ATLAS Searches for Resonances Decaying to Boson Pairs

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Introduction

Many models beyond SM predict heavy resonances:

- Spin-0 high mass Higgs boson: extended Higgs sector
- Spin-1 new gauge bosons (W', Z'): Heavy Vector Triplets (HVT)
- Spin-2 graviton: warped extra dimensions (Randall-Sundrum) bulk model

Diboson searches in ATLAS:

- **VV → qqqq**, **WV → lvqq, ZV → llqq, vvqq**
- WZ → lvll, ZZ → llll, WW → lvlv, ZZ → llvv
- **VH → qqbb**, lvbb, llbb, vvbb
- **HH → bbbb**, bbγγ, bb$\tau\tau$, γγlvjj
- Zγ → llγ, qqγ
- γγ

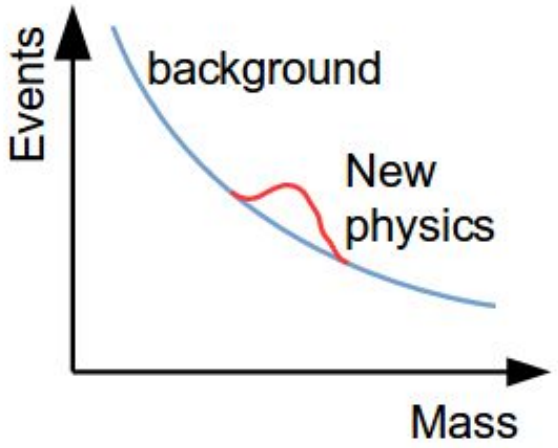
where V = W or Z boson, H = Higgs boson, l = *e*, μ

Concentrate on latest 2015+2016 data-set **exotics group analyses**!

Techniques

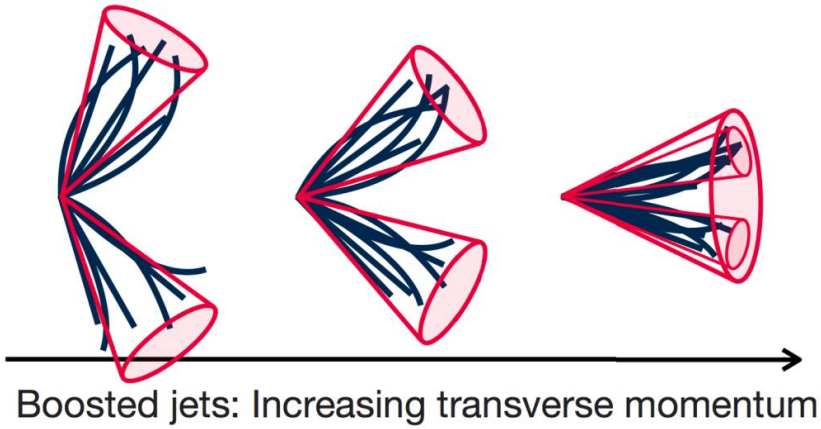
Search for narrow resonances:

- Reconstruct decay products of resonance X
- Look for peak in invariant mass spectrum over a smooth background



Boson decay topology:

- **Resolved**: optimization for low mass resonances; reconstruct two small-R jets (anti-kt *R*=0.4), j
- **Merged**: optimization for high mass resonances; decay products are detected as one object, a boosted large-R jet (anti-kt *R*=1.0), J

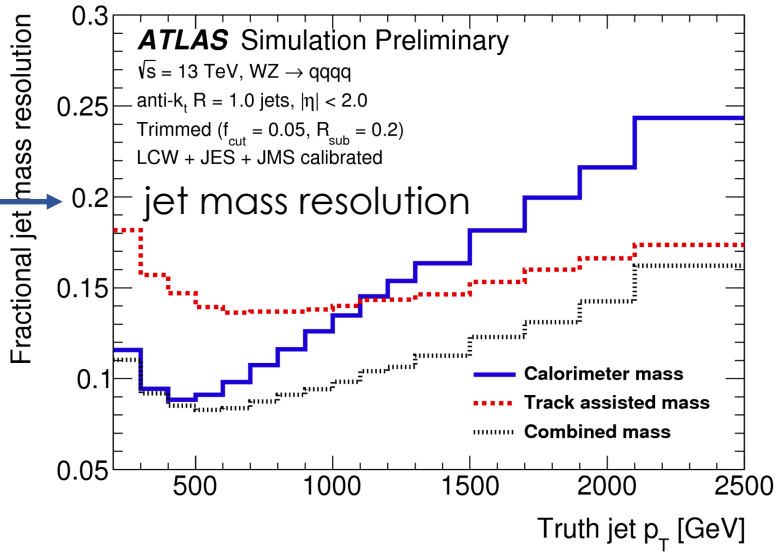


Techniques: Boosted boson tagging

*ATLAS-CONF-2016-035
**ArXiv:1305.0007, 1409.6298; JHEP 05 (2016)117, etc.

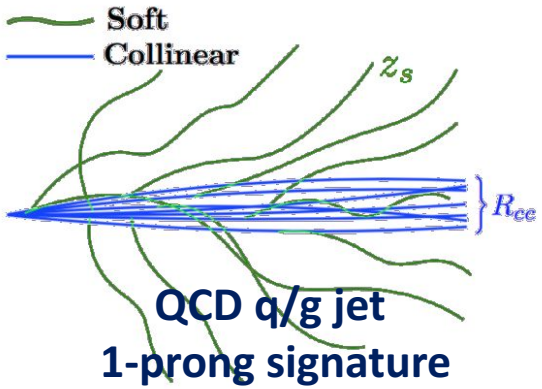
W/Z boson tagging:

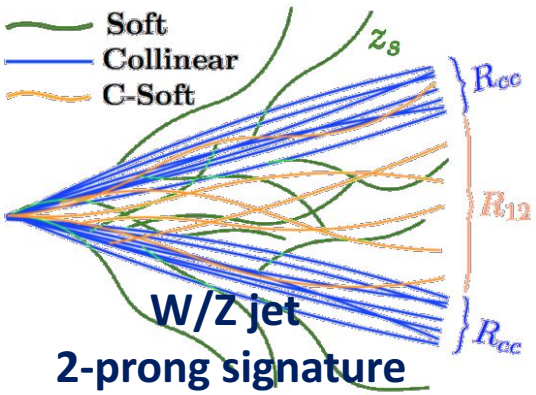
- Mass requirements: consistent with Z or W within ±15 GeV
- NEW [VH → qqbb] mass computed from calo and tracking information. Figure demonstrates the significant improvement in resolution achieved by the combined mass definition [*]
- "D_2" substructure variable [**] consistent with 2 prong decay. The goal is to distinguish: **QCD q/g jets (1-prong) vs. W/Z jets (2-prong)**



Higgs boson tagging:

- b-tagging on associated anti-kt track-jets with R=0.2
- Mass requirements





VV → qqqq

ATLAS-CONF-2016-055

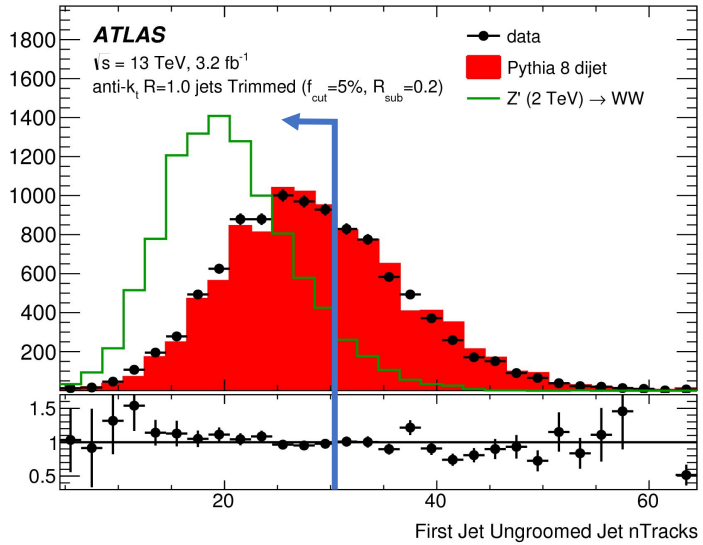
VV searches in fully hadronic final state (15.5 fb^{-1})

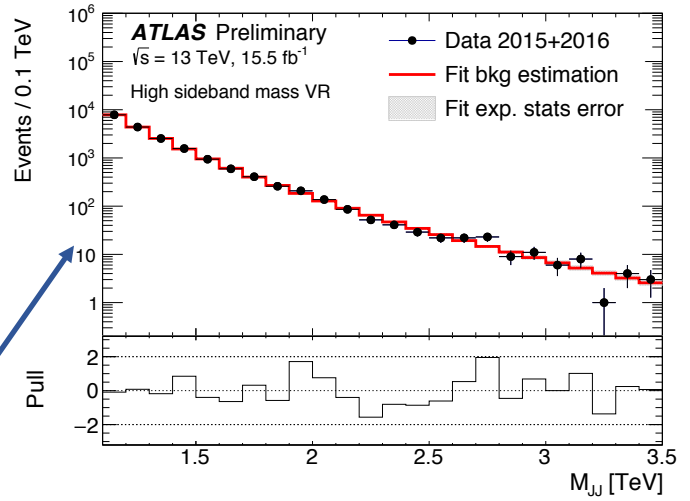
- V → qq identified as 1 large-R jet

- Merged regime only:
  - P_T > 450 and 200 GeV
  - W/Z boson tagged

- Need for additional QCD rejection:
  - Number of tracks associated to the jet: N_{trk}<30
  - $|\Delta y_{JJ}|$<1.2
  - $(P_{T,1}-P_{T,2})/(P_{T,1}+P_{T,2})$<0.15

- QCD multi-jet background is dominant:
  - Data-driven estimation
  - Double polynomial for shape
  - Tested on dijet MC and *data validation regions*



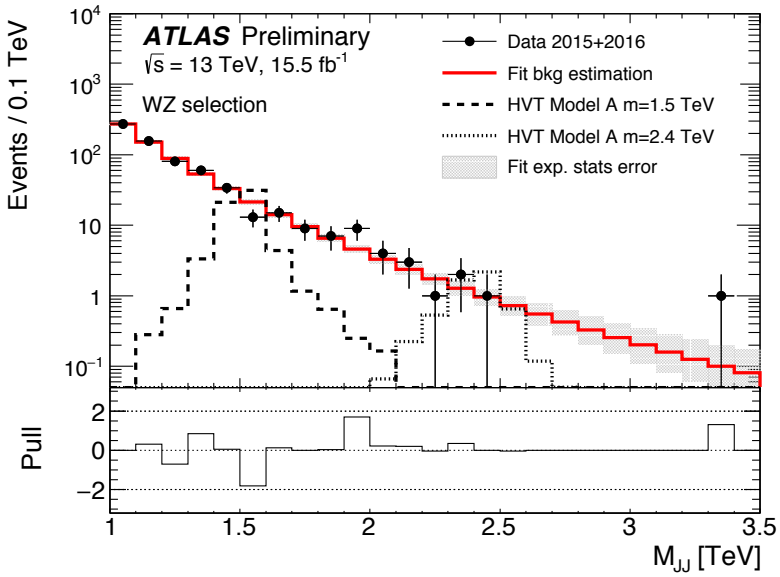


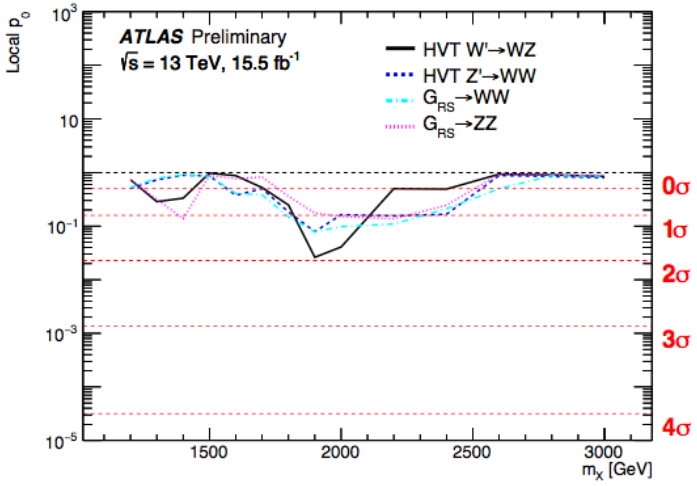
VV → qqqq: Results

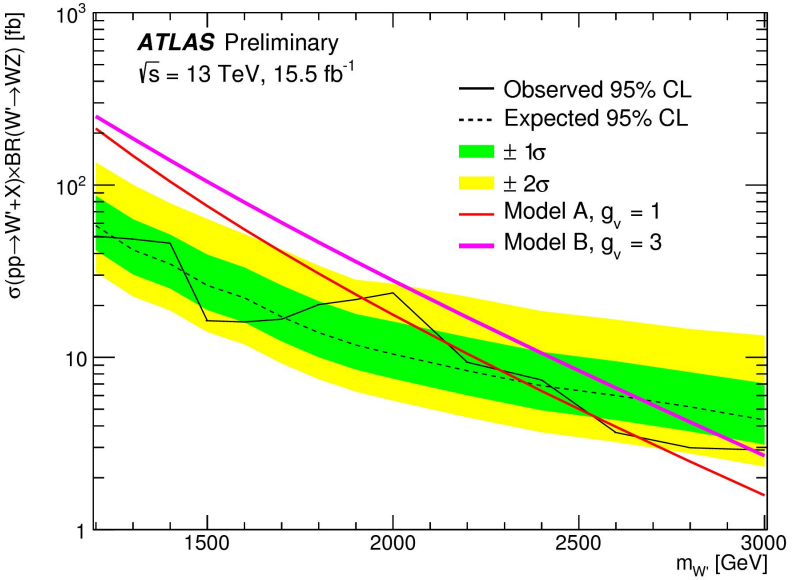
ATLAS-CONF-2016-055

- Tested WW, WZ and ZZ signal regions
- No significant excess found
- Largest deviation 1.9 σ local in HVT W' to WZ hypothesis with m(W')=1.9 TeV

	HVT W' g_V=1 (g_V=3) $M_{W'}$ [TEV]	HVT Z' g_V=1 (g_V=3) $M_{Z'}$ [TEV]
95% CL exclusion	1.2-1.9 (1.2-1.3)	1.2-1.8 (1.2-1.9)





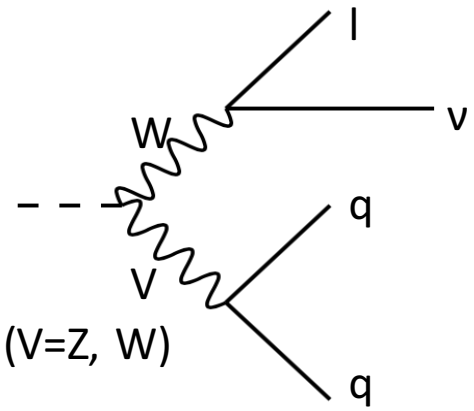


WV → lvqq

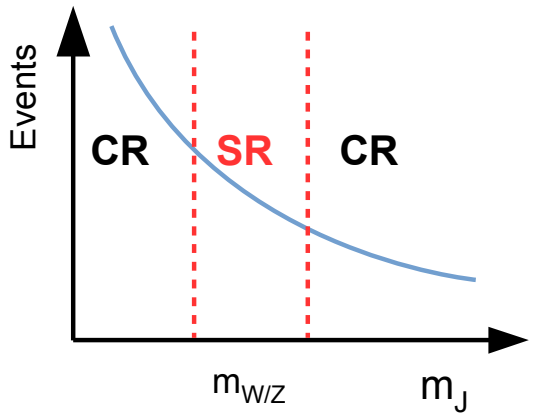
ATLAS-CONF-2016-062

W → lν, V → qq (13.2 fb^{-1})

- W → lν: E_T^{miss} > 100 GeV, $p_T(lν)$ > 200 GeV
- V → qq: large R-jet with highest p_T; define high/low purity categories using D_2



- *Signal Region (SR):* the fat jet m_J within 15 GeV of the W/Z mass window
- *Control Regions (CR):* ttbar (b-tagged small-R jet and large-R jet ΔR>1.0); W+jets (m_J in sideband region)



- Dominant background coming from W+jets and ttbar
  - The background shapes (W+jets, $t\bar{t}$) are modeled using simulated events.
  - Their normalizations are determined from a combined fit to the events in the signal and control regions

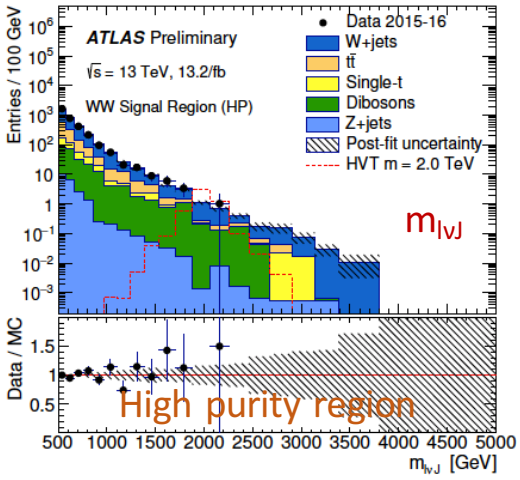
- Final discriminant: WW/WZ invariant mass $m_{lνJ}$

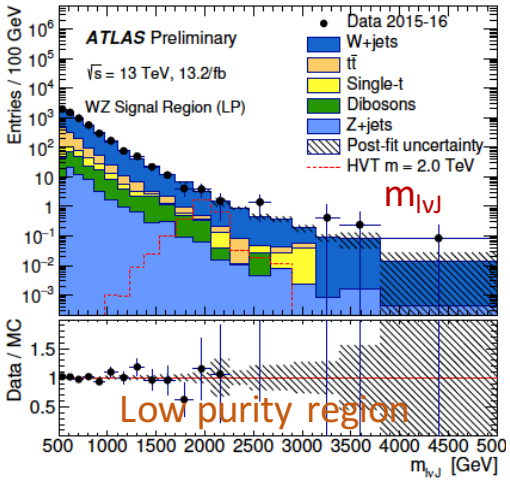
WV → lvqq: Results

ATLAS-CONF-2016-062

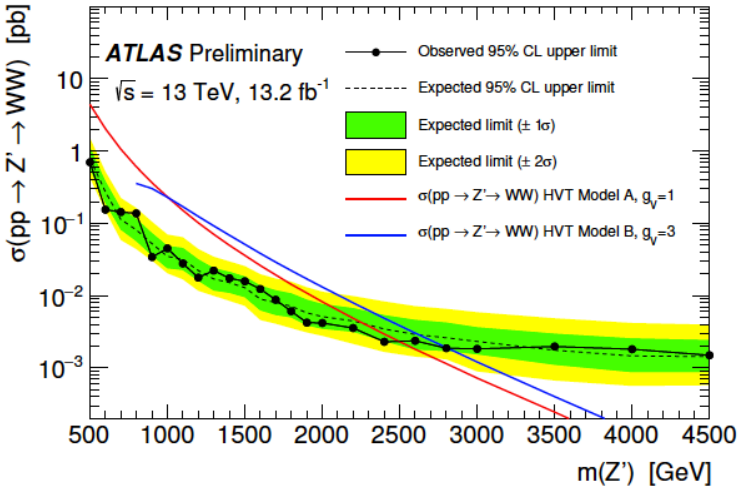
m_{lvJ} distributions in SR:

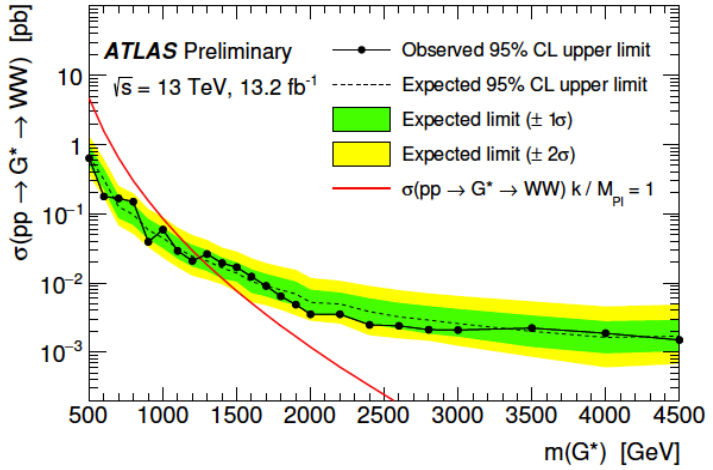
- no excess in data over background is observed





	HVT W' g_V=1 (g_V=3) $M_{W'}$ [TEV]	HVT Z' g_V=1 (g_V=3) $M_{Z'}$ [TEV]	RS G* M_{G^*} [TEV]
95% CL exclusion	0.5-2.4 (0.5-2.54)	0.5-2.5 (0.5-2.81)	0.5-1.24





ZV → llqq

ATLAS-CONF-2016-082

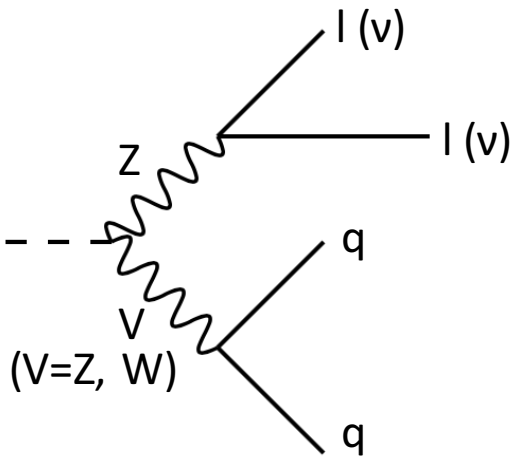
Z → ll, V → qq (13.2 fb^{-1})

- Z → ll: Two isolated electrons or muons: m_{ll} within Z mass window
- V → qq:
  - merged analysis - large R-jet with highest p_T > 200 GeV; define high/low purity categories using D_2
  - resolved analysis - two small-R jets; define tagged (with 2 b-tagged jets) and untagged category (with fewer than 2 b-tagged jets)

- Neutral heavy Higgs from VBF production: two additional small-R jets m_{jj}^{tag} > 600 GeV and $|\Delta\eta_{jj}^{tag}|$ > 3.1, if not: ggF candidates

- Dominant background coming from Z+jets, top-quark and diboson

- Final discriminant: ZZ/ZW invariant mass m_{llJ} *and* m_{lljj}



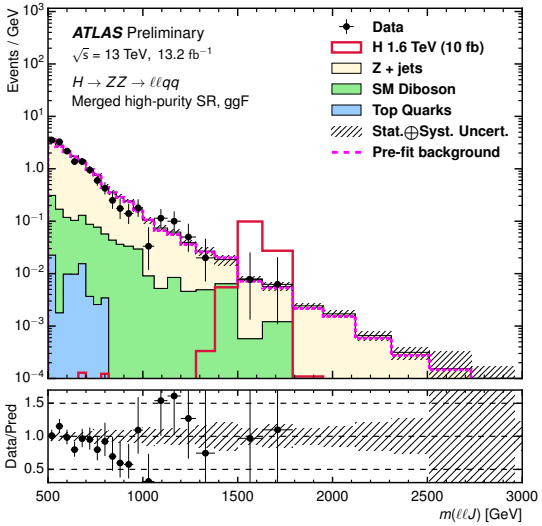
ZV → llqq: Results

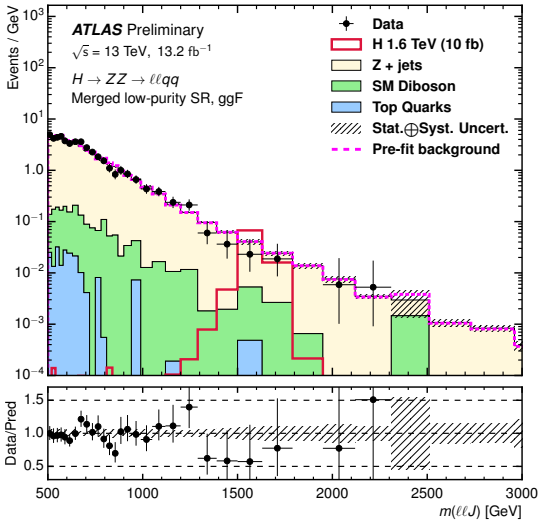
ATLAS-CONF-2016-082

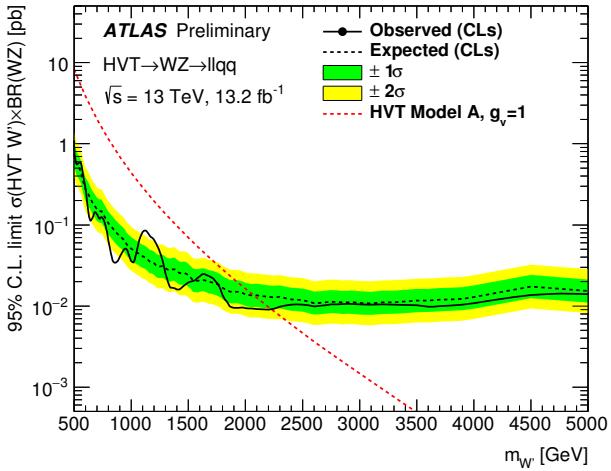
m_{llJ} and m_{lljj} distributions in SR:

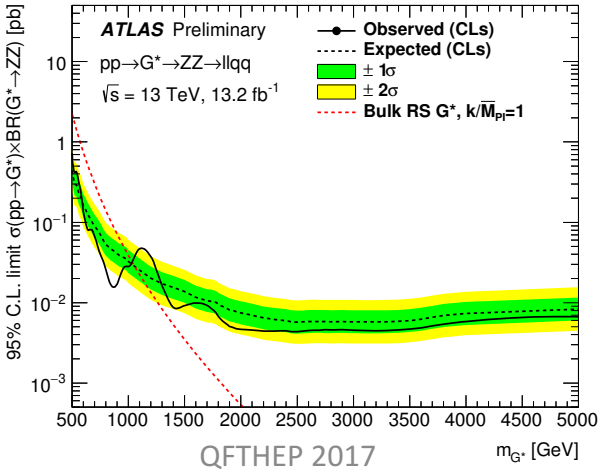
- The data are found to be consistent with the background expectations

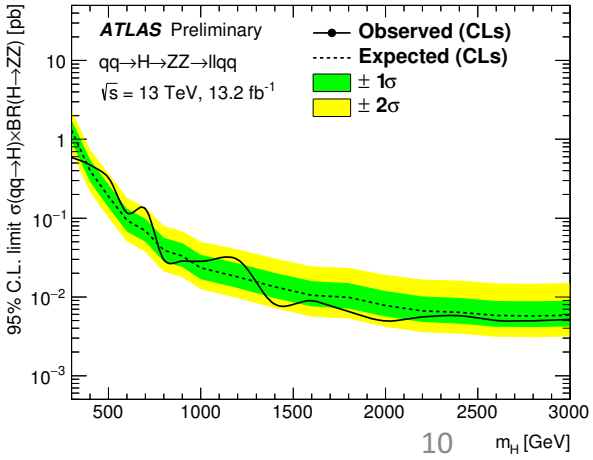
	HVT W' g_V=1 $M_{W'}$ [TEV]	RS G* M_{G^*} [TEV]
95% CL exclusion	0.5-2.225	0.5-1.035









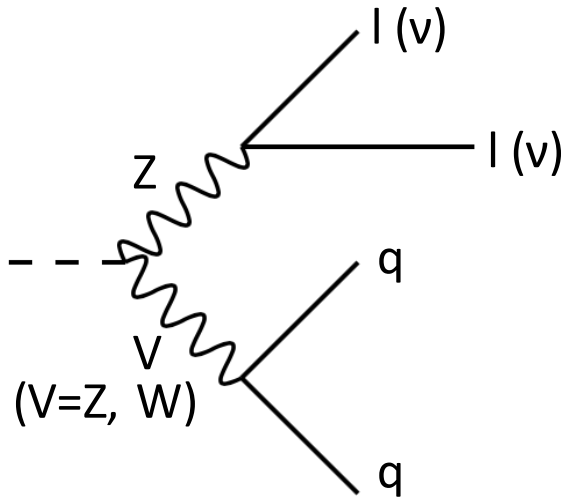


ZV → ννqq

ATLAS-CONF-2016-082

Z → νν, V → qq (13.2 fb^{-1})

- Z → νν: E_T^{miss} > 250 GeV; vetoing events with charged leptons
- V → qq: leading large-R jet with high/low purity selection categories defined by D_2



- Merged regime only
- Multi-jet removal:
  - p_T^{miss} > 50 GeV
  - $(\Delta\phi(\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, \vec{p}_{\mathrm{T}}^{\mathrm{miss}}) < 1$
  - $\min[\Delta\phi(\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, \mathrm{small}-R\ \mathrm{jet})] > 0.4$
- Main backgrounds: Z+jets, W+jets and ttbar estimated from simulation
- Final discriminant: $m_{\mathrm{T}} = \sqrt{(E_{\mathrm{T},J} + E_{\mathrm{T}}^{\mathrm{miss}})^2 - (\vec{p}_{\mathrm{T},J} + \vec{E}_{\mathrm{T}}^{\mathrm{miss}})^2}$, where $E_{\mathrm{T},J} = \sqrt{m_J^2 + p_{\mathrm{T},J}^2}$.

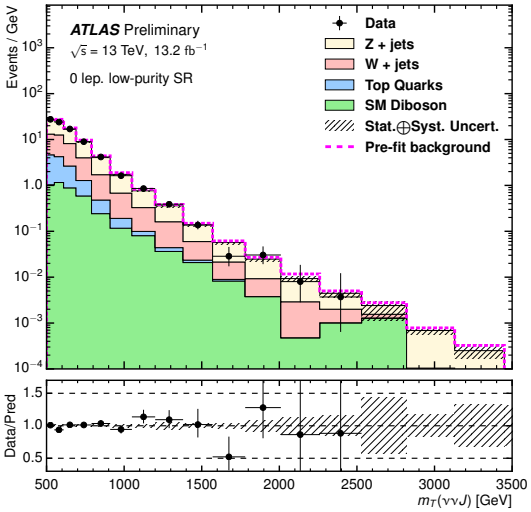
ZV → vvqq: Results

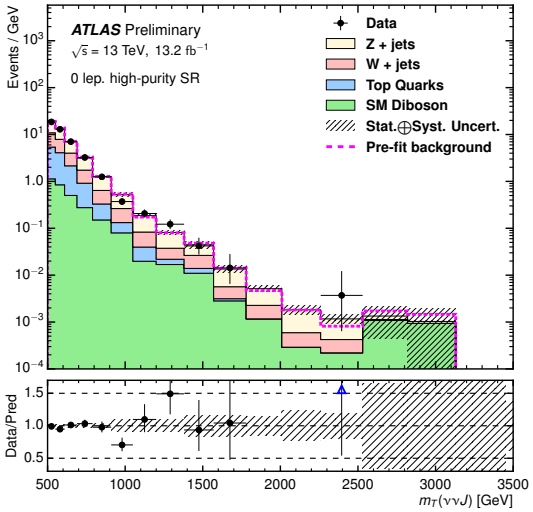
ATLAS-CONF-2016-082

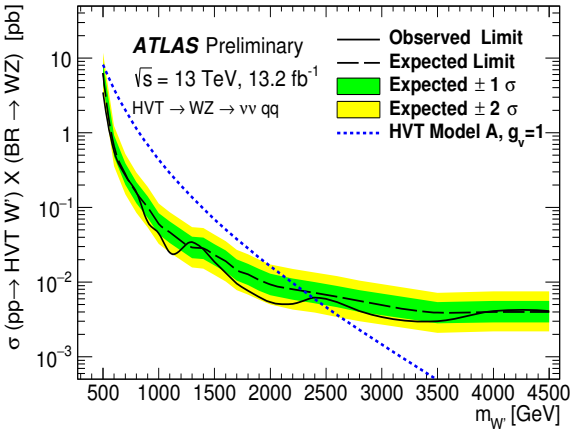
$m_T(vvJ)$ in SR:

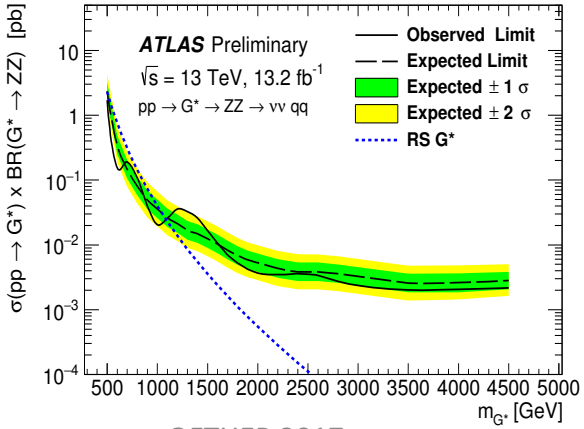
- No significant excess in data over backgrounds is observed

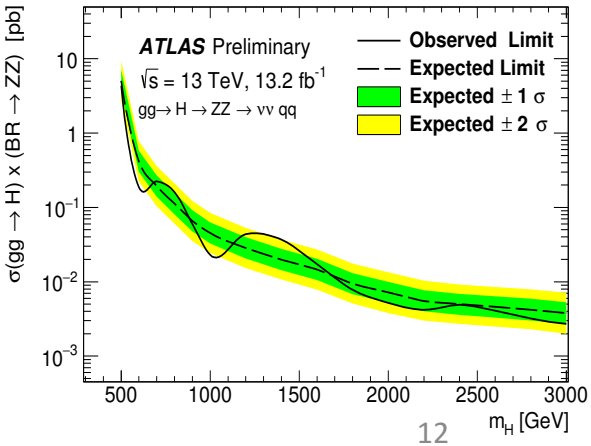
	HVT W' g_V=1 $M_{W'}$ [TEV]	RS G* M_{G^*} [TEV]
95% CL exclusion	0.5-2.4	0.5-1.1



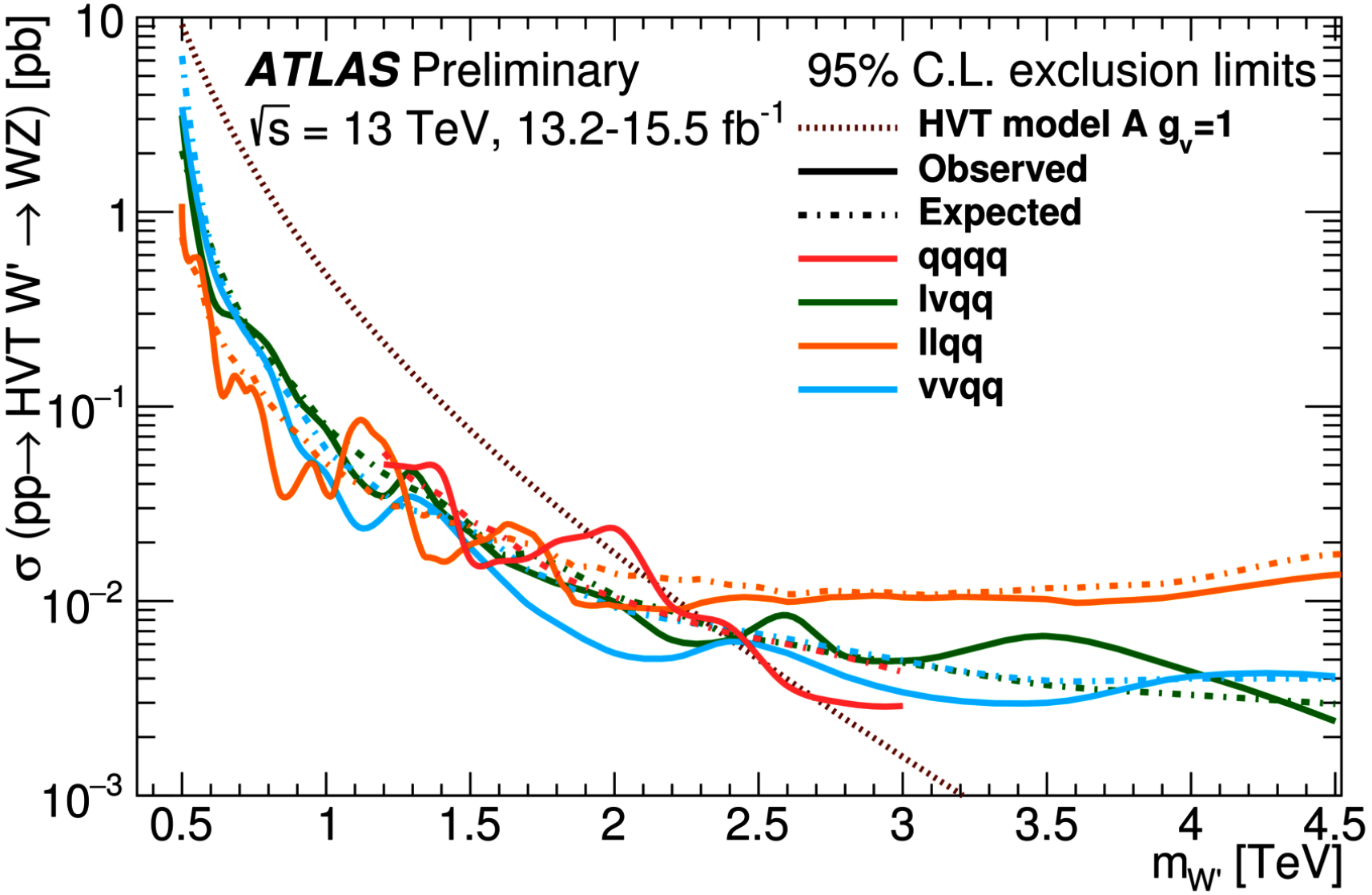








W’ → WZ: Summary

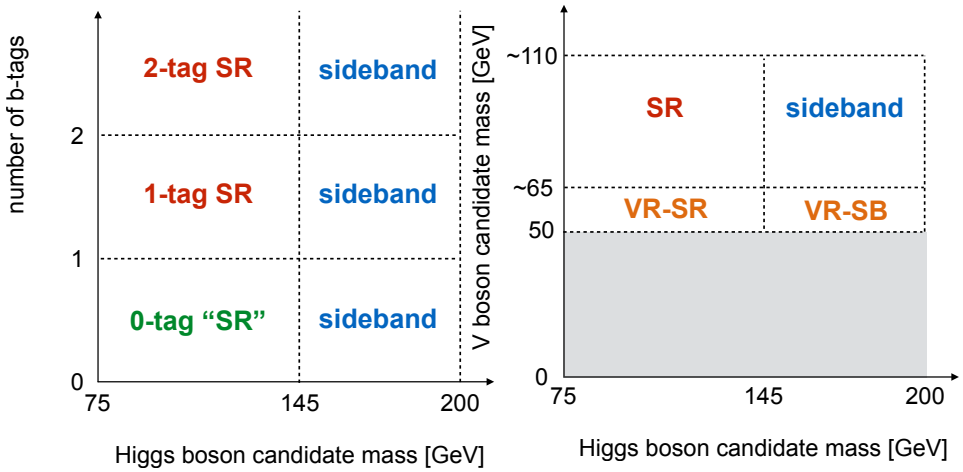

ATLAS Preliminary
√s = 13 TeV, 13.2-15.5 fb-1
95% C.L. exclusion limits
HVT model A gv=1
Observed
Expected
qqqq
lvqq
llqq
vvqq
σ (pp→ HVT W' → WZ) [pb]
10
1
10−1
10−2
10−3
0.5
1
1.5
2
2.5
3
3.5
4
4.5
mW' [TeV]

VH → qqbb

ATLAS-CONF-2017-018

H → bb, V → qq (36.1 fb^{-1})

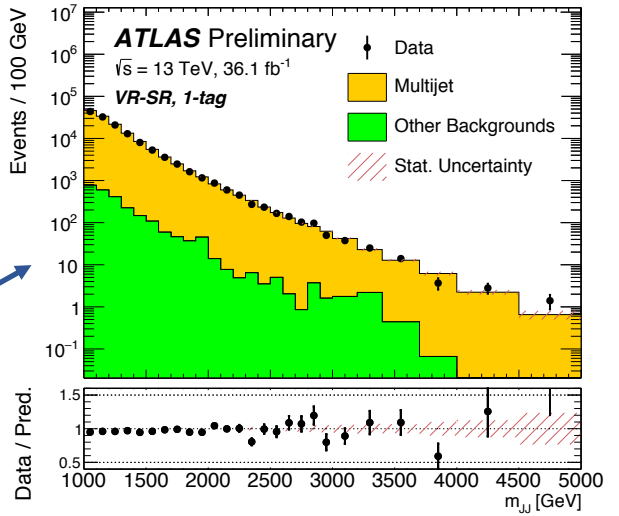
- V → qq (H → bb) identified as 1 large-R jet



- Only merged regime

- Uses combined mass algorithm for boson tagging

- Backgrounds: multi-jet (90%), ttbar (10%), V+jets (<1%)
  - Background shape: extracted from 0-btag "SR"
  - Normalization and kinematic reweighing corrections: extracted from sidebands
  - Verify background predictions in VR-SR regions



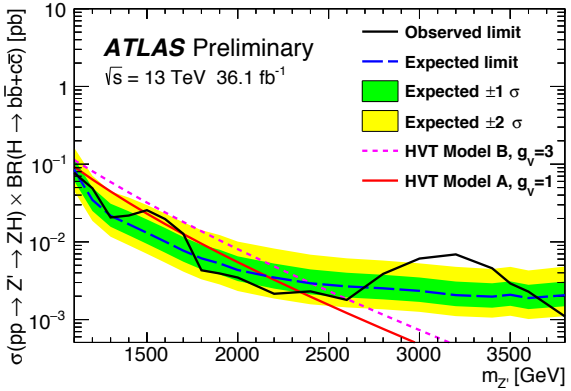
- Final discriminant: ZH/WH invariant mass m_{JJ}

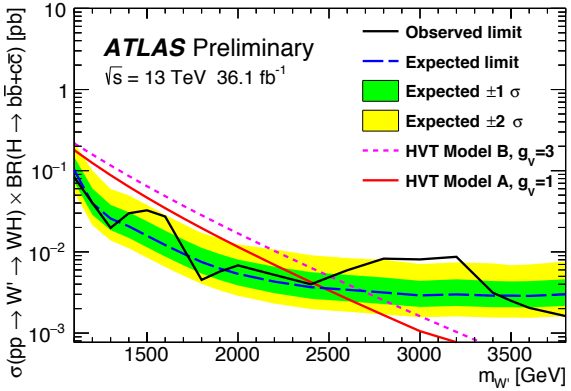
VH → qqbb: Results

ATLAS-CONF-2017-018

- Largest excess at ~ 3.0 TeV with a local significance of 3.3 σ and a global significance of 2.2 σ

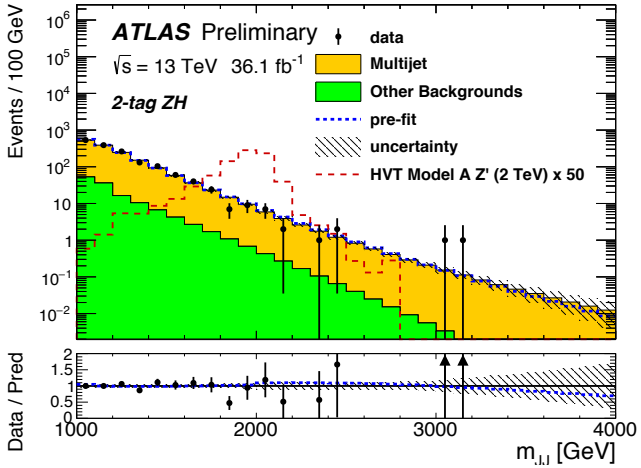
	HVT W' g_V=1 (g_V=3) $M_{W'}$ [TEV]	HVT Z' g_V=1 (g_V=3) $M_{Z'}$ [TEV]
95% CL exclusion	1.1-2.4 (1.1-2.5)	1.1-1.48; 1.7-2.35 (1.1-2.6)

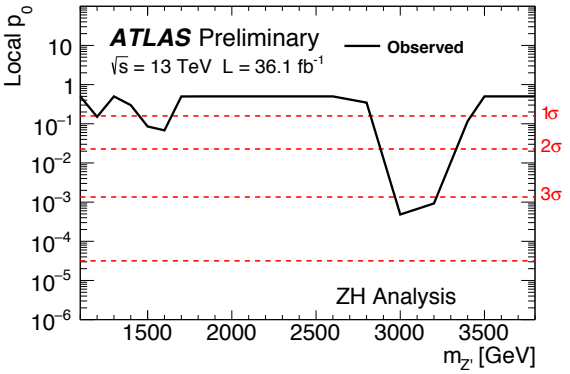


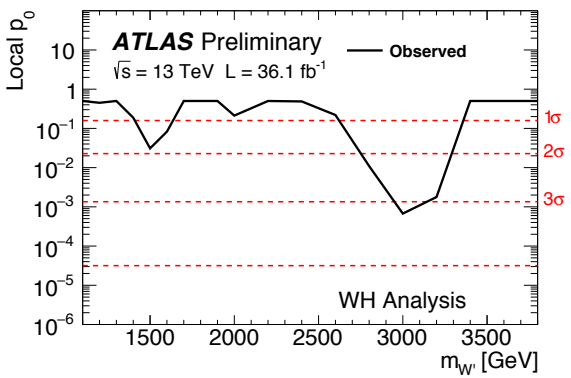


local significance: 3.3 σ
global significance: 2.2 σ

local significance: 3.3 σ
global significance: 2.2 σ







HH → bbbb

H → bb, H → bb (13.3 fb^{-1})

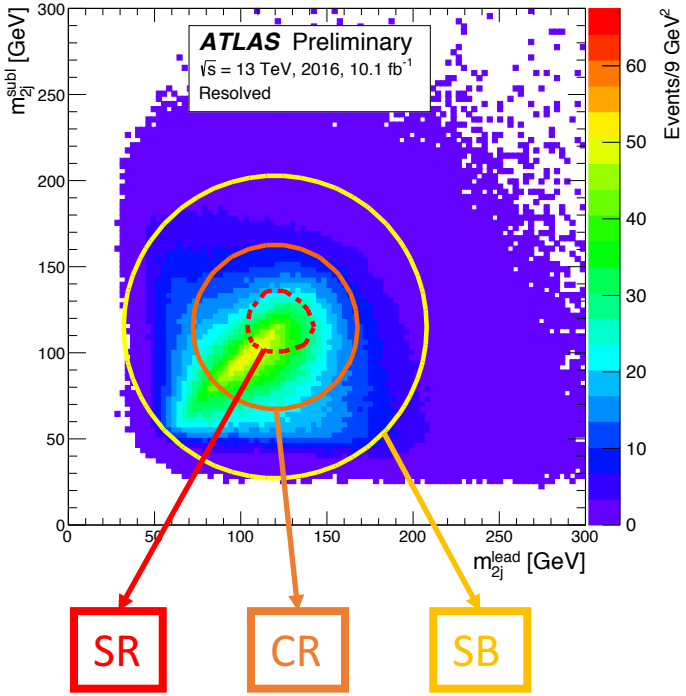
- H → bb identified as 1 large-R jet or 2 small-R jets

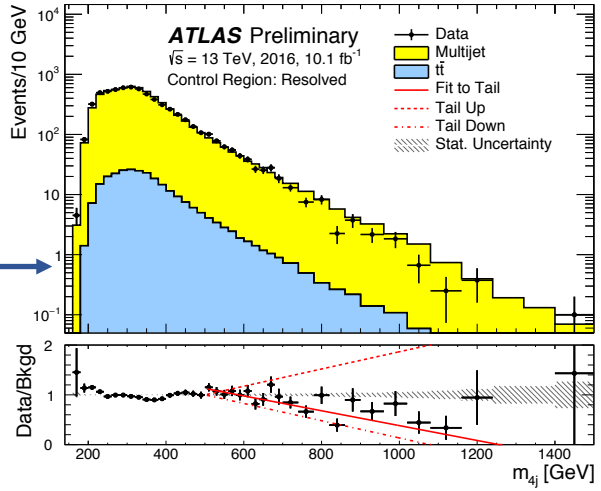
- Resolved analysis:
  - 4 small-R (R = 0.4) b-tagged anti-kt jets

- Boosted analysis:
  - 2 large-R (R = 1.0) anti-kt jets
  - at least 2 b-tagged ghost associated track jets

- Backgrounds: multi-jet (90%), ttbar (10%)
  - multi-jet estimated with (2-tag (0-tag) SR) * $\mu_{sideband}$
  - validated in CR with (2-tag (0-tag) CR) * $\mu_{sideband}$
  - Resolved: $\mu_{sideband}$ from ratio (4-tag / 2-tag)
  - Boosted: $\mu_{sideband}$ corresponds to ratio (2,3,4-tag / 0-tag)

ATLAS-CONF-2016-049



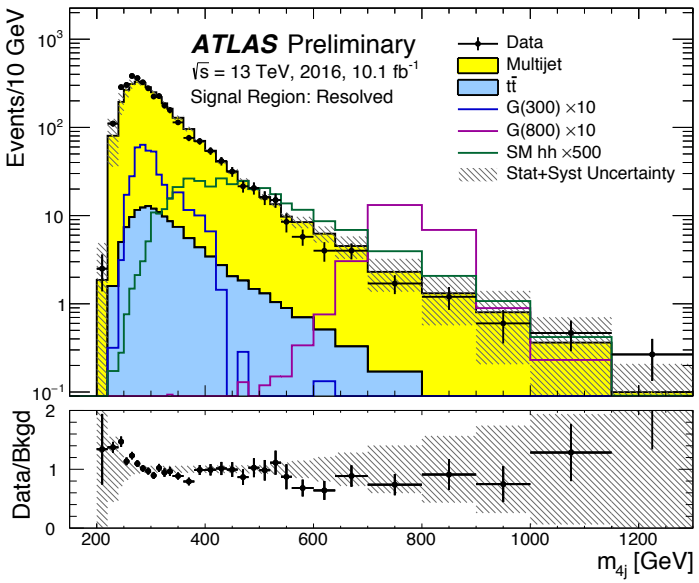


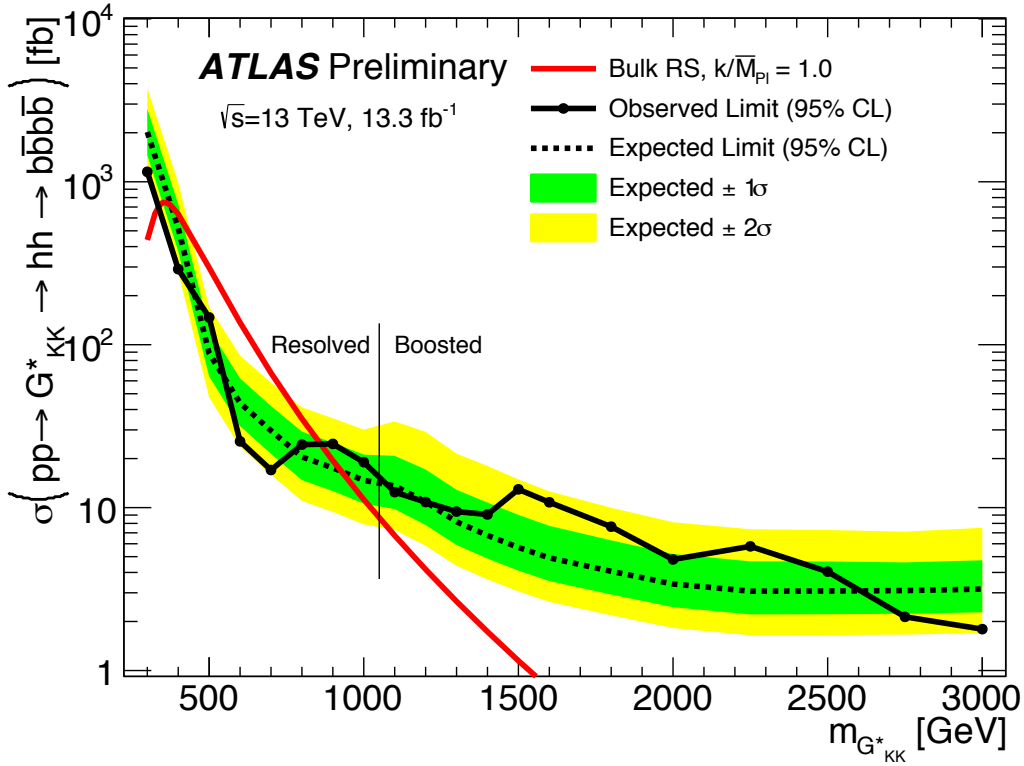
HH → bbbb: Results

ATLAS-CONF-2016-049

- No significant data excess is observed above the estimated background

	RS G* M_{G^*} [TEV]
95% CL exclusion	0.36-0.86





Conclusion

- Presented several analyses using the 13-36 fb^{-1} of 2015+2016 data
- No significant excess observed in most channels
- Advanced tagging techniques help to effectively reject QCD background
- Many other results with the full 36 fb^{-1} dataset are expected to come out this summer
- Waiting for more data!

Channel	Lumi (fb^{-1})	Documentation	Date
VV → qqqq	15.5	ATLAS-CONF-2016-055	04.08.2016
WV → lvqq	13.2	ATLAS-CONF-2016-062	30.08.2016
ZV → llqq	13.2	ATLAS-CONF-2016-082	04.08.2016
ZV → vvqq	13.2	ATLAS-CONF-2016-082	04.08.2016
VH → qqbb	36.1	ATLAS-CONF-2017-018	21.03.2017
HH → bbbb	13.3	ATLAS-CONF-2016-049	04.08.2016

Back-up

Techniques: Grooming

*JHEP02(2010)084

- Boosted large-R jets can be easily contaminated by pileup interactions
- Jet "Grooming": remove those pileup contaminations, improve the resolution of V/H-jet mass
- ATLAS "grooming": **Trimming [*] algorithm:** re-cluster sub-jets with R=0.2 cone, and remove sub-jets with $p_T^{subjet} / p_T^{jet} < 0.05$