COLUMBIA UNIVERSITY
IN THE CITY OF NEW YORK

Searches for Heavy Resonances Decaying to a W or Z Boson and a Higgs Boson with the ATLAS experiment

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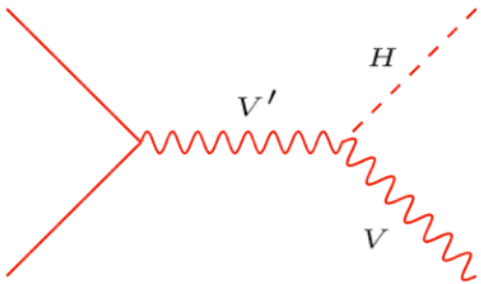
ATLAS EXPERIMENT

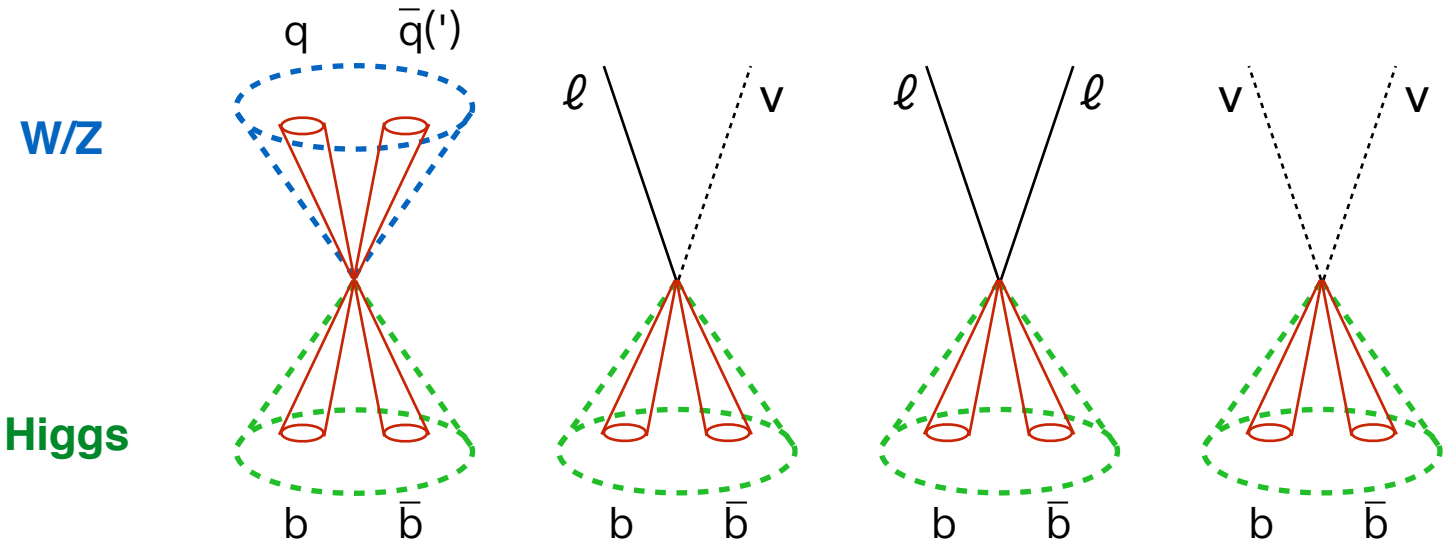
What are we searching for?



- A solution to the **naturalness problem**:
  - New physics at the TeV energy scale, reachable at the LHC.
  - BSM models typically predict new heavy vector resonances: **W'** and **Z'**.
- Heavy vector resonances:
  - **W'** and **Z'** can be expected to couple to W/Z and Higgs bosons.
  - Results can be interpreted in the context of a simplified model with additional SU(2) vector triplet: Heavy Vector Triplet (HVT) **V'**. **JHEP09(2014)060**
  - In this talk: ATLAS searches in the WH and ZH decay channels.
    - Using 2015+2016 dataset with a luminosity of 36.1 fb^{-1} at $\sqrt{s}$ = 13 TeV.
  - 2HDM interpretation also included for neutral resonances: not covered here.

➡ Introduction to Heavy Vector Triplets in C. Vernieri's talk.

The VH channels

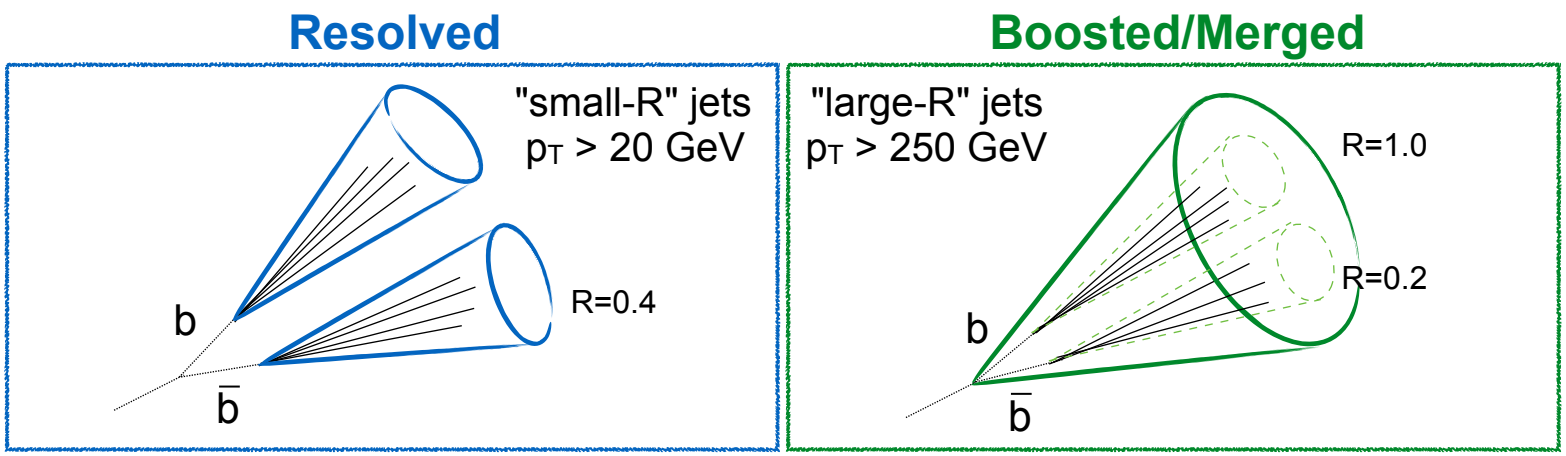


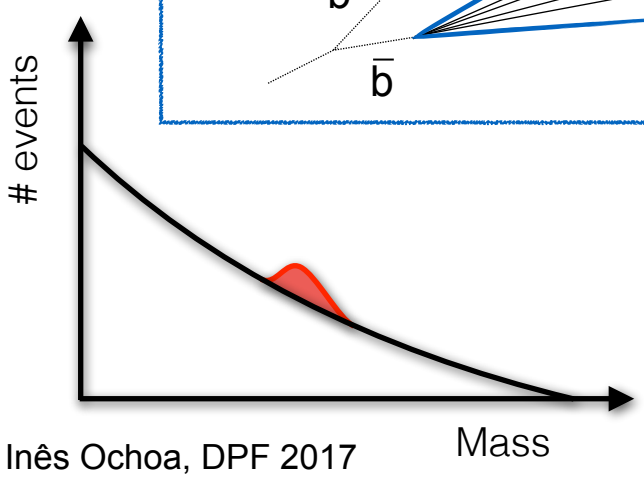
- Different analyses target different **W and Z boson decays** and the **Higgs boson** decay to a pair of b-quarks:
  - The largest branching fraction of the Standard Model Higgs, of ~60%.
- Suite of analyses built such that there is no event overlap.

arXiv:1707.06958, **ATLAS-CONF-2017-055**

Search strategy

- Resonance mass range covered: from 500 GeV to 5 TeV!
- Boost of the decay products will depend on the mass of the new resonance.
- Two regimes are targeted for the Higgs reconstruction:





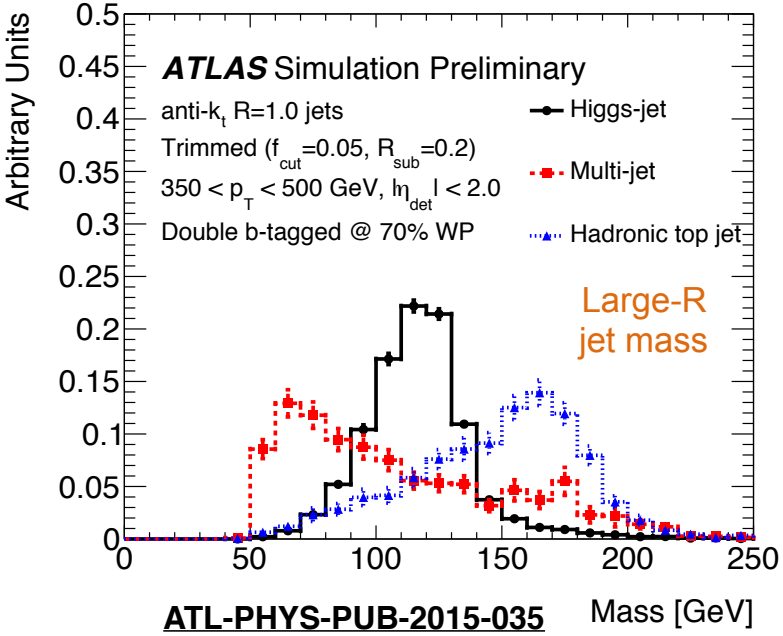
Bump search: the search strategy is to scan the invariant or transverse mass distributions of WH and ZH for evidence of a resonant excess.

The Higgs boson as a discovery tool

- **Invariant mass** of large-R jet or di-jet system compatible with Higgs boson mass.
  - Mass resolutions improved by correcting for semi-leptonic decays of the b-hadrons.
  - Large-R jets further improved at high momentum by combining calorimeter and tracking information:

$$m_J \equiv w_{\text{calo}} \times m_J^{\text{calo}} + w_{\text{track}} \times \left(m_J^{\text{track}} \frac{p_{\text{T}}^{\text{calo}}}{p_{\text{T}}^{\text{track}}} \right)$$

- **b-tagging**: at least one b-tagged (track-)jet associated with the Higgs jet.
  - Events with only one b-tag are crucial at high boosts, as track-jets start merging.



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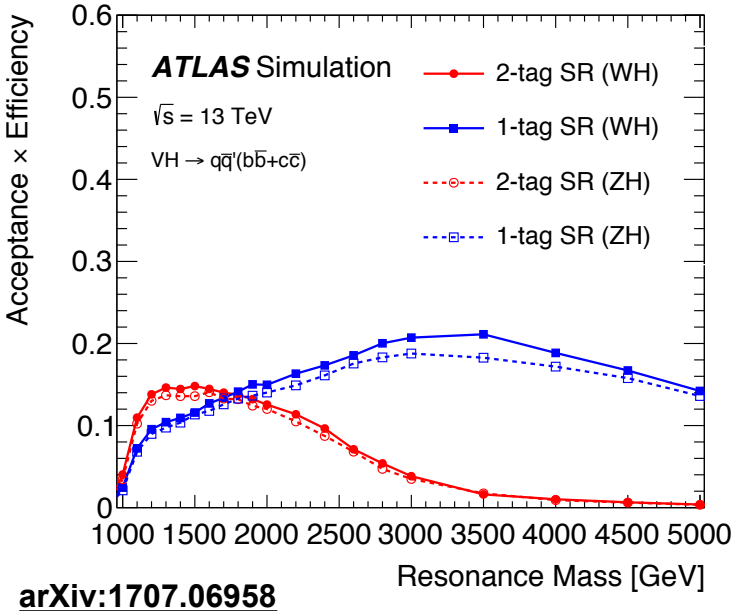
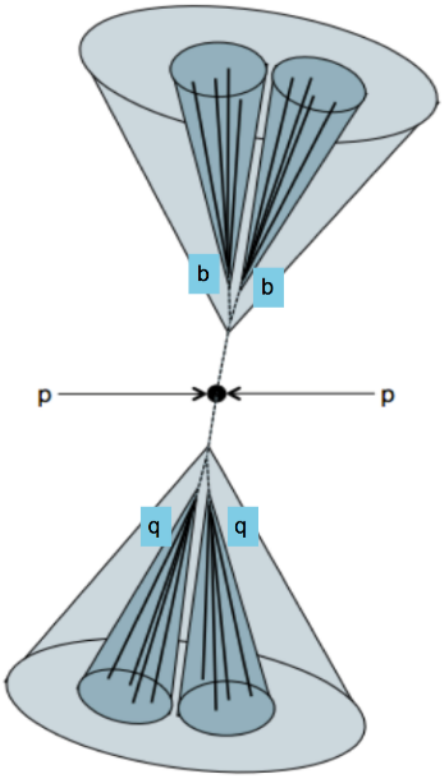


arXiv:1707.06958

V'→VH in the all-hadronic final state

- Profits from the large branching ratios of W/Z to quarks.
  - BR(W→qq') ~ 67% and BR(Z→qq) ~ 69%
- Only boosted scenario is considered for this final state:
  - Two large-R jets required in the event: higher mass jet is assigned as Higgs candidate.
- Multijet QCD processes are the main background to this search (>90%).
  - Strong rejection coming from W/Z and Higgs jet substructure cuts and b-tagging.
  - Can't rely on simulation: large cross-sections coupled with low background efficiencies.
  - **A data-driven method is used instead.**
- Top-pair and V+jets estimated from simulation.



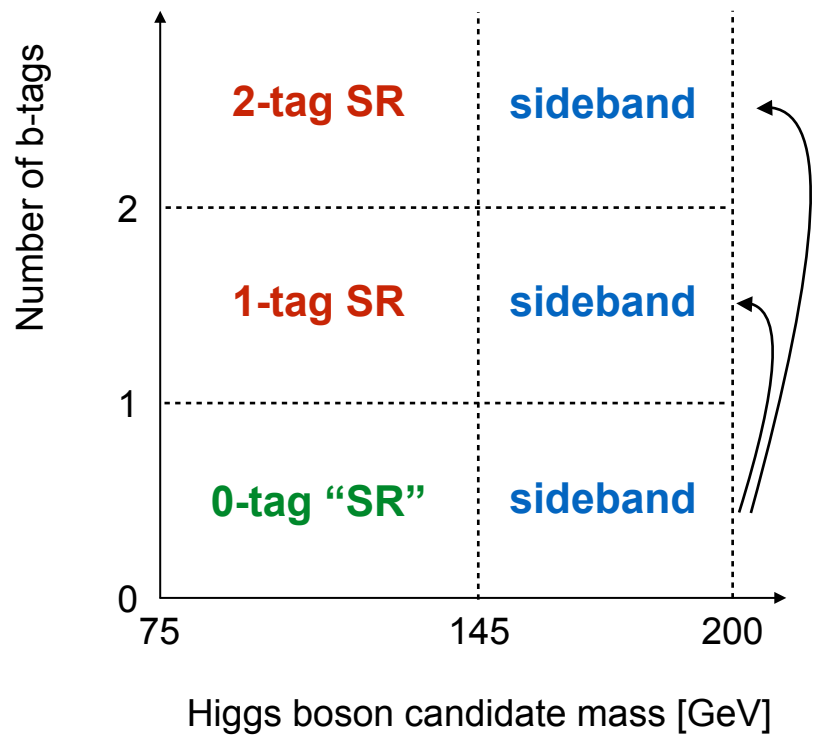
Higgs-tagging:
$75 < m_J < 145$ GeV
b-tagging @ 77% efficiency
W/Z-tagging at 50% efficiency:
p_T-dependent mass window
p_T-dependent D_2 selection
(two-prong decay structures)
JHEP12(2014)009

V'→VH in the all-hadronic final state

- **Signal regions:**
  - **2 channels** depending on mass of vector-boson candidate: WH or ZH.
  - **1-tag and 2-tag categories** for the #b-tagged jets associated with Higgs jet.

- **Background estimation:**
  1. Extract template from region with **0-tags** and normalization from **high-mass sidebands** of the "Higgs".

$$\mu_{\text{Multijet}}^{1(2)-\text{tag}} = \frac{N_{\text{Multijet}}^{1(2)-\text{tag}}}{N_{\text{Multijet}}^{0-\text{tag}}} = \frac{N_{\text{data}}^{1(2)-\text{tag}} - N_{t\bar{t}}^{1(2)-\text{tag}} - N_{V+\text{jets}}^{1(2)-\text{tag}}}{N_{\text{data}}^{0-\text{tag}} - N_{t\bar{t}}^{0-\text{tag}} - N_{V+\text{jets}}^{0-\text{tag}}}$$



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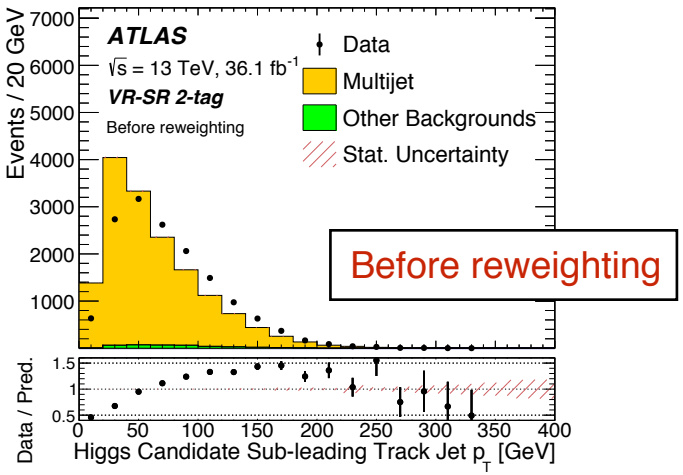

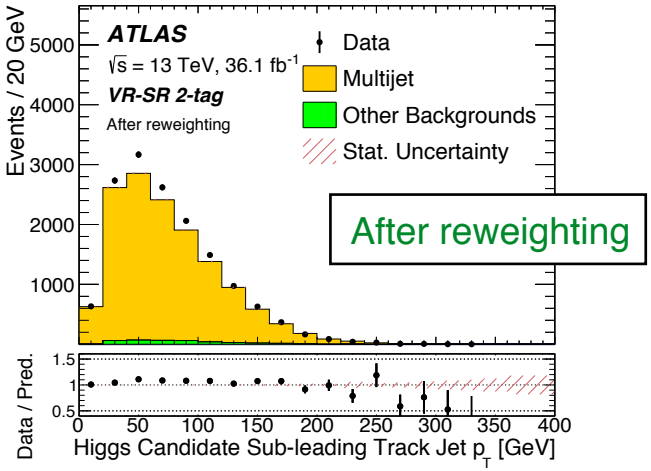

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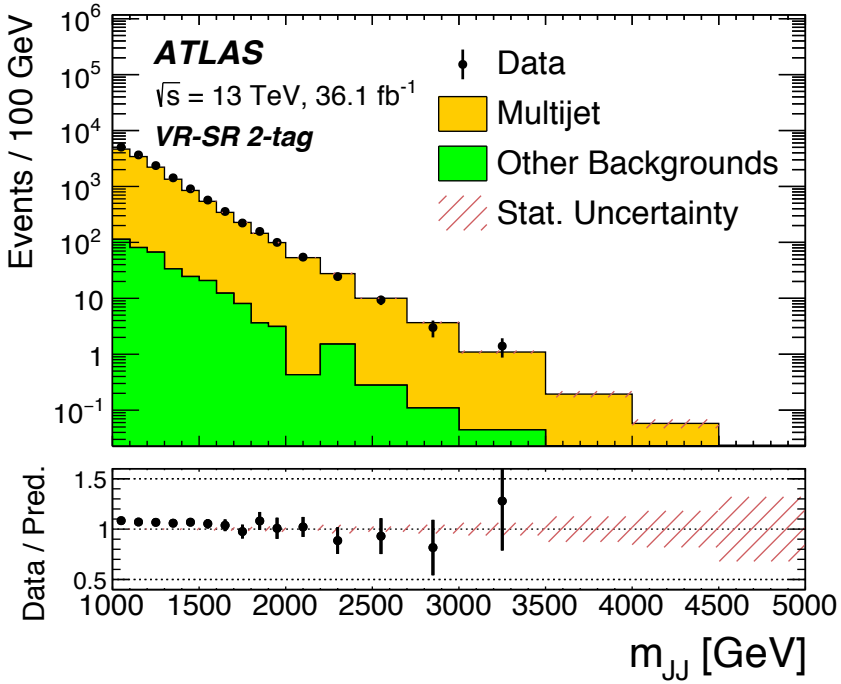
  3. Validation and shape uncertainties in multi-jet from **validation regions**.



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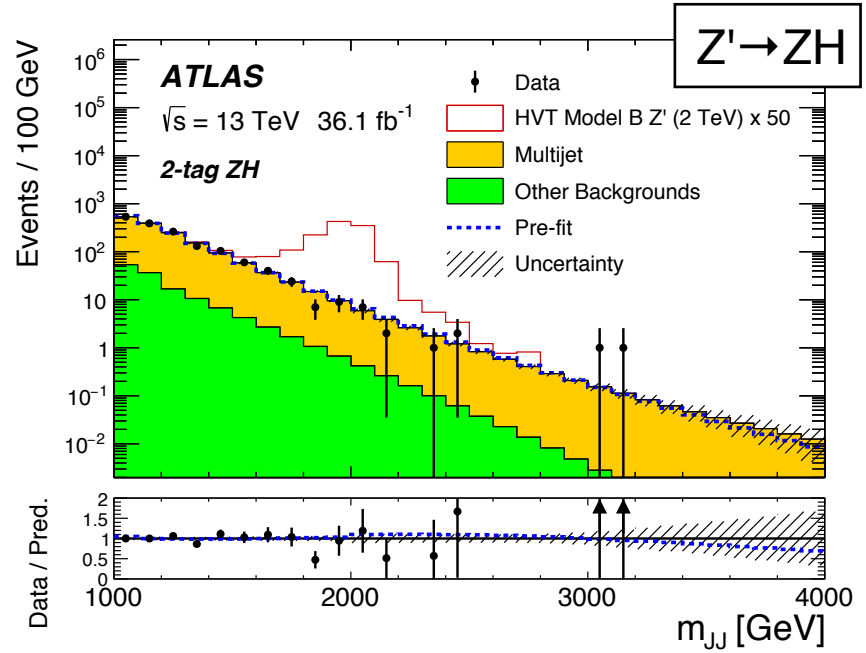
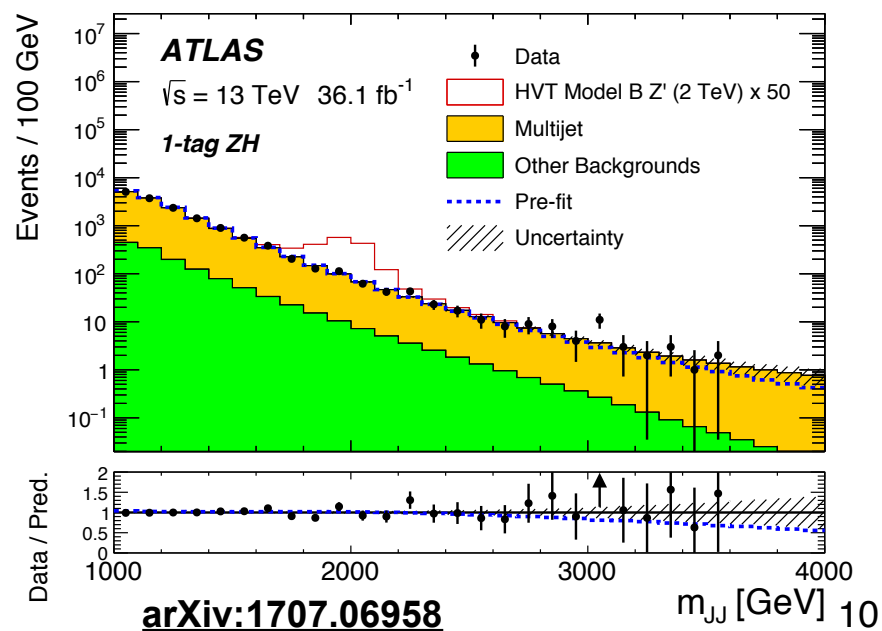
V'→VH in the all-hadronic final state

- A likelihood fit with the 1-tag and 2-tag signal regions.
- Largest experimental uncertainties from jet mass resolution, jet energy scale and b-tagging efficiencies.
- Largest excess at a mass of ~3 TeV with a local (global) significance of 3.3 (2.1) σ.
- Cross-section limits derived for W' and Z' production. Exclusions for Model B:
  - **$m_{W'}$ < 2.5 TeV and $m_{Z'}$ < 2.6 TeV**
- WH cross-section limits and signal regions shown in backup slides. Note: WH/ZH overlap by ~60%.





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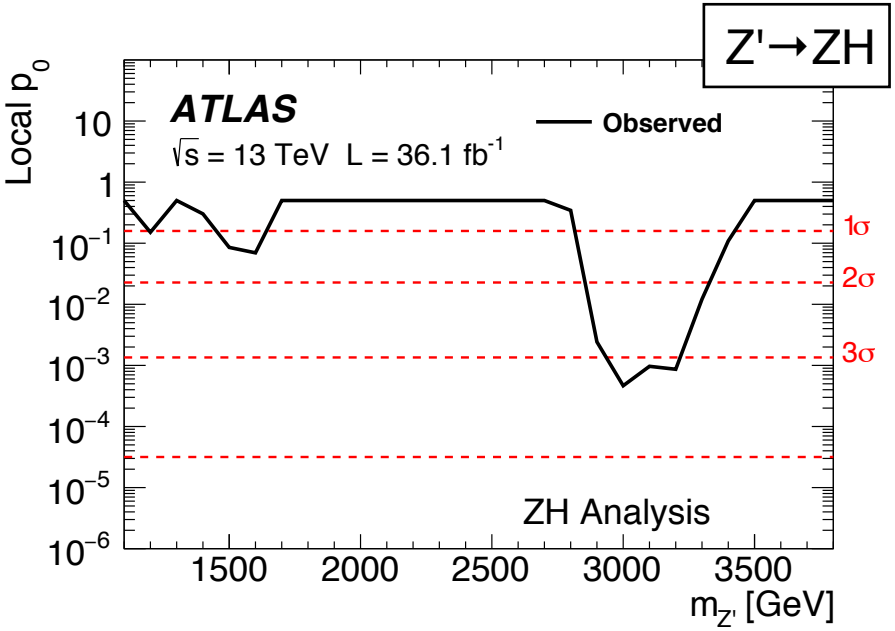
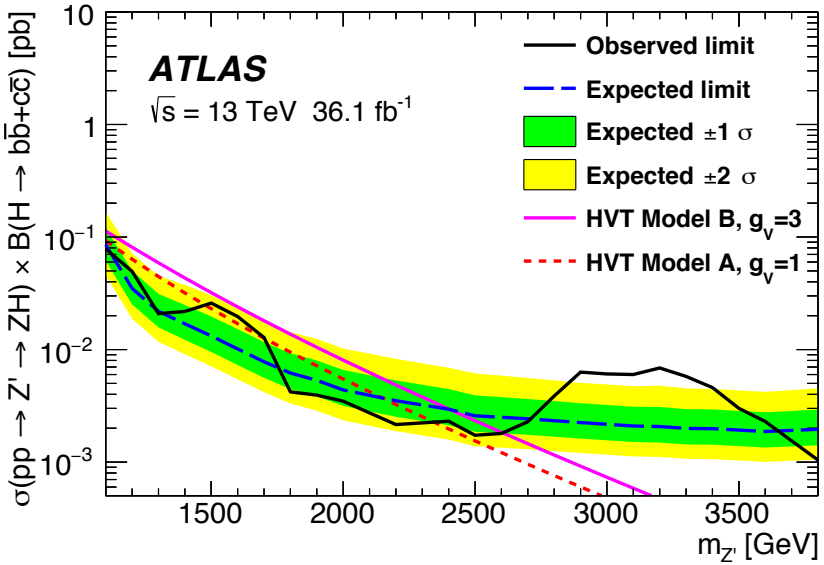
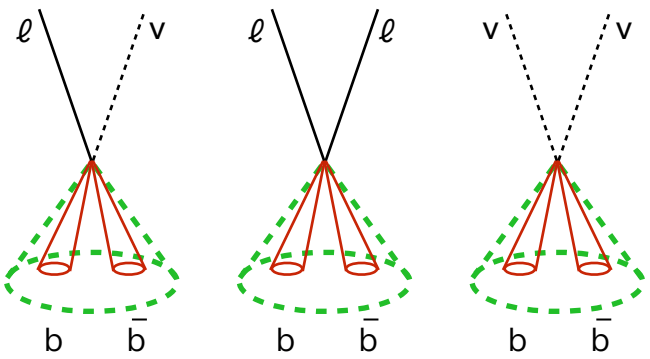




arXiv:1707.06958

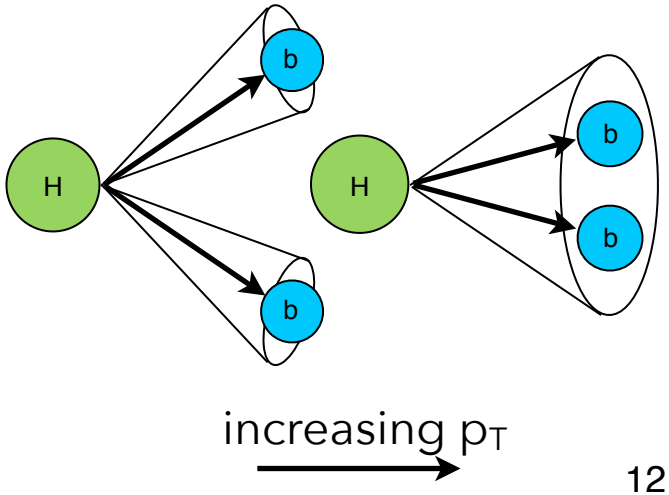
V'→VH in semi-leptonic final states



- **Signal regions:**
  - **Merged and resolved** categories.
  - **3 (orthogonal) channels** based on W/Z decay:
    - 0, 1 or 2-leptons.
  - 2 lepton flavor channels: electron and muon decays.
  - **1-tag and 2-tag categories** for the #b-tagged jets associated with Higgs jet.

- **Backgrounds:** main contributions from top-pair and V+jets production, with varying contributions depending on lepton channel.

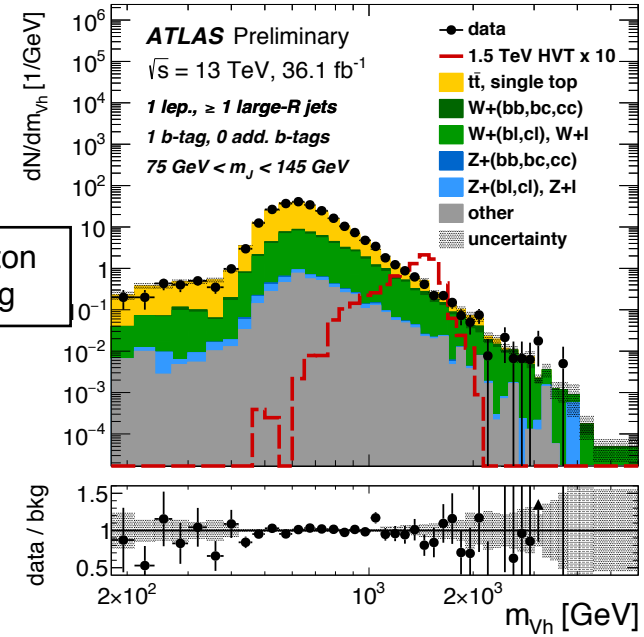
- Transition regime (~ 1 TeV) where events can be reconstructed in both the resolved and merged strategies.
  - Prioritizing the resolved category leads to better sensitivity due to better mass resolution.



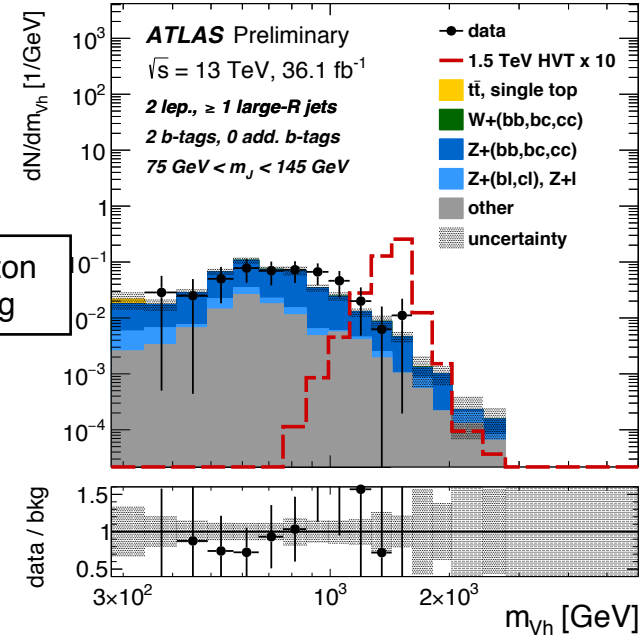
V'→VH in semi-leptonic final states

- Shape of most backgrounds estimated from simulation with normalizations of main backgrounds estimated from data.
- Largest backgrounds can be constrained in dedicated control regions:
  - e.g. a 90% pure top-pair region is defined using resolved events with different flavor ($e\mu$) and oppositely charged leptons.
- A combined fit is performed to all signal and control regions.
- Largest systematic uncertainties from small and large-R jet energy scales, large-R mass scales and b-tagging efficiencies.

1-lepton 1-tag



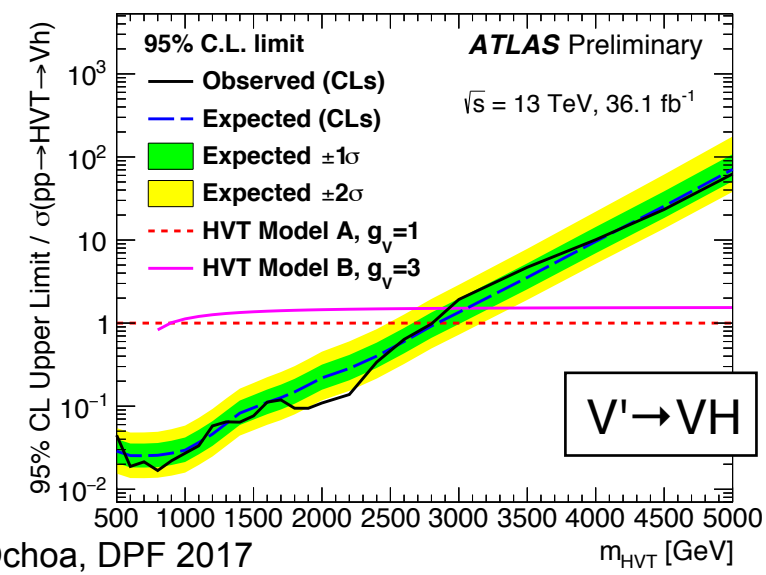
2-lepton 2-tag

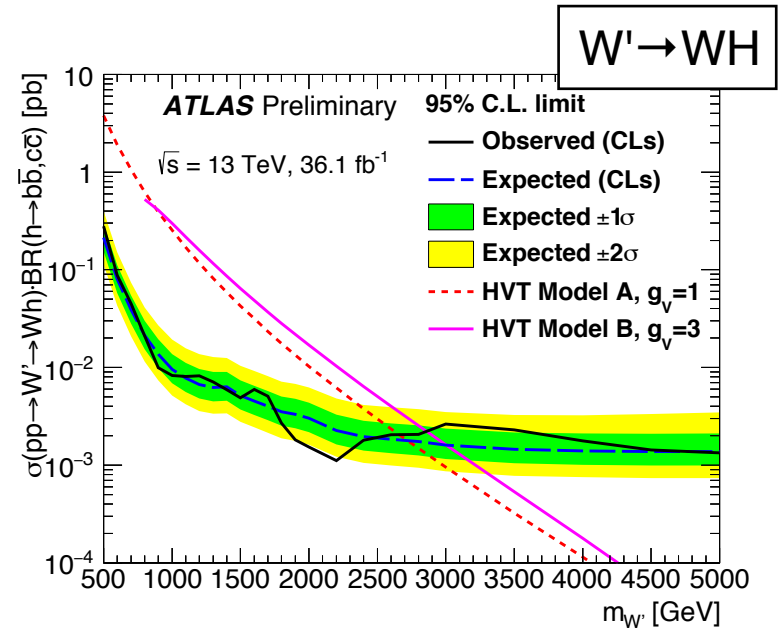


ATLAS-CONF-2017-055

V'→VH in semi-leptonic final states

- No significant excess is observed in any channel.
- Cross-section limits derived for:
  - W' (0+1 lepton)
  - Z' (0+2 lepton)
  - HVT model assuming simultaneous production of mass-degenerate W′ and Z′ bosons
- Exclusions for Model B:
  - **$m_{W'}$ < 2.9 TeV and $m_{Z'}$ < 2.8 TeV**





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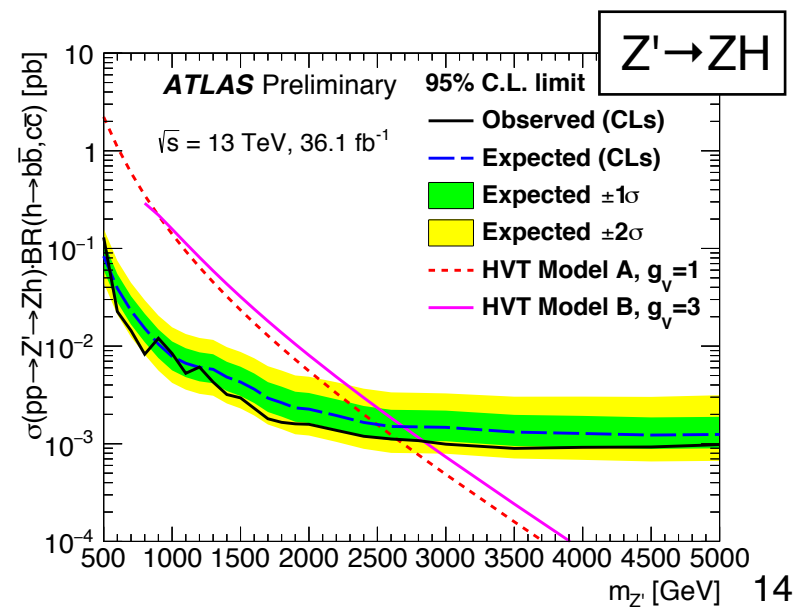
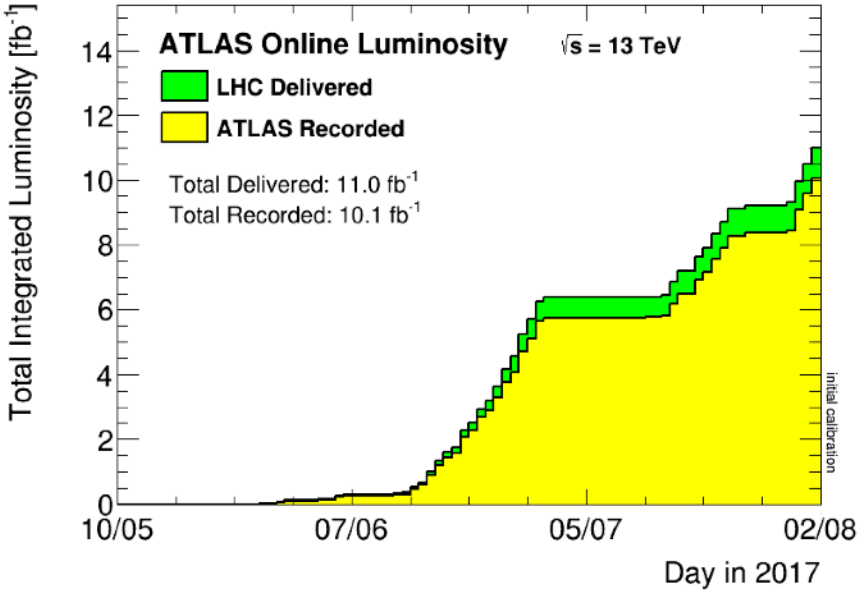
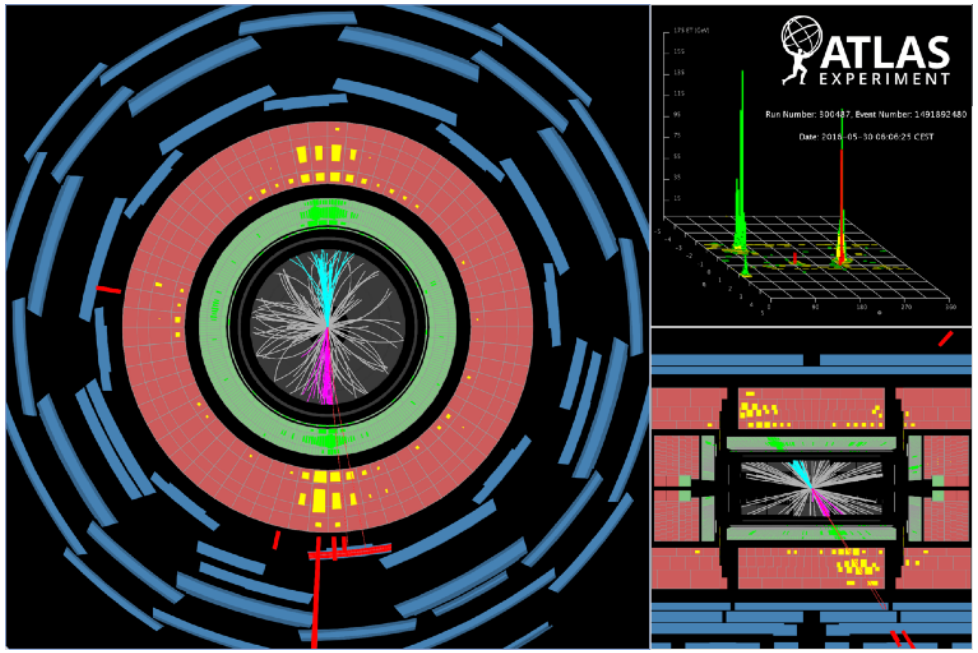


Summary

- Searches in diboson final states are a powerful tool for probing physics at the TeV scale.
- The VH channels are part of a large effort in diboson resonance searches at ATLAS.
  - A combination of the VH/VV channels is expected before the end of the year.



Stay tuned for more LHC data!



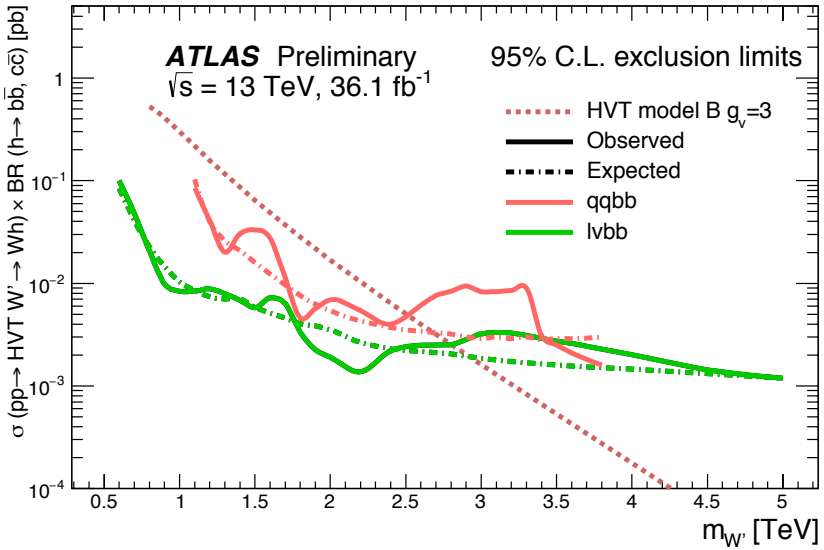
A high mass event from the all-hadronic VH analysis:

m_{VH} = 3023 GeV

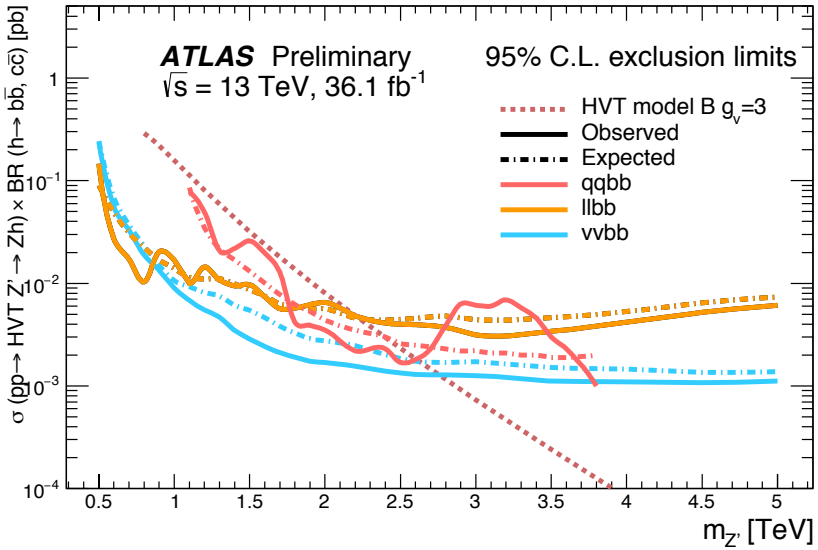
Backup slides

Combined plots

W'→WH

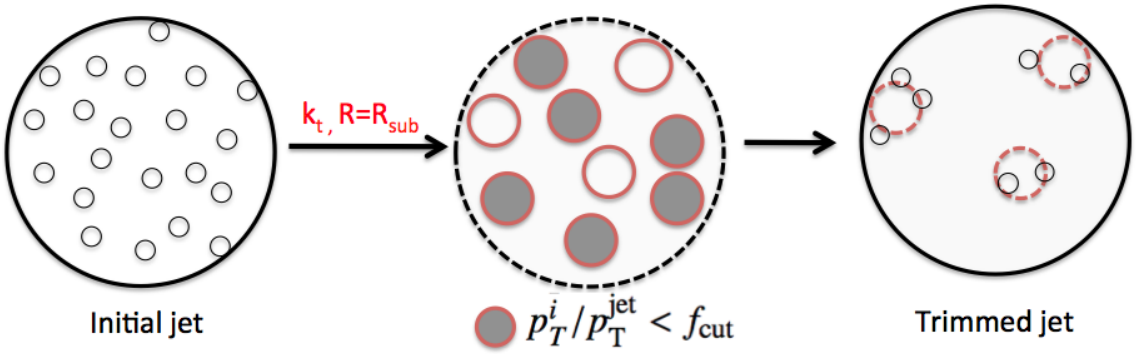


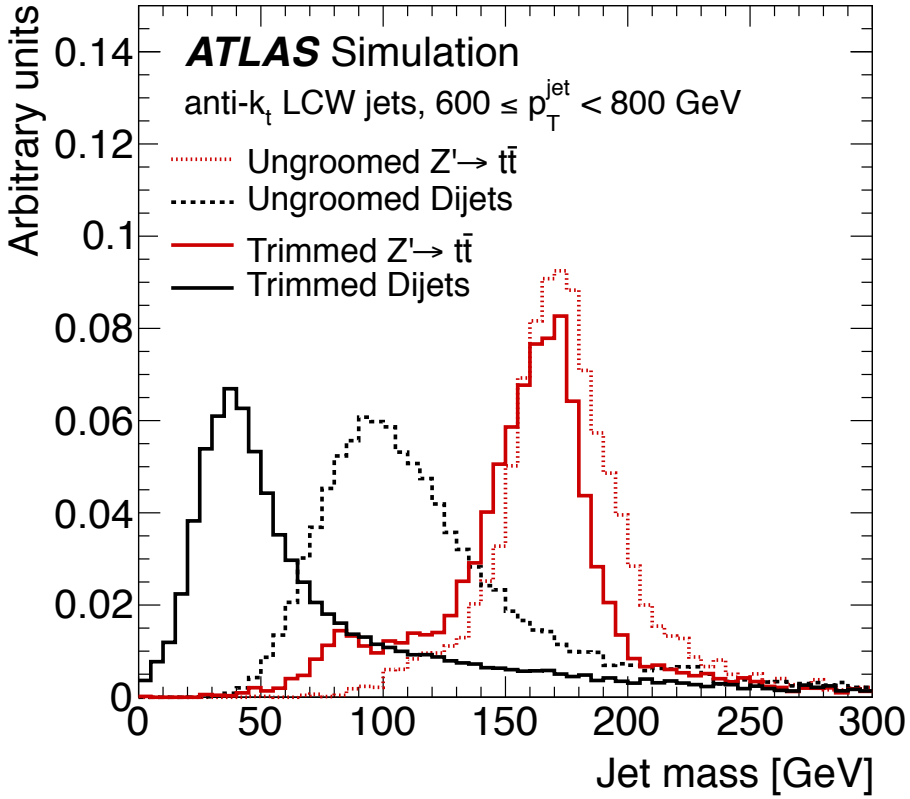
Z'→ZH



Link to Exotics Summary plots

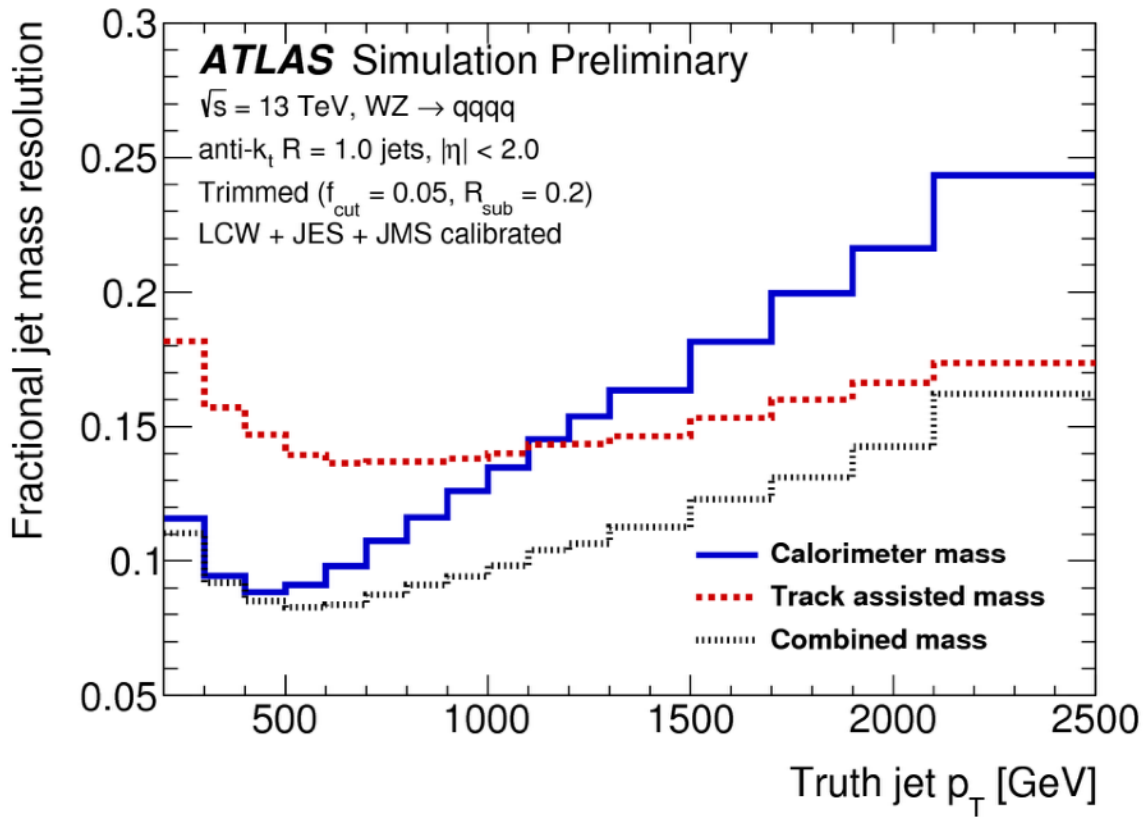
Jet trimming





JHEP 1309 (2013) 076

Jet mass



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Jet substructure

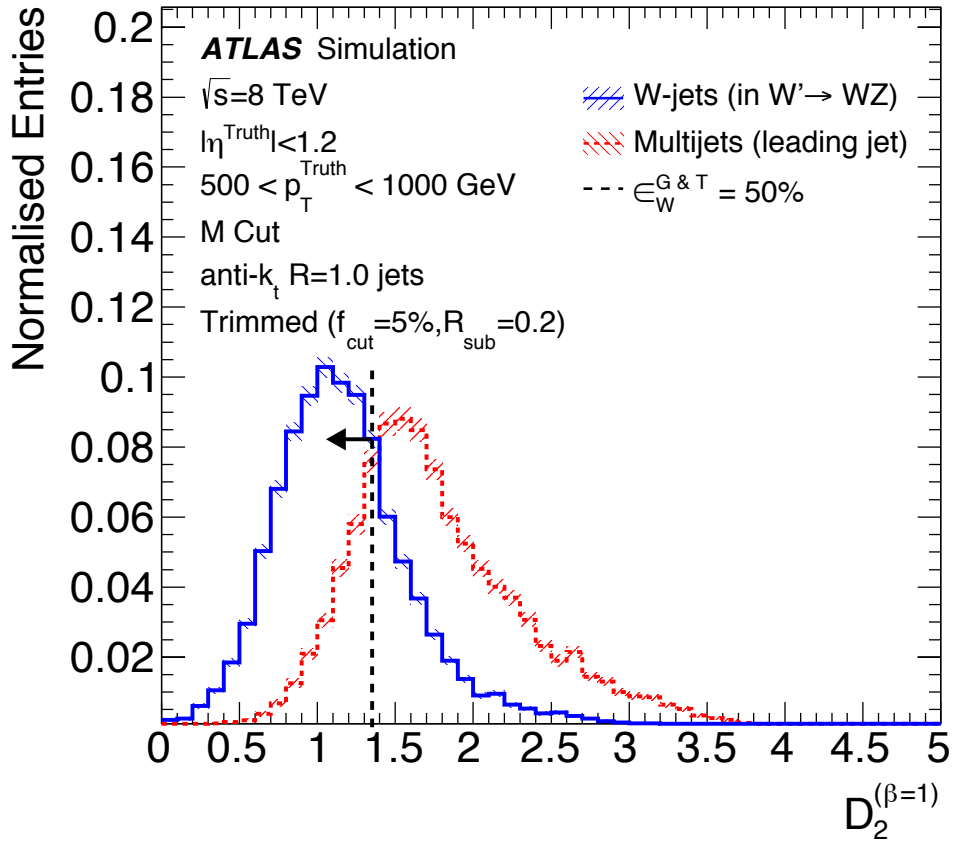
- The $D_2^{\beta=1}$ variable is useful in identifying jets with two-prong substructures.
- Defined from n-point energy correlation functions:

$$E_{CF1}(\beta) = \sum_{i \in J} p_{T_i},$$

$$E_{CF2}(\beta) = \sum_{i<j \in J} p_{T_i} p_{T_j} \left(\Delta R_{ij}\right)^{\beta},$$

$$E_{CF3}(\beta) = \sum_{i<j<k \in J} p_{T_i} p_{T_j} p_{T_k} \left(\Delta R_{ij} \Delta R_{ik} \Delta R_{jk}\right)^{\beta}$$

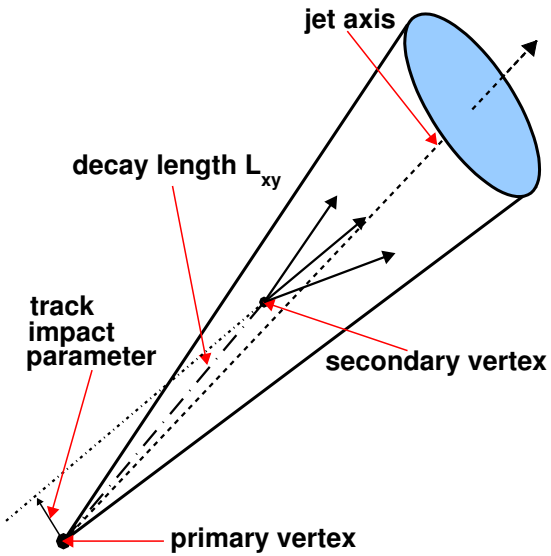
$$D_2^{\beta=1} = E_{CF3} \left(\frac{E_{CF1}}{E_{CF2}}\right)^3$$

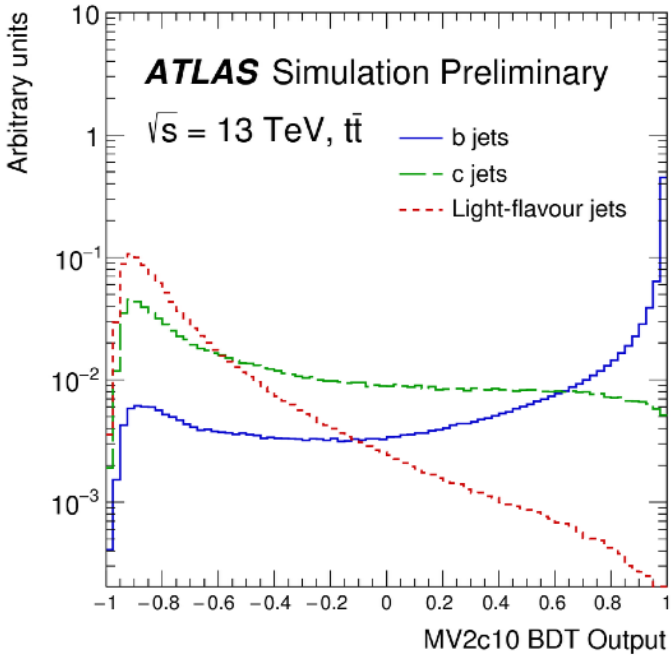


EPJC 76(3), 1-47

Flavor tagging

- A multivariate tagging algorithm combines information from vertexing and impact parameter tagging algorithms to a set of tracks associated to a jet/track-jet, in order to identify jets containing b-hadrons.





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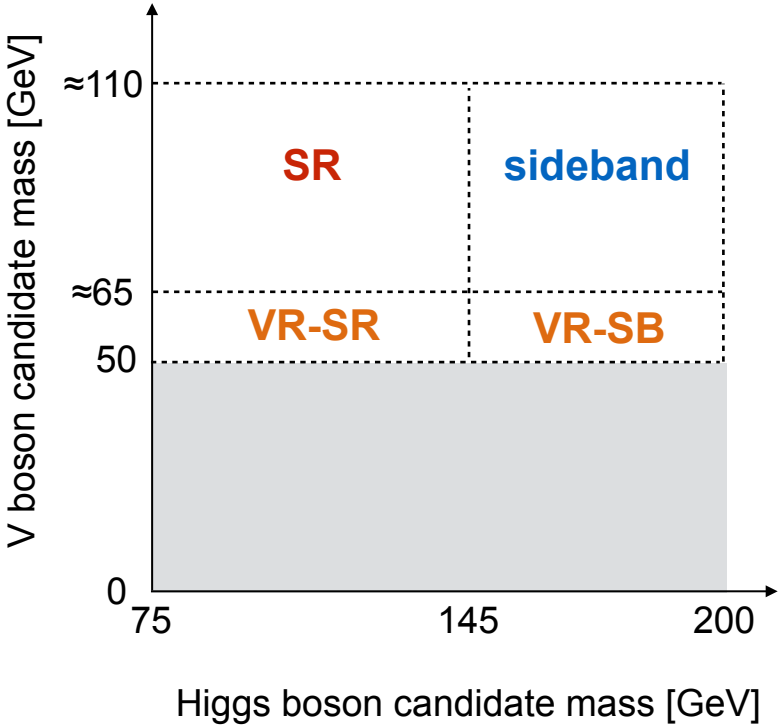
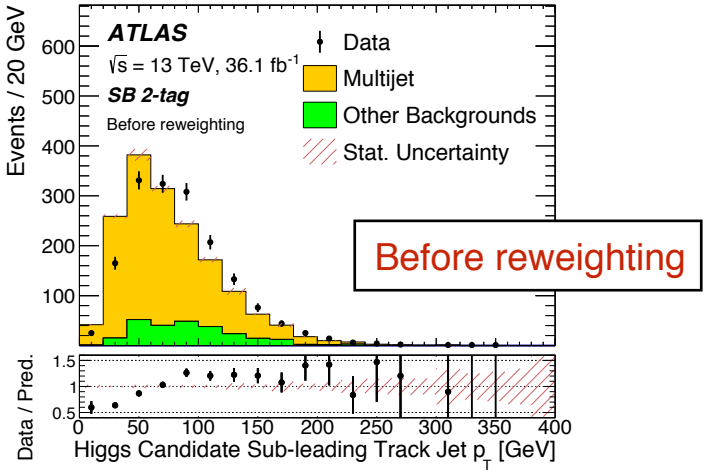
Event selections
All-hadronic VH

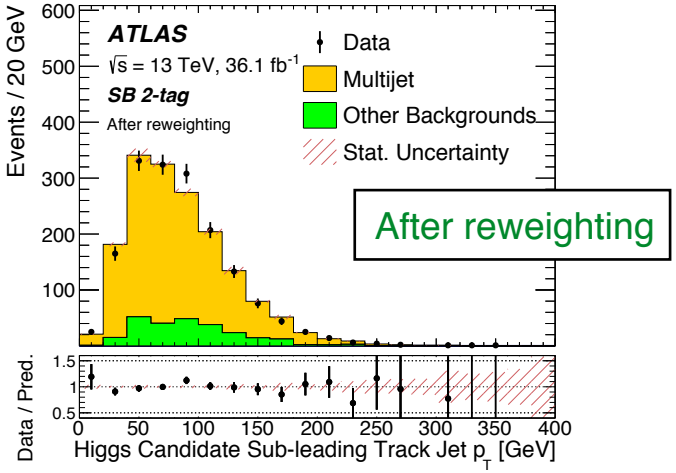
Selection	Description
Lepton veto	Remove events with leptons
> 1 large-R jets	$p_{\mathrm{T}} > 250$ GeV, $\lvert\eta\rvert < 2.0$
Leading large-R jet p_{T}	> 450 GeV
V/H assignment	larger mass jet is H-jet, smaller mass jet is V-jet
Rapidity difference	$\lvert\Delta y_{12}\rvert < 1.6$
$E_{\mathrm{T}}^{\mathrm{miss}}$ veto	Remove events with $E_{\mathrm{T}}^{\mathrm{miss}} > 150$ GeV and $\Delta\phi(\vec{E}_{\mathrm{T}}^{\mathrm{miss}},\ H-\mathrm{jet}) > 120$ degrees
Higgs tagging	mass window, track-jet b-tagging
W/Z-tagging	mass window + $D_2^{\beta=1}$ selection
Dijet mass	$m_{\mathrm{JJ}} > 1$ TeV

arXiv:1707.06958

Event selections
All-hadronic VH

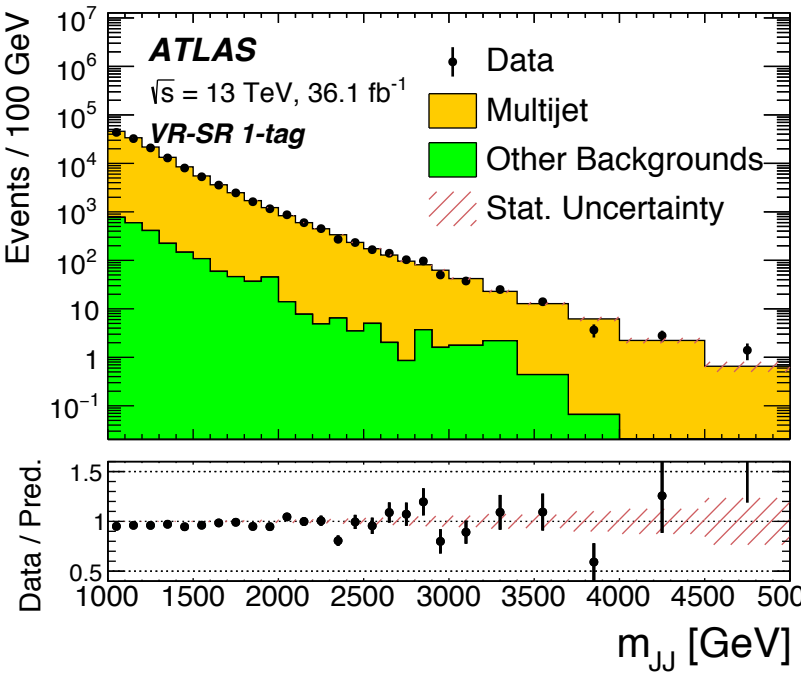


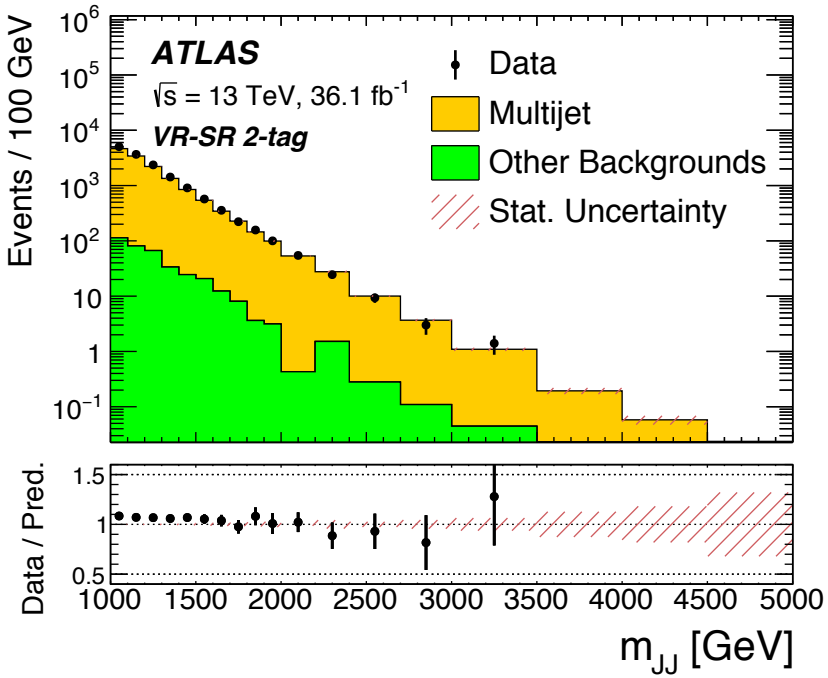




arXiv:1707.06958

Validation regions
All-hadronic VH





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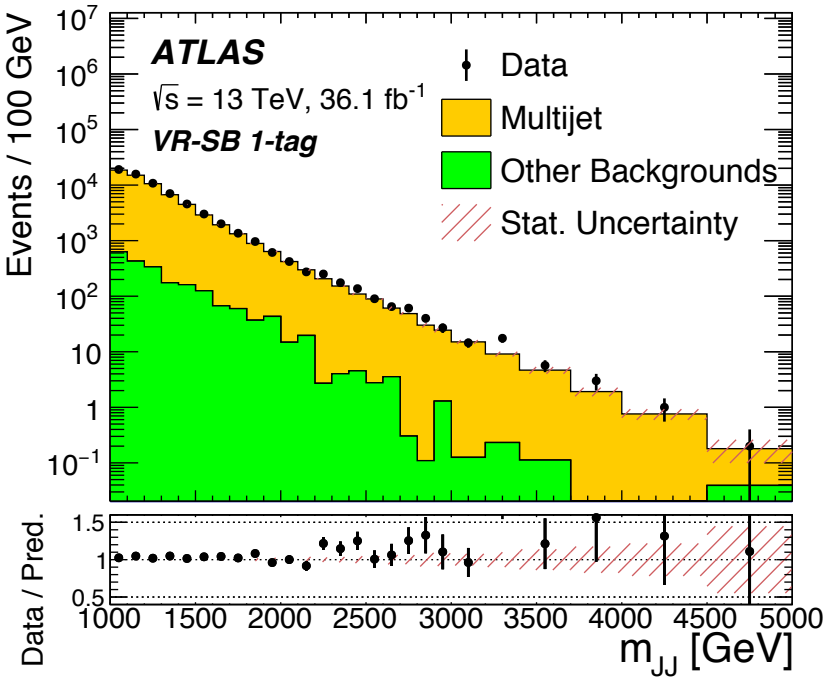

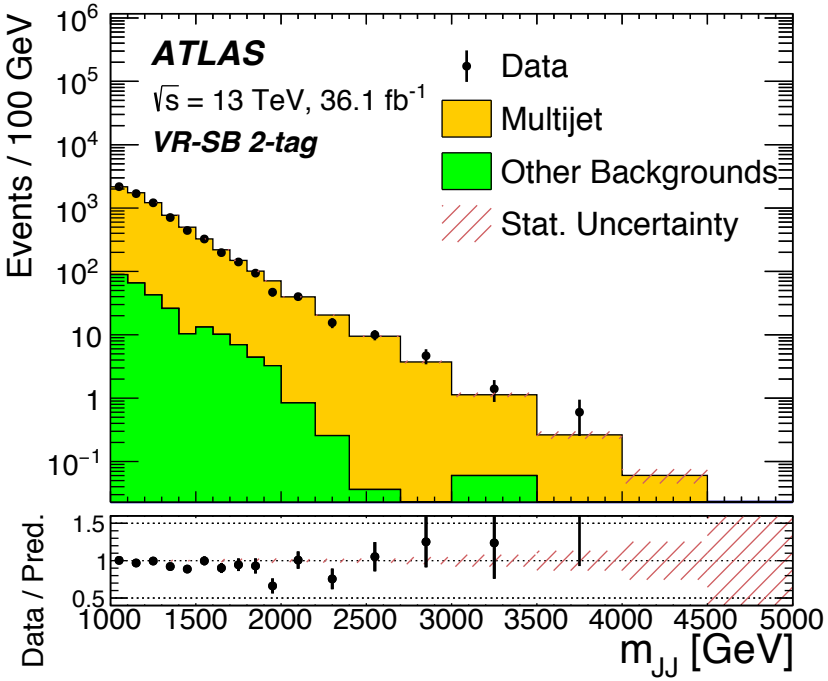

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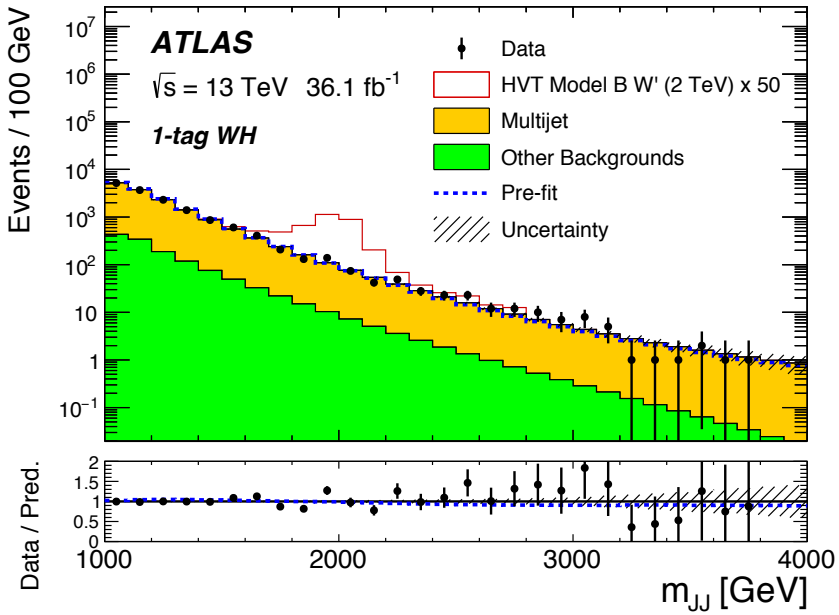
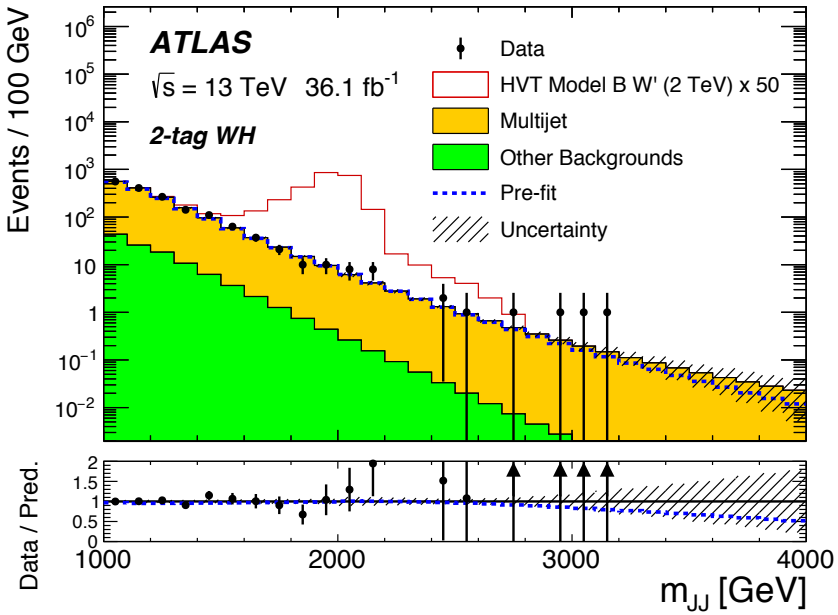
WH signal regions
All-hadronic VH

W'→WH

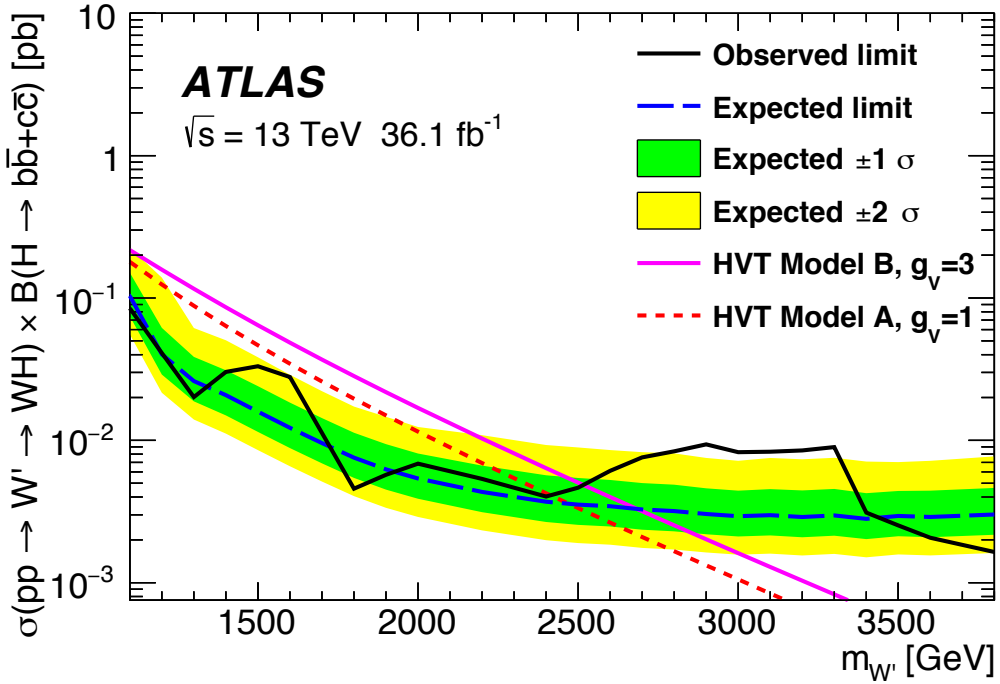




arXiv:1707.06958

WH limits
All-hadronic VH

W'→WH



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Events selections
Semi-leptonic VH

variable	Resolved	Merged
	Common selections	
number of jets	$\geq$2 small-R jets (==2 or 3 1-lep.)	$\geq$1 large-R jet
leading jet p_{T} [GeV]	> 45	> 250
m_{jj}, m_{J} [GeV]	110–140 (0,1-lep.), 100–145 (2-lep.)	75–145
	0-lepton selection	
$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	> 150	> 200
$\sum p_T^{\mathrm{jet}_i}$ [GeV]	> 150 ($120^{(*)}$)	–
$\Delta\phi$(j, j)	$< 7\pi/9$	–
$p_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	> 30	
$\Delta\phi(\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, \vec{p}_{\mathrm{T}}^{\mathrm{miss}})$	$< \pi/2$	
$\Delta\phi(\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, h)$	$> 2\pi/3$	
min[$\Delta\phi(\vec{E}_{\mathrm{T}}^{\mathrm{miss}}$, small-$R$ jet)]	$> \pi/9$ (2 or 3 jets) , $> \pi/6$ ($\geq$ 4 jets)	
$\mathrm{N}_{\tau_{\mathrm{had}}}$	0 **	
	1-lepton selection	
leading lepton p_{T} [GeV]	> 27	> 27
$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	$> 40(80^{(\ddagger)})$	> 100
p_{T}^{W} [GeV]	$> \max[150,\ 710 - 3.3 \cdot 10^5\ GeV/m_{Vh}]$	$> \max[150,\ 394 \cdot \ln(m_{Vh}/1\ GeV) - 2350]$
$m_T(W)$ [GeV]	¡300	
	2-lepton selection	
leading lepton p_{T} [GeV]	> 27	> 27
sub-leading lepton p_{T} [GeV]	> 7	> 25
$E_{\mathrm{T}}^{\mathrm{miss}}/\sqrt{H_{\mathrm{T}}}$ [$\sqrt{\mathrm{GeV}}$]	$< 1.15\ + 8 \cdot 10^{-3}\ m_{Vh}/1\ GeV$	
$p_{T,\ell\ell}$ [GeV]	$> 20 + 9 \cdot \sqrt{m_{Vh}/1GeV - 320}^{\ddagger\ddagger}$	
$m_{\ell\ell}$ [GeV]	[87 - $0.030 \cdot m_{Vh}/1\ GeV$, $97 + 0.013 \cdot m_{Vh}/1\ GeV$]	

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