Columbia University
In the City of New York

ATLAS Searches for Diboson Resonances

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CIPANP2018

ATLAS EXPERIMENT

Motivation for diboson final states

New physics

- There are many well-motivated extensions to the Standard Model that predict new resonances decaying to boson pairs (W/Z/H/ɣ), with different sets of properties.
- Rich phenomenology, from e.g. Composite Higgs to Extra Dimensions.

What are we looking for?

- A solution to the **naturalness problem**:
  - New physics at the TeV energy scale, reachable at the LHC.
  - New resonances can generally be expected to couple to massive bosons: W/Z and Higgs.
- Presenting results with minimal model dependence is of particular importance.
  - Can translate experimental limits into results for different models.

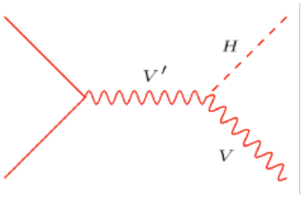
Theoretical Frameworks

- Results are interpreted using different benchmark models, assuming narrow width approximation:
  - **Spin-0:** extended Higgs sector (e.g. 2HDM), gluon-gluon and vector boson fusion.
  - **Spin-1:** heavy vector triplets - HVT (W', Z')
  - **Spin-2:** Kaluza-Klein graviton from bulk Randall-Sundrum model

Heavy Vector Triplets:

- Simplified model with additional SU(2) vector triplet.
- Small set of parameters: couplings to fermions, bosons and resonance mass.
- Production via Drell-Yan or vector boson fusion

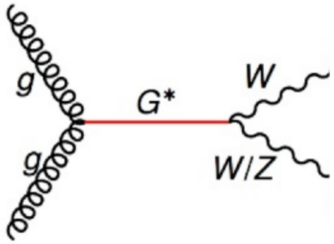
JHEP09(2014)060



"bulk" KK gravitons:

- Extension of KK graviton in RS1 framework with SM particles extending into the "bulk".
- Couplings to light fermions suppressed.
- Gluon-gluon fusion dominant production channel.

PhysRevD.76.036006

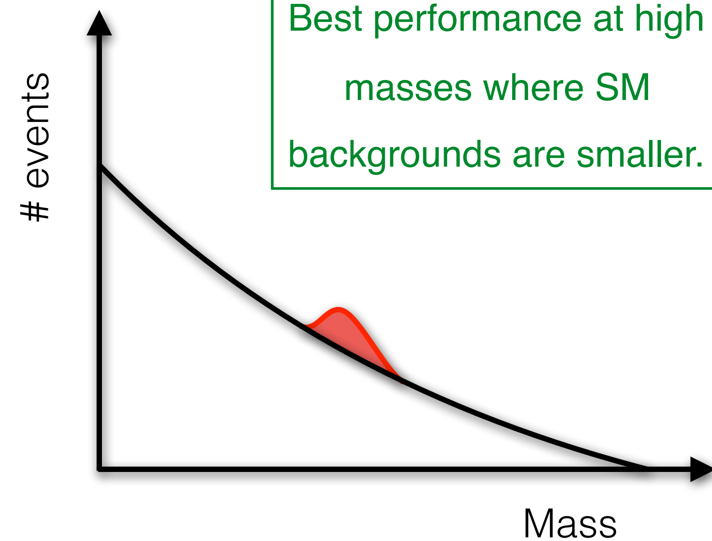


ATLAS searches in diboson final states

- In this talk: recent ATLAS searches, with focus on **hadronic** decay channels.
  - W/Z/H+ɣ→qqɣ: arXiv:1805.01908 NEW RESULT
  - WZ/WW/ZZ→qqqq: Phys. Lett. B 777 (2017) 91
  - VH→qqbb: Phys. Lett. B 774 (2017) 494
  - Y→XH→qqbb: Phys. Lett. B 779 (2018) 24

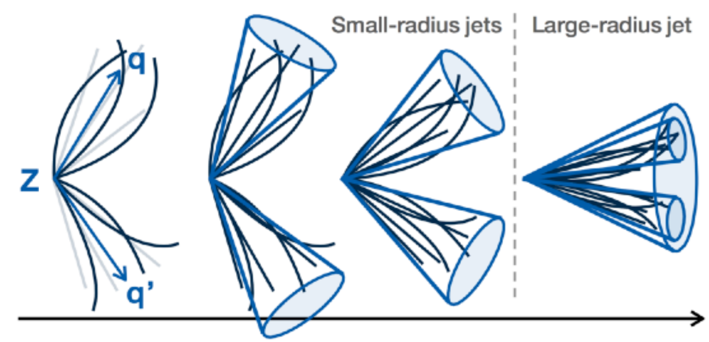
W/Z→qq, H→bb

Largest branching ratios. Best performance at high masses where SM backgrounds are smaller.



Common search strategy:

- Scanning of invariant mass distributions of diboson systems for evidence of a **narrow** resonant excess.
- Large range of resonance masses covered: from 200 GeV to 6.8 TeV: boost of decay products will depend on the mass.
- Two general methods for background estimation.



Boosted jets: Increasing transverse momentum, p_T

Reconstructing W/Z/H hadronic decays

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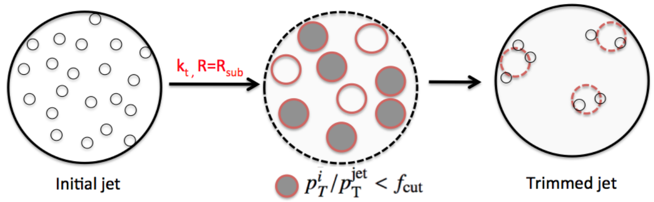
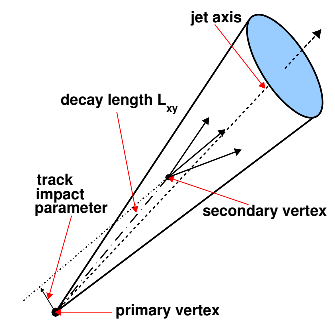
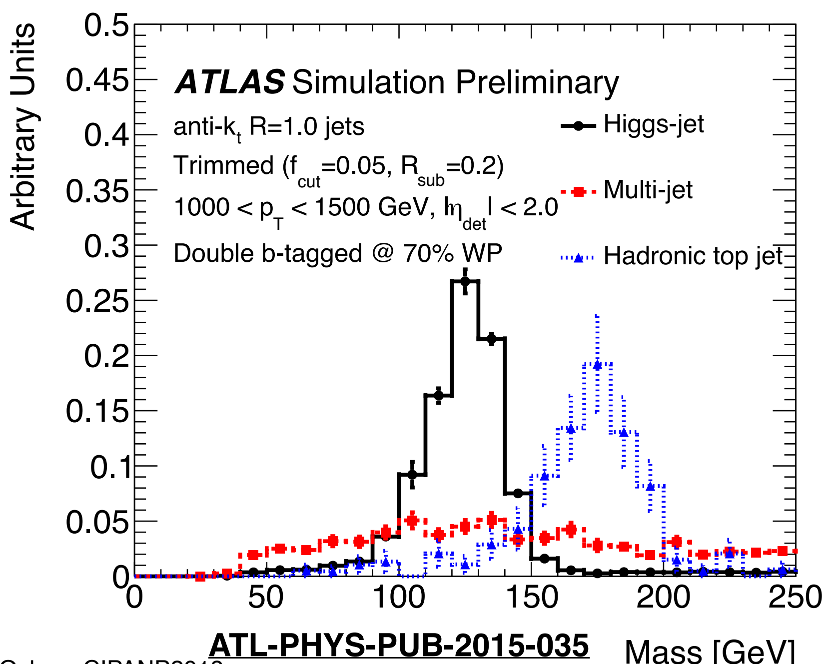
- **Jet trimming** of large-R jets to reduce contributions from underlying event and pile-up.
- **W/Z tagging** via a combination of p_T-dependent cuts on the calibrated, **jet mass** and **$D_2^{\beta=1}$** variable for identifying jets with two-prong substructures.
- **Higgs tagging** via **jet mass** cuts and **b-tagging** of associated track-jets.



R_{cut} = 0.2
f_{cut} = 5%





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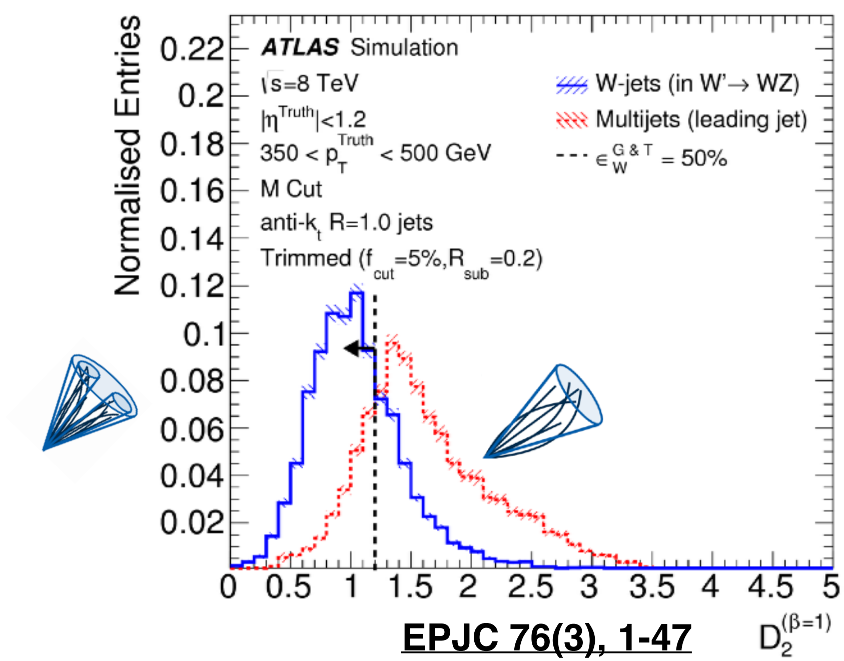

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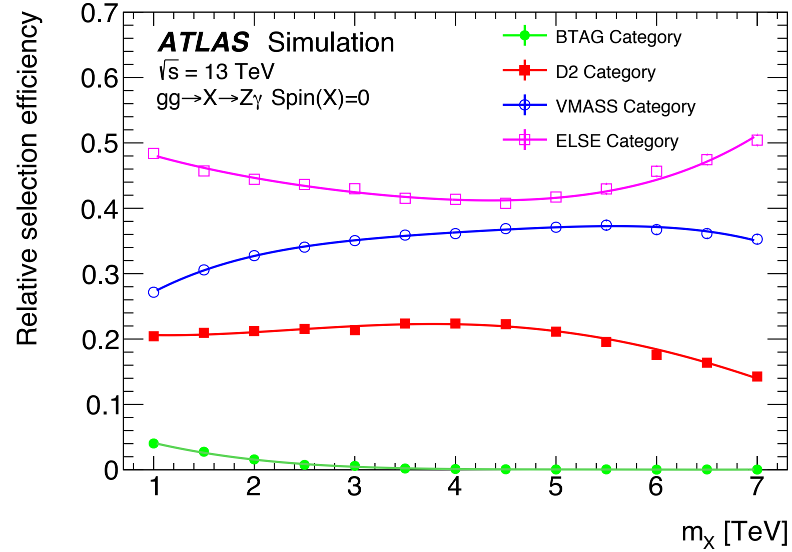
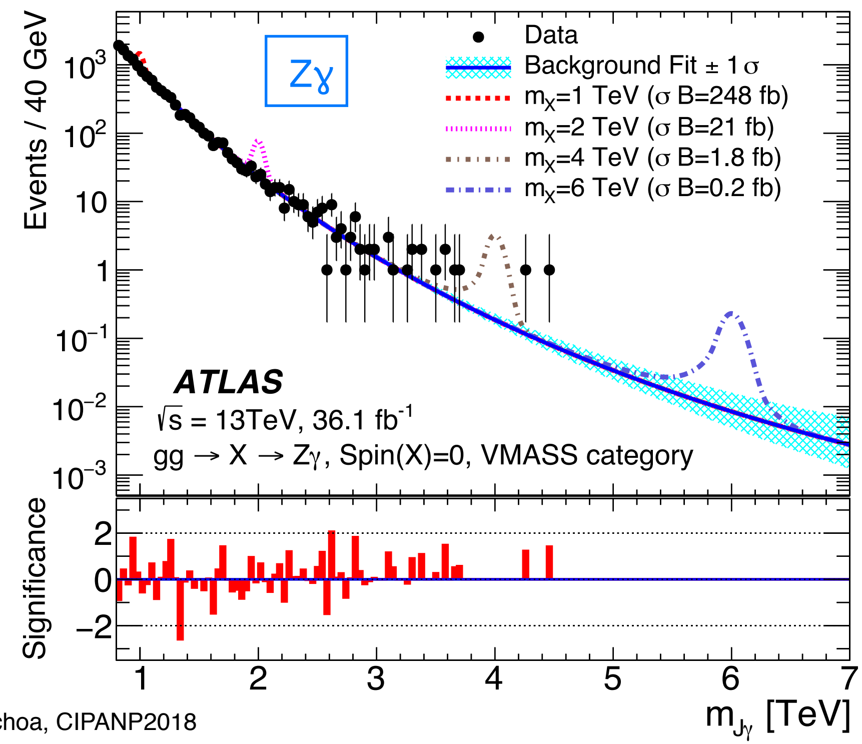
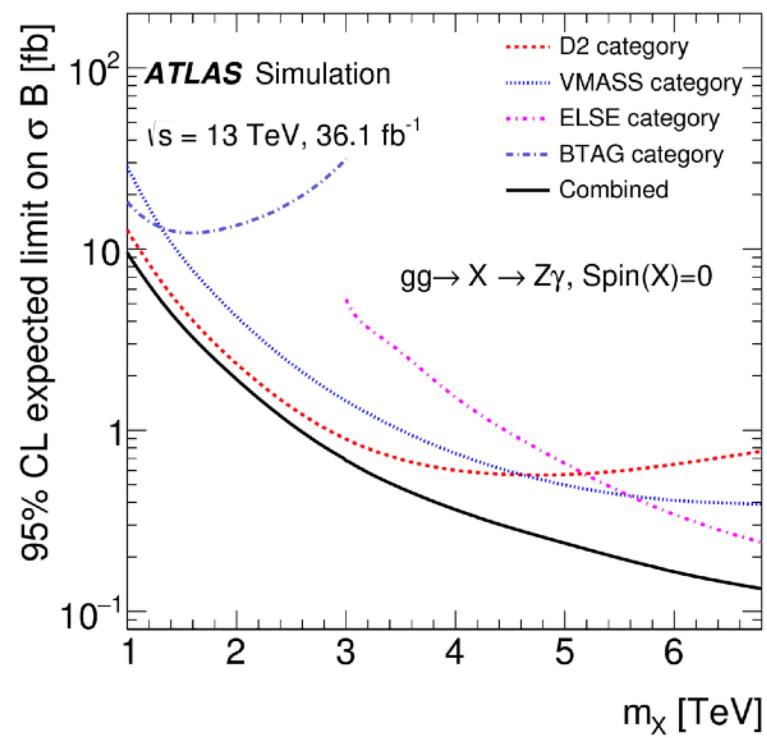
W/H/Z+ɣ searches (I)

NEW RESULT

- **Strategy:** one large-R jet and one photon: event triggered by photon candidates with p_T > 140 GeV.
- Event categorization to improve signal sensitivity.
- E.g. Zɣ, defined by (double) b-tagging, D_2 and jet mass of large-R jet. Additional cut on n_{tracks} associated with jet for rejection of gluon-initiated jets.







W/H/Z+ɣ searches (II)

NEW RESULT

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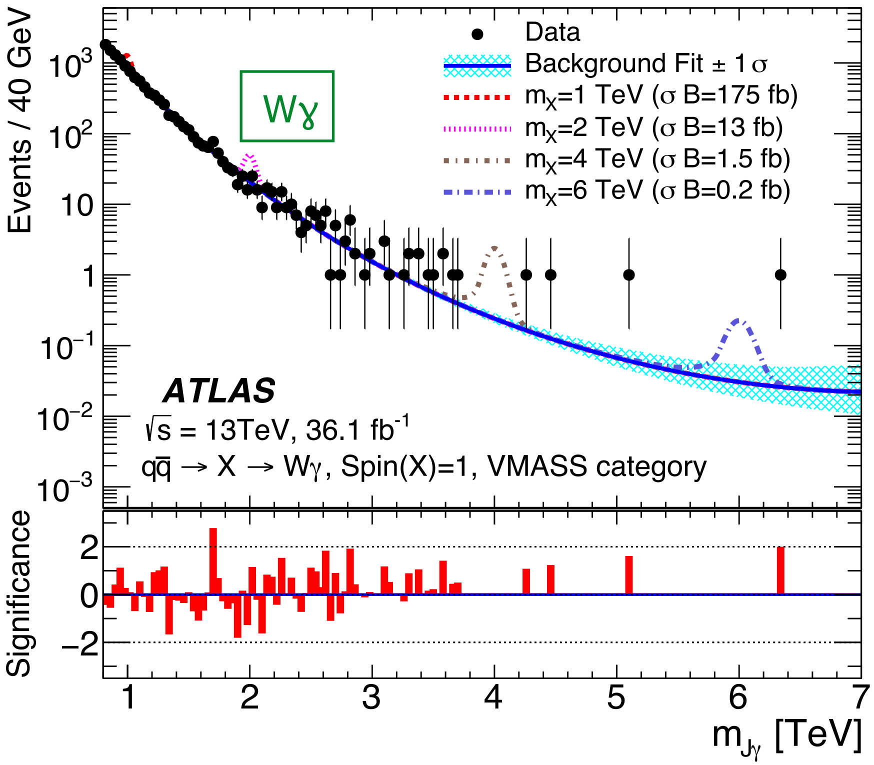
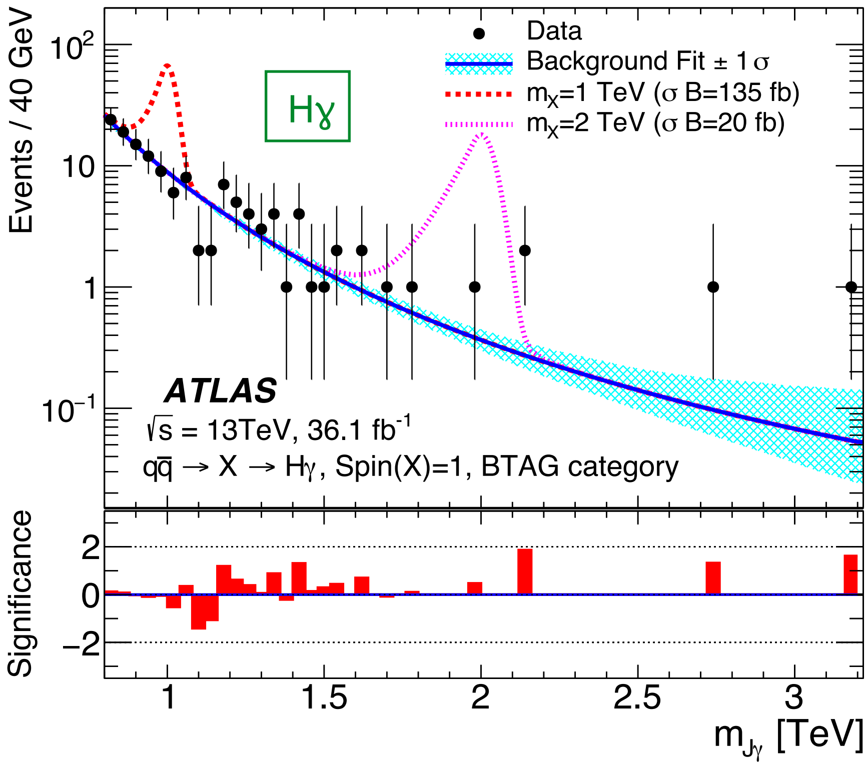
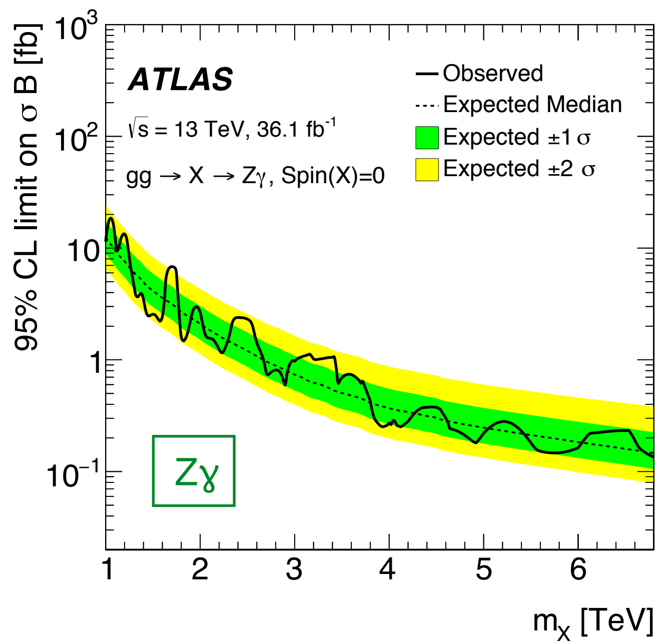
- **Main backgrounds:** SM ɣ + jet production, smaller contributions from ɣ + top, ɣ + V.
- Background model: $B(m_{J\gamma};\mathbf{p}) = (1-x)^{p_1} x^{p_2+p_3 \log x}$ $\quad x = m_{J\gamma}/\sqrt{s}$
- Unbinned fits of the $m_{J\gamma}$ distribution performed in each category, in range 800 GeV up to 7 TeV.

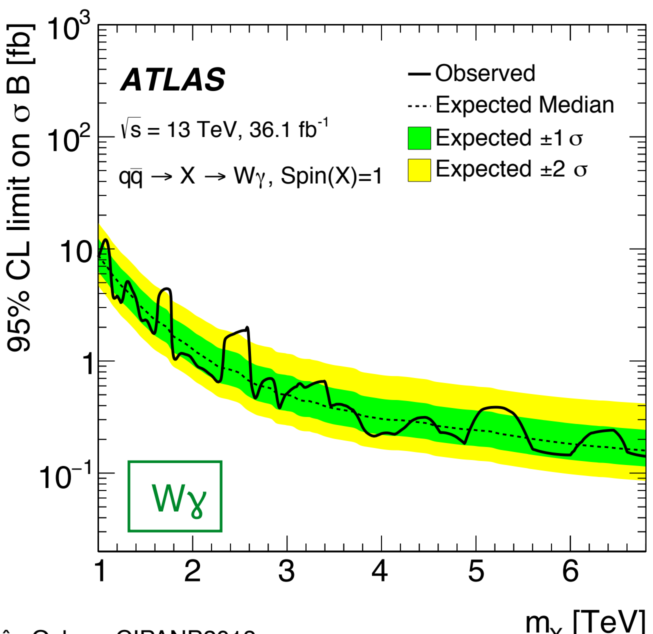


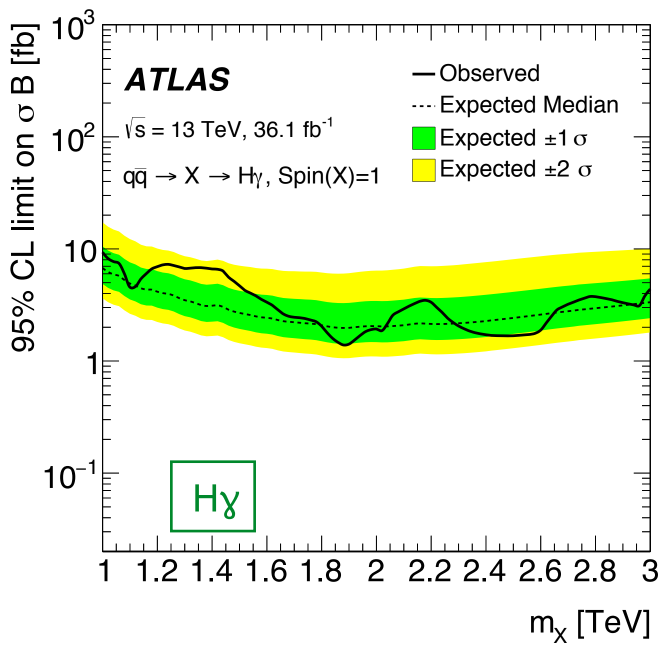


W/H/Z+ɣ searches (III) NEW RESULT

- Largest uncertainties are statistical, followed by spurious signal uncertainties (Vɣ). For Hɣ, large impact also from b-tagging efficiencies.
- **Results:** no significant deviations found. Cross-section x branching ratio limits derived combining signal regions, for Zɣ (different spin and production hypotheses), Wɣ and Hɣ production.







First limits on the production of Hɣ resonances.

VV→qqqq search (I)

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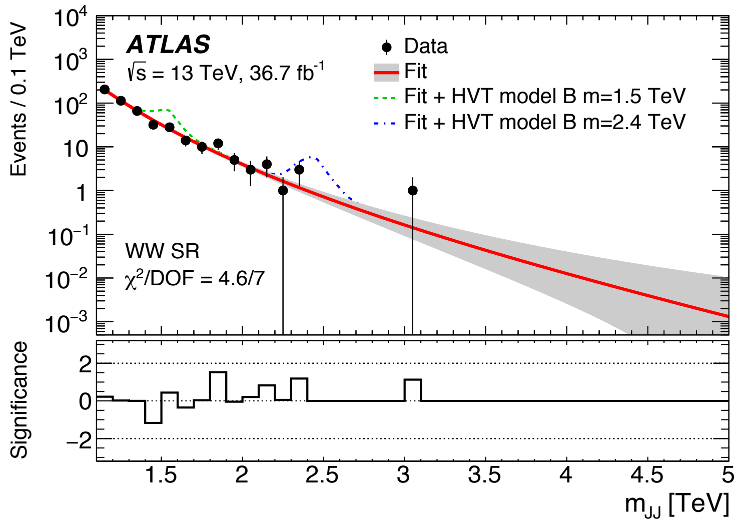
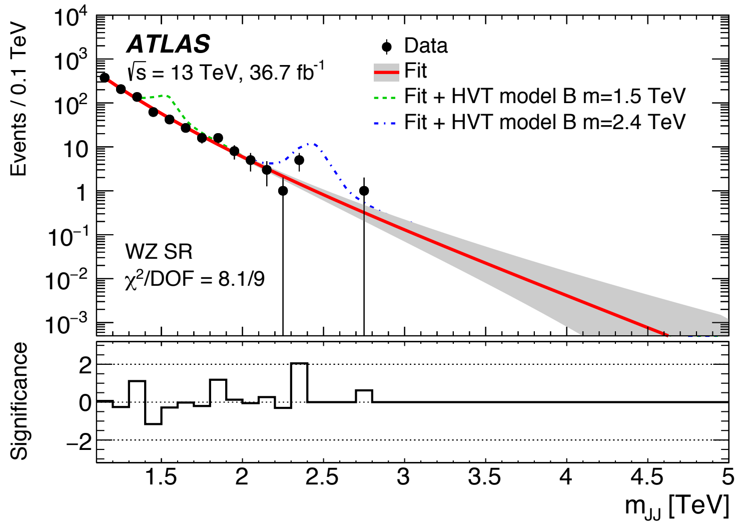
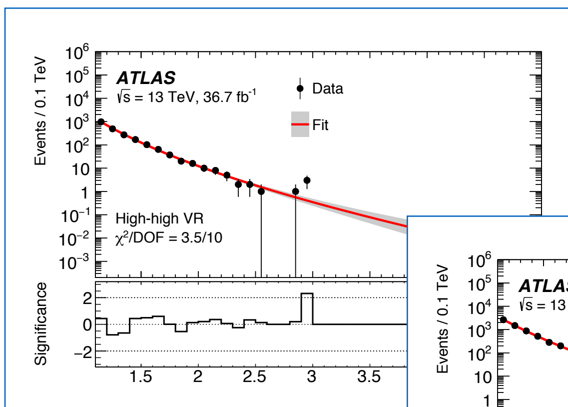
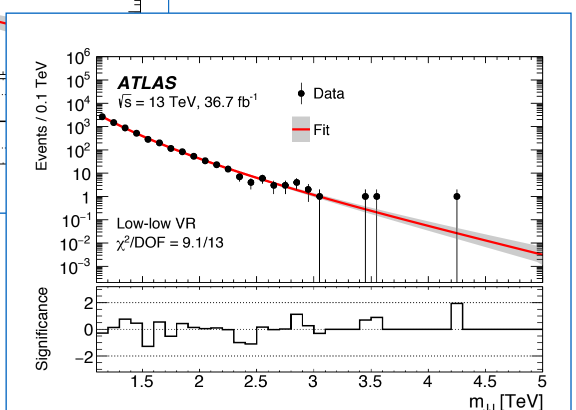
- Two large-R jets, W/Z tagging @ 50% efficiency and cut on n_{tracks} associated with jets.
- Multijet processes dominate background.
- Binned maximum-likelihood fit to observed m_{JJ} spectrum assuming a smoothly falling distribution:

$$\frac{dn}{dx} = p_1(1-x)^{p_2-\xi p_3}x^{-p_3}, x = m_{JJ}/\sqrt{s}$$







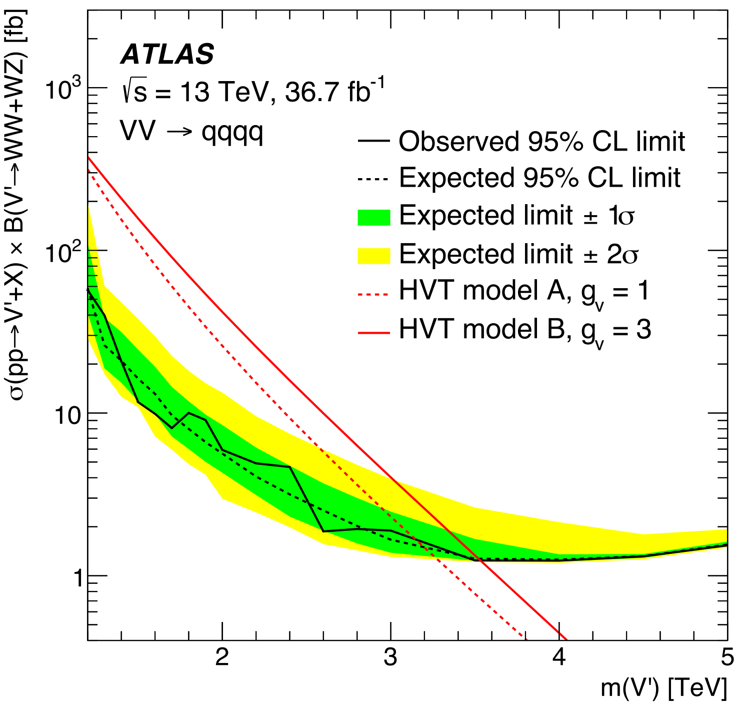


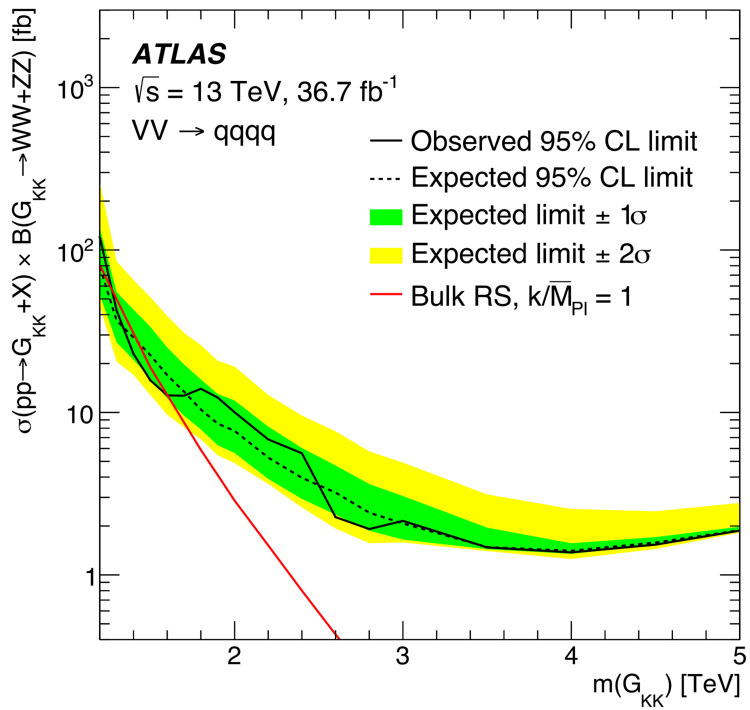
VV→qqqq search (II)

- **Results:** data compatible with SM backgrounds.
- Approximately 20% of events included in all three regions.

Model A: comparable BRs to fermions and bosons.

Model B: couplings to fermions suppressed.





- **Limits @ 95% C.L.:**
  - $M_{V'}$ exclusion in 1.2-3.1 (1.2-3.5) TeV for HVT model A (B).
  - G_{KK} exclusion in range 1.3 - 1.6 TeV in bulk RS model with k/M_{Pl} = 1.
  - Upper limits set on σ × B of 9.7 fb at m(Scalar) = 2 TeV and 3.5 fb at m(Scalar) = 3 TeV.

VH→qqbb search (I)

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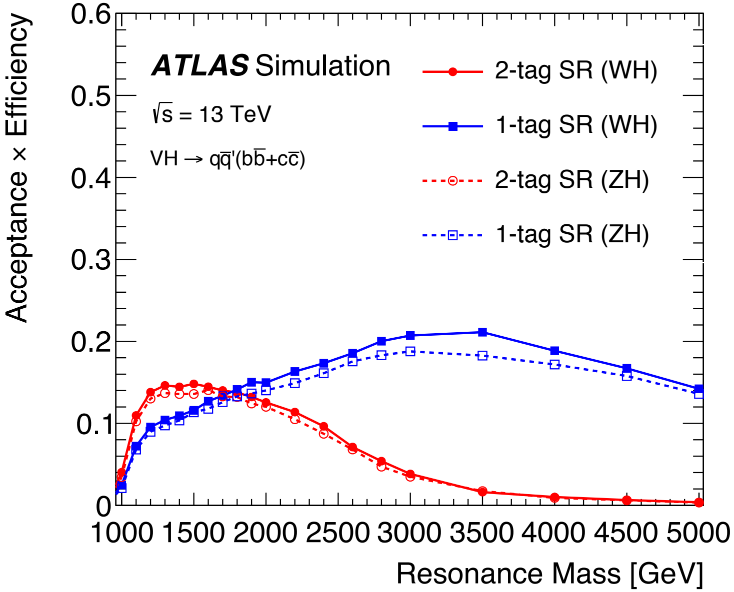
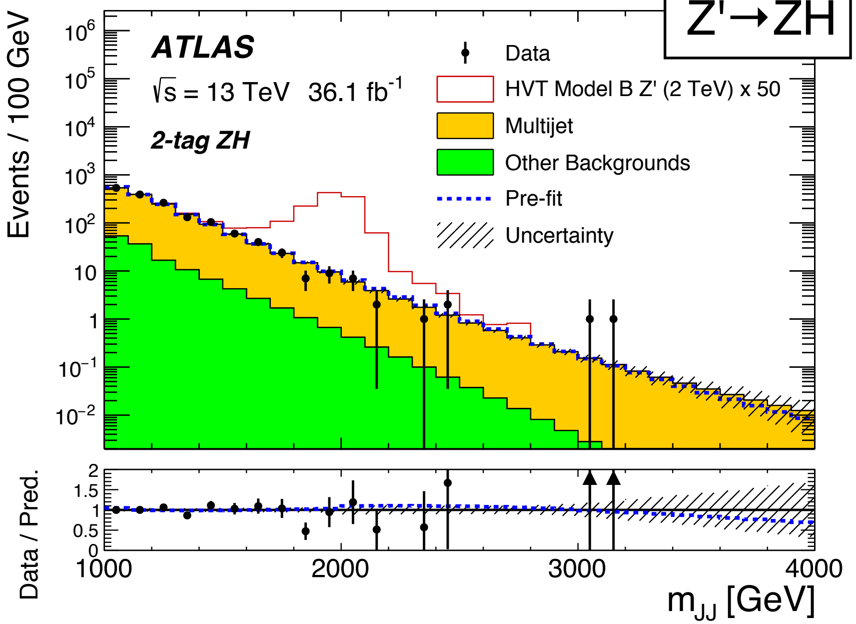
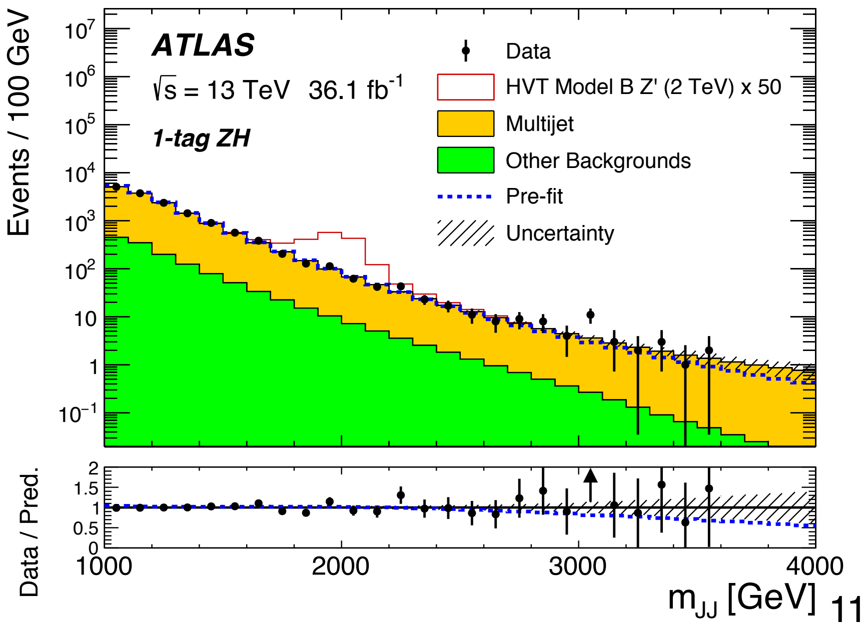
- Two large-R jets required in the event: higher mass jet is assigned as Higgs candidate, the other as W/Z.
- Multijet QCD processes are the main background (>90%). Data-driven estimation: template from region with 0-tags, normalization and corrections from high-mass sidebands of the Higgs candidate.



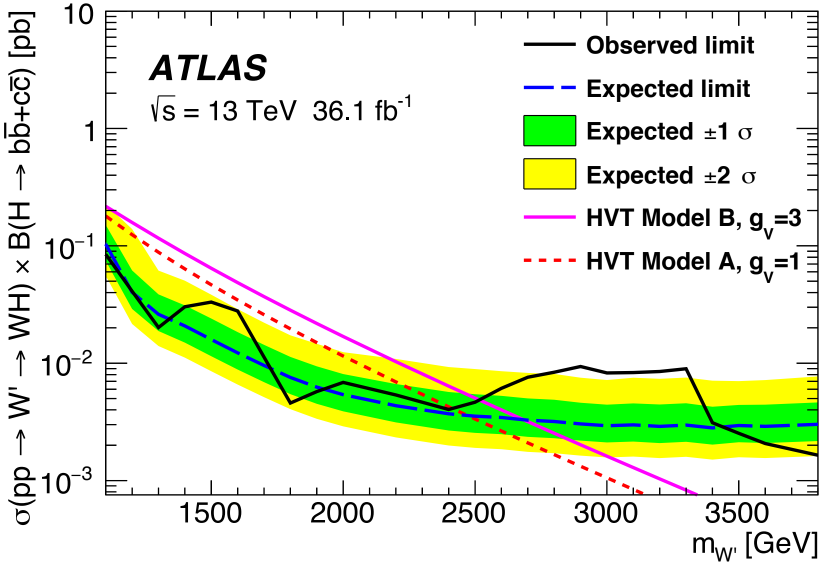
Z'→ZH

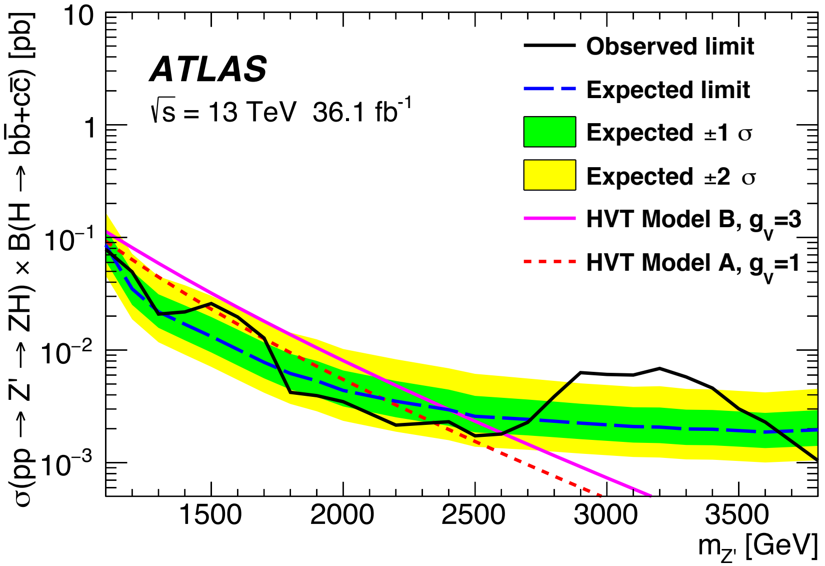




VH→qqbb search (II)

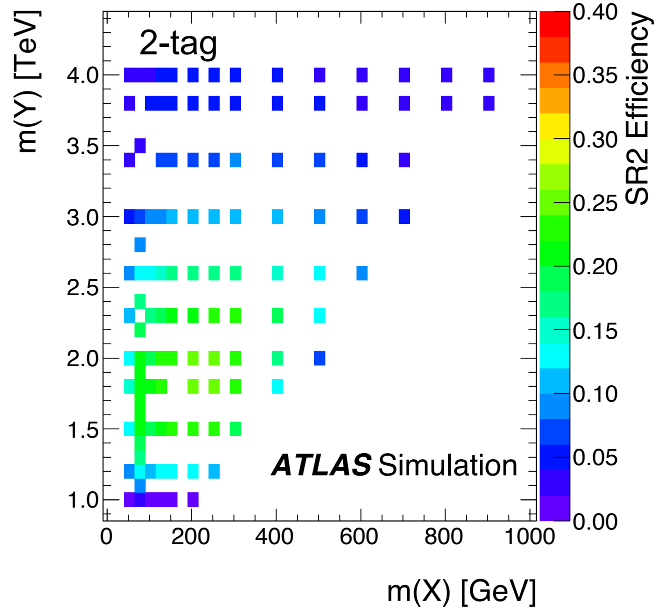
- Largest experimental uncertainties from jet mass resolution, jet energy scale and b-tagging efficiencies.
- **Results:** largest excess at a mass of ~3 TeV with a local (global) significance of 3.3 (2.1) σ.
- Cross-section limits derived for W' and Z' production. Exclusions for HVT Model B (suppressed couplings to fermions):
  - **$m_{W'}$ < 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%.

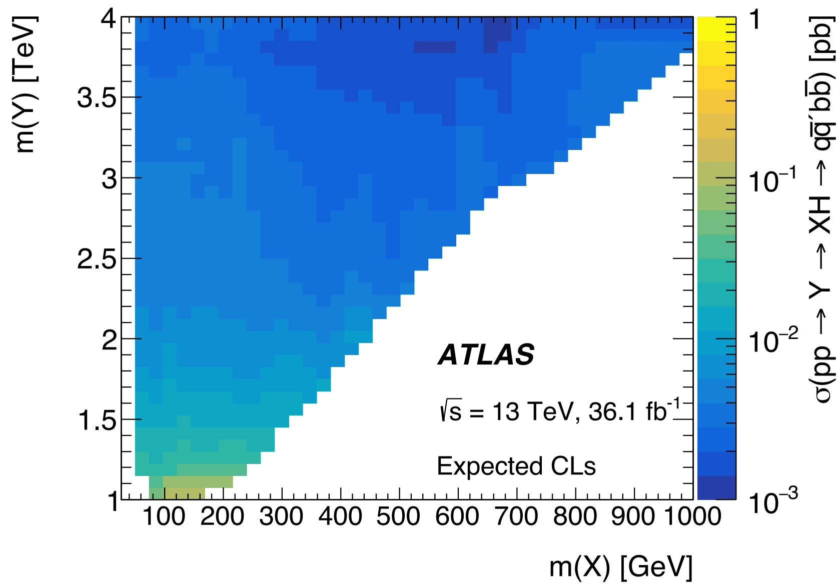


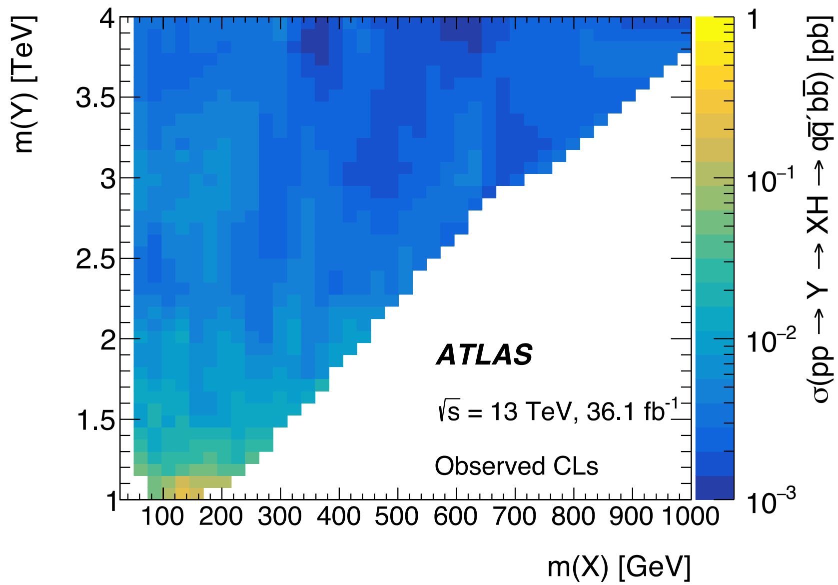


Other hadronic searches: Y→XH→qqbb

- A search for heavy resonances decaying into a Higgs boson and a new particle (X).
- Two-dimensional phase space of Y resonance mass values between 1 and 4 TeV, and X masses from 50 to 1000 GeV.
- Similar strategy to VH search.

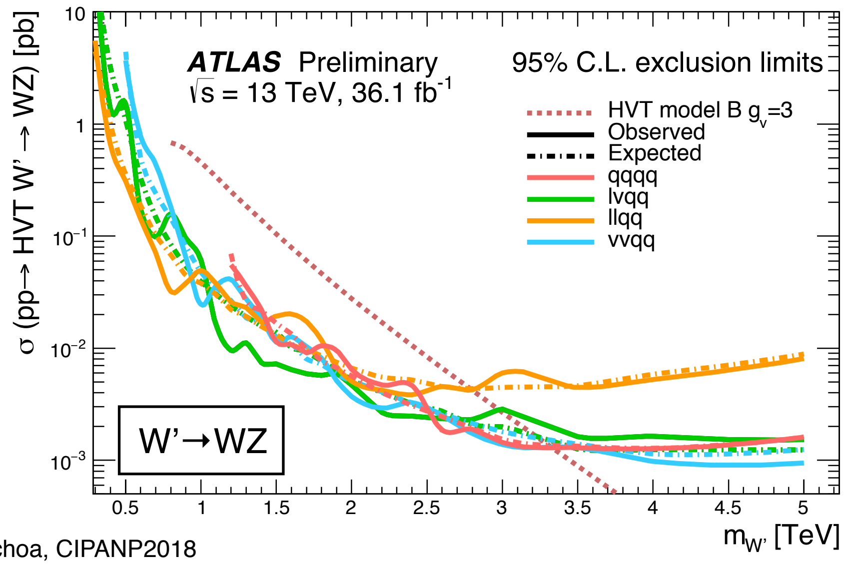


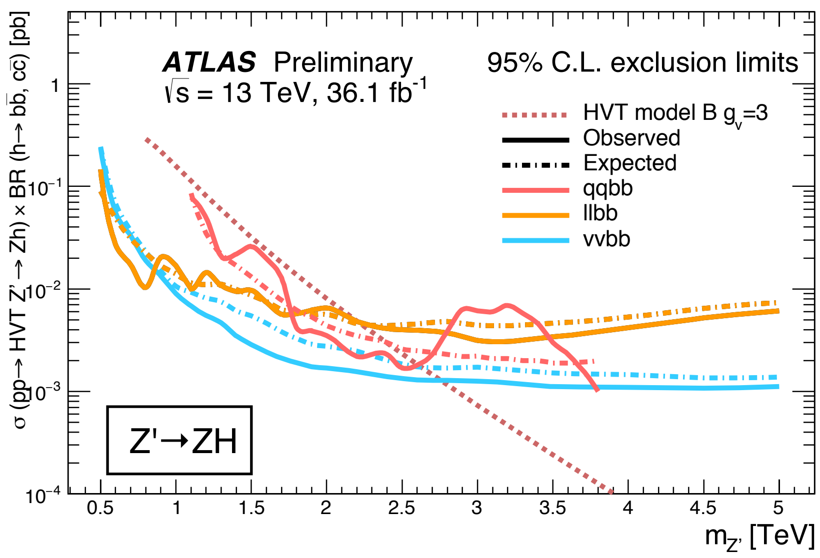




Moving forward…

- Results shown correspond to 2015+2016 data, with an integrated luminosity of 36.1 fb^{-1}.
- 2017 data will more than double the integrated luminosity and more collisions are currently taking place, with the expected Run II luminosity to reach 140 fb^{-1}.
- By continually improving reconstruction and analyses techniques we can get the most out of the data we have:
  - **New techniques:** developments in b-tagging and jet reconstruction (e.g. combining tracker and calorimeter information).
  - **Statistical combinations** of analyses targeting different decay modes, providing stronger constraints on particular models.

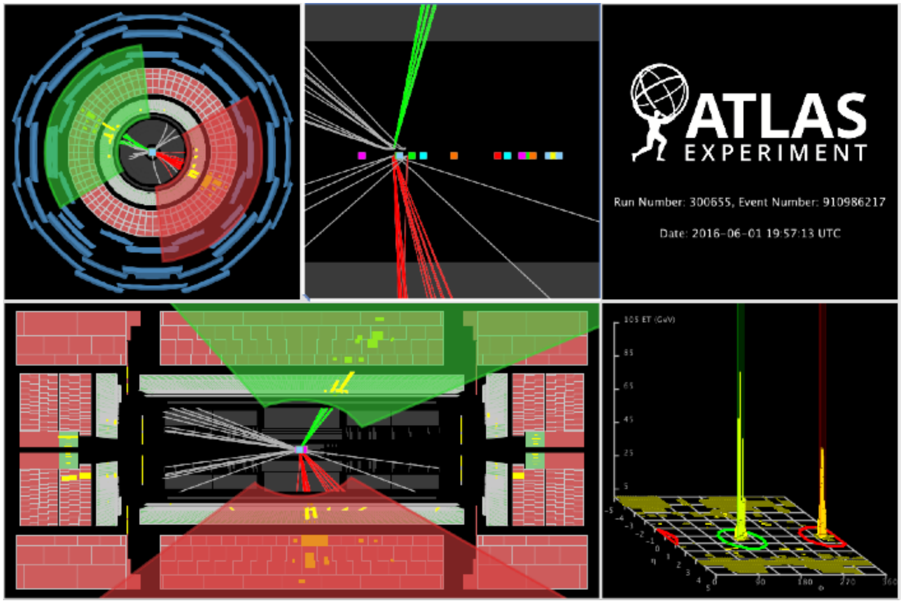




Summary

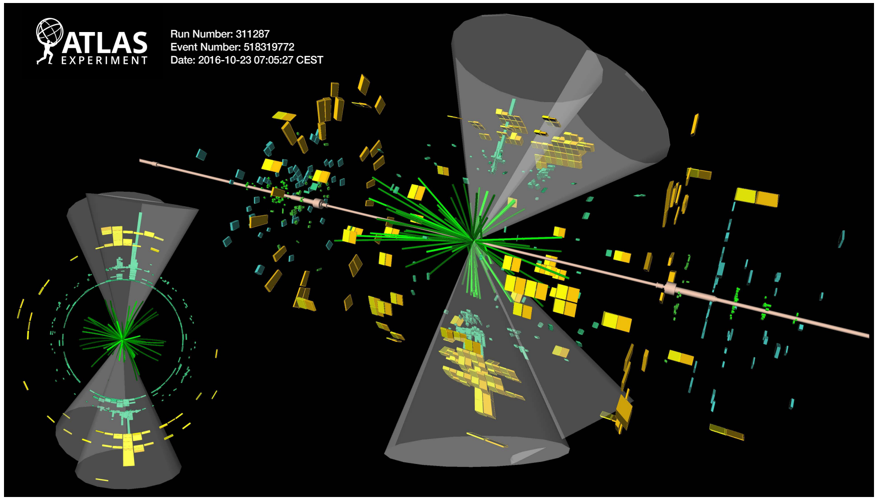
- Diboson final states are a powerful tool to look for new physics.
  - Latest ATLAS Run II results shown today, using 36.1 fb^{-1} of 2015+2016 data.
  - Motivated by multiple models to probe the TeV scale.
  - Taking advantage of advanced analysis techniques to maximize search sensitivity.
- There are new searches on the pipeline, more data to analyze and more data rolling in…

Stay tuned for more LHC data!



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

m_{VV} = 1.8 TeV

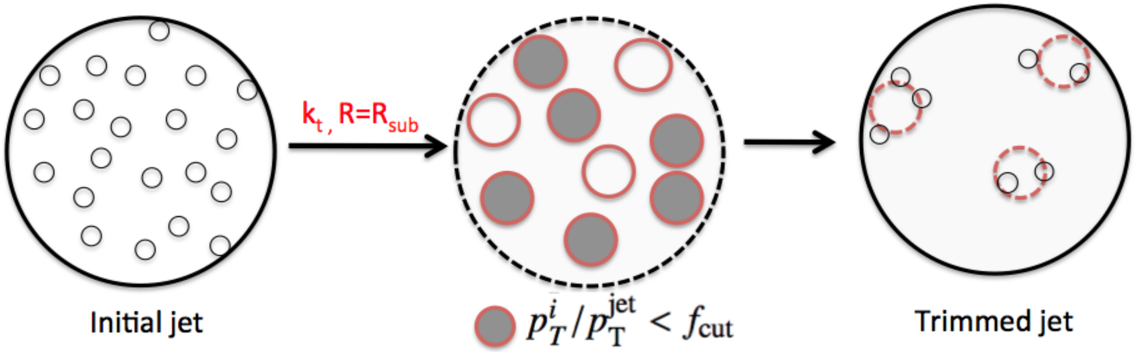


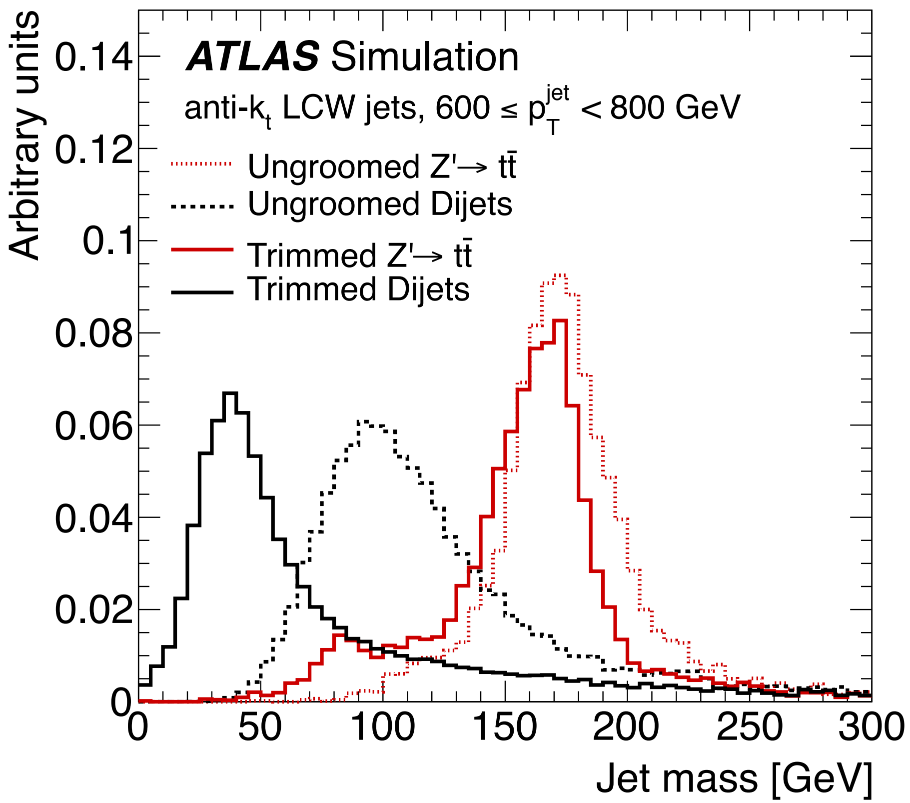
A high mass event from the all-hadronic VV analysis:

m_{4j} = 1.0 TeV

Backup

Jet trimming





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Jet substructure

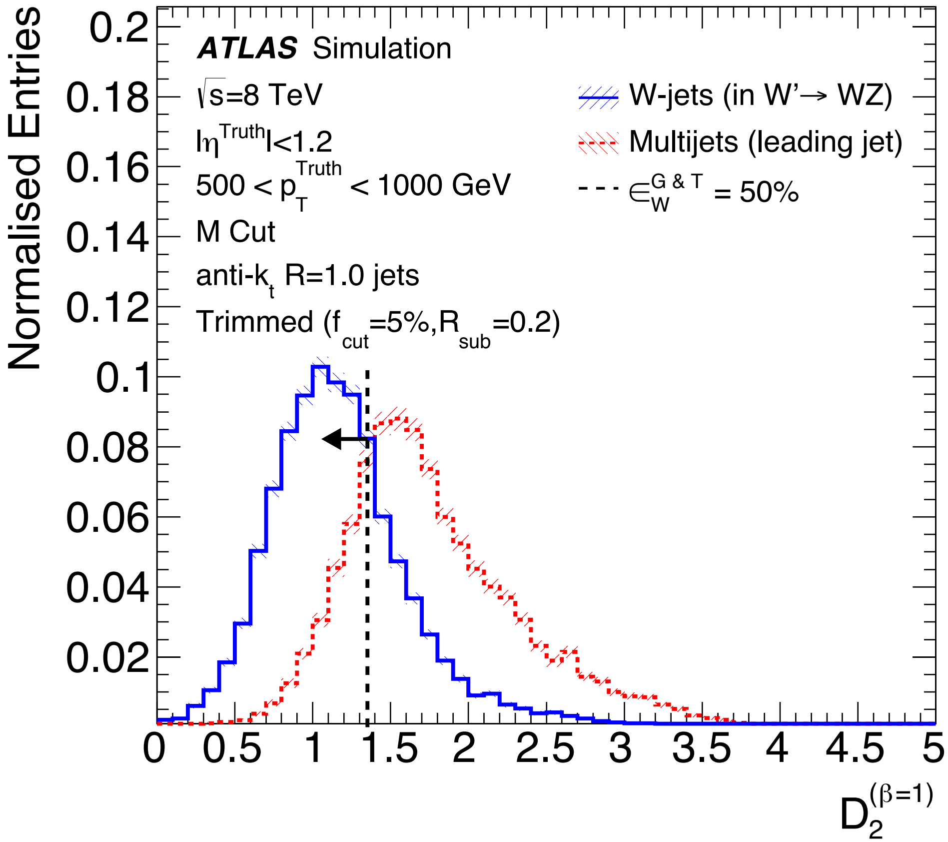
- The $D_2^{\beta=1}$ variable is useful in identifying jets with two-prong substructures.
- Defined from n-point energy correlation functions:

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

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

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

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



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“Combined" jet mass

- The jet mass resolution is further improved by combining calorimeter and tracking information:

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

- ω_{calo} and ω_{track} are inversely proportional to the square of the resolution of each mass term and are optimized to minimize the combined jet mass resolution.

- Resolution is improved especially at high jet p_T, due to the coarser angular resolution of the calorimeter.

- For Higgs boson reconstruction in the bb decay channel, the mass resolution can also be improved by correcting for semi-leptonic decays of the b-hadrons.

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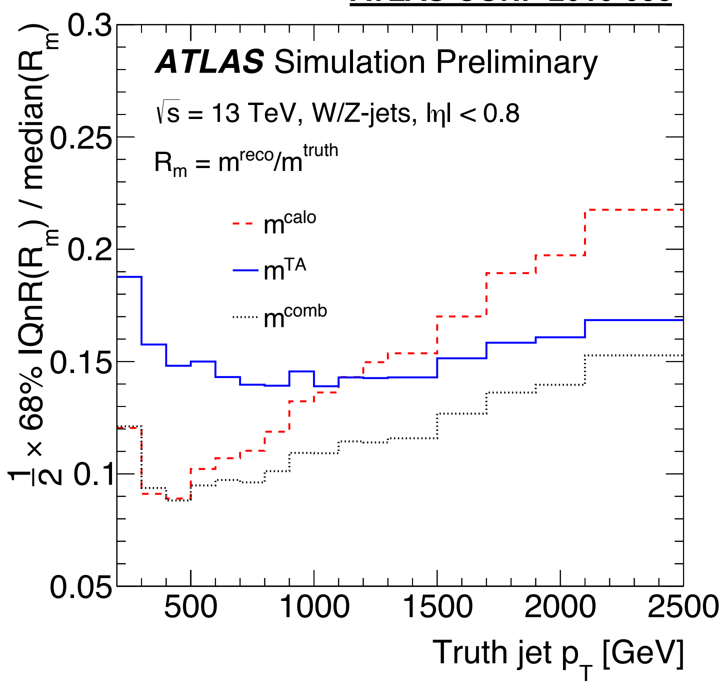
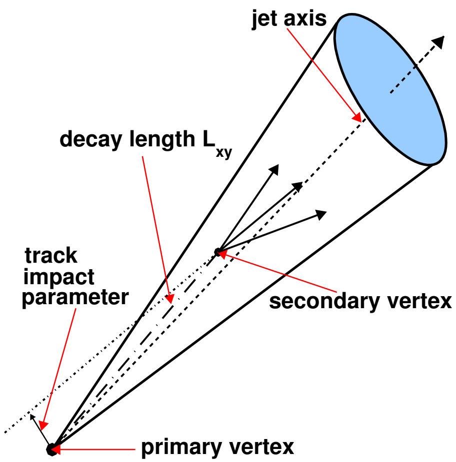
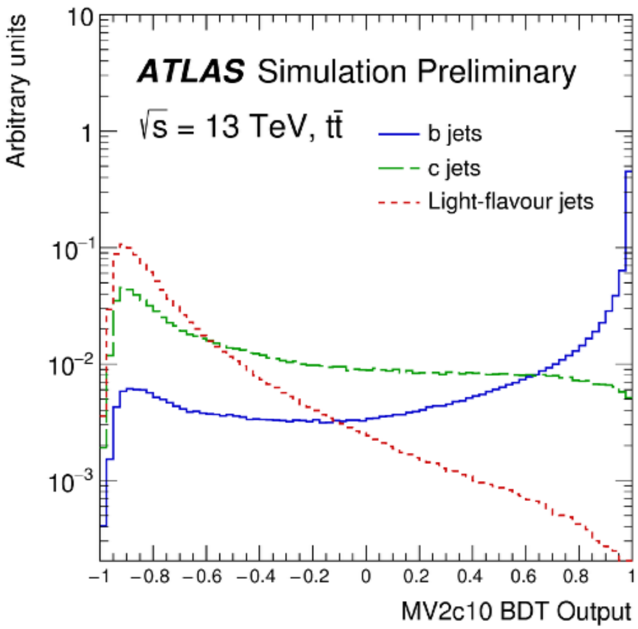
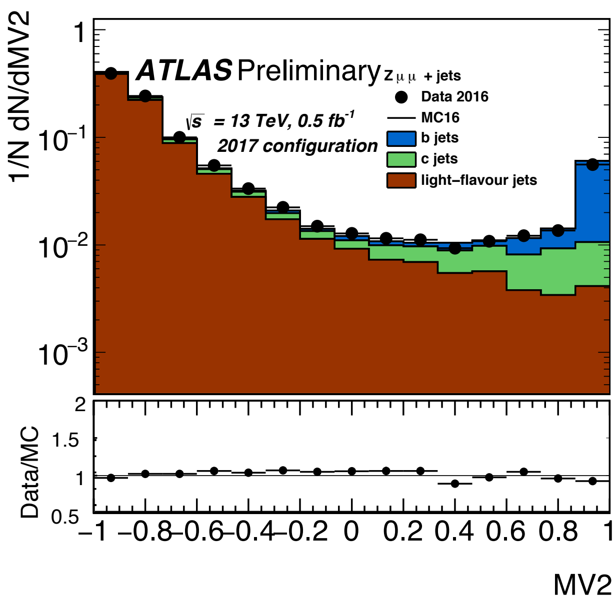


b-tagging

- Crucial for reconstructing Higgs to bb-bar decays but also for rejecting top backgrounds.
- A b-hadron decay in the detector provides a measurable displaced secondary vertex.
- 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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Vɣ searches

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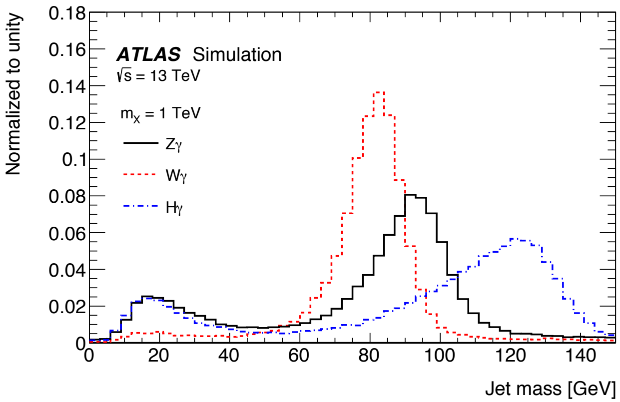
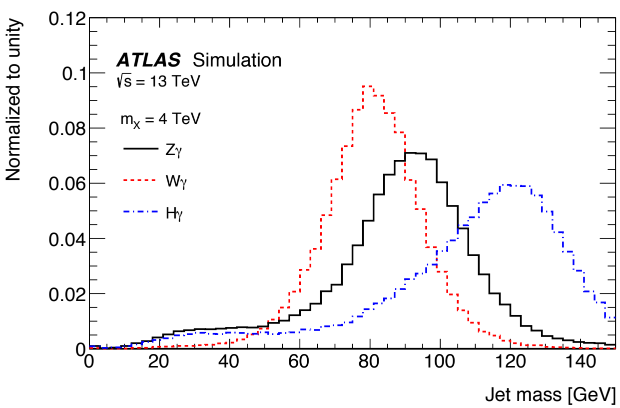
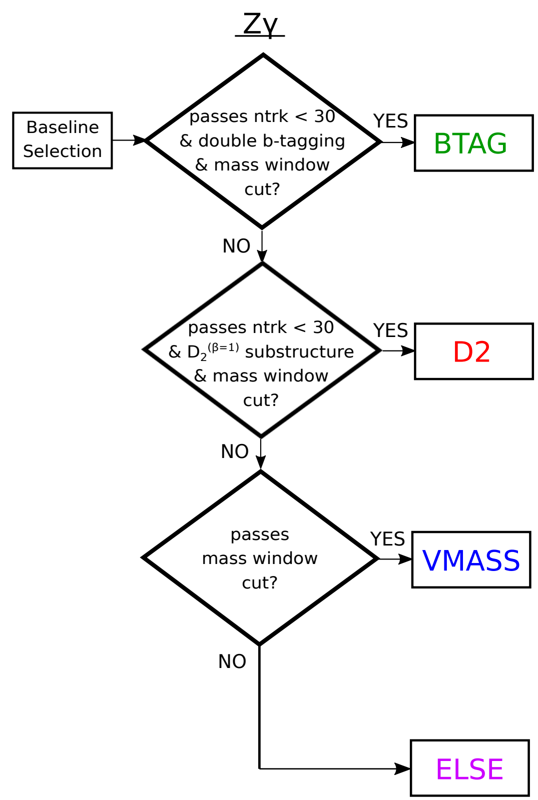
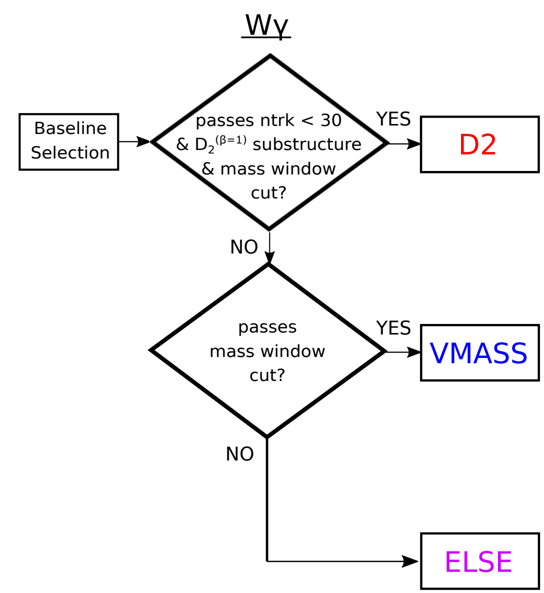
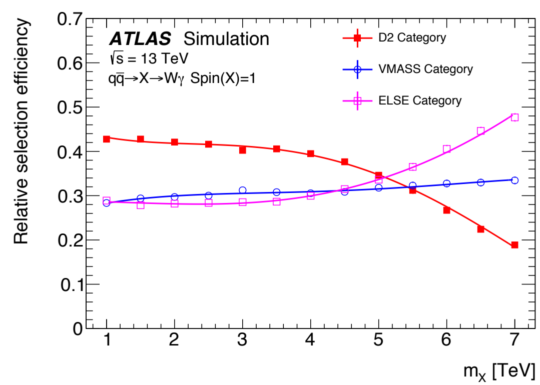
- Event selection

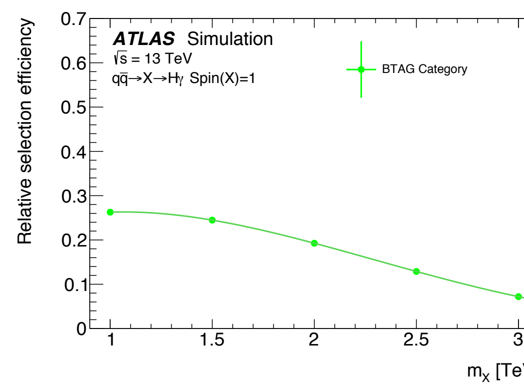












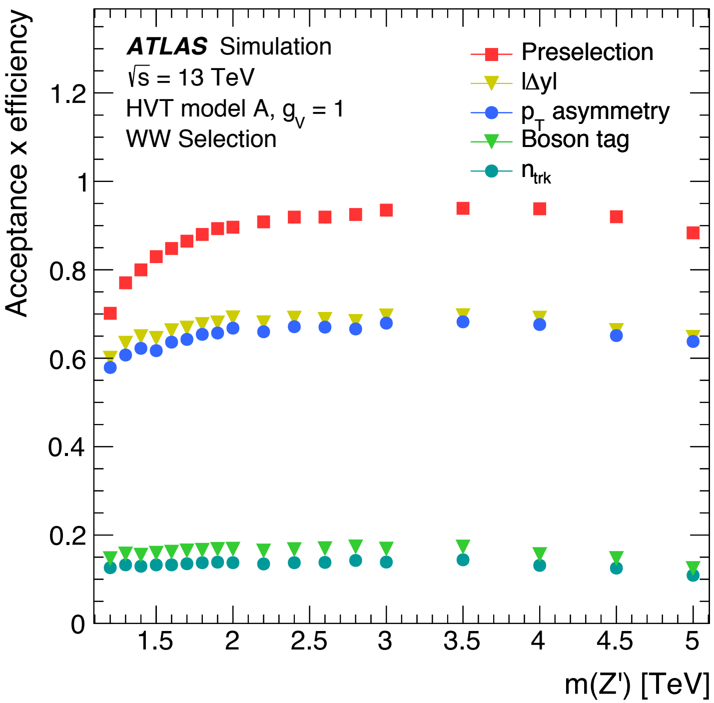
- Systematic uncertainties on signal

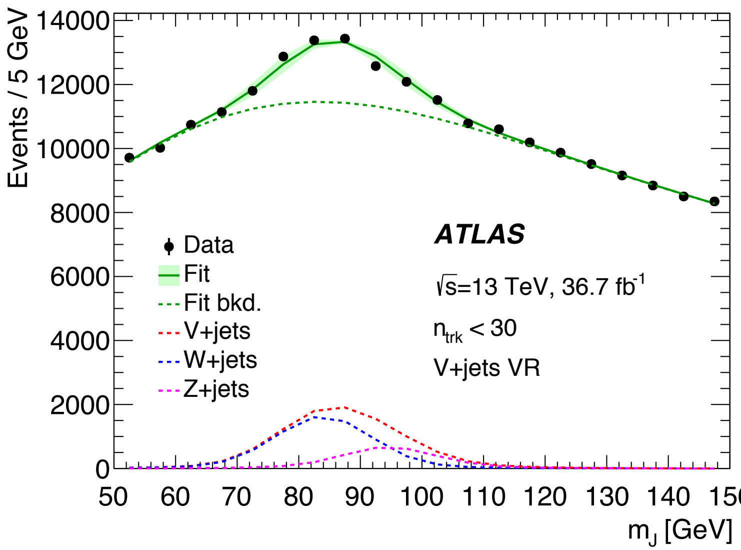
	Impact on normalization and efficiency [%]
Luminosity	2.1
Jet energy scale	2–6
Photon identification and isolation	0.5–1.5
Flavor tagging	10–20
n_{trk} associated with the jet	6
Jet mass resolution	3–6
scale and resolution	< 1
Pileup modeling	1–2
	Impact on signal peak position [%]
Jet energy and mass scale	1–3
Photon energy scale	< 0.5
	Impact on signal peak resolution [%]
Jet energy resolution	5 ($m_X < 2.5$ TeV)–15 ($m_X > 2.5$ TeV)
Photon energy resolution	1–3
	Impact on acceptance [%]
PDF	2–12
Parton shower	2

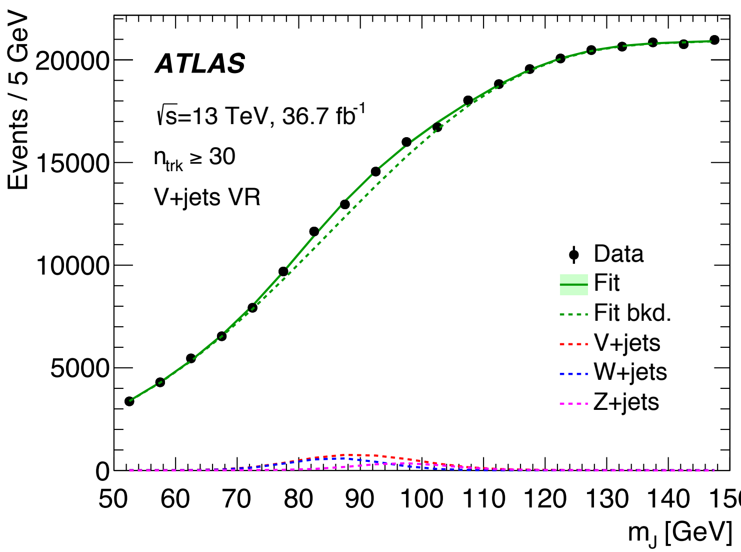
- Event yields

Selection	Event yield in each category (> 1 TeV)				
	Baseline	BTAG	D2	VMASS	ELSE
$Z\gamma$ search	60,237	25	784	5,569	53,859
$W\gamma$ search	60,237	—	661	5,216	54,360
$H\gamma$ search	60,237	59	—	—	—

VV→qqqq search







VV→qqqq search

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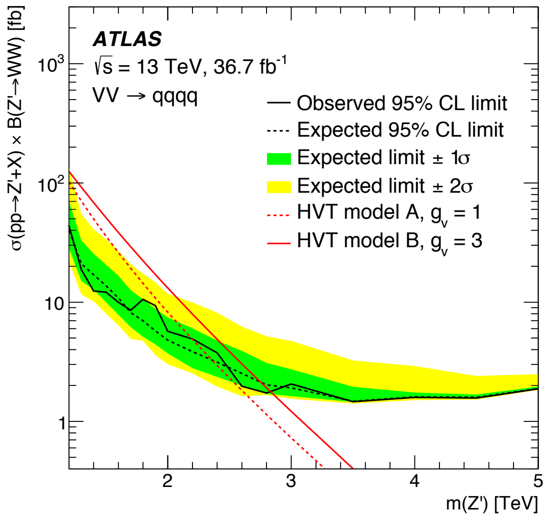

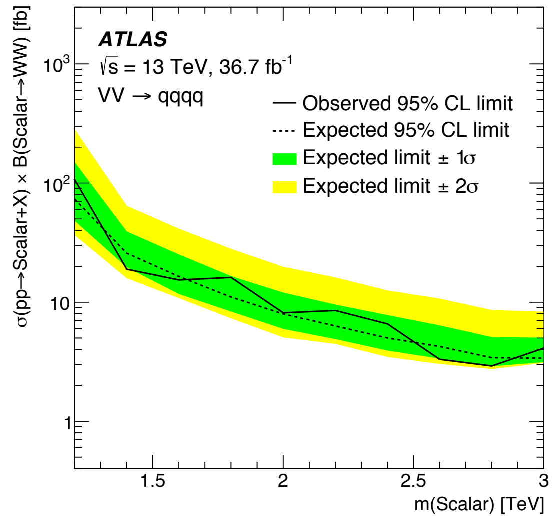

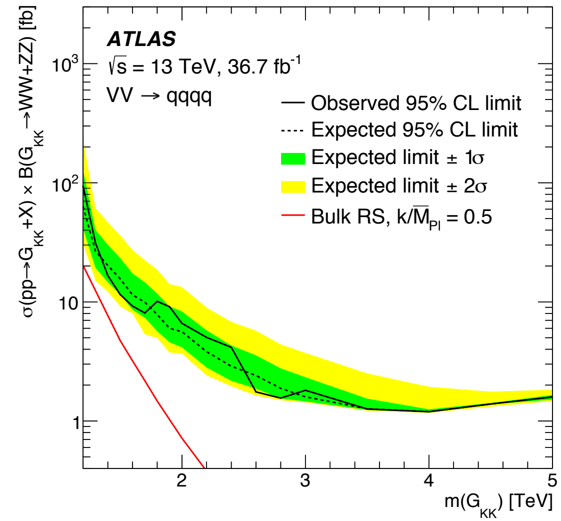

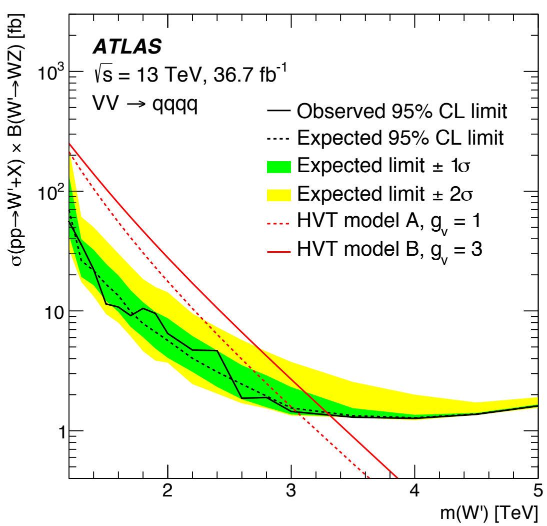

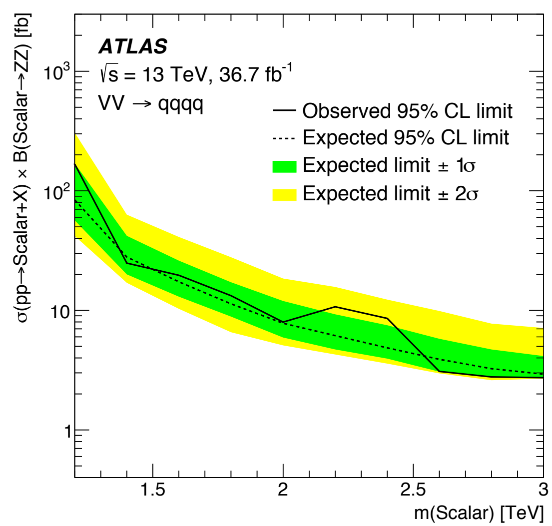

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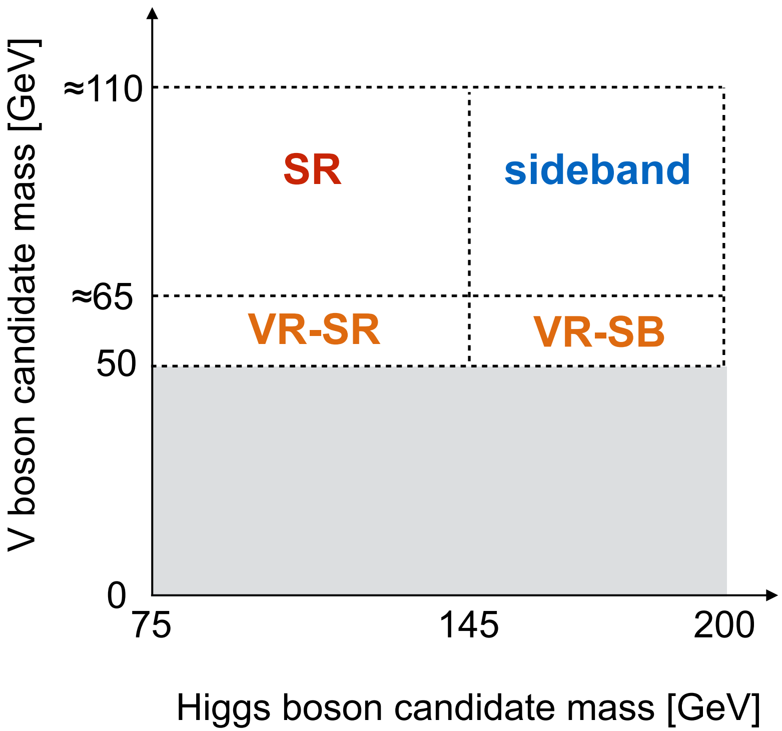

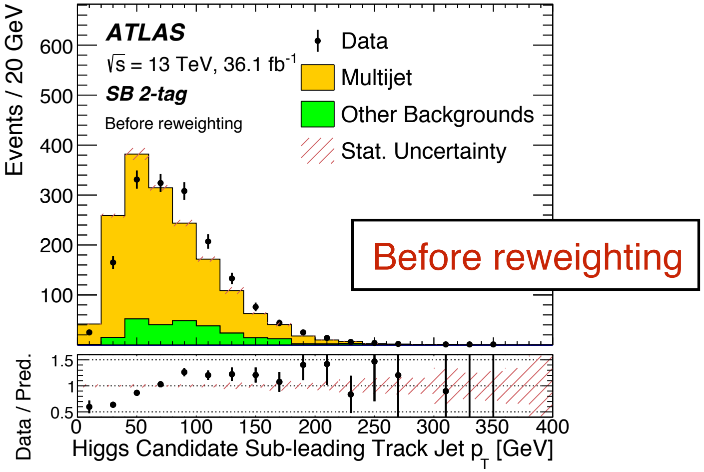

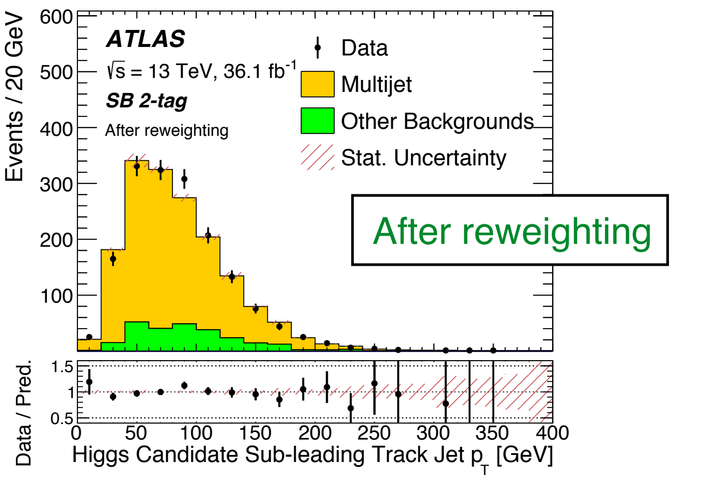

VH→qqbb search

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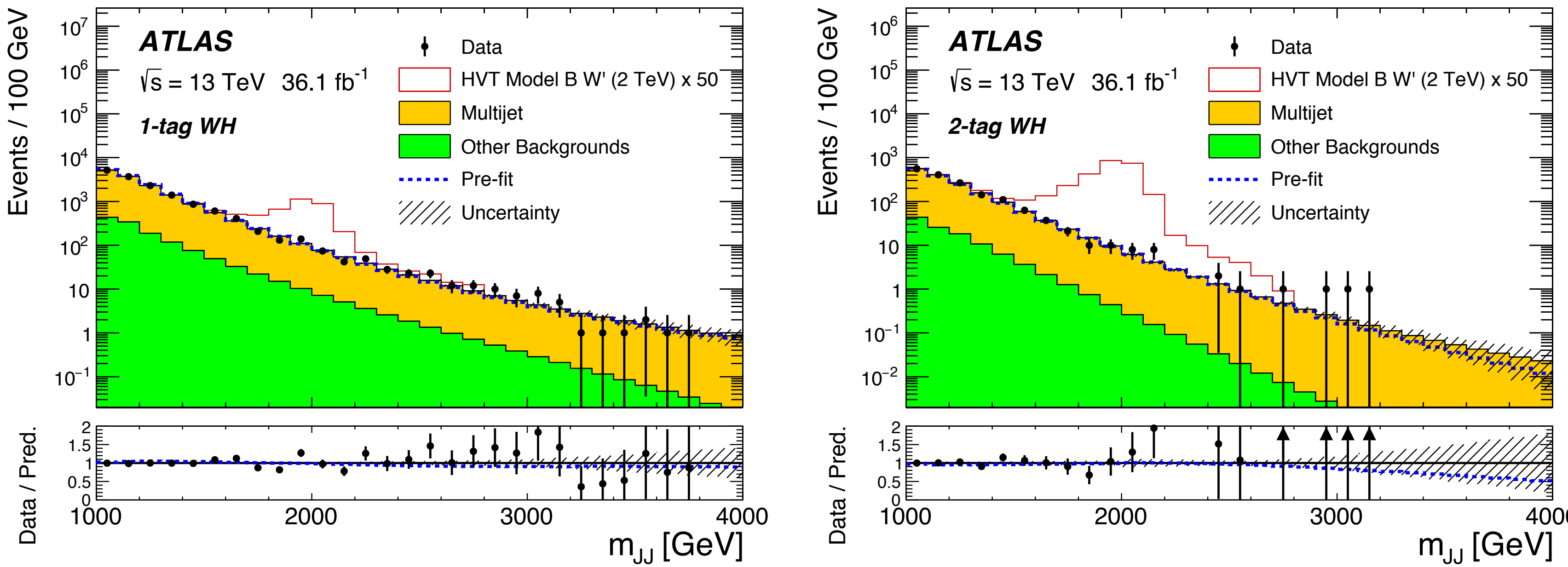

Y→XH→qqbb search