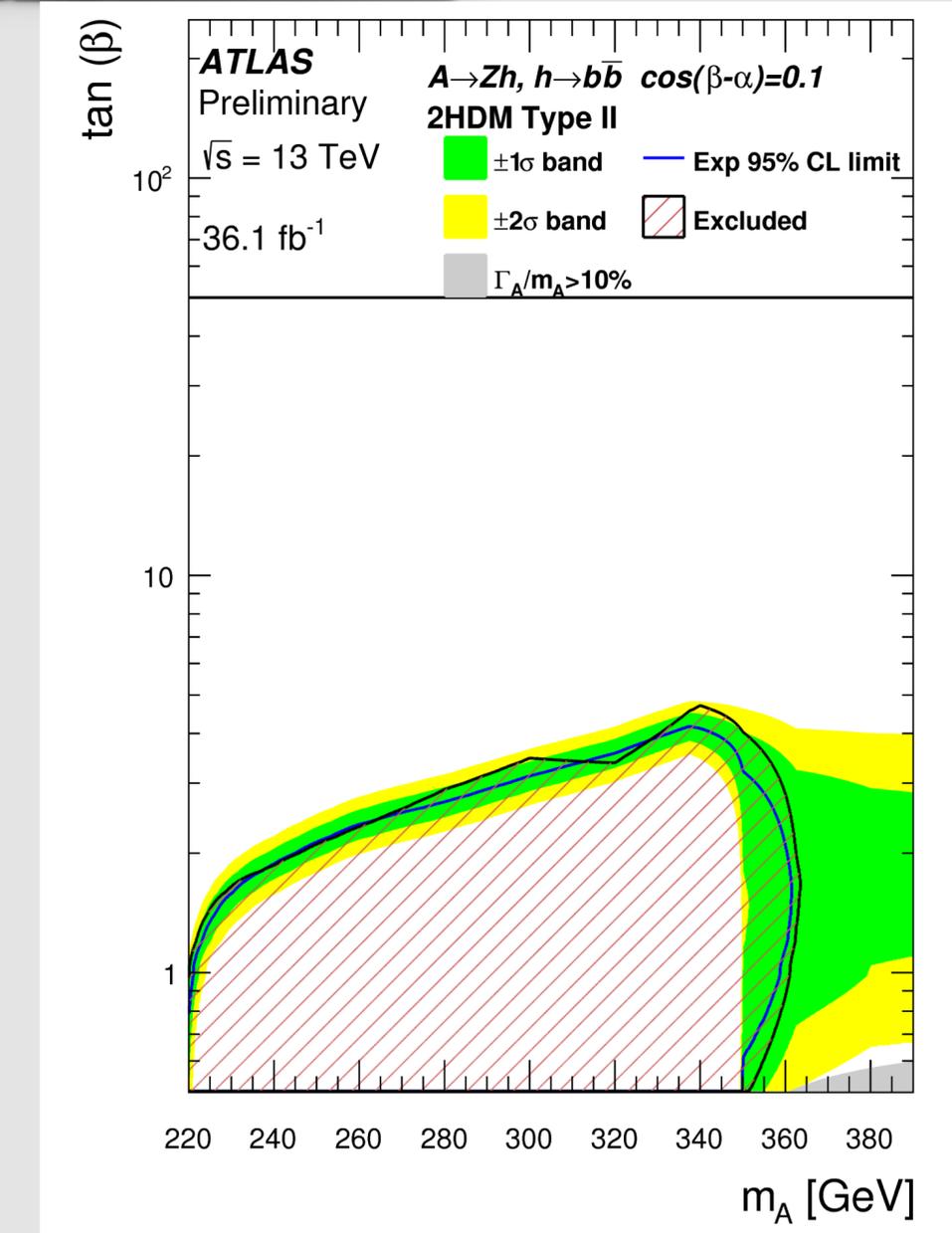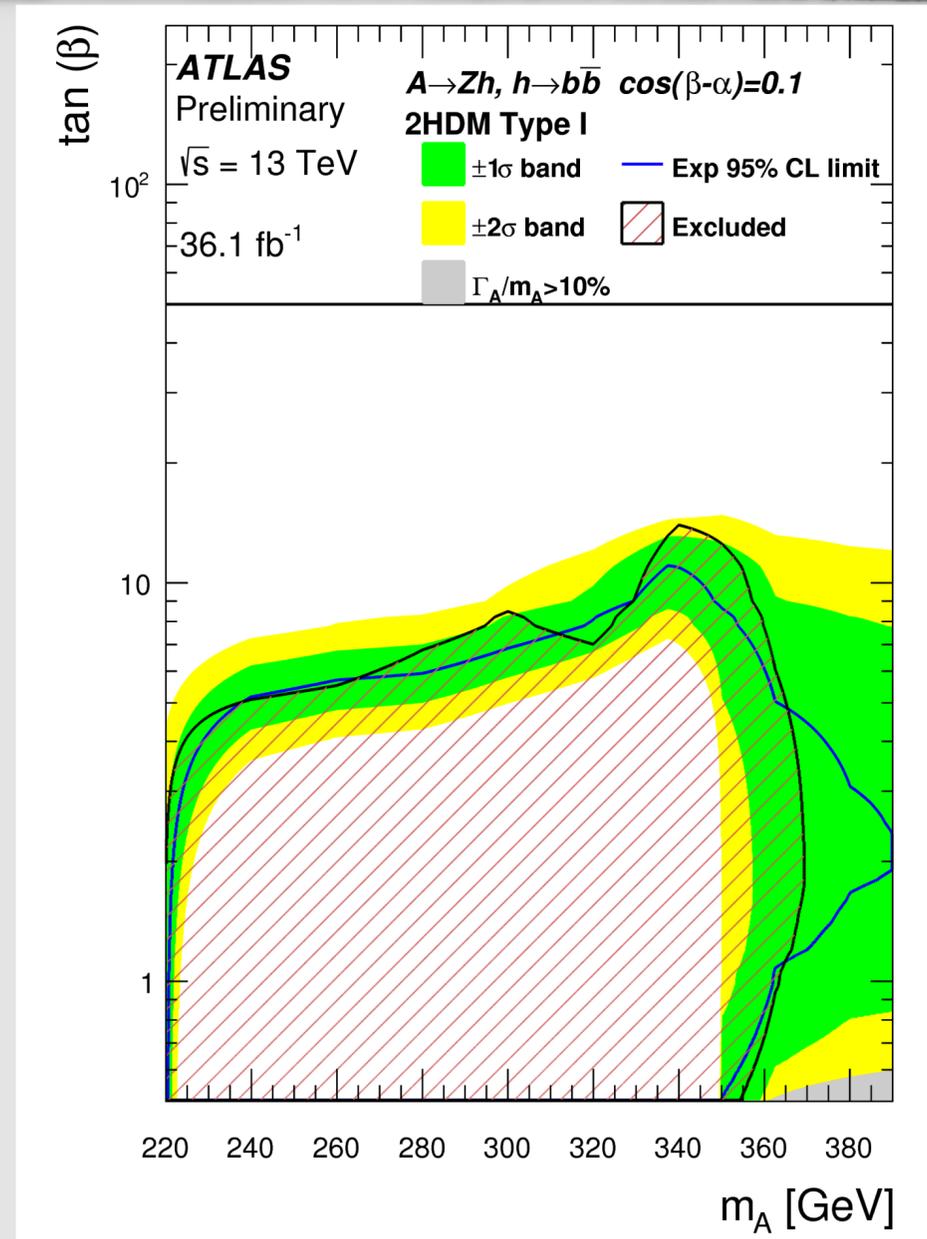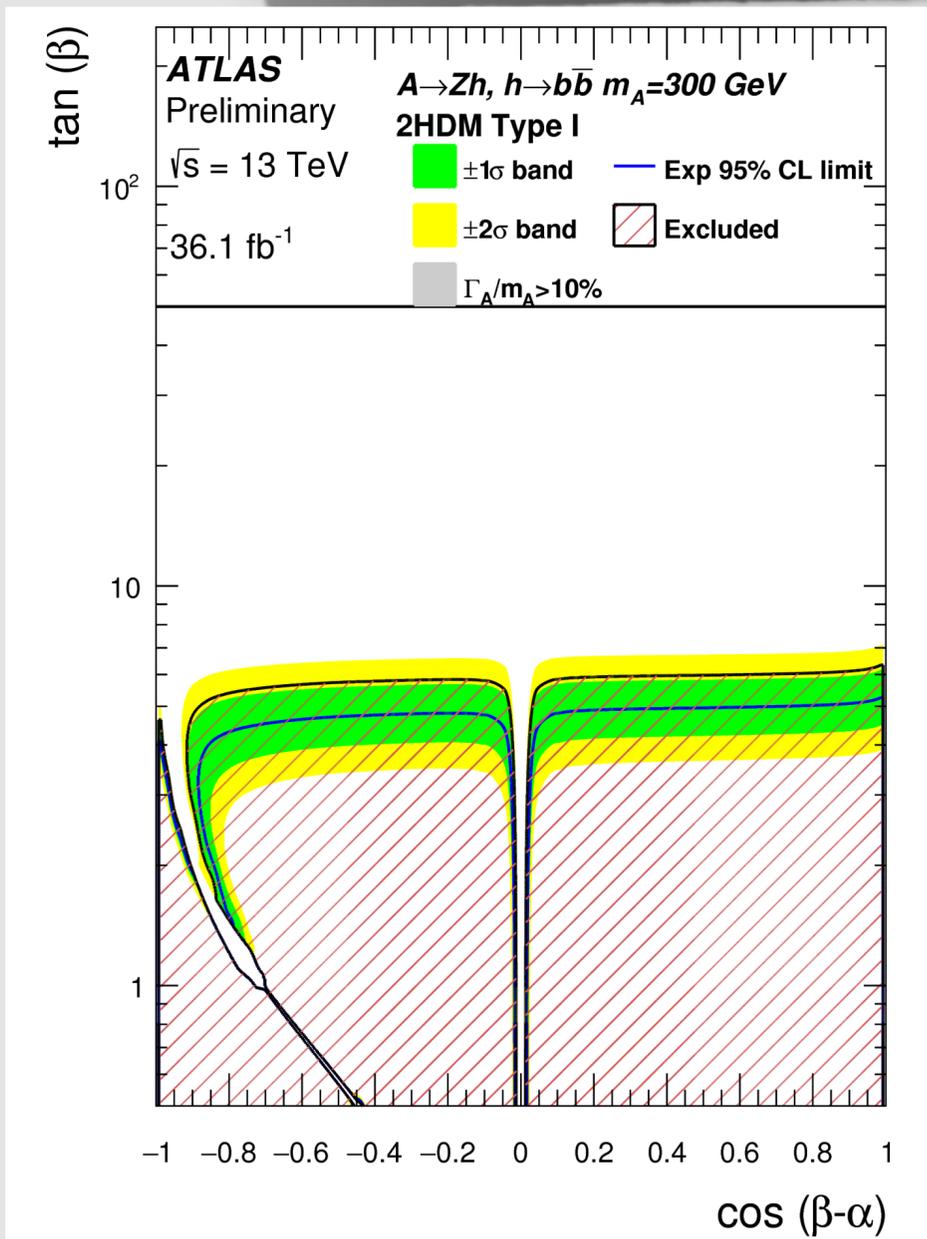| | Model | $\ell, \gamma$ | Jets† | $E_T^{miss}$ | $\int \mathcal{L}\, dt[\text{fb}^{-1}]$ | Limit | | Reference |
|---|---|---|---|---|---|---|---|---|
| **Extra dimensions** | ADD $G_{KK} + g/q$ | $0\ e,\mu$ | $1-4\ j$ | Yes | 36.1 | $M_D$ 7.75 TeV | $n=2$ | ATLAS-CONF-2017-060 |
| | ADD non-resonant $\gamma\gamma$ | $2\gamma$ | – | – | 36.7 | $M_S$ 8.6 TeV | $n=3$ HLZ NLO | CERN-EP-2017-132 |
| | ADD QBH | – | $2\ j$ | – | 37.0 | $M_{th}$ 8.9 TeV | $n=6$ | 1703.09217 |
| | ADD BH high $\sum p_T$ | $\geq 1\ e,\mu$ | $\geq 2\ j$ | – | 3.2 | $M_{th}$ 8.2 TeV | $n=6$, $M_D = 3$ TeV, rot BH | 1606.02265 |
| | ADD BH multijet | – | $\geq 3\ j$ | – | 3.6 | $M_{th}$ 9.55 TeV | $n=6$, $M_D = 3$ TeV, rot BH | 1512.02586 |
| | RS1 $G_{KK} \to \gamma\gamma$ | $2\gamma$ | – | – | 36.7 | $G_{KK}$ mass 4.1 TeV | $k/\overline{M}_{Pl} = 0.1$ | CERN-EP-2017-132 |
| | Bulk RS $G_{KK} \to WW \to qq\ell\nu$ | $1\ e,\mu$ | $1\ J$ | Yes | 36.1 | $G_{KK}$ mass 1.75 TeV | $k/\overline{M}_{Pl} = 1.0$ | ATLAS-CONF-2017-051 |
| | 2UED / RPP | $1\ e,\mu$ | $\geq 2\ b, \geq 3\ j$ | Yes | 13.2 | KK mass 1.6 TeV | Tier (1,1), $\mathcal{B}(A^{(1,1)} \to tt) = 1$ | ATLAS-CONF-2016-104 |
| **Gauge bosons** | SSM $Z' \to \ell\ell$ | $2\ e,\mu$ | – | – | 36.1 | $Z'$ mass 4.5 TeV | | ATLAS-CONF-2017-027 |
| | SSM $Z' \to \tau\tau$ | $2\tau$ | – | – | 36.1 | $Z'$ mass 2.4 TeV | | ATLAS-CONF-2017-050 |
| | Leptophobic $Z' \to bb$ | – | $2\ b$ | – | 3.2 | $Z'$ mass 1.5 TeV | | 1603.08791 |
| | Leptophobic $Z' \to tt$ | $1\ e,\mu$ | $\geq 1\ b, \geq 1J/2j$ | Yes | 3.2 | $Z'$ mass 2.0 TeV | $\Gamma/m = 3\%$ | ATLAS-CONF-2016-014 |
| | SSM $W' \to \ell\nu$ | $1\ e,\mu$ | – | Yes | 36.1 | $W'$ mass 5.1 TeV | | 1706.04786 |
| | HVT $V' \to WV \to qqqq$ model B | $0\ e,\mu$ | $2\ J$ | – | 36.7 | $V'$ mass 3.5 TeV | $g_V = 3$ | CERN-EP-2017-147 |
| | HVT $V' \to WH/ZH$ model B | multi-channel | | | 36.1 | $V'$ mass 2.93 TeV | $g_V = 3$ | ATLAS-CONF-2017-055 |
| | LRSM $W'_R \to tb$ | $1\ e,\mu$ | $2\ b, 0\text{-}1\ j$ | Yes | 20.3 | $W'$ mass 1.92 TeV | | 1410.4103 |
| | LRSM $W'_R \to tb$ | $0\ e,\mu$ | $\geq 1\ b, 1\ J$ | – | 20.3 | $W'$ mass 1.76 TeV | | 1408.0886 |
| **CI** | CI $qqqq$ | – | $2\ j$ | – | 37.0 | $\Lambda$ 21.8 TeV | $\eta_{LL}^-$ | 1703.09217 |
| | CI $\ell\ell qq$ | $2\ e,\mu$ | – | – | 36.1 | $\Lambda$ 40.1 TeV | $\eta_{LL}^-$ | ATLAS-CONF-2017-027 |
| | CI $uutt$ | $2(SS)/\geq 3\ e,\mu$ | $\geq 1\ b, \geq 1\ j$ | Yes | 20.3 | $\Lambda$ 4.9 TeV | $|C_{RR}| = 1$ | 1504.04605 |
| **DM** | Axial-vector mediator (Dirac DM) | $0\ e,\mu$ | $1-4\ j$ | Yes | 36.1 | $m_{med}$ 1.5 TeV | $g_q=0.25$, $g_\chi=1.0$, $m(\chi) < 400$ GeV | ATLAS-CONF-2017-060 |
| | Scalar mediator $t$-ch. (Dirac DM) | $0\ e,\mu$ | $1-4\ j$ | Yes | 36.1 | $m_{med}$ 1.65 TeV | $g=1$, $m(\chi) - m(\eta) < 500$ GeV | ATLAS-CONF-2017-060 |
| | Vector mediator (Dirac DM) | $0\ e,\mu, 1\gamma$ | $\leq 1\ j$ | Yes | 36.1 | $m_{med}$ 1.2 TeV | $g_q=0.25$, $g_\chi=1.0$, $m(\chi) < 480$ GeV | 1704.03848 |
| | $VV\chi\chi$ EFT (Dirac DM) | $0\ e,\mu$ | $1\ J, \leq 1\ j$ | Yes | 3.2 | $M_*$ 700 GeV | $m(\chi) < 150$ GeV | 1608.02372 |
| **LQ** | Scalar LQ 1st gen | $2\ e$ | $\geq 2\ j$ | – | 3.2 | LQ mass 1.1 TeV | $\beta = 1$ | 1605.06035 |
| | Scalar LQ 2nd gen | $2\mu$ | $\geq 2\ j$ | – | 3.2 | LQ mass 1.05 TeV | $\beta = 1$ | 1605.06035 |
| | Scalar LQ 3rd gen | $1\ e,\mu$ | $\geq 1\ b, \geq 3\ j$ | Yes | 20.3 | LQ mass 640 GeV | $\beta = 0$ | 1508.04735 |
| **Heavy quarks** | VLQ $TT \to Ht + X$ | 0 or $1\ e,\mu$ | $\geq 2\ b, \geq 3\ j$ | Yes | 13.2 | T mass 1.2 TeV | $\mathcal{B}(T \to Ht) = 1$ | ATLAS-CONF-2016-104 |
| | VLQ $TT \to Zt + X$ | $1\ e,\mu$ | $\geq 1\ b, \geq 3\ j$ | Yes | 36.1 | T mass 1.16 TeV | $\mathcal{B}(T \to Zt) = 1$ | 1705.10751 |
| | VLQ $TT \to Wb + X$ | $1\ e,\mu$ | $\geq 1\ b, \geq 1J/2j$ | Yes | 36.1 | T mass 1.35 TeV | $\mathcal{B}(T \to Wb) = 1$ | CERN-EP-2017-094 |
| | VLQ $BB \to Hb + X$ | $1\ e,\mu$ | $\geq 2\ b, \geq 3\ j$ | Yes | 20.3 | B mass 700 GeV | $\mathcal{B}(B \to Hb) = 1$ | 1505.04306 |
| | VLQ $BB \to Zb + X$ | $2/\geq 3\ e,\mu$ | $\geq 2/\geq 1\ b$ | – | 20.3 | B mass 790 GeV | $\mathcal{B}(B \to Zb) = 1$ | 1409.5500 |
| | VLQ $BB \to Wt + X$ | $1\ e,\mu$ | $\geq 1\ b, \geq 1J/2j$ | Yes | 36.1 | B mass 1.25 TeV | $\mathcal{B}(B \to Wt) = 1$ | CERN-EP-2017-094 |
| | VLQ $QQ \to WqWq$ | $1\ e,\mu$ | $\geq 4\ j$ | Yes | 20.3 | Q mass 690 GeV | | 1509.04261 |
| **Excited fermions** | Excited quark $q^* \to qg$ | – | $2\ j$ | – | 37.0 | $q^*$ mass 6.0 TeV | only $u^*$ and $d^*$, $\Lambda = m(q^*)$ | 1703.09127 |
| | Excited quark $q^* \to q\gamma$ | $1\gamma$ | $1\ j$ | – | 36.7 | $q^*$ mass 5.3 TeV | only $u^*$ and $d^*$, $\Lambda = m(q^*)$ | CERN-EP-2017-148 |
| | Excited quark $b^* \to bg$ | – | $1\ b, 1\ j$ | – | 13.3 | $b^*$ mass 2.3 TeV | | ATLAS-CONF-2016-060 |
| | Excited quark $b^* \to Wt$ | 1 or $2\ e,\mu$ | $1\ b, 2\text{-}0\ j$ | Yes | 20.3 | $b^*$ mass 1.5 TeV | $f_g = f_L = f_R = 1$ | 1510.02664 |
| | Excited lepton $\ell^*$ | $3\ e,\mu$ | – | – | 20.3 | $\ell^*$ mass 3.0 TeV | $\Lambda = 3.0$ TeV | 1411.2921 |
| | Excited lepton $\nu^*$ | $3\ e,\mu,\tau$ | – | – | 20.3 | $\nu^*$ mass 1.6 TeV | $\Lambda = 1.6$ TeV | 1411.2921 |
| **Other** | LRSM Majorana $\nu$ | $2\ e,\mu$ | $2\ j$ | – | 20.3 | $N^0$ mass 2.0 TeV | $m(W_R) = 2.4$ TeV, no mixing | 1506.06020 |
| | Higgs triplet $H^{\pm\pm} \to \ell\ell$ | $2,3,4\ e,\mu$ (SS) | – | – | 36.1 | $H^{\pm\pm}$ mass 870 GeV | DY production | ATLAS-CONF-2017-053 |
| | Higgs triplet $H^{\pm\pm} \to \ell\tau$ | $3\ e,\mu,\tau$ | – | – | 20.3 | $H^{\pm\pm}$ mass 400 GeV | DY production, $\mathcal{B}(H_L^{\pm\pm} \to \ell\tau) = 1$ | 1411.2921 |
| | Monotop (non-res prod) | $1\ e,\mu$ | $1\ b$ | Yes | 20.3 | spin-1 invisible particle mass 657 GeV | $a_{non-res} = 0.2$ | 1410.5404 |
| | Multi-charged particles | – | – | – | 20.3 | multi-charged particle mass 785 GeV | DY production, $|q| = 5e$ | 1504.04188 |
| | Magnetic monopoles | – | – | – | 7.0 | monopole mass 1.34 TeV | DY production, $|g| = 1g_D$, spin 1/2 | 1509.08059 |

$\sqrt{s} = 8$ TeV    $\sqrt{s} = 13$ TeV

$10^{-1}$    1    10    **Mass scale [TeV]**

*\*Only a selection of the available mass limits on new states or phenomena is shown.*
*†Small-radius (large-radius) jets are denoted by the letter j (J).*

ATLAS Exotics Searches* - 95% CL Exclusion

Status: August 2016

ATLAS Preliminary

$\int \mathcal{L}\,dt = (3.2 - 20.3)$ fb$^{-1}$   $\sqrt{s} = 8, 13$ TeV

| Model | $\ell, \gamma$ | Jets† | $E_T^{miss}$ | $\int \mathcal{L}\,dt[\text{fb}^{-1}]$ | Limit | | Reference |
|---|---|---|---|---|---|---|---|
| **Extra dimensions** | | | | | | | |
| ADD $G_{KK} + g/q$ | – | $\geq 1$ j | Yes | 3.2 | $M_D$ 6.58 TeV | $n = 2$ | 1604.07773 |
| ADD non-resonant $\ell\ell$ | $2\,e,\mu$ | – | – | 20.3 | $M_S$ 4.7 TeV | $n = 3$ HLZ | 1407.2410 |
| ADD QBH $\to \ell q$ | $1\,e,\mu$ | 1 j | – | 20.3 | $M_{th}$ 5.2 TeV | $n = 6$ | 1311.2006 |
| ADD QBH | – | 2 j | – | 15.7 | $M_{th}$ 8.7 TeV | $n = 6$ | ATLAS-CONF-2016-069 |
| ADD BH high $\sum p_T$ | $\geq 1\,e,\mu$ | $\geq 2$ j | – | 3.2 | $M_{th}$ 8.2 TeV | $n = 6$, $M_D = 3$ TeV, rot BH | 1606.02265 |
| ADD BH multijet | – | $\geq 3$ j | – | 3.6 | $M_{th}$ 9.55 TeV | $n = 6$, $M_D = 3$ TeV, rot BH | 1512.02586 |
| RS1 $G_{KK} \to \ell\ell$ | $2\,e,\mu$ | – | – | 20.3 | $G_{KK}$ mass 2.68 TeV | $k/\overline{M}_{Pl} = 0.1$ | 1405.4123 |
| RS1 $G_{KK} \to \gamma\gamma$ | $2\,\gamma$ | – | – | 3.2 | $G_{KK}$ mass 3.2 TeV | $k/\overline{M}_{Pl} = 0.1$ | 1606.03833 |
| Bulk RS $G_{KK} \to WW \to qq\ell\nu$ | $1\,e,\mu$ | 1 J | Yes | 13.2 | $G_{KK}$ mass 1.24 TeV | $k/\overline{M}_{Pl} = 1.0$ | ATLAS-CONF-2016-062 |
| Bulk RS $G_{KK} \to HH \to bbbb$ | – | 4 b | – | 13.3 | $G_{KK}$ mass 360-860 GeV | $k/\overline{M}_{Pl} = 1.0$ | ATLAS-CONF-2016-049 |
| Bulk RS $g_{KK} \to tt$ | $1\,e,\mu$ | $\geq 1$ b, $\geq 1$J/2j | Yes | 20.3 | $g_{KK}$ mass 2.2 TeV | BR = 0.925 | 1505.07018 |
| 2UED / RPP | $1\,e,\mu$ | $\geq 2$ b, $\geq 4$ j | Yes | 3.2 | KK mass 1.46 TeV | Tier (1,1), BR($A^{(1,1)} \to tt$) = 1 | ATLAS-CONF-2016-013 |
| **Gauge bosons** | | | | | | | |
| SSM $Z' \to \ell\ell$ | $2\,e,\mu$ | – | – | 13.3 | $Z'$ mass 4.05 TeV | | ATLAS-CONF-2016-045 |
| SSM $Z' \to \tau\tau$ | $2\,\tau$ | – | – | 19.5 | $Z'$ mass 2.02 TeV | | 1502.07177 |
| Leptophobic $Z' \to bb$ | – | 2 b | – | 3.2 | $Z'$ mass 1.5 TeV | | 1603.08791 |
| SSM $W' \to \ell\nu$ | $1\,e,\mu$ | – | Yes | 13.3 | $W'$ mass 4.74 TeV | | ATLAS-CONF-2016-061 |
| HVT $W' \to WZ \to qq\nu\nu$ model A | $0\,e,\mu$ | 1 J | Yes | 13.2 | $W'$ mass 2.4 TeV | $g_V = 1$ | ATLAS-CONF-2016-082 |
| HVT $W' \to WZ \to qqqq$ model B | – | 2 J | – | 15.5 | $W'$ mass 3.0 TeV | $g_V = 3$ | ATLAS-CONF-2016-055 |
| HVT $V' \to WH/ZH$ model B | multi-channel | | | 3.2 | $V'$ mass 2.31 TeV | $g_V = 3$ | 1607.05621 |
| LRSM $W'_R \to tb$ | $1\,e,\mu$ | 2 b, 0-1 j | Yes | 20.3 | $W'$ mass 1.92 TeV | | 1410.4103 |
| LRSM $W'_R \to tb$ | $0\,e,\mu$ | $\geq 1$ b, 1 J | – | 20.3 | $W'$ mass 1.76 TeV | | 1408.0886 |
| **CI** | | | | | | | |
| CI $qqqq$ | – | 2 j | – | 15.7 | $\Lambda$ 19.9 TeV | $\eta_{LL} = -1$ | ATLAS-CONF-2016-069 |
| CI $\ell\ell qq$ | $2\,e,\mu$ | – | – | 3.2 | $\Lambda$ 25.2 TeV | $\eta_{LL} = -1$ | 1607.03669 |
| CI $uutt$ | 2(SS)/$\geq$3 $e,\mu$ | $\geq 1$ b, $\geq 1$ j | Yes | 20.3 | $\Lambda$ 4.9 TeV | $\|C_{RR}\| = 1$ | 1504.04605 |
| **DM** | | | | | | | |
| Axial-vector mediator (Dirac DM) | $0\,e,\mu$ | $\geq 1$ j | Yes | 3.2 | $m_A$ 1.0 TeV | $g_q$=0.25, $g_\chi$=1.0, $m(\chi) < 250$ GeV | 1604.07773 |
| Axial-vector mediator (Dirac DM) | $0\,e,\mu, 1\,\gamma$ | 1 j | Yes | 3.2 | $m_A$ 710 GeV | $g_q$=0.25, $g_\chi$=1.0, $m(\chi) < 150$ GeV | 1604.01306 |
| $ZZ\chi\chi$ EFT (Dirac DM) | $0\,e,\mu$ | 1 J, $\leq 1$ j | Yes | 3.2 | $M_*$ 550 GeV | $m(\chi) < 150$ GeV | ATLAS-CONF-2015-080 |
| **LQ** | | | | | | | |
| Scalar LQ 1st gen | $2\,e$ | $\geq 2$ j | – | 3.2 | LQ mass 1.1 TeV | $\beta = 1$ | 1605.06035 |
| Scalar LQ 2nd gen | $2\,\mu$ | $\geq 2$ j | – | 3.2 | LQ mass 1.05 TeV | $\beta = 1$ | 1605.06035 |
| Scalar LQ 3rd gen | $1\,e,\mu$ | $\geq 1$ b, $\geq 3$ j | Yes | 20.3 | LQ mass 640 GeV | $\beta = 0$ | 1508.04735 |
| **Heavy quarks** | | | | | | | |
| VLQ $TT \to Ht + X$ | $1\,e,\mu$ | $\geq 2$ b, $\geq 3$ j | Yes | 20.3 | T mass 855 GeV | T in (T,B) doublet | 1505.04306 |
| VLQ $YY \to Wb + X$ | $1\,e,\mu$ | $\geq 1$ b, $\geq 3$ j | Yes | 20.3 | Y mass 770 GeV | Y in (B,Y) doublet | 1505.04306 |
| VLQ $BB \to Hb + X$ | $1\,e,\mu$ | $\geq 2$ b, $\geq 3$ j | Yes | 20.3 | B mass 735 GeV | isospin singlet | 1505.04306 |
| VLQ $BB \to Zb + X$ | 2/$\geq$3 $e,\mu$ | $\geq 2/\geq 1$ b | – | 20.3 | B mass 755 GeV | B in (B,Y) doublet | 1409.5500 |
| VLQ $QQ \to WqWq$ | $1\,e,\mu$ | $\geq 4$ j | Yes | 20.3 | Q mass 690 GeV | | 1509.04261 |
| VLQ $T_{5/3}T_{5/3} \to WtWt$ | 2(SS)/$\geq$3 $e,\mu$ | $\geq 1$ b, $\geq 1$ j | Yes | 3.2 | $T_{5/3}$ mass 990 GeV | | ATLAS-CONF-2016-032 |
| **Excited fermions** | | | | | | | |
| Excited quark $q^* \to q\gamma$ | $1\,\gamma$ | 1 j | – | 3.2 | $q^*$ mass 4.4 TeV | only $u^*$ and $d^*$, $\Lambda = m(q^*)$ | 1512.05910 |
| Excited quark $q^* \to qg$ | – | 2 j | – | 15.7 | $q^*$ mass 5.6 TeV | only $u^*$ and $d^*$, $\Lambda = m(q^*)$ | ATLAS-CONF-2016-069 |
| Excited quark $b^* \to bg$ | – | 1 b, 1 j | – | 8.8 | $b^*$ mass 2.3 TeV | | ATLAS-CONF-2016-060 |
| Excited quark $b^* \to Wt$ | 1 or 2 $e,\mu$ | 1 b, 2-0 j | Yes | 20.3 | $b^*$ mass 1.5 TeV | $f_g = f_L = f_R = 1$ | 1510.02664 |
| Excited lepton $\ell^*$ | $3\,e,\mu$ | – | – | 20.3 | $\ell^*$ mass 3.0 TeV | $\Lambda = 3.0$ TeV | 1411.2921 |
| Excited lepton $\nu^*$ | $3\,e,\mu,\tau$ | – | – | 20.3 | $\nu^*$ mass 1.6 TeV | $\Lambda = 1.6$ TeV | 1411.2921 |
| **Other** | | | | | | | |
| LSTC $a_T \to W\gamma$ | $1\,e,\mu, 1\,\gamma$ | – | Yes | 20.3 | $a_T$ mass 960 GeV | | 1407.8150 |
| LRSM Majorana $\nu$ | $2\,e,\mu$ | 2 j | – | 20.3 | $N^0$ mass 2.0 TeV | $m(W_R) = 2.4$ TeV, no mixing | 1506.06020 |
| Higgs triplet $H^{\pm\pm} \to ee$ | 2 e (SS) | – | – | 13.9 | $H^{\pm\pm}$ mass 570 GeV | DY production, BR($H_L^{\pm\pm} \to ee$)=1 | ATLAS-CONF-2016-051 |
| Higgs triplet $H^{\pm\pm} \to \ell\tau$ | $3\,e,\mu,\tau$ | – | – | 20.3 | $H^{\pm\pm}$ mass 400 GeV | DY production, BR($H_L^{\pm\pm} \to \ell\tau$)=1 | 1411.2921 |
| Monotop (non-res prod) | $1\,e,\mu$ | 1 b | Yes | 20.3 | spin-1 invisible particle mass 657 GeV | $a_{non-res} = 0.2$ | 1410.5404 |
| Multi-charged particles | – | – | – | 20.3 | multi-charged particle mass 785 GeV | DY production, $\|q\| = 5e$ | 1504.04188 |
| Magnetic monopoles | – | – | – | 7.0 | monopole mass 1.34 TeV | DY production, $\|g\| = 1g_D$, spin 1/2 | 1509.08059 |

$\sqrt{s} = 8$ TeV   $\sqrt{s} = 13$ TeV

$10^{-1}$   1   10   **Mass scale [TeV]**

*Only a selection of the available mass limits on new states or phenomena is shown. Lower bounds are specified only when explicitly not excluded.

†Small-radius (large-radius) jets are denoted by the letter j (J).

8 July 2017

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# ATLAS Exotics Searches* - 95% CL Exclusion

Status: March 2016

**ATLAS** Preliminary

$\int \mathcal{L}\, dt = (3.2 - 20.3)\ \text{fb}^{-1}$  $\sqrt{s} = 8, 13\ \text{TeV}$

| | Model | $\ell, \gamma$ | Jets† | $E_T^{miss}$ | $\int \mathcal{L}\, dt[\text{fb}^{-1}]$ | Limit | | Reference |
|---|---|---|---|---|---|---|---|---|
| **Extra dimensions** | ADD $G_{KK} + g/q$ | – | $\geq 1$ j | Yes | 3.2 | $M_D$ 6.58 TeV | $n = 2$ | 1604.07773 |
| | ADD non-resonant $\ell\ell$ | 2 $e, \mu$ | – | – | 20.3 | $M_S$ 4.7 TeV | $n = 3$ HLZ | 1407.2410 |
| | ADD QBH $\to \ell q$ | 1 $e, \mu$ | 1 j | – | 20.3 | $M_{th}$ 5.2 TeV | $n = 6$ | 1311.2006 |
| | ADD QBH | – | 2 j | – | 3.6 | $M_{th}$ 8.3 TeV | $n = 6$ | 1512.01530 |
| | ADD BH high $\sum p_T$ | $\geq 1\ e, \mu$ | $\geq 2$ j | – | 3.2 | $M_{th}$ 8.2 TeV | $n = 6$, $M_D = 3$ TeV, rot BH | 1606.02265 |
| | ADD BH multijet | – | $\geq 3$ j | – | 3.6 | $M_{th}$ 9.55 TeV | $n = 6$, $M_D = 3$ TeV, rot BH | 1512.02586 |
| | RS1 $G_{KK} \to \ell\ell$ | 2 $e, \mu$ | – | – | 20.3 | $G_{KK}$ mass 2.68 TeV | $k/\overline{M}_{Pl} = 0.1$ | 1405.4123 |
| | RS1 $G_{KK} \to \gamma\gamma$ | 2 $\gamma$ | – | – | 20.3 | $G_{KK}$ mass 2.66 TeV | $k/\overline{M}_{Pl} = 0.1$ | 1504.05511 |
| | Bulk RS $G_{KK} \to WW \to qq\ell\nu$ | 1 $e, \mu$ | 1 J | Yes | 3.2 | $G_{KK}$ mass 1.06 TeV | $k/\overline{M}_{Pl} = 1.0$ | ATLAS-CONF-2015-075 |
| | Bulk RS $G_{KK} \to HH \to bbbb$ | – | 4 b | – | 3.2 | $G_{KK}$ mass 480-770 GeV | $k/\overline{M}_{Pl} = 1.0$ | 1606.04782 |
| | Bulk RS $g_{KK} \to tt$ | 1 $e, \mu$ | $\geq 1$ b, $\geq 1$J/2j | Yes | 20.3 | $g_{KK}$ mass 2.2 TeV | BR $= 0.925$ | 1505.07018 |
| | 2UED / RPP | 1 $e, \mu$ | $\geq 2$ b, $\geq 4$ j | Yes | 3.2 | KK mass 1.46 TeV | Tier $(1,1)$, BR$(A^{(1,1)} \to tt) = 1$ | ATLAS-CONF-2016-013 |
| **Gauge bosons** | SSM $Z' \to \ell\ell$ | 2 $e, \mu$ | – | – | 3.2 | $Z'$ mass 3.4 TeV | | ATLAS-CONF-2015-070 |
| | SSM $Z' \to \tau\tau$ | 2 $\tau$ | – | – | 19.5 | $Z'$ mass 2.02 TeV | | 1502.07177 |
| | Leptophobic $Z' \to bb$ | – | 2 b | – | 3.2 | $Z'$ mass 1.5 TeV | | 1603.08791 |
| | SSM $W' \to \ell\nu$ | 1 $e, \mu$ | – | Yes | 3.2 | $W'$ mass 4.07 TeV | | 1606.03977 |
| | HVT $W' \to WZ \to qq\nu\nu$ model A | 0 $e, \mu$ | 1 J | Yes | 3.2 | $W'$ mass 1.6 TeV | $g_V = 1$ | ATLAS-CONF-2015-068 |
| | HVT $W' \to WZ \to qqqq$ model A | – | 2 J | – | 3.2 | $W'$ mass 1.38-1.6 TeV | $g_V = 1$ | ATLAS-CONF-2015-073 |
| | HVT $W' \to WH \to \ell\nu bb$ model B | 1 $e, \mu$ | 1-2 b, 1-0 j | Yes | 3.2 | $W'$ mass 1.62 TeV | $g_V = 3$ | ATLAS-CONF-2015-074 |
| | HVT $Z' \to ZH \to \nu\nu bb$ model B | 0 $e, \mu$ | 1-2 b, 1-0 j | Yes | 3.2 | $Z'$ mass 1.76 TeV | $g_V = 3$ | ATLAS-CONF-2015-074 |
| | LRSM $W_R' \to tb$ | 1 $e, \mu$ | 2 b, 0-1 j | Yes | 20.3 | $W'$ mass 1.92 TeV | | 1410.4103 |
| | LRSM $W_R' \to tb$ | 0 $e, \mu$ | $\geq 1$ b, 1 J | – | 20.3 | $W'$ mass 1.76 TeV | | 1408.0886 |
| **CI** | CI $qqqq$ | – | 2 j | – | 3.6 | $\Lambda$ 17.5 TeV | $\eta_{LL} = -1$ | 1512.01530 |
| | CI $qq\ell\ell$ | 2 $e, \mu$ | – | – | 3.2 | $\Lambda$ 23.1 TeV | $\eta_{LL} = -1$ | ATLAS-CONF-2015-070 |
| | CI $uutt$ | 2 $e, \mu$ (SS) | $\geq 1$ b, 1-4 j | Yes | 20.3 | $\Lambda$ 4.3 TeV | $|C_{LL}| = 1$ | 1504.04605 |
| **DM** | Axial-vector mediator (Dirac DM) | 0 $e, \mu$ | $\geq 1$ j | Yes | 3.2 | $m_A$ 1.0 TeV | $g_q = 0.25$, $g_\chi = 1.0$, $m(\chi) < 250$ GeV | 1604.07773 |
| | Axial-vector mediator (Dirac DM) | 0 $e, \mu, 1\gamma$ | 1 j | Yes | 3.2 | $m_A$ 710 GeV | $g_q = 0.25$, $g_\chi = 1.0$, $m(\chi) < 150$ GeV | 1604.01306 |
| | $ZZ\chi\chi$ EFT (Dirac DM) | 0 $e, \mu$ | 1 J, $\leq 1$ j | Yes | 3.2 | $M_*$ 550 GeV | $m(\chi) < 150$ GeV | ATLAS-CONF-2015-080 |
| **LQ** | Scalar LQ 1st gen | 2 $e$ | $\geq 2$ j | – | 3.2 | LQ mass 1.1 TeV | $\beta = 1$ | 1605.06035 |
| | Scalar LQ 2nd gen | 2 $\mu$ | $\geq 2$ j | – | 3.2 | LQ mass 1.05 TeV | $\beta = 1$ | 1605.06035 |
| | Scalar LQ 3rd gen | 1 $e, \mu$ | $\geq 1$ b, $\geq 3$ j | Yes | 20.3 | LQ mass 640 GeV | $\beta = 0$ | 1508.04735 |
| **Heavy quarks** | VLQ $TT \to Ht + X$ | 1 $e, \mu$ | $\geq 2$ b, $\geq 3$ j | Yes | 20.3 | T mass 855 GeV | T in (T,B) doublet | 1505.04306 |
| | VLQ $YY \to Wb + X$ | 1 $e, \mu$ | $\geq 1$ b, $\geq 3$ j | Yes | 20.3 | Y mass 770 GeV | Y in (B,Y) doublet | 1505.04306 |
| | VLQ $BB \to Hb + X$ | 1 $e, \mu$ | $\geq 2$ b, $\geq 3$ j | Yes | 20.3 | B mass 735 GeV | isospin singlet | 1505.04306 |
| | VLQ $BB \to Zb + X$ | 2/$\geq 3\ e, \mu$ | $\geq 2/\geq 1$ b | – | 20.3 | B mass 755 GeV | B in (B,Y) doublet | 1409.5500 |
| | VLQ $QQ \to WqWq$ | 1 $e, \mu$ | $\geq 4$ j | Yes | 20.3 | Q mass 690 GeV | | 1509.04261 |
| | $T_{5/3} \to Wt$ | 1 $e, \mu$ | $\geq 1$ b, $\geq 5$ j | Yes | 20.3 | $T_{5/3}$ mass 840 GeV | | 1503.05425 |
| **Excited fermions** | Excited quark $q^* \to q\gamma$ | 1 $\gamma$ | 1 j | – | 3.2 | $q^*$ mass 4.4 TeV | only $u^*$ and $d^*$, $\Lambda = m(q^*)$ | 1512.05910 |
| | Excited quark $q^* \to qg$ | – | 2 j | – | 3.6 | $q^*$ mass 5.2 TeV | only $u^*$ and $d^*$, $\Lambda = m(q^*)$ | 1512.01530 |
| | Excited quark $b^* \to bg$ | – | 1 b, 1 j | – | 3.2 | $b^*$ mass 2.1 TeV | | 1603.08791 |
| | Excited quark $b^* \to Wt$ | 1 or 2 $e, \mu$ | 1 b, 2-0 j | Yes | 20.3 | $b^*$ mass 1.5 TeV | $f_g = f_L = f_R = 1$ | 1510.02664 |
| | Excited lepton $\ell^*$ | 3 $e, \mu$ | – | – | 20.3 | $\ell^*$ mass 3.0 TeV | $\Lambda = 3.0$ TeV | 1411.2921 |
| | Excited lepton $\nu^*$ | 3 $e, \mu, \tau$ | – | – | 20.3 | $\nu^*$ mass 1.6 TeV | $\Lambda = 1.6$ TeV | 1411.2921 |
| **Other** | LSTC $a_T \to W\gamma$ | 1 $e, \mu, 1\gamma$ | – | Yes | 20.3 | $a_T$ mass 960 GeV | | 1407.8150 |
| | LRSM Majorana $\nu$ | 2 $e, \mu$ | 2 j | – | 20.3 | $N^0$ mass 2.0 TeV | $m(W_R) = 2.4$ TeV, no mixing | 1506.06020 |
| | Higgs triplet $H^{\pm\pm} \to \ell\ell$ | 2 $e, \mu$ (SS) | – | – | 20.3 | $H^{\pm\pm}$ mass 551 GeV | DY production, BR$(H_L^{\pm\pm} \to \ell\ell) = 1$ | 1412.0237 |
| | Higgs triplet $H^{\pm\pm} \to \ell\tau$ | 3 $e, \mu, \tau$ | – | – | 20.3 | $H^{\pm\pm}$ mass 400 GeV | DY production, BR$(H_L^{\pm\pm} \to \ell\tau) = 1$ | 1411.2921 |
| | Monotop (non-res prod) | 1 $e, \mu$ | 1 b | Yes | 20.3 | spin-1 invisible particle mass 657 GeV | $a_{non-res} = 0.2$ | 1410.5404 |
| | Multi-charged particles | – | – | – | 20.3 | multi-charged particle mass 785 GeV | DY production, $|q| = 5e$ | 1504.04188 |
| | Magnetic monopoles | – | – | – | 7.0 | monopole mass 1.34 TeV | DY production, $|g| = 1g_D$, spin 1/2 | 1509.08059 |

$\sqrt{s} = 8$ TeV   $\sqrt{s} = 13$ TeV

$10^{-1}$   1   10   **Mass scale [TeV]**

*Only a selection of the available mass limits on new states or phenomena is shown. Lower bounds are specified only when explicitly not excluded.

†Small-radius (large-radius) jets are denoted by the letter j (J).

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