Searches for heavy ZZ and ZW resonances

in the $\ell\ell qq$ and $\nu\nu qq$ final states at 13 TeV with the ATLAS detector

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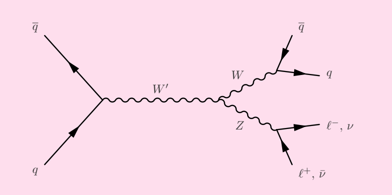
Motivation

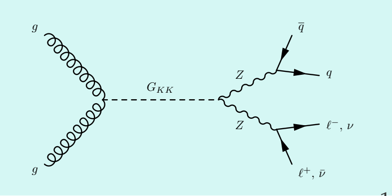
Many models beyond the Standard Model of particle physics predict heavy particles that could decay into diboson final states

- 3 classes of models used as benchmarks for the interpretation of the results:
  - Spin-0 Heavy Higgs - H
  - Spin-1 Heavy Vector Triplet - W', Z'
  - Spin-2 Kaluza Klein excitations of the Randall Sundrum Graviton - G_{KK}

HVT

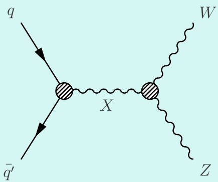


RS Graviton

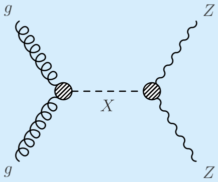


Production modes

Drell-Yan - produces HVT (W')

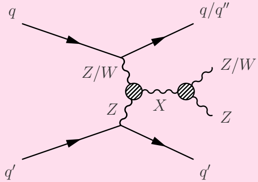


Gluon-gluon fusion - H and G_{KK}



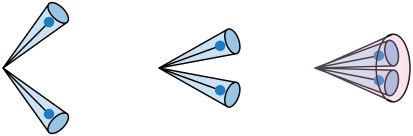
Vector-boson fusion - HVT and H

- Two extra jets with large $|\Delta\eta|$ and m_{jj}
- VBF cross-section is 47% of the ggF cross-section of ggF spin-0 at 1 TeV and increases with increasing signal mass

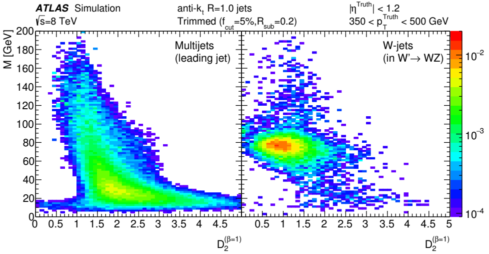


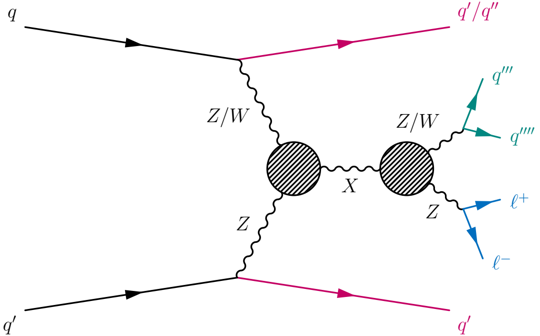
Object selection: boosted jets

The $\ell\ell qq$ and $\nu\nu qq$ analyses use boosted jets that merge into a single large-R jet.



- Uses the ratio of 3- and 2-point energy correlation functions, $D_2^{\beta=1}$, to select two-prong large-R jets
- arXiv:1510.05821 [hep-ex]

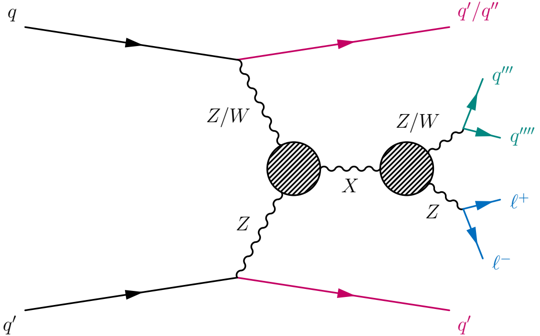




Lepton selection: two leptons $p_T > 7\,\mathrm{GeV}$, one with $> 28\,\mathrm{GeV}$, quality and isolation requirements and $m_{\ell\ell}$ Z mass window

Object selection $VZ \to \ell\ell qq$

Jet selection: ≥ 2 small-R jets no events with > 2 b-tagged jets.
Or ≥ 1 large-R jet with boson tagging to identify W and Z jets.

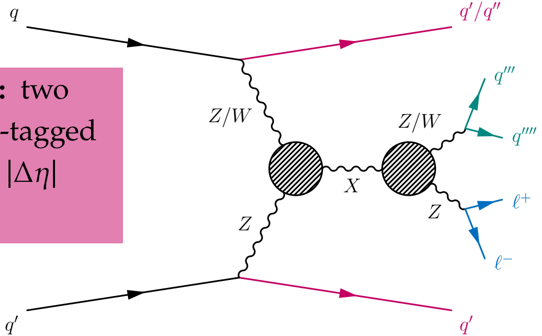


Lepton selection: two leptons $p_T > 7\,\text{GeV}$, one with $> 28\,\text{GeV}$, quality and isolation requirements and $m_{\ell\ell}$ Z mass window

Object selection $VZ \to \ell\ell qq$

Jet selection: ≥ 2 small-R jets no events with > 2 b-tagged jets.
Or ≥ 1 large-R jet with boson tagging to identify W and Z jets.

VBF selection: two forward non b-tagged jets with large $|\Delta\eta|$ and m_{jj}

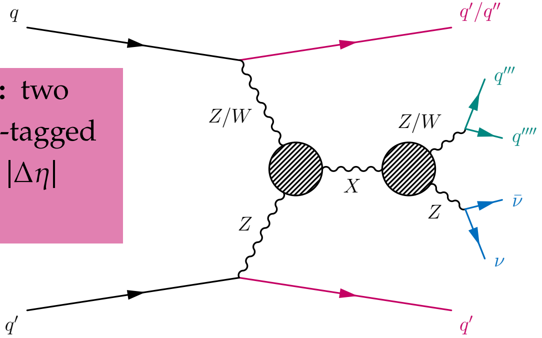


Lepton selection: two leptons $p_T > 7\,\text{GeV}$, one with $> 28\,\text{GeV}$, quality and isolation requirements and $m_{\ell\ell}$ Z mass window

Object selection $ZV \to \nu\nu qq$

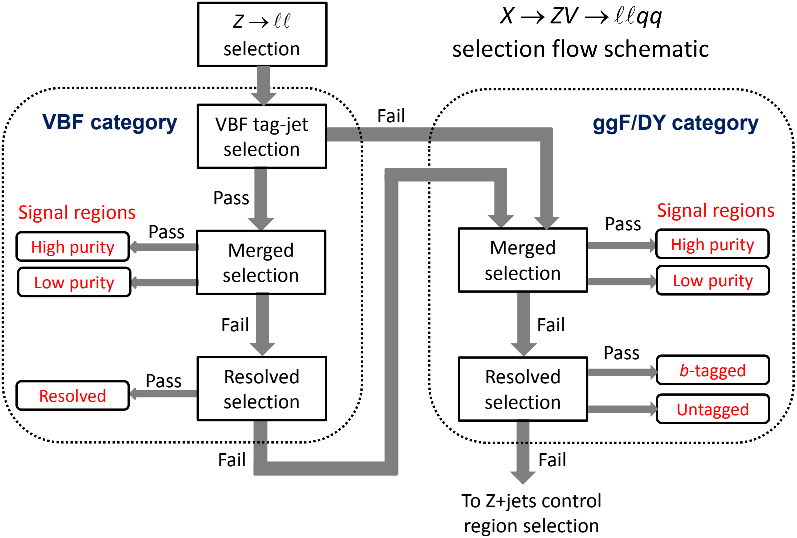
Jet selection: $\geq$ 1 large-R jet with boson tagging to identify W and Z jets.

VBF selection: two forward non b-tagged jets with large $|\Delta\eta|$ and m_{jj}

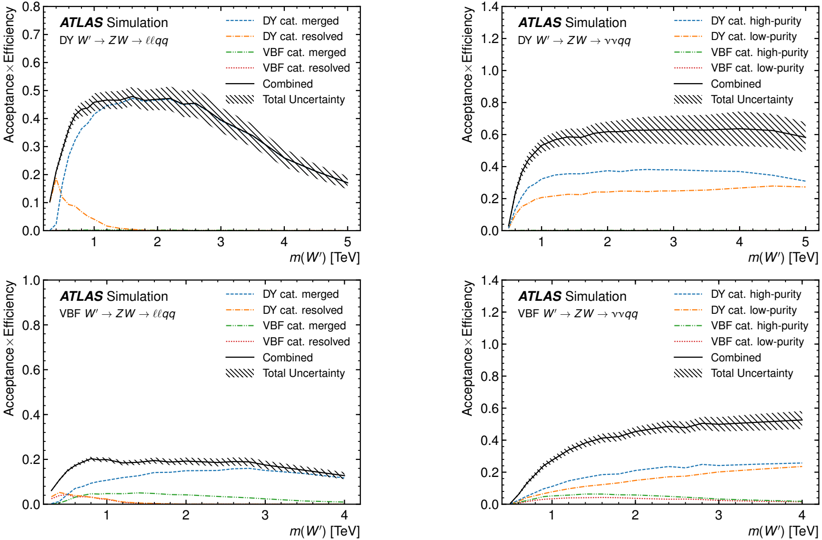


MET selection: $E_T^{\text{miss}} > 250\,\text{GeV}$, multijet removal using track based p_T^{miss}

Selection regions



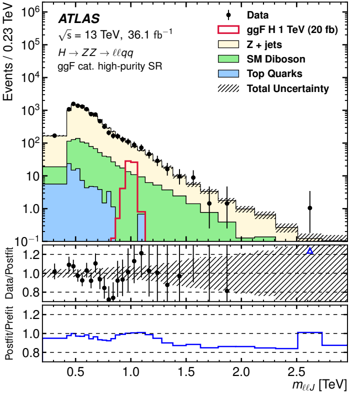
Acceptance×Efficiency

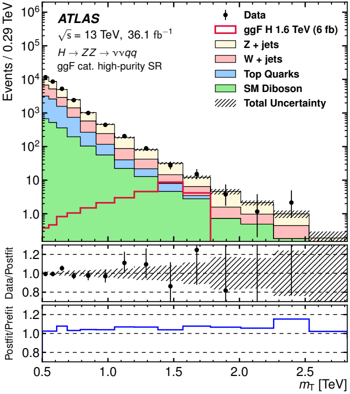


Paper link

Results: ggH high purity

No new physics observed in either $\ell\ell qq$ or $\nu\nu qq$ channels. Paper link

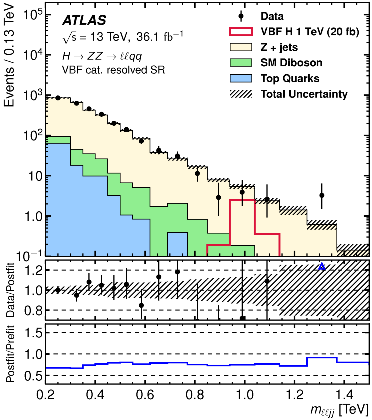


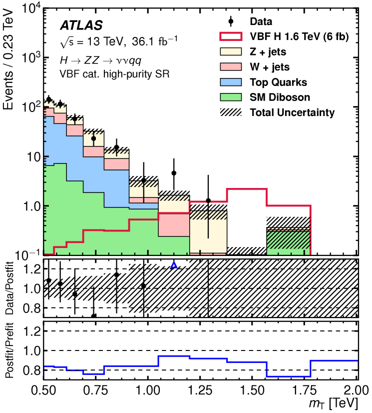


$$m_T = \sqrt{\left(E_{T,J} + E_T^{\text{miss}}\right)^2 - \left(\vec{p}_{T,J} + \vec{E}_T^{miss}\right)}$$

Results: VBF H

No new physics seen in VBF H channels. Paper link





Uncertainty sources

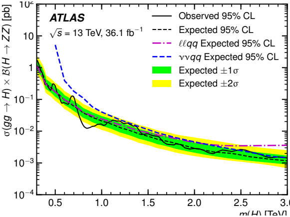
Dominant sources of uncertainty are:

$m(H) = 600$ GeV		$m(H) = 1.2$ TeV	
Uncertainty source	$\Delta\mu/\mu$ [%]	Uncertainty source	$\Delta\mu/\mu$ [%]
Pseudo-data statistics	36	Pseudo-data statistics	41
Total systematics	33	Total systematics	29
MC statistics	20	Large-R jet	20
Large-R jet	16	Background modelling	13
$E_{\mathrm{T}}^{\mathrm{miss}}$ uncertainties	13	MC statistics	13
Small-R jet	11	Luminosity	6.5
Background modelling	9.6	Small-R jet	5.9
Luminosity	9.1	Leptons	3.9

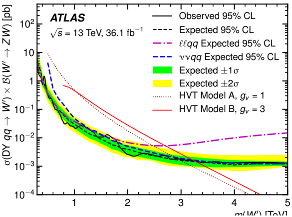
Limits

Limits set on the production of the models. Paper link

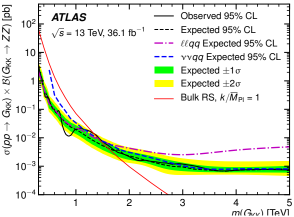
Spin-0



Spin-1



Spin-2



$\sigma \times \mathcal{B}(H \to ZZ)$ range from 1.7 pb at $m(H) = 300$ GeV to 1.4 (1.1) fb at $m(H) = 3$ TeV

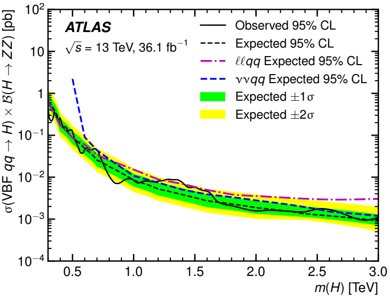
Model A (*Model B*) with coupling constant $g_V = 1$ ($g_V = 3$), spin-1 HVT is excluded for $m(W') < 2.9$ (3.2) TeV

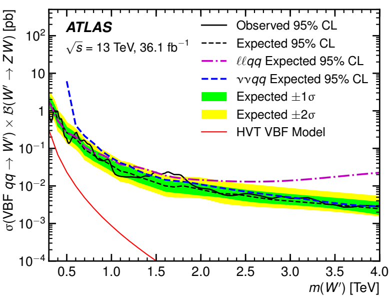
$k/\bar{M}_{Pl} = 1$ ($k/\bar{M}_{Pl} = 0.5$), a spin-2 Kaluza–Klein graviton is excluded for $m(G_{KK}) < 1.3$ (1.0) TeV

Limits

$\sigma \times \mathcal{B}(H \to ZZ)$ for a H *VBF Model* set to 0.42 pb at $m(H) = 300$ GeV to 1.1 pb at $m(H) = 3$ TeV.

$\sigma \times \mathcal{B}(W' \to ZW)$ for an HVT *VBF Model* set to 0.98 pb at $m(W') = 300$ GeV and 2.8 fb at $m(W') = 4$ TeV





Paper link

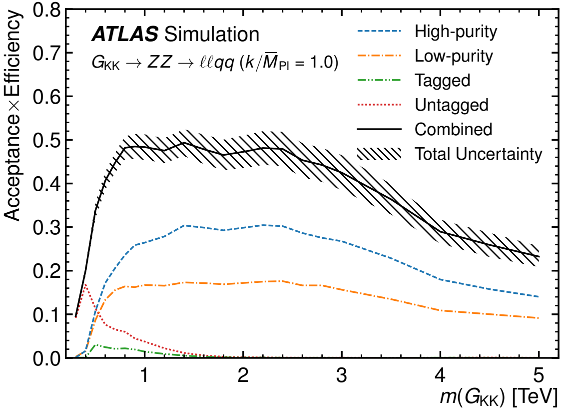
Current work

Work on the analyses using simulation datasets to optimise acceptance:

- Improving the selection efficiency of boosted electrons
- Using multivariate analysis
- Including b-tagging for merged regions
- Excluding h mass window, orthogonality requirement with Vh analysis

Current work: boosted electrons

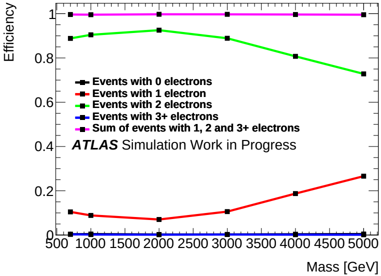
Acceptance begins to fall after $\sim 2.5\,\text{TeV}$ due to boosted electrons not being reconstructed well.

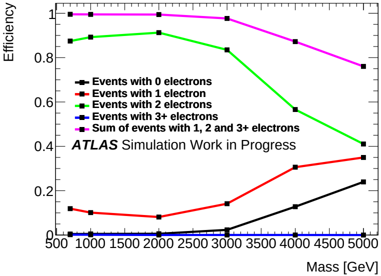


Current work: boosted electrons

Studies show the loss of efficiency is in part caused by the electron quality requirement, the loose likelihood requirement.

$$Eff = \frac{\text{Number of selected reconstructed events}}{\text{Number of events with two truth electrons}}$$





Conclusion

Results of previous analysis

- No new physics found
- Set limits on the production of spin-0, spin-1 and spin-2 heavy resonances decaying to vector bosons
- Paper link: https://arxiv.org/pdf/1708.09638.pdf

Future work

- Improving acceptance of close by boosted electrons
- Using multivariate analysis
- Including b-tagging for merged regions
- Excluding h mass window, orthogonal requirement with Vh analysis

Backup

Backup: Object selection $VZ \to \ell\ell qq$

Selection	$ZV \to \ell\ell J$	$ZV \to \ell\ell jj$
$Z \to \ell\ell$	2 opposite flavour leptons with $p_T(E_T) > 7$ GeV leading lepton with $p_T(E_T) > 28$ GeV Quality requirements depending on a number of variables $83 < m_{ee} < 99$ GeV $85.6\,\text{GeV} - 0.0117 \times p_T^{\ell\ell} < m_{\mu\mu} < 94.0\,\text{GeV} + 0.0185 \times p_T^{\ell\ell}$	
Tag jet selection for VBF selection	Two non b-tagged small-R jets with $\eta_1 \dot{\eta}_2 < 0$, $\left\|\Delta\eta_{jj}^{\text{tag}}\right\| > 4.7$ and $m_{jj}^{\text{tag}} > 770$ GeV	
Jet requirements	> 1 large-R jet	≥ 2 small-R jets with $p_T > 30$ GeV $p_T > 60$ GeV for the leading jet no events with > 2 b-tagged jets
Kinematic criteria	$\min(p_T^{\ell\ell}, p_T^J)/m_{\ell\ell J}$	$\sqrt{\left(p_T^{jj}\right)^2 + \left(p_T^{jj})\right)^2}/m_{\ell\ell jj}$
H	> 0.3	> 0.4
W' or G_{KK}	> 0.35	> 0.5
V boson tagging	p_T-dependent criteria in D_2 and m_J	$70 < m_{jj} < 105$ GeV (V=Z) $62 < m_{jj} < 97$ GeV (V=W)

Backup: Object selection $ZV \to \nu\nu qq$

Selection	$ZV \to \nu\nu q$
$Z \to \nu\nu$	$E_T^{\text{miss}} > 250\,\text{GeV}$
Multijet removal	$p_T^{\text{miss}} > 50\,\text{GeV}$ $\Delta\phi(\vec{E}_T^{\text{miss}}, \vec{p}^{\text{miss}_T}) < 1$ $\min\left[\Delta\phi(\vec{E}_T^{\text{miss}}, \text{small} - R, \text{jet})\right] > 0.4$
Tag-jet selection for VBF selection	Two non b-tagged small-R jets with $\eta_1 \dot{\eta}_2 < 0$, $\left\|\Delta\eta_{jj}^{\text{tag}}\right\| > 4.7$ and $m_{jj}^{\text{tag}} > 630\,\text{GeV}$
Jet requirements	≥ 1 large-R jet with $p_T > 200\,\text{GeV}$
V boson tagging	p_T-dependent criteria in D_2 and m_J

Backup: Spin-0 $\ell\ell qq$ results

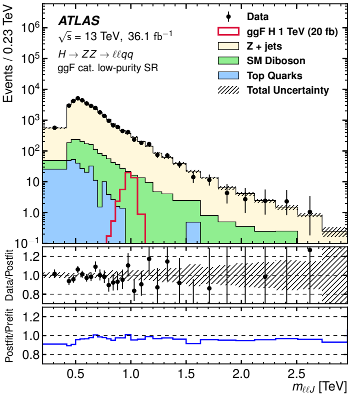


Figure 1: Merged low purity ggF spin-0 signal region for $ZZ \to \ell\ell qq$

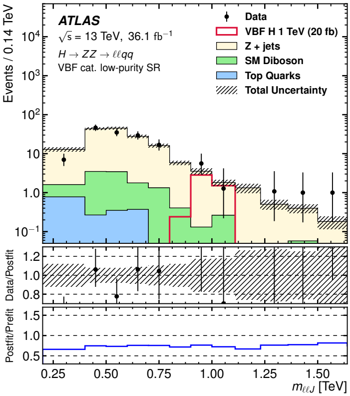


Figure 2: Merged low purity VBF spin-0 signal region for $ZZ \to \nu\nu qq$

Backup: Spin-0 $\ell\ell qq$ results

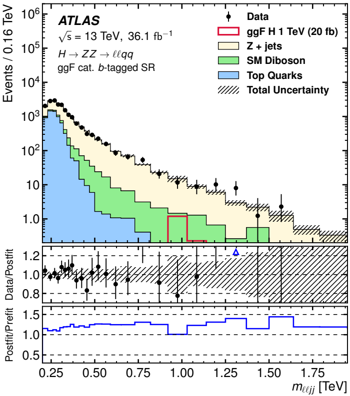


Figure 3: Resolved tagged ggF spin-0 signal region for $ZZ \to \ell\ell qq$

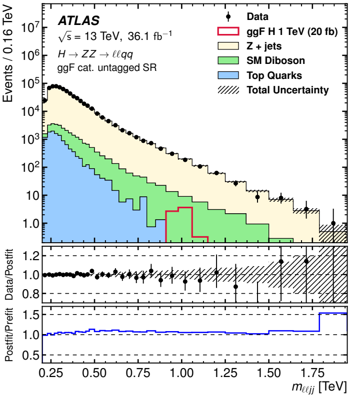


Figure 4: Resolved untagged ggF spin-0 signal region for $ZZ \to \nu\nu qq$

Backup: Spin-0 $\ell\ell qq$ results

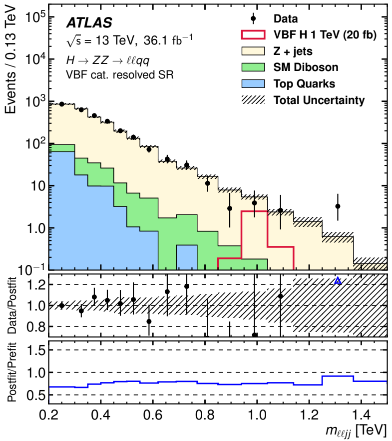


Figure 5: Resolved VBF spin-0 signal region for $ZZ \to \nu\nu qq$

Backup: Spin-0 $\nu\nu qq$ results

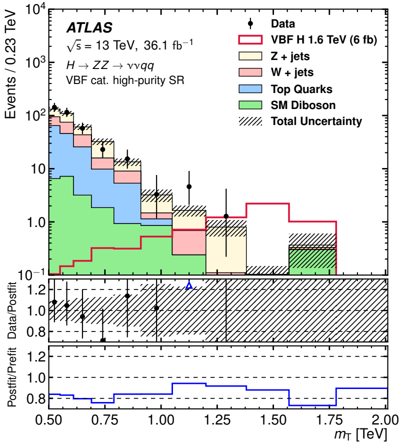


Figure 6: Merged high purity VBF spin-0 signal region for $ZZ \to \nu\nu qq$

Backup: Spin-0 $\nu\nu qq$ results

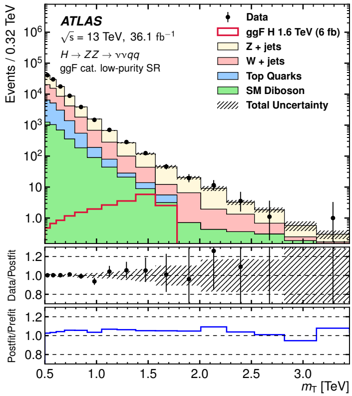


Figure 7: Merged low purity ggF spin-0 signal region for $ZZ \to \nu\nu qq$

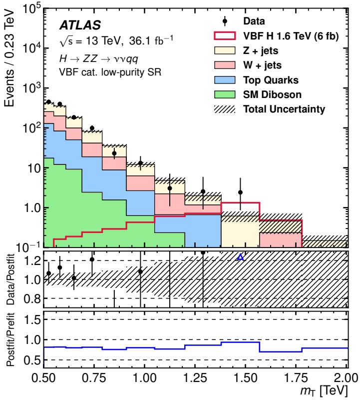
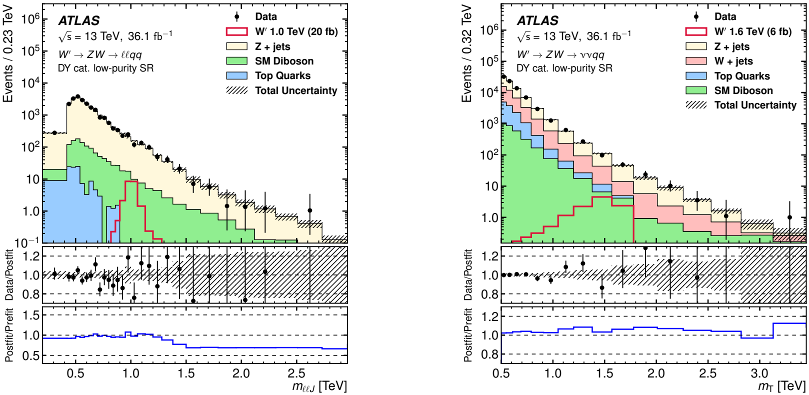
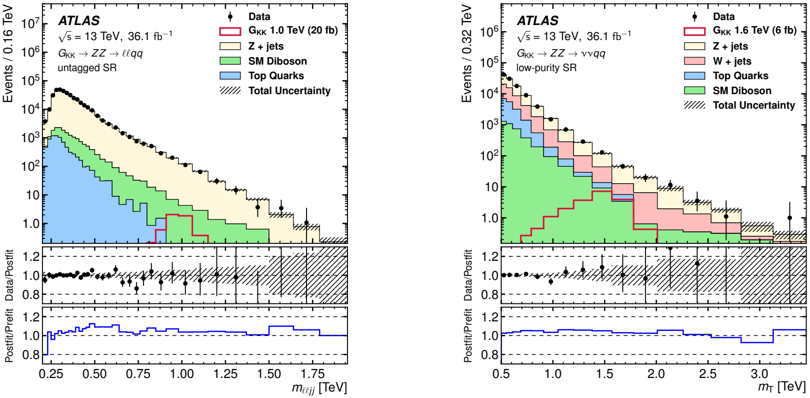


Figure 8: Merged low purity VBF spin-0 signal region for $ZZ \to \nu\nu qq$

Results: Drell-Yan W' low purity



Results: ggF G_{KK}



Backup: VBF and Kp5 Limits

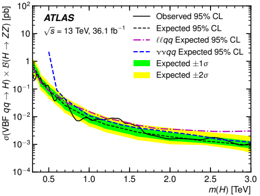


Figure 9: Combined limits set on VBF Spin-0 particle decaying to ZZ

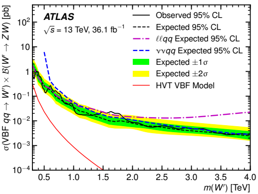


Figure 10: Combined limits set on VBF Spin-1 particle decaying to ZZ

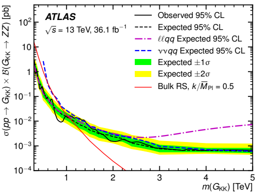


Figure 11: Combined limits set on Spin-2 particle decaying to ZZ

Backup: Results

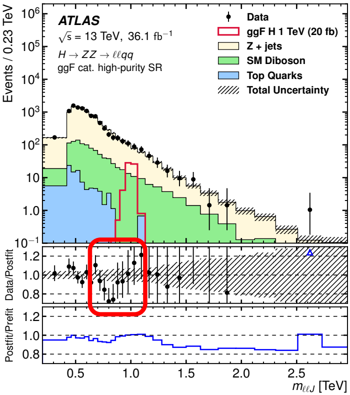


Figure 12: Merged high purity ggF spin-0 signal region for $ZZ \rightarrow \ell\ell qq$

Deficit seen in the $m_{\ell\ell J}$ spectrum at ~ 800 GeV:

- 3σ in $m_{\ell\ell J}$, 1.9σ using look elsewhere effect in full $m_{\ell\ell J}$
- Not a statistical fluctuation but a systematics effect independent of data taking period