Searches for Boosted Di-Bosons Resonances with the ATLAS and CMS detectors

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On behalf of
ATLAS and CMS
Collaborations

Preamble

★ Searches done with 8 TeV data cover many final states
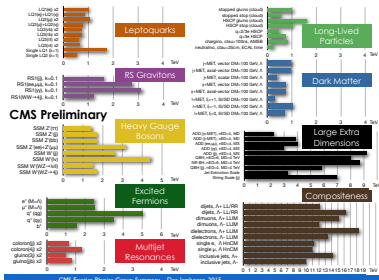
  ✓ Semi-leptonic and fully hadronic signatures
  ✓ I.e. spin-1 resonance (HVT) excluded for $m \lesssim 1.8(1.5)$ TeV with VV combined ($VH \to \ell\nu b\bar{b}$) search
  ✓ I.e. spin-2 resonance (RSG) excluded for $m \lesssim 750$ GeV with $VV \to q\bar{q}\ell\bar{\ell}, q\bar{q}\ell\nu$ searches
  ✓ Data excesses of $2.5\,\sigma$ at ~ 2 TeV in WZ fully hadronic channel (ATLAS[1])
    and of $1.9\,\sigma$ at ~ 1.8 TeV in WH $\ell\nu b\bar{b}$ channel (CMS[2])

Outline

★ Search Strategies

   ✓ Identification of boosted W, Z (V) and h bosons that decay hadronically [3] [4]

★ Presented searches for heavy resonances decaying into W, Z or h pairs

   ✓ $hh \to b\bar{b}b\bar{b}$, ATLAS 13 TeV [5], CMS 8 TeV [6]

   ✓ $Vh \to \ell\bar{\ell}b\bar{b}$, $q\bar{q}\tau\bar{\tau}$, $q\bar{q}q\bar{q}$, ATLAS 13 TeV [7]

   ✓ $VV \to q\bar{q}q\bar{q}$, ATLAS 13 TeV [8], CMS 13 TeV [9]

   ✓ $VV \to \ell\nu q\bar{q}$, ATLAS 13 TeV [10], CMS 13 TeV [9]

   ✓ $VV \to \ell\bar{\ell}q\bar{q}$, ATLAS 13 TeV [11], CMS 8 TeV [12]

   ✓ $VV \to \nu\bar{\nu}q\bar{q}$, ATLAS 13 TeV [13]

★ Summary and Conclusions

★ Theoretical Interpretations considered in this presentation

   ✓ Heavy Vector Triplet (HVT) (spin-1) model [14]

   ✓ Randall-Sundrum Graviton (RSG) (spin-2) model [15]

   ✓ Radion in Warped Extra Dimensions (WED) (spin-0) model [16]

★ For a detailed scalar interpretation please see A. McCarn's report on Wednesday

Search Strategies

Heavy resonances decay results in boosted di-bosons, hadronic decays enhancing the rates
→ it is crucial to identify boosted $V \to qq$ decays

- ★ ATLAS, anti-k_t jets with $R = 1.0$, trimmed with subjet $R = 0.2$ and p_T^{min} fraction of 5%

- ★ Substructure exploited mainly with energy correlation (D_2), others variables studied

- ★ b-tagging on ghost associated anti-k_t track-jets with $R = 0.2$

- ★ CMS, anti-k_t jets with $R = 0.8$, pruned with CA re-clustering with p_T^{min} fraction of 10%

- ★ Substructure exploited mainly with N-subjettiness (τ_{21}), other variables studied

- ★ b-tagging on anti-k_t jets with $R = 0.4$
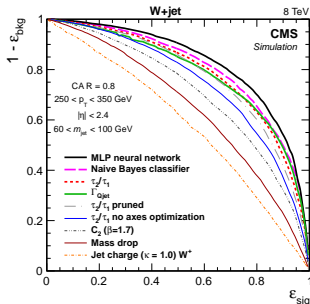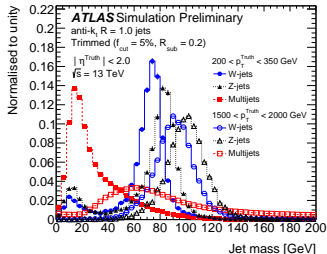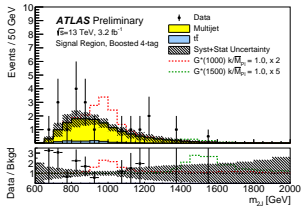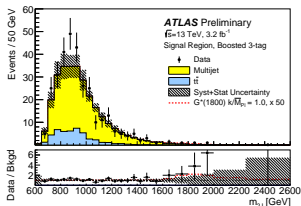
SEARCH FOR RESONANCES DECAYING IN $hh \to b\bar{b}b\bar{b}$

★ Events selected with 3 or 4 b-tagged track-jets with $p_T^j > 10$ GeV matched to R=1.0 jets with $p_T^J > 250, 350$ GeV

★ Higgs-tagging based on $m_J \sim m_h$

★ Main backgrounds from dijets and $t\bar{t}$ estimated with N_{btag} and m_J control regions

★ Events selected with $p_T^J > 40$ GeV, $m_{JJ} > 1$ TeV and $N_{btag} \geq 2$

★ Higgs-tagging based on τ_{21} and $m_J \sim m_h$

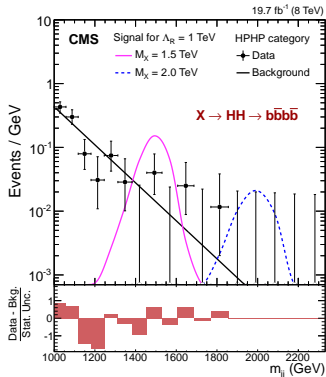★ Main backgrounds from dijets and $t\bar{t}$ modelled with exp. function validated in m_J control region

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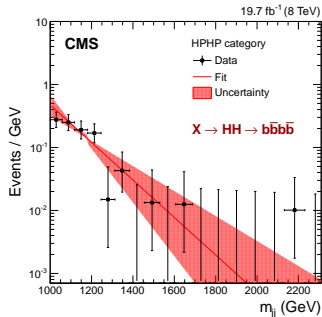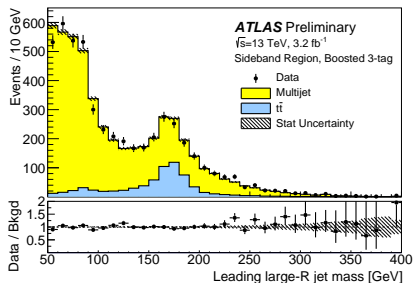
SEARCH FOR RESONANCES DECAYING IN $hh \to b\bar{b}b\bar{b}$

- ★ Two signal regions, 3 and 4 b-tags

- ★ Main uncertainties from b-tagging and jet energy/mass scale

- ★ Three signal regions based on τ_{21}

- ★ Main uncertainties due to b-tagging and jet mass tagging

SEARCH FOR RESONANCES DECAYING IN $hh \to b\bar{b}b\bar{b}$

★ Data interpreted in RS Graviton
  ($k/M_{Pl} = 1.0, 2.0$) model

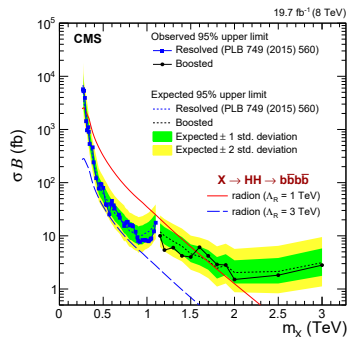★ 95% CL exclusions:
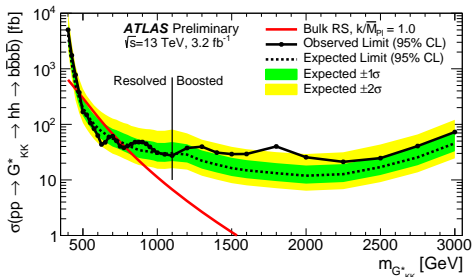 $475 < m_{G*} < 785$ GeV ($k/M_{Pl} = 1.0$)
  $m_{G*} < 980$ GeV ($k/M_{Pl} = 2.0$)

★ Data interpreted in WED Radion
  ($\Lambda_R = 1, 3$ TeV) model

★ 95% CL exclusions for $\Lambda_R = 1$ TeV
  $1.15 < m_X < 1.55$ TeV
  $0.3 < m_X < 1.1$ TeV (resolved search [17])

SEARCH FOR RESONANCES DECAYING IN Wh, $Zh \to 2lep. + b\bar{b}$

★ Search in $\nu\nu$, $\ell\nu$, $\ell\ell$ channels requiring $p_T^J > 250$ GeV, $m_{lead}^J \sim m_h$

★ ≥ 1 track-jet b-tagged assoc. to lead. Jet

★ 1ℓ and 2ℓ events selected with isol. leptons $p_T > 20 - 24$ GeV, 0ℓ with $E_T^{miss} > 80$ GeV

★ Main bkg. Z+jets (0ℓ, 2ℓ) and W+jets, $t\bar{t}$ (1ℓ)

★ Fit to m_{VH} in control (m^J sidebands and $N_{btag} = 1, 2$) and signal regions (lepton flavors and $N_{btag} = 1, 2$)

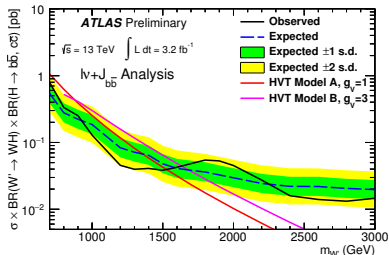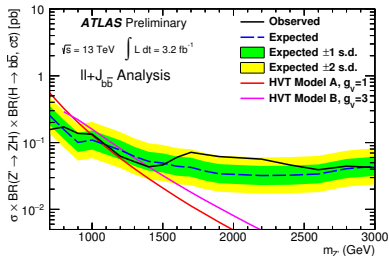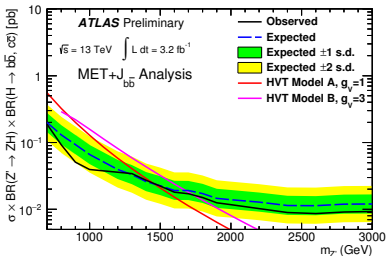★ Main uncertainties from large R jet energy/mass scale and b-tagging
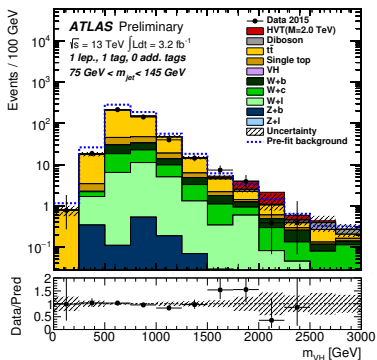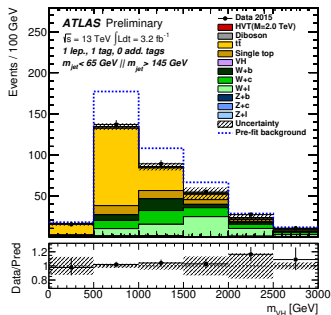
Search for resonances decaying in Wh, $Zh \to 2lep. + b\bar{b}$

★ Data interpreted in HVT (A and B) models

   √ (A): $m_{V'^0} < 1480$ GeV and $m_{V'^\pm} < 1490$ GeV

   √ (B): $m_{V'^0} < 1760$ GeV and $m_{V'^\pm} < 1620$ GeV

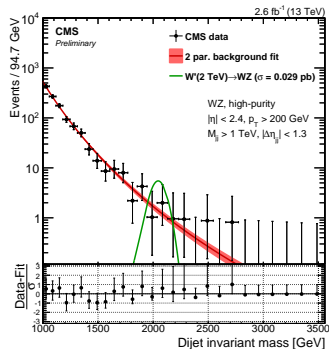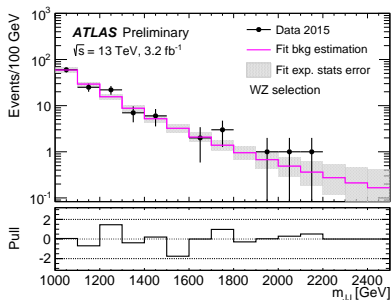# SEARCH FOR RESONANCES DECAYING IN WW, WZ, $ZZ \rightarrow q\bar{q}q\bar{q}$

* Events selected with 2 jets $p_T^J > 200$ GeV, $p_T^{leadJ} > 450\,GeV$ and $m_{JJ} > 1$ TeV

* $V \rightarrow q\bar{q}$ tagger based on D_2, m_J and N_{tracks}

* Main backgrounds from di-jets events modelled with a power-law function validated in MC and data control regions

* Events selected with $p_T^J > 30$ GeV, $m_{JJ} > 1$ TeV

* High-p_T bosons $p_T^V > 200$ GeV

* $V \rightarrow q\bar{q}$ tagger based on τ_{21} and m_J

* Main backgrounds from di-jets events modelled with a power-law function validated in MC and data control regions

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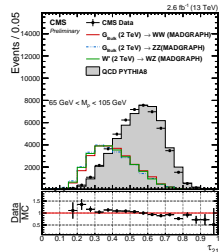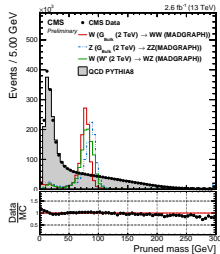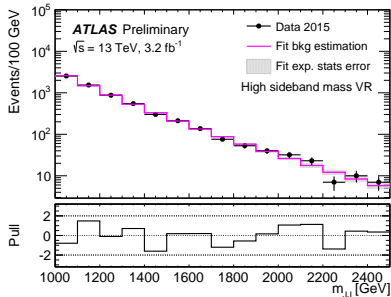
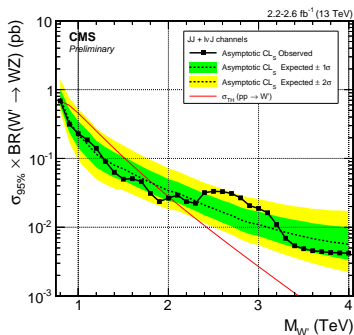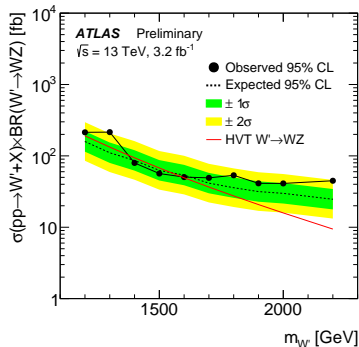# SEARCH FOR RESONANCES DECAYING IN WW, WZ, $ZZ \to q\bar{q}q\bar{q}$

★ Three signal regions defined based on V-tag

★ Main uncertainties from large R jet energy/mass scale and D_2

★ Six signal regions defined based on V-tag and τ_{21}

★ Main uncertainties due to bkg. fit and V-tagging efficiency for signal

SEARCH FOR RESONANCES DECAYING IN WW, WZ, $ZZ \to q\bar{q}q\bar{q}$

★ Data interpreted in RS Graviton ($k/M_{Pl} = 1.0$) and HVT (A) models

★ 95% CL exclusions: $1380 < m_{W'} < 1600$ GeV

★ Data interpreted in RS Graviton ($k/M_{Pl} = 0.5$) and HVT (B) models

★ 95% CL exclusions: $m_{W'} < 2000$ GeV, combined with $WZ, WW \to \ell\nu q\bar{q}$ analysis

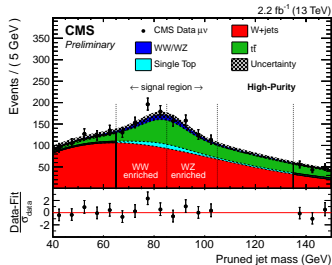# SEARCH FOR RESONANCES DECAYING IN WZ, $WW \to \ell\nu q\bar{q}$

- ★ Events selected with $p_T^J > 200$ GeV, $E_T^{miss} > 100$ GeV, $p_T^{W\ell\nu} > 200$ GeV

- ★ High-p_T bosons $p_T^{\ell\ell}, p_T^J > 0.4\, m_{\ell\ell J}$

- ★ $V \to q\bar{q}$ tagger based on D_2 and m_J

- ★ Main backgrounds from $W + jets$ and $t\bar{t}$ from fits to control regions
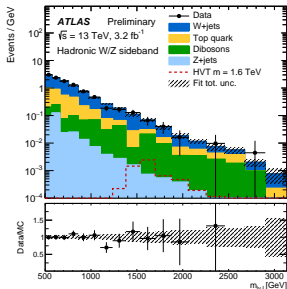
- ★ Events selected with $p_T^J > 30$ GeV, $E_T^{miss} > 40(80)$ GeV, $p_T^{W\ell\nu} > 200$ GeV

- ★ High-p_T bosons $p_T^V > 200$ GeV

- ★ $V \to q\bar{q}$ tagger based on τ_{21} and m_J

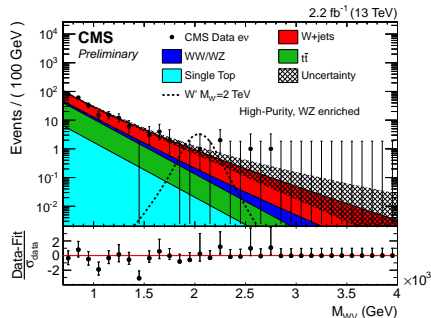- ★ Main backgrounds from $W + jets$ and $t\bar{t}$ normalized in control regions

Search for resonances decaying in WZ, $WW \to \ell\nu q\bar{q}$

* Fit to $m_{\ell\nu J}$ in signal and control regions

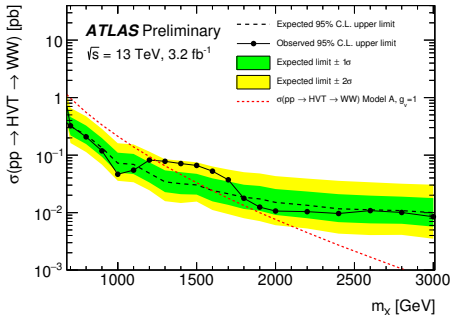* Main uncertainties from bkg. shapes, large R jet energy/mass scale
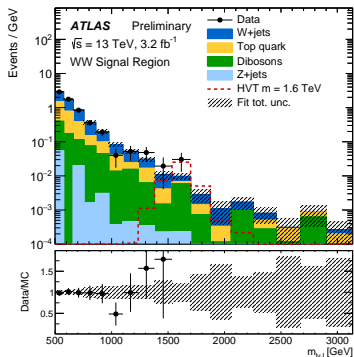
* Background prediction shape from the sideband and extrap. to signal region

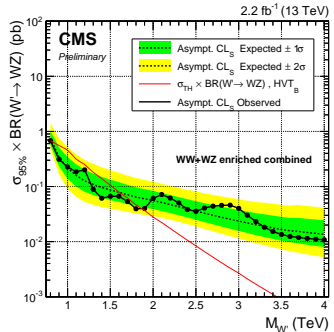* Main uncertainties due to background normalization and V-tagging

SEARCH FOR RESONANCES DECAYING IN WZ, $WW \to \ell\nu q\bar{q}$

★ Data interpreted in RS Graviton
  ($k/M_{Pl} = 1.0$) and HVT (A) models

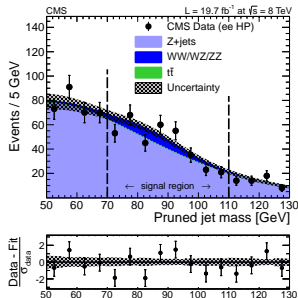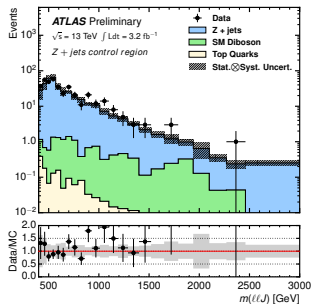★ 95% CL exclusions: $m_{W'} < 1250$ GeV and
  $m_{G*} < 1060$ GeV

★ Data interpreted in RS Graviton
  ($k/M_{Pl} = 0.5$) and HVT (B) models

★ 95% CL exclusions: $m_{W'} < 2000$ GeV,
  combined with WZ, $WW \to qqqq$ analysis

SEARCH FOR RESONANCES DECAYING IN $WZ, ZZ \to \ell\bar{\ell}q\bar{q}$

* Events selected with $p_T^J > 200$ GeV, isol. leptons $p_T > 25$ GeV and $m_{\ell\ell}$ cuts

* High-p_T bosons $p_T^{\ell\ell}, p_T^J > 0.4\, m_{\ell\ell J}$

* $V \to q\bar{q}$ tagger based on D_2 and m_J

* Main backgrounds from $V + jets$ estimated with control regions and MC extrap.

* Events sel. with $p_T^J > 30$ GeV, isol. leptons $p_T > 20(40)$ GeV and $m_{\ell\ell}$ cuts

* High-p_T bosons $p_T^{\ell\ell} > 80\, GeV$

* $V \to q\bar{q}$ tagger based on τ_{21} and m_J

* Main backgrounds from $V + jets$ estimated with control regions and MC extrap.

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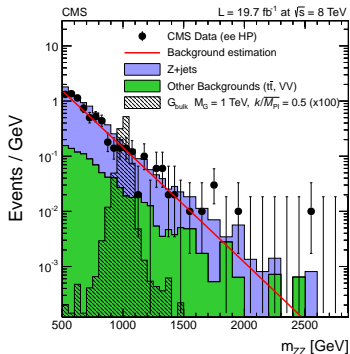# SEARCH FOR RESONANCES DECAYING IN WZ, $ZZ \to \ell\bar{\ell}q\bar{q}$

* Fit to $m_{\ell\ell J}$ in signal regions
* Main uncertainties from large R jet energy/mass scale and D_2 and $Z + jets$ background
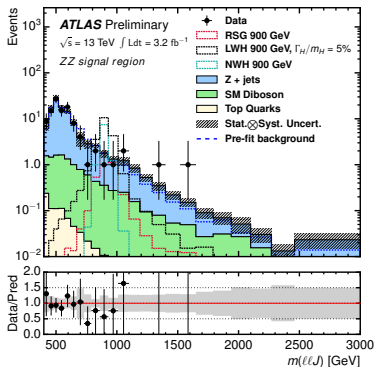
* Background prediction shape from the sideband and extrap. to signal region
* Main uncertainties due to background normalization and V-tagging

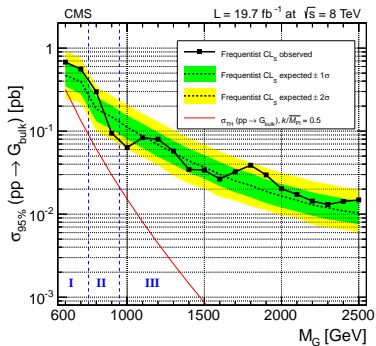# SEARCH FOR RESONANCES DECAYING IN $WZ, ZZ \to \ell\ell q\bar{q}$

* Data interpreted in RS Graviton ($k/M_{Pl} = 1.0$) and HVT (A) models

* 95% CL exclusions: $m_{W'} < 1400$ GeV and $m_{G*} < 850$ GeV
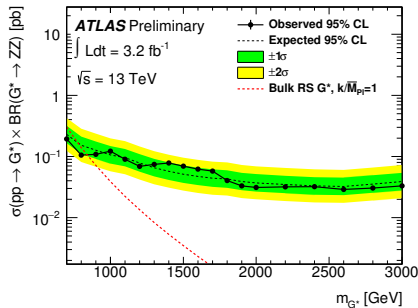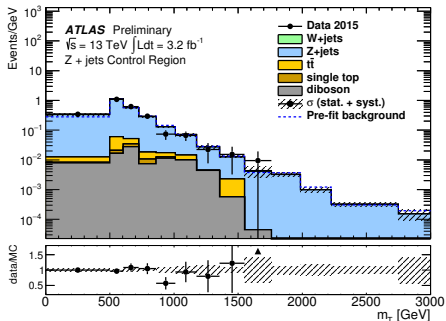
* Data interpreted in RS Graviton ($k/M_{Pl} = 0.5$) and HVT (B) models

* Combined with $WW, WZ \to \ell\nu q\bar{q}$ (region "II") and with $VV \to q\bar{q}q\bar{q}$ (region "III")

# Search for resonances decaying in WZ, $ZZ \rightarrow \nu\bar{\nu}q\bar{q}$

★ Events selected with $p_T^J > 200$ GeV, $E_T^{miss} > 250\ GeV$, ch. leptons veto

★ $V \rightarrow q\bar{q}$ tagger based on D_2 and m_J

★ Main backgrounds from $V + jets$, $t\bar{t}$ estimated with fits to control regions

★ Fit to m_T built from E_T^{miss} and $E_{T,J}$ in signal and control regions

★ Main uncertainties from large R jet energy/mass scale, D_2 and E_T^{miss} modelling
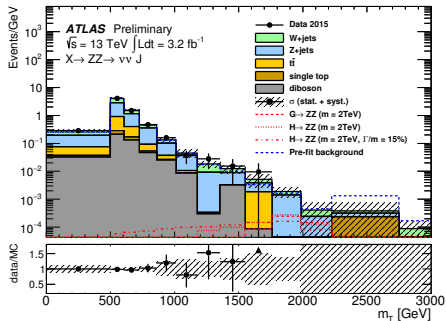
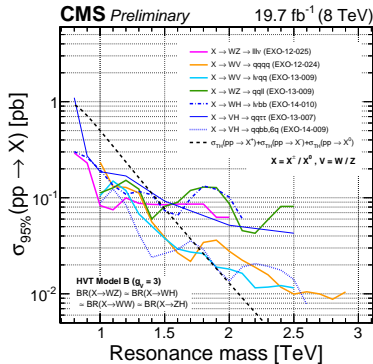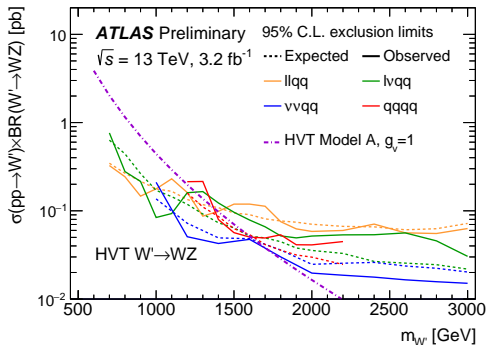# SEARCH FOR RESONANCES DECAYING IN WZ, $ZZ \to \nu\bar{\nu}q\bar{q}$

* Data interpreted in RS Graviton ($k/M_{Pl} = 1.0$) and HVT (A) models
* 95% CL exclusions: $m_{HVT} < 1600$ GeV
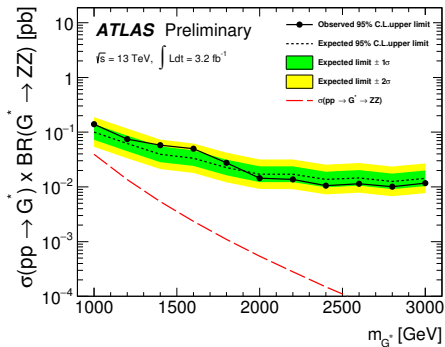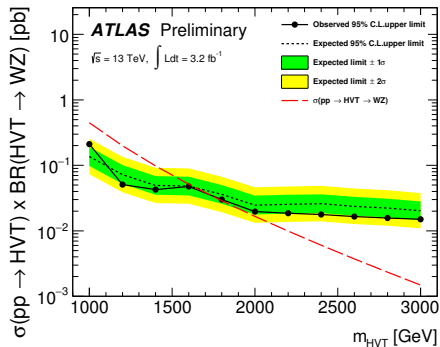
SUMMARY OF *VV* SEARCHES

★ Summary of searches with 13 TeV data from ATLAS and 8 TeV data from CMS

★ Data interpreted in the HVT model (using different couplings)

Conclusions

⋆ ATLAS and CMS released new results of searches for boosted di-bosons resonances at 13 TeV

  ✓ ATLAS covered various final states looking at semi-leptonic ($\ell\nu q\bar{q}$, $\nu\bar{\nu}q\bar{q}$, $\ell\bar{\ell}q\bar{q}$) and fully hadronic VV, VH semi-leptonic decays with b-tagged jets and di-Higgs production

  ✓ CMS searches carried out with VV production decaying to $\ell\nu q\bar{q}$ and fully hadronic final states (most sensitive ones) plus of course the 8 TeV searches

⋆ Data excesses (2-2.5 σ) at $\sim$ 2 TeV not confirmed, more data needed to fully (dis-)prove them

⋆ Improved limits on cross-sections for spin-1 and spin-2 resonances production

⋆ More data is coming soon ... stay tuned!

REFERENCES I

[1] Georges Aad et al. "Search for high-mass diboson resonances with boson-tagged jets in proton-proton collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector". In: *JHEP* 12 (2015), p. 055. DOI: 10.1007/JHEP12(2015)055. arXiv: 1506.00962 [hep-ex].

[2] CMS Collaboration. "Search for massive WH resonances decaying to $\ell\nu b\bar{b}$ final state in the boosted regime at $\sqrt{s} = 8$ TeV". In: (2015).

[3] *Identification of boosted, hadronically-decaying W and Z bosons in $\sqrt{s} = 13$ TeV Monte Carlo Simulations for ATLAS*. Tech. rep. ATL-PHYS-PUB-2015-033. Geneva: CERN, 2015. URL: https://cds.cern.ch/record/2041461.

[4] *Identifying Hadronically Decaying Vector Bosons Merged into a Single Jet*. Tech. rep. CMS-PAS-JME-13-006. Geneva: CERN, 2013. URL: https://cds.cern.ch/record/1577417.

[5] *Search for pair production of Higgs bosons in the $b\bar{b}b\bar{b}$ final state using proton-proton collisions at $\sqrt{s}$=13 TeV with the ATLAS detector*. Tech. rep. ATLAS-CONF-2016-XXX. Geneva: CERN, 2016.

[6] Vardan Khachatryan et al. "Search for heavy resonances decaying to two Higgs bosons in final states containing four b quarks". In: (2016). arXiv: 1602.08762 [hep-ex].

References II

[7] *Search for new resonances decaying to a W or Z boson and a Higgs boson in the $\ell\ell b\bar{b}$, $\ell\nu b\bar{b}$, and $\nu\nu b\bar{b}$ channels in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector*. Tech. rep. ATLAS-CONF-2015-074. Geneva: CERN, 2015. url: https://cds.cern.ch/record/2114846.

[8] *Search for resonances with boson-tagged jets in $3.2\,fb^{-1}$ of pp collisions at $\sqrt{s} = 13$ TeV collected with the ATLAS detector*. Tech. rep. ATLAS-CONF-2015-073. Geneva: CERN, 2015. url: https://cds.cern.ch/record/2114845.

[9] *Search for massive resonances decaying into pairs of boosted W and Z bosons at $\sqrt{s} = 13$ TeV*. Tech. rep. CMS-PAS-EXO-15-002. Geneva: CERN, 2015. url: https://cds.cern.ch/record/2117062.

[10] *Search for WW/WZ resonance production in the $\ell\nu qq$ final state at $\sqrt{s} = 13$ TeV with the ATLAS detector at the LHC*. Tech. rep. ATLAS-CONF-2015-075. Geneva: CERN, 2015. url: https://cds.cern.ch/record/2114847.

[11] *Search for diboson resonances in the llqq final state in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector*. Tech. rep. ATLAS-CONF-2015-071. Geneva: CERN, 2015. url: https://cds.cern.ch/record/2114843.

REFERENCES III

[12] Vardan Khachatryan et al. "Search for massive resonances in dijet systems containing jets tagged as W or Z boson decays in pp collisions at $\sqrt{s} = 8$ TeV". In: *JHEP* 08 (2014), p. 173. DOI: 10.1007/JHEP08(2014)173. arXiv: 1405.1994 [hep-ex].

[13] *Search for diboson resonances in the $\nu\nu qq$ final state in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector*. Tech. rep. ATLAS-CONF-2015-068. Geneva: CERN, 2015. URL: https://cds.cern.ch/record/2114840.

[14] Duccio Pappadopulo et al. "Heavy Vector Triplets: Bridging Theory and Data". In: *JHEP* 09 (2014), p. 060. DOI: 10.1007/JHEP09(2014)060. arXiv: 1402.4431 [hep-ph].

[15] Kaustubh Agashe et al. "Warped Gravitons at the LHC and Beyond". In: *Phys. Rev.* D76 (2007), p. 036006. DOI: 10.1103/PhysRevD.76.036006. arXiv: hep-ph/0701186 [hep-ph].

[16] Lisa Randall and Raman Sundrum. "A Large mass hierarchy from a small extra dimension". In: *Phys. Rev. Lett.* 83 (1999), pp. 3370–3373. DOI: 10.1103/PhysRevLett.83.3370. arXiv: hep-ph/9905221 [hep-ph].

References IV

[17] Vardan Khachatryan et al. "Search for resonant pair production of Higgs bosons decaying to two bottom quarkâĂŞantiquark pairs in protonâĂŞproton collisions at 8 TeV". In: *Phys. Lett.* B749 (2015), pp. 560–582. doi: `10.1016/j.physletb.2015.08.047`. arXiv: `1503.04114 [hep-ex]`.

Back-up slides

Search for resonances decaying in $hh \rightarrow b\bar{b}b\bar{b}$
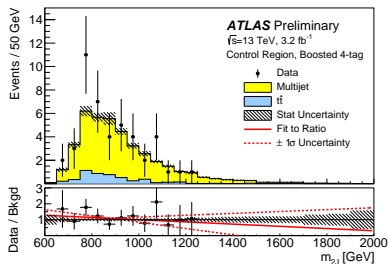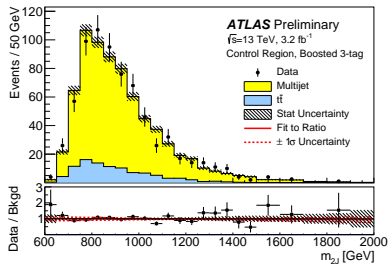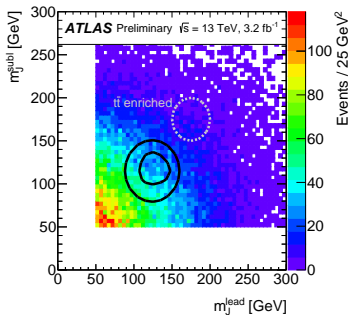
SEARCH FOR RESONANCES DECAYING IN $hh \to b\bar{b}b\bar{b}$
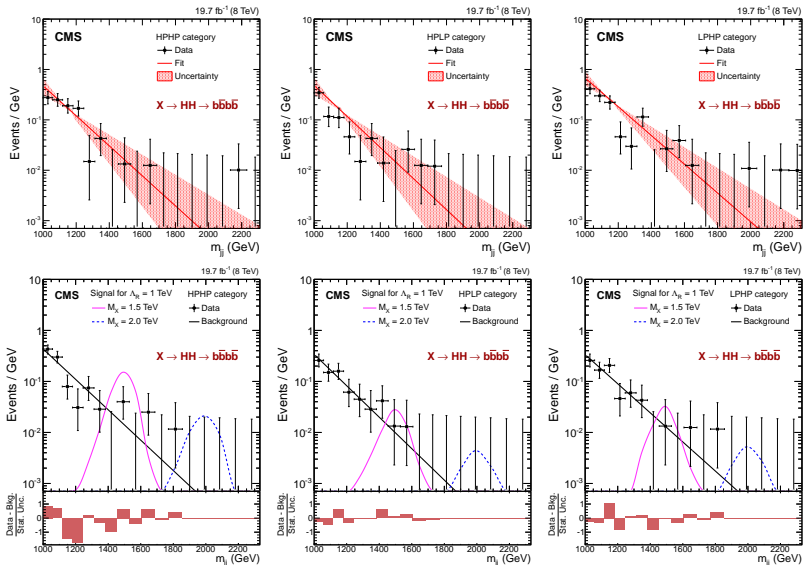
SEARCH FOR RESONANCES DECAYING IN Wh, $Zh \to 2lep. + b\bar{b}$

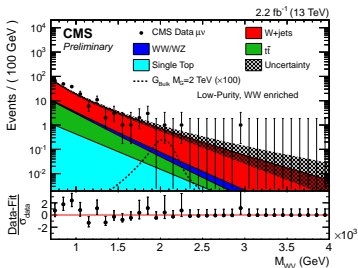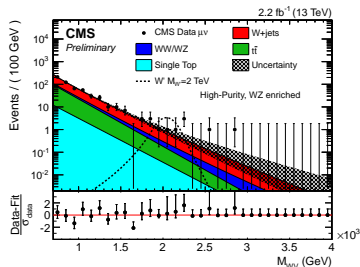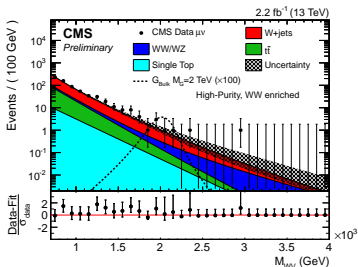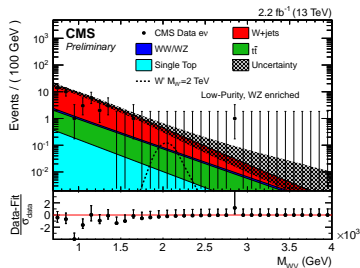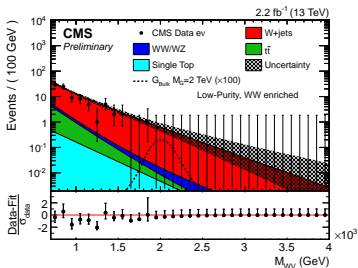# SEARCH FOR RESONANCES DECAYING IN WW, WZ, $ZZ \rightarrow q\bar{q}q\bar{q}$

SEARCH FOR RESONANCES DECAYING IN WW, WZ, $ZZ \to q\bar{q}q\bar{q}$

SEARCH FOR RESONANCES DECAYING IN WW, WZ, $ZZ \to q\bar{q}q\bar{q}$

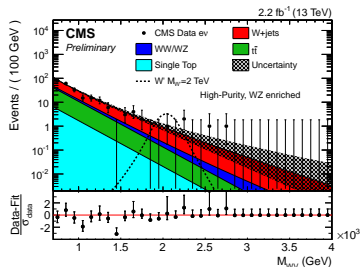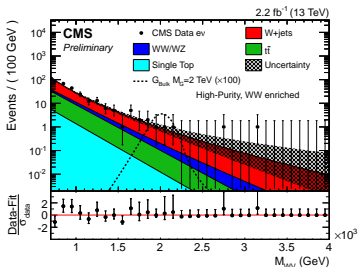## SEARCH FOR RESONANCES DECAYING IN WW, WZ, $ZZ \to q\bar{q}q\bar{q}$

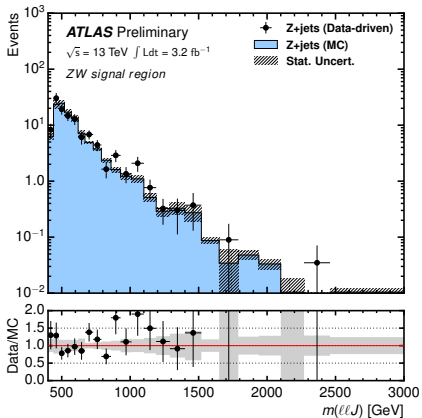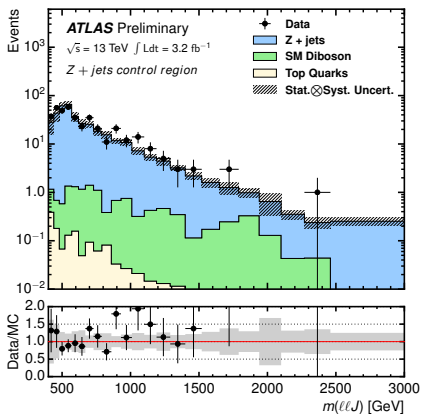# Search for resonances decaying in WZ, $WW \rightarrow \ell\nu q\bar{q}$

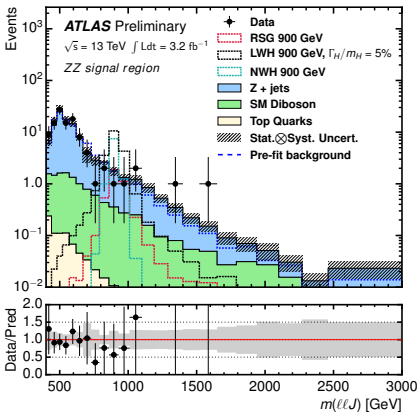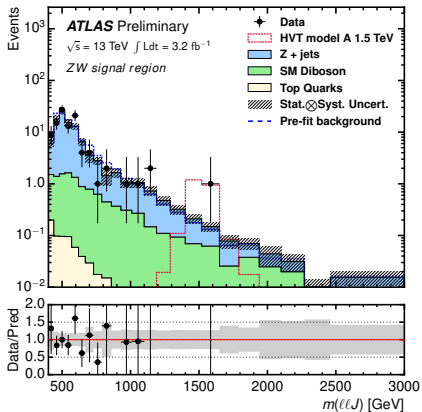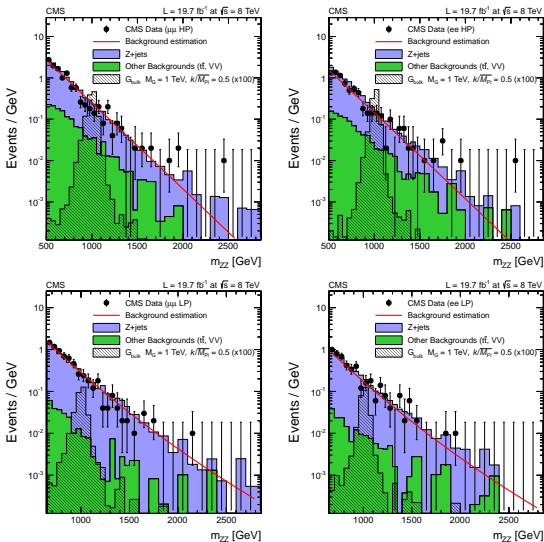## SEARCH FOR RESONANCES DECAYING IN WZ, $WW \to \ell\nu q\bar{q}$

Search for resonances decaying in WZ, $WW \to \ell\nu q\bar{q}$

Search for resonances decaying in $WZ, ZZ \to \ell\bar{\ell}q\bar{q}$

SEARCH FOR RESONANCES DECAYING IN WZ, $ZZ \to \ell\bar{\ell}q\bar{q}$

SEARCH FOR RESONANCES DECAYING IN WZ, $ZZ \to \ell\bar{\ell}q\bar{q}$

SEARCH FOR RESONANCES DECAYING IN WZ, $ZZ \to \nu\bar{\nu}q\bar{q}$