ATLAS Searches for VV and Vγ Resonances

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On behalf of the ATLAS Collaboration

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How to find new physics - the easy way!

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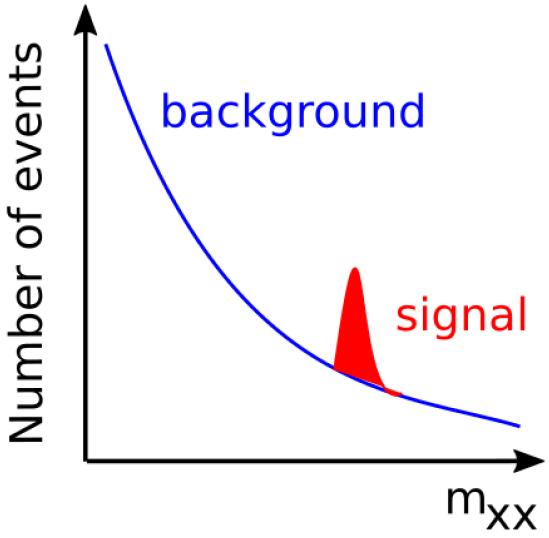
General idea

- Search for new particle Z $\rightarrow$ XX or XY
- Reconstruct invariant mass $m_{\mathrm{XX/XY}}$
- Search for narrow resonance on top of background



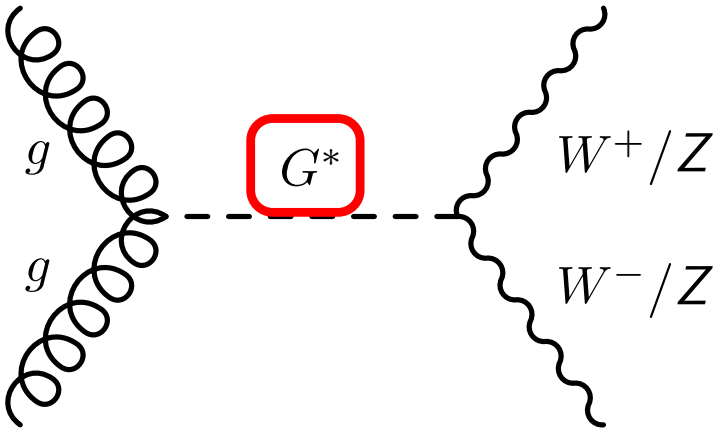
Analyses presented today based on 13.2 - 15.5 fb^{-1} taken in 2015+2016

1. $WZ/ZZ \rightarrow \ell\ell qq$ ATLAS-CONF-2016-082
2. $WZ/ZZ \rightarrow \nu\nu qq$ ATLAS-CONF-2016-082
3. $WW/WZ \rightarrow \ell\nu qq$ ATLAS-CONF-2016-062
4. $WW/WZ/ZZ \rightarrow qqqq$ ATLAS-CONF-2016-055
5. $Z\gamma \rightarrow \ell\ell\gamma$ ATLAS-CONF-2016-044

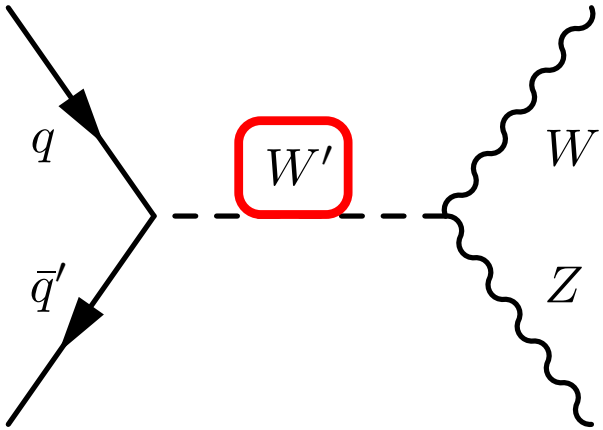
*See Mark Oreglia's talk on VH and HH resonances
**Diboson resonance searches with hadronic decays rely on substructure techniques

Benchmark models for VV and $V\gamma$ resonances

1. **Bulk Randall-Sundrum model**
   - Model of warped extra dimensions
   - Spin-2 Kaluza-Klein graviton (G*)
   - $G^* \to WW, ZZ$
   - BR(G* $\to WW/ZZ$) $\approx$ 20/10%



2. **Heavy Vector Triplet**
   - Simplified phenomenological Lagrangian
   - Spin-1 gauge bosons (W', Z')
   - $W' \to WZ$ and $Z' \to WW$
   - BR(W' $\to$ WZ) $\approx$ 2%

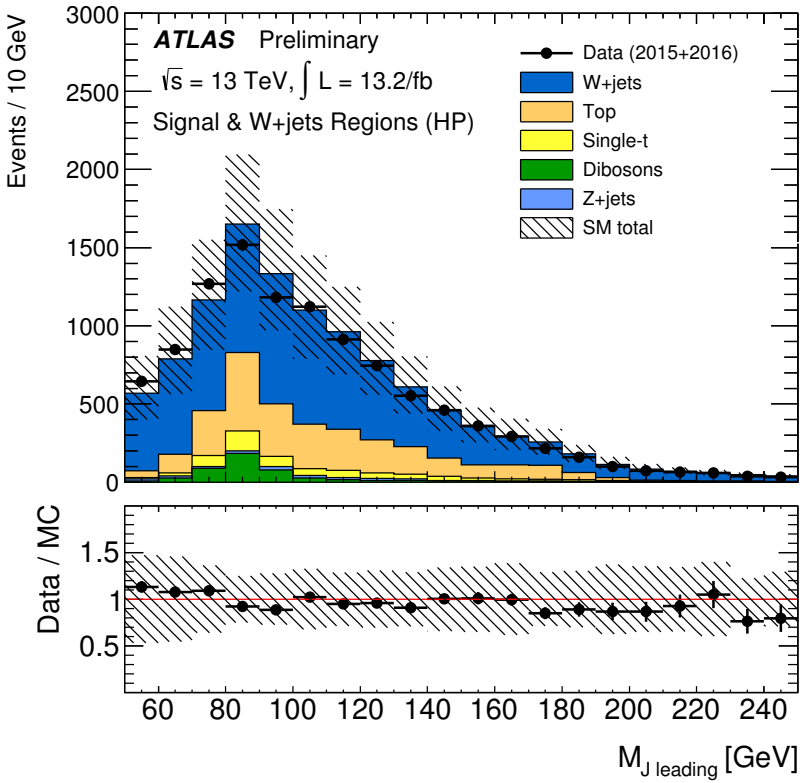


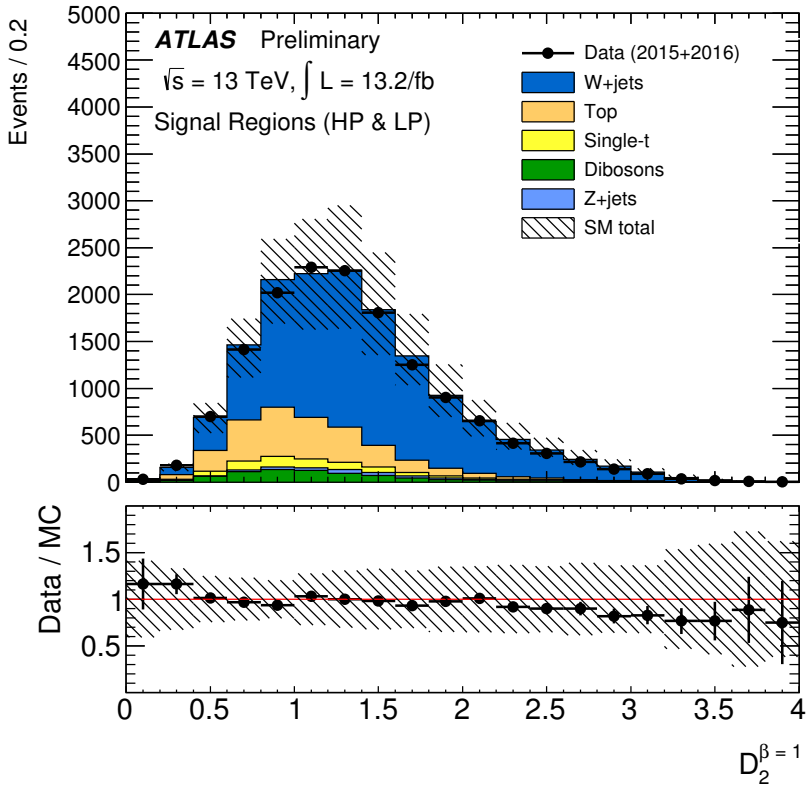
3. **Heavy Higgs**
   - Spin-0 H boson, narrow width approx.
   - $H \to WW/ZZ$
   - *Naive dimensional analysis* and *unsuppressed* gluon coupling

4. **Scalar boson X**
   - gg fusion production
   - X $\to Z + \gamma$
   - Intrinsic decay width of 4 MeV to $Z + \gamma$

Boosted boson tagging in Run-II searches in ATLAS

1. **Jet algorithm:** anti-k_t jets with radius parameter $R = 1.0$
2. **Grooming algorithm:** trimming with $R_{\rm sub} = 0.2$ and $f_{\rm cut} = 5\%$ (subjets are re-clustered with k_t algorithm)
3. **Boson tagging:** 50% flat signal efficiency ($\sim$ 2% QCD eff.)
   - large-radius jet mass ($\pm$15 GeV window around boson mass)
   - Energy correlation variable $D_2^{\beta=1}$

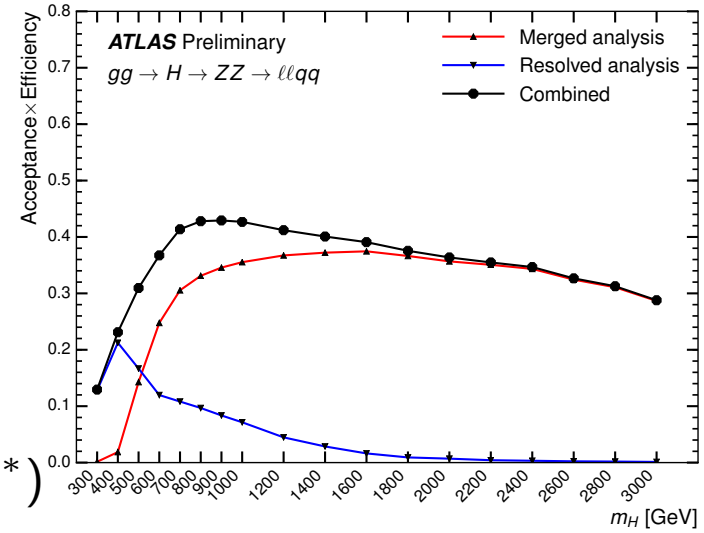


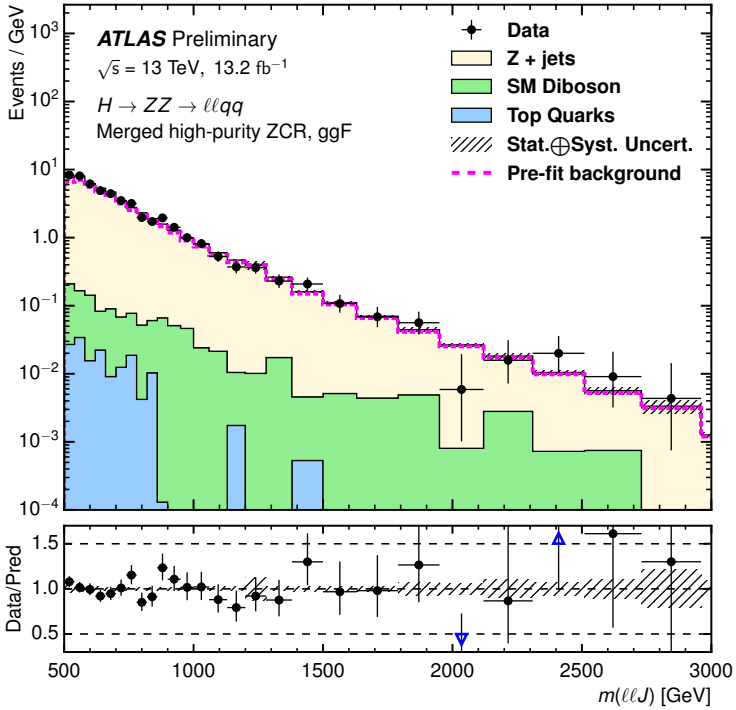


$ZV \to \ell\ell qq$

Event selection

- 2 isolated same flavour leptons, $m_{\ell\ell}$ compatible with Z boson mass
- Merged (one large-R jet) and resolved (two $R = 0.4$ jets) analyses
- High and low purity signal regions based on D_2
- $\sqrt{p_T^2(\ell\ell) + p_T^2(jj)}/m_{\ell\ell jj} > 0.4(0.5)$ for H (W', G^*)





Background estimation

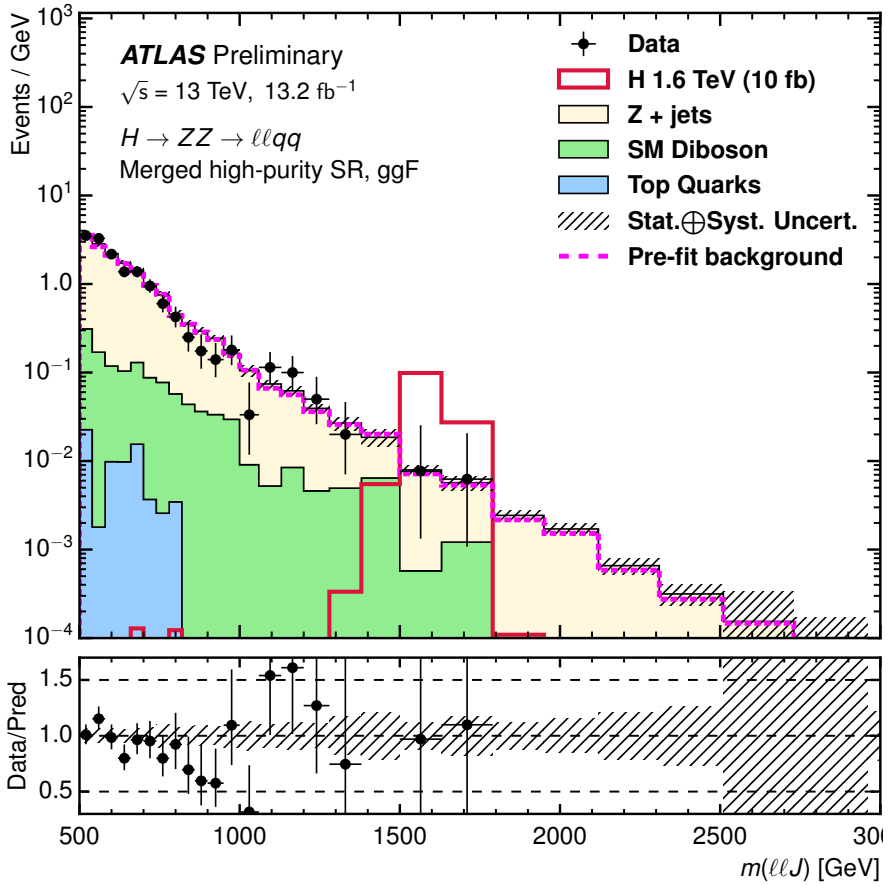
- Shape estimated from MC
- Z+jets and $t\bar{t}$ normalisation estimated in CR
- $t\bar{t}$ CR: diff. flavour leptons, 2 b-tagged jets
- Z+jets CR: invert Z boson mass window

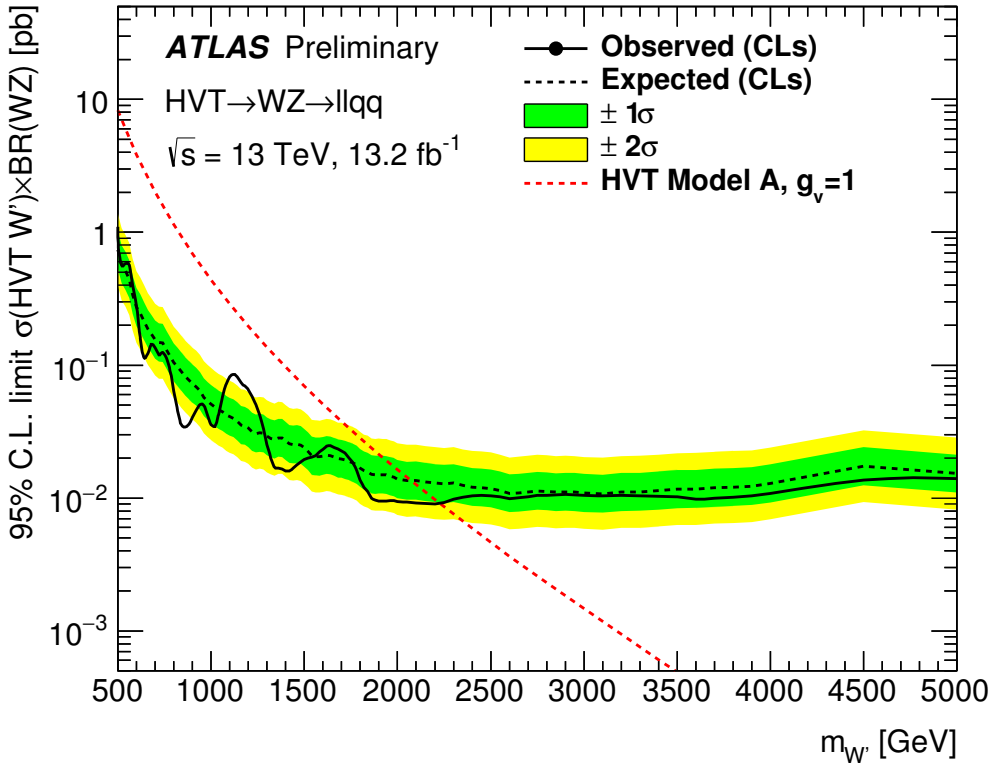
Dominating systematic uncertainties

- Jet energy & D_2 scale and resolution unc.
- Z+jets modelling

ZV $\rightarrow \ell\ell qq$ - Results

- Observable: invariant mass of decay products $m_{\ell\ell jj}$, $m_{\ell\ell J}$
- No significant deviations from SM prediction: 95% CL upper limits on $\sigma\times$ BR
- Exclude RS Graviton with masses below 1035 GeV ($\sim$ 200 GeV improvement with respect to 2015 analysis based on 3.2 fb^{-1})
- Exclude W' with $m_{W'} < 2225$ GeV ($\sim$ 800 GeV improvement)

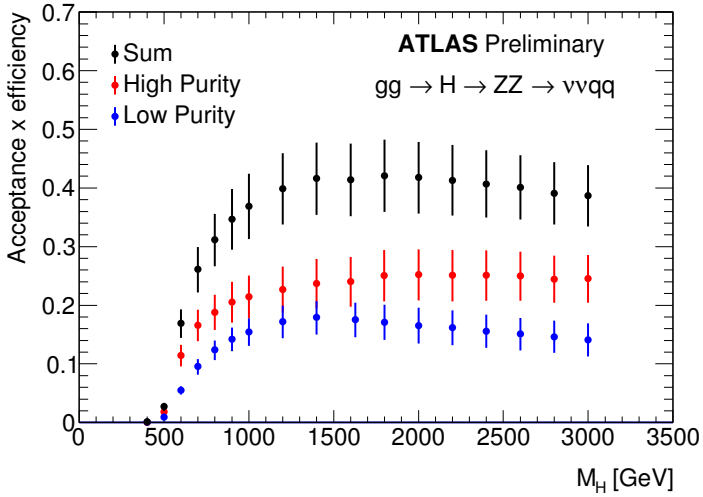


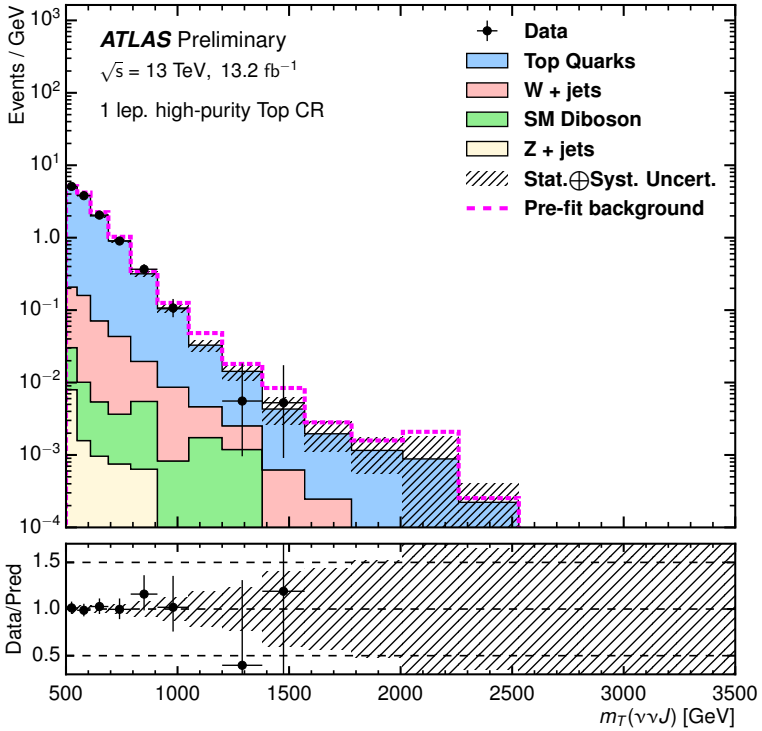


$ZV \to \nu\nu qq$

Event selection

- Veto leptons, $E_{\mathrm{T}}^{\mathrm{miss}} > 250$ GeV
- Multijet and non-collision bkg suppression
  - $p_{\mathrm{T}}^{\mathrm{miss}} > 50$ GeV, $\Delta\Phi(\vec{p}_{\mathrm{T}}^{\mathrm{miss}}, \vec{E}_{\mathrm{T}}^{\mathrm{miss}}) < 1$
  - $\min[\Delta\Phi(\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, \mathrm{small}{-}R\ \mathrm{jet})] > 0.4$
- Only merged analysis
- High and low purity signal regions based on D





$$m_{\mathrm{T}} = \sqrt{(E_{\mathrm{T,J}} + E_{\mathrm{T}}^{\mathrm{miss}})^2 - (\vec{p}_{\mathrm{T,J}} + \vec{E}_{\mathrm{T}}^{\mathrm{miss}})^2}$$

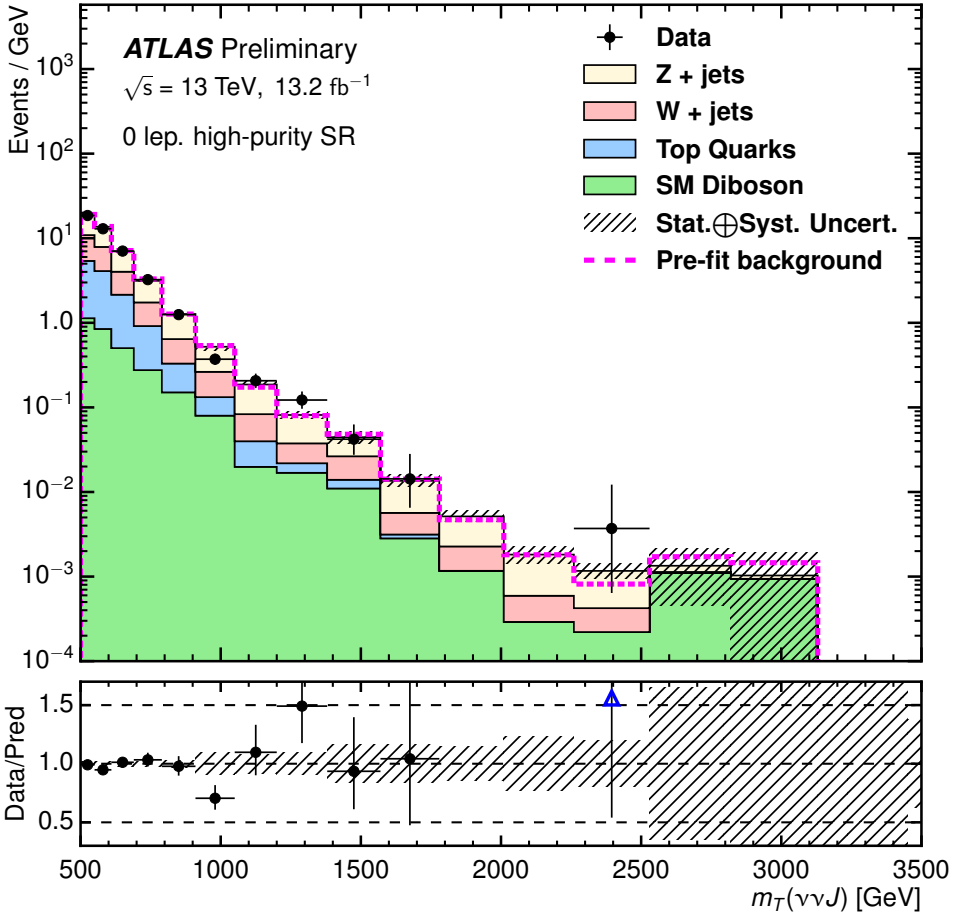
$$E_{\mathrm{T,J}} = \sqrt{m_{\mathrm{J}}^2 + p_{\mathrm{T,J}}^2}$$

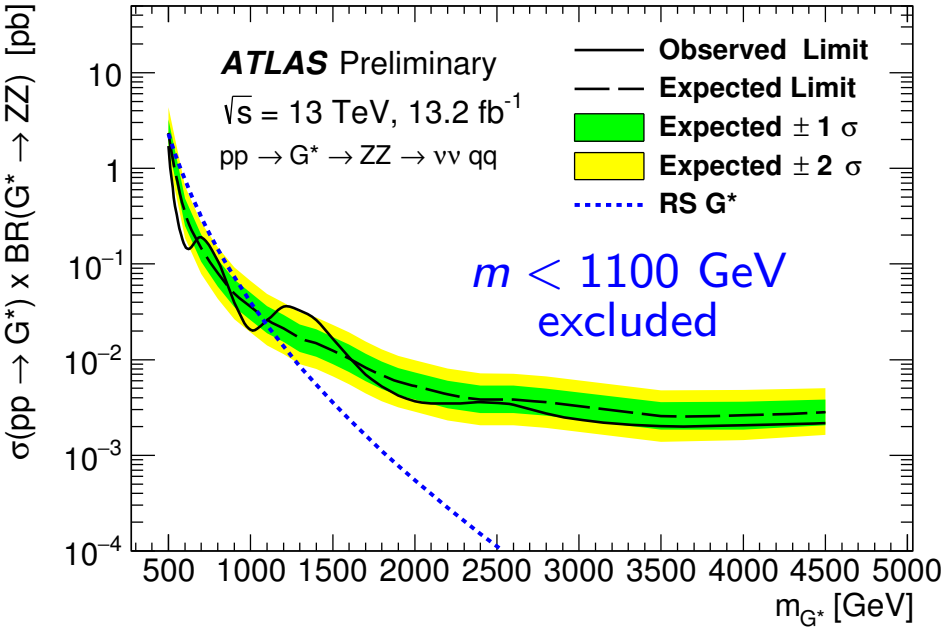
Background estimation

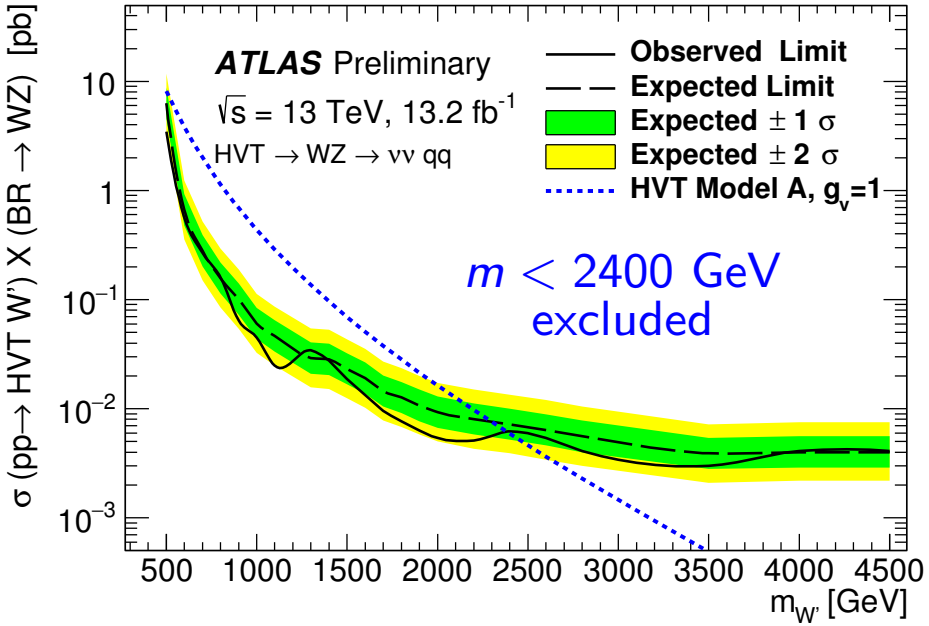
- Normalisation of Z+jets, W+jets and $t\bar{t}$ in signal region determined in control regions
- Z+jets CR: $Z \to \mu\mu + \mathrm{J}$ with new $E_{\mathrm{T}}^{\mathrm{miss}}$ definition (muon contribution removed)

ZV $\rightarrow \nu\nu qq$ - Results

- Simulataneous fit to two signal regions and six control regions
- No significant deviations observed from SM prediction
  $\rightarrow$ 95% CL upper limits on $\sigma\times$ BR



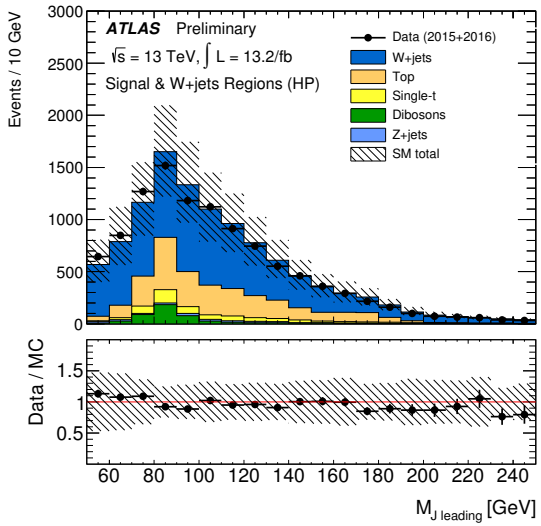


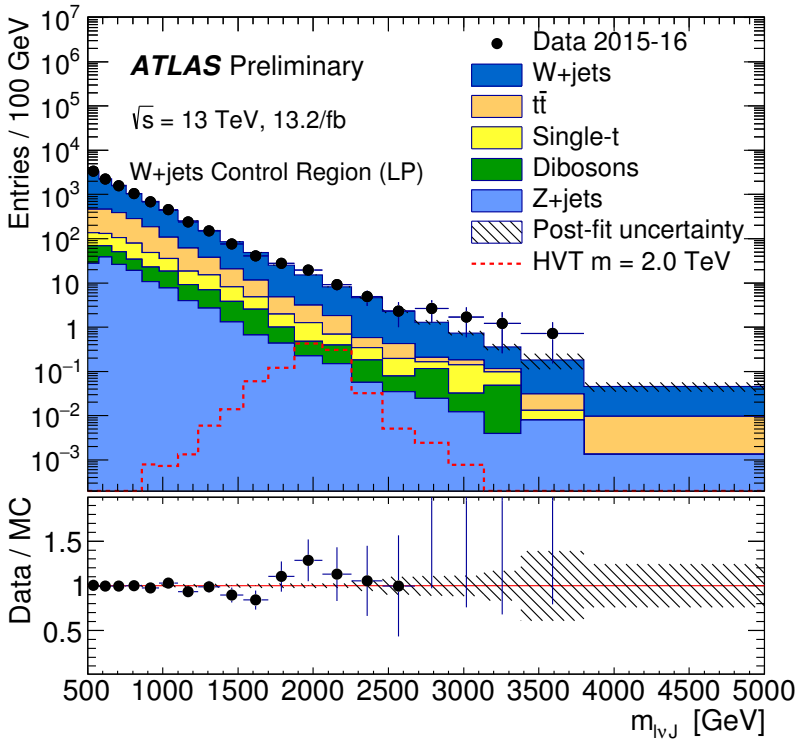


$WV \to \ell\nu qq$

Event selection

- Only merged analysis
- One lepton and $E_{\mathrm{T}}^{\mathrm{miss}} > 200$ GeV
- ≥ 1 large-R jet
- $p_{\mathrm{T}}(J)/m_{\ell\nu J} > 0.4$, $p_{\mathrm{T}}(\ell\nu)/m_{\ell\nu J} > 0.4$
- Reject events with close-by small-R b-tagged jet





Background estimation

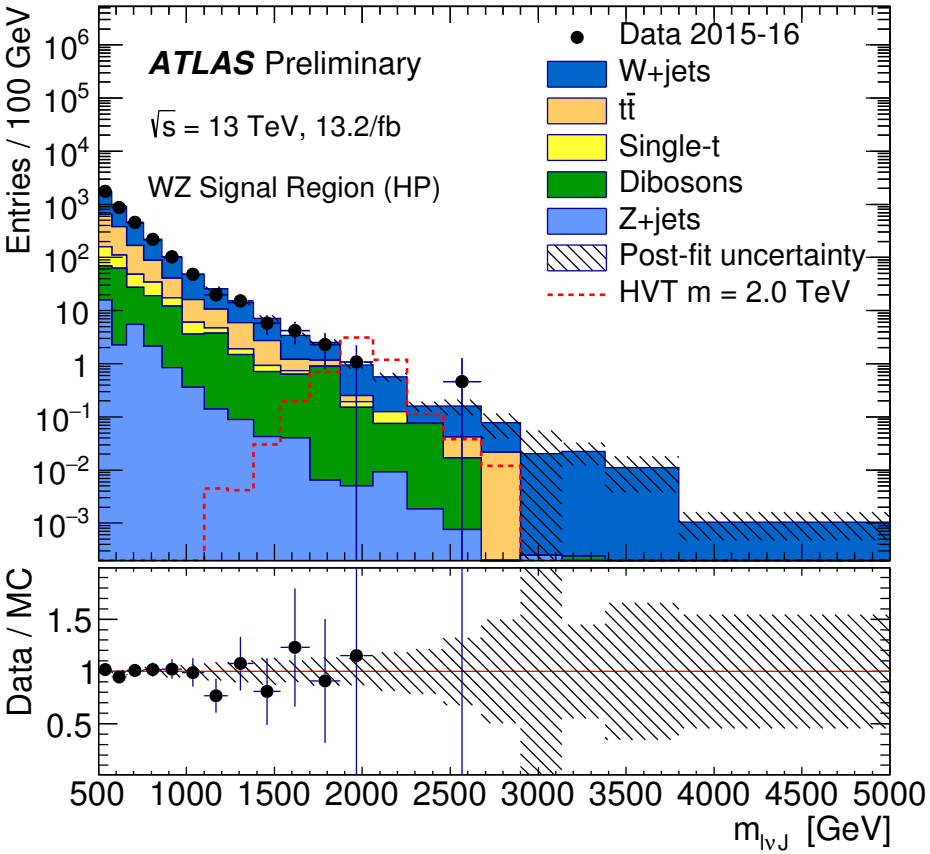
- Shape estimated from MC
- W+jets & $t\bar{t}$ normalisation estimated in CR
- $t\bar{t}$ CR: require close-by b-tagged jet

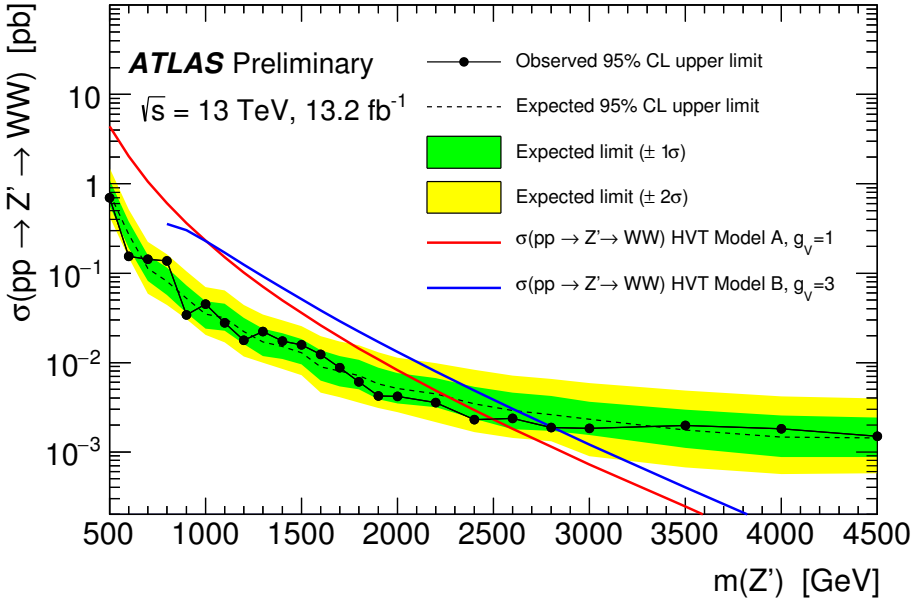
Dominating systematic uncertainties

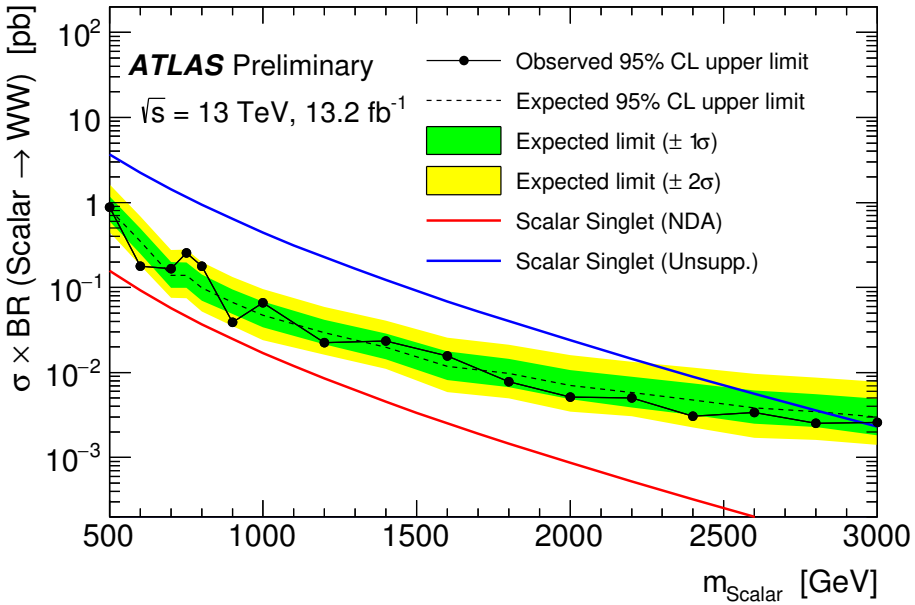
- Energy, mass and D_2 scale and resolution uncertainties
- Modelling of background shape
- $\sim$ 10-20% effect on signal strength

WV $\rightarrow \ell\nu qq$ - Results

- No significant deviations observed from SM prediction
  $\rightarrow$ 95% CL upper limits on $\sigma\times$ BR
- $\sim$ 1 (0.2) TeV improvement in mass exclusion limits for HVT (Graviton) with respect to 3.2 fb^{-1} analysis







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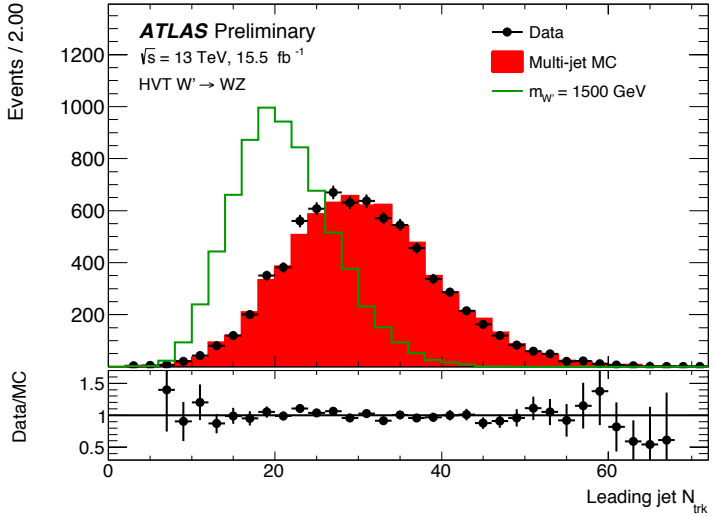
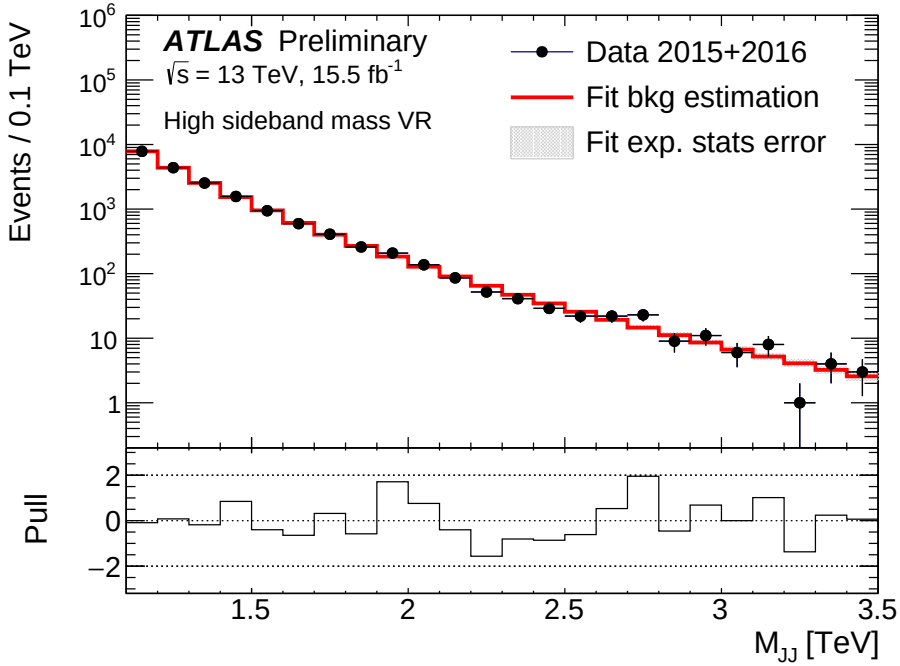
Event selection

- Require two large-R boson-tagged jets
- Additional criteria on number of tracks ghost-associated to ungroomed jet: n_{trk}
- Efficiency of n_{trk} measured in V+jets data
- Overlap between WW, WZ, ZZ selection



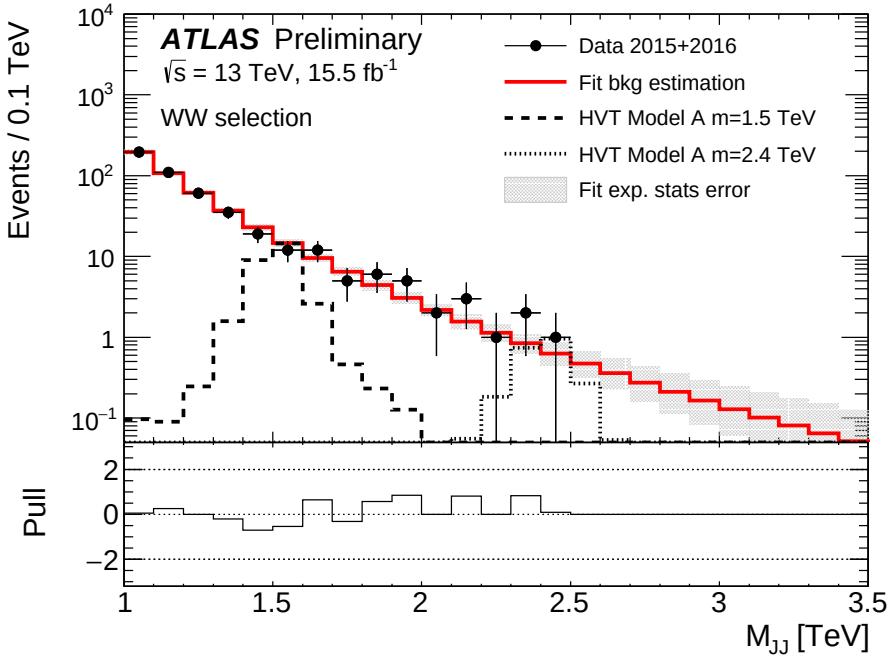


- Dominating background: QCD dijets
- Background parameterised by:

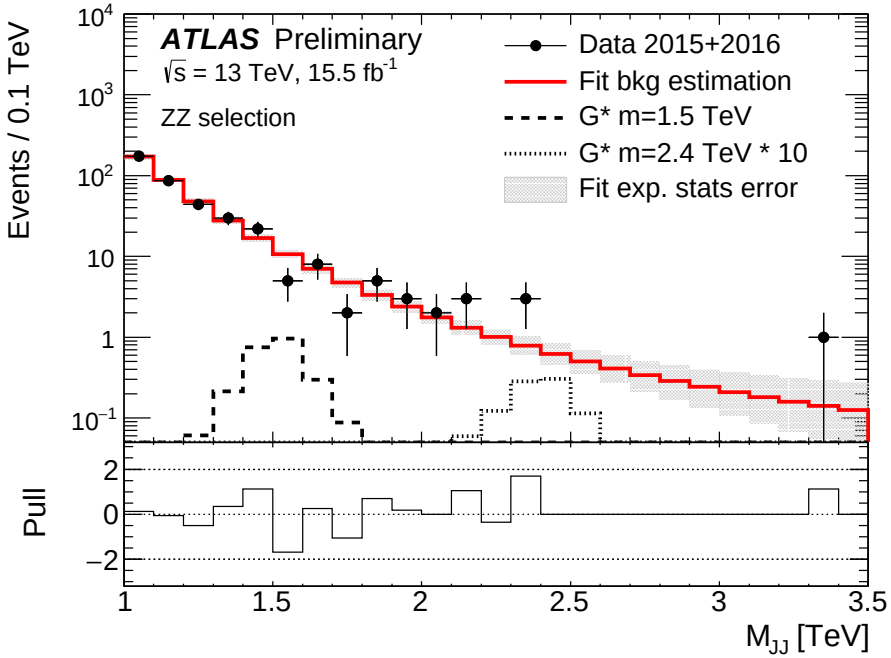
$$\frac{\mathrm{d}n}{\mathrm{d}x} = p_1(1-x)^{p_2+\xi p_3}x^{p_3}, \quad x = m_{jj}/\sqrt{s}$$

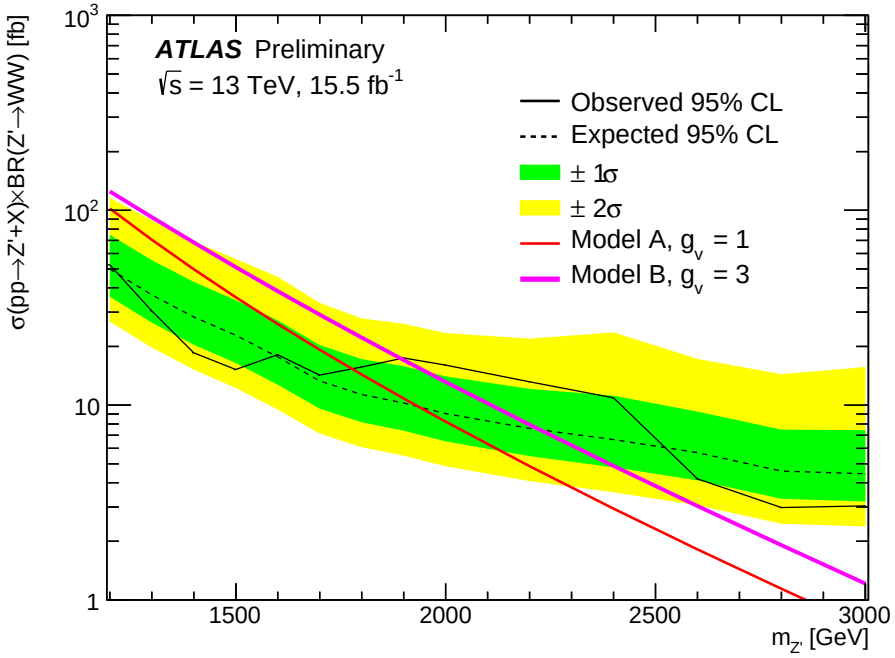
- p_1: normalisation, p_2, p_3 dimensionless shape parameters, ξ constant
- Binned maximum-likelihood fit performed to data to estimate bkg

VV→JJ - Results



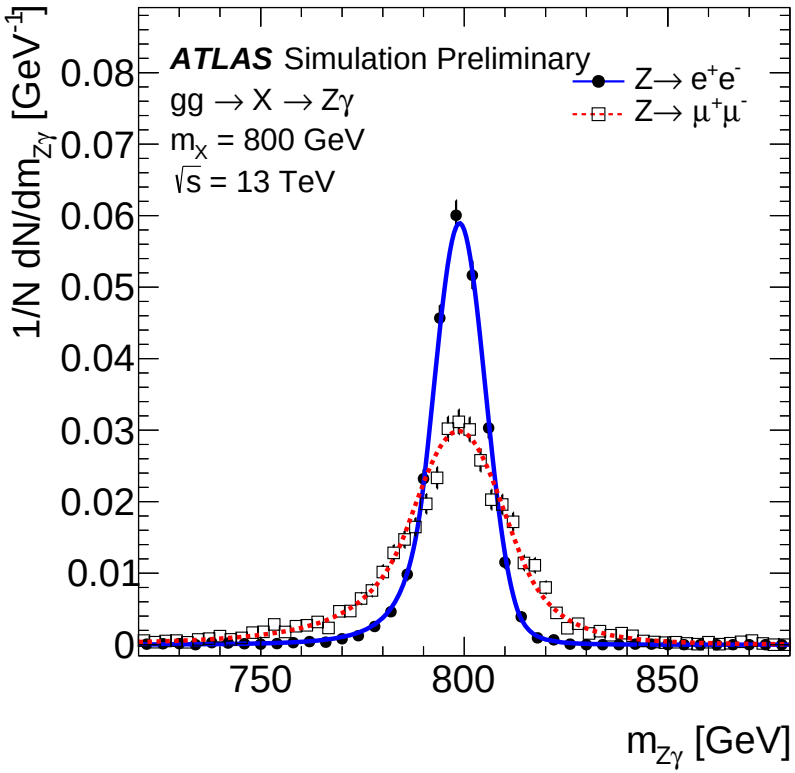
- No significant deviations from SM prediction observed
  → 95% CL upper limits on $\sigma\times$ BR
- For $g_V = 1$ (3), exclude
  - $1.2 < m_{Z'} < 1.8$ (1.9) TeV
  - $1.2 < m_{W'} < 1.9$ (3.0) TeV
  - No sensitivity to exclude gravitons with studied parameters





Event selection

- Z-boson candidate:
  - 2 opposite-sign, same-flavour leptons within $\pm$ 15 GeV of Z-boson mass
- Choose photon with highest p_{T}
- X mass resolution improvement by kinematic Z-boson mass constraint fit
- Two categories based on lepton flavour

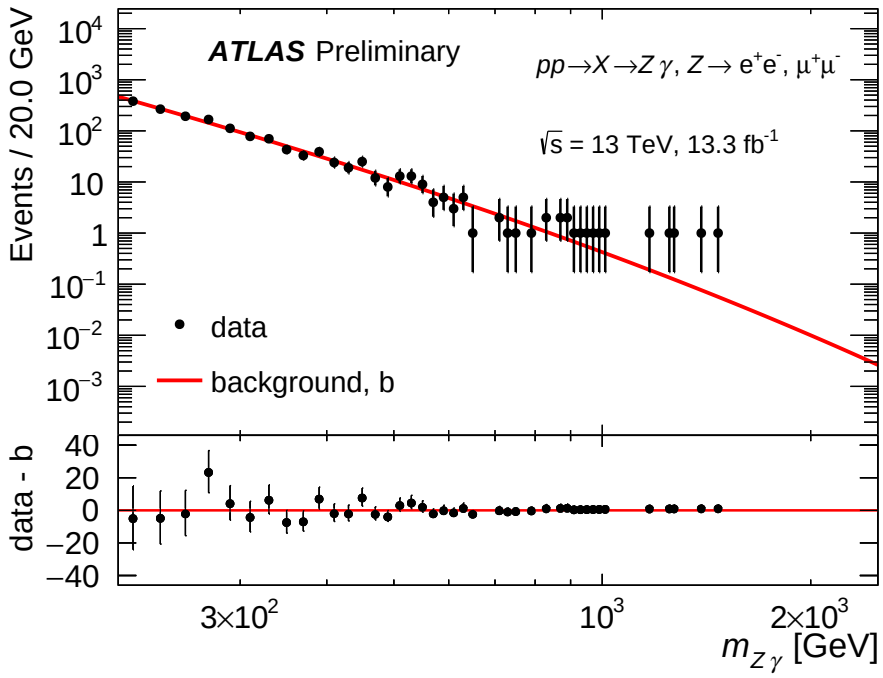


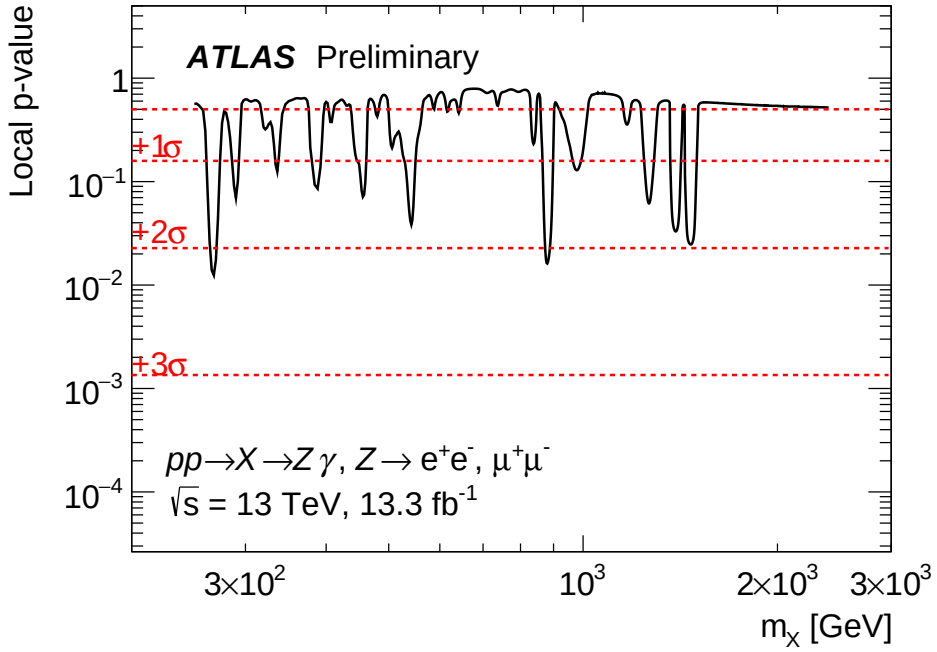
Signal and background modelling:

- Signal: double-sided Crystal Ball function
- Bkg: non-resonant production of a prompt photon & Z boson, Z+jets (smoothly falling background)
- Bkg parameterised with:

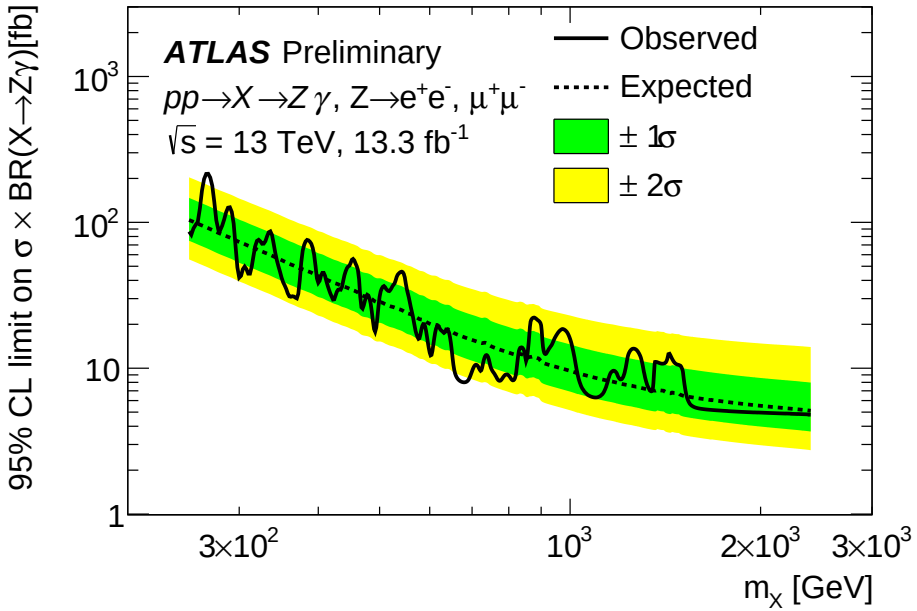
$$\frac{\mathrm{d}n}{\mathrm{d}x} = \mathcal{N}(1 - x^k)^{p1} x^{p2}, \quad x = m_{Z\gamma}/\sqrt{s}$$

$V\gamma \to \ell\ell\gamma$ - Results





- Selected 306 (485) candidates for $Z \to e^+e^-/\mu^+\mu^-$
- No significant deviations from bkg prediction
  $\to$ 95% CL upper limits on $\sigma\times$ BR
- Results dominated by stat. uncert.



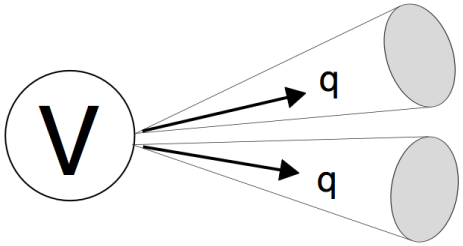
Summary

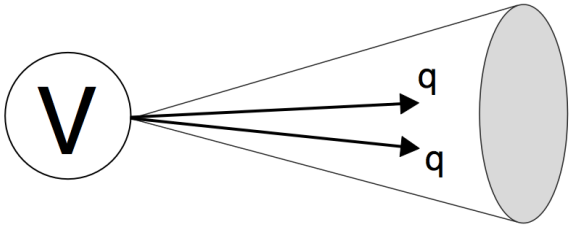
- The diboson and $Z + \gamma$ final state provides a direct key to new physics beyond the Standard Model
- The diboson resonance searches rely on using jet substructure techniques to reconstruct boosted hadronically decaying W/Z bosons (challenging when going to higher transverse momenta)
- No significant deviation from background expectation observed at 13 TeV
  $\rightarrow$ set upper limits on cross-section $\times$ BR for benchmark models
- The increased luminosity allowed to improve the exclusion limits of the benchmark models significantly with respect to previous analyses
- Analyses using the full 2015+2016 dataset will allow to extend the mass reach of these searches even further

Backup

Challenges of final states with hadronic decays

1. How do we handle the high transverse momentum?





Low p_{T} vector bosons

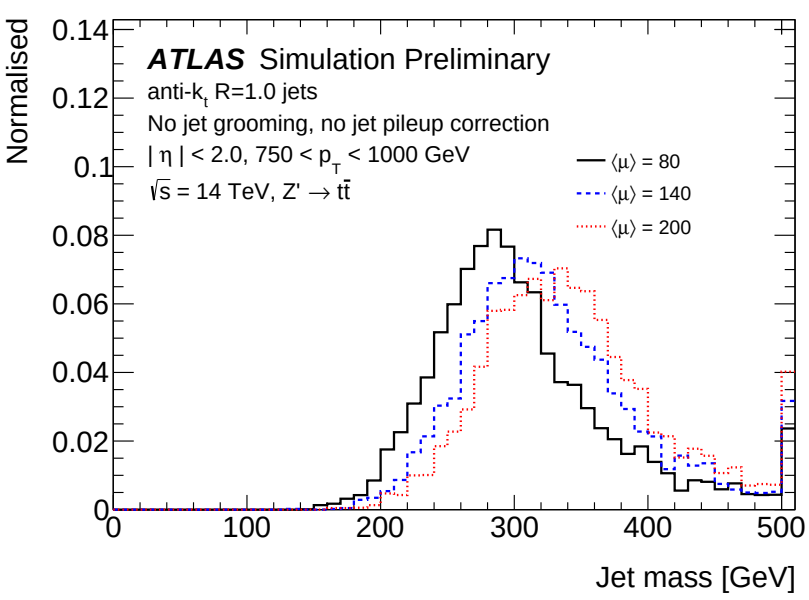
- Decay products well separated
- Two **small-R** jets ($R \approx 0.4$)

High p_{T} vector bosons

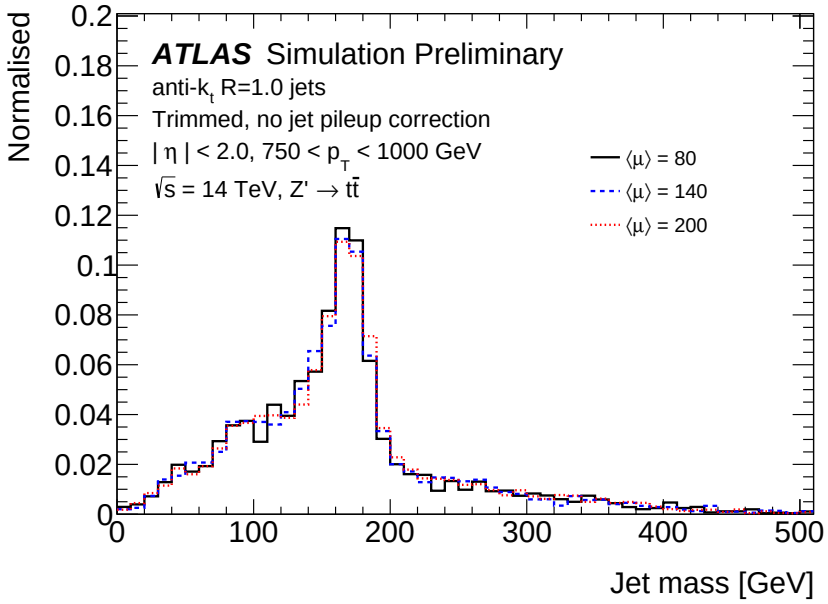
- Decay products are collimated
- One **large-R** jet ($R \approx 1.0$)

Challenges of final states with hadronic decays

1. How do we handle the high transverse momentum?
2. How can we handle the high pile-up?
   - Jet mass depends on pile-up and mass resolution diminishes with $\langle\mu\rangle$
   - Grooming techniques remove soft gluon radiation and pile-up effects
   - **Trimming:** remove subjets of size R_{subjet} if $p_{\mathrm{T}}^{\mathrm{subjet}} < f_{\mathrm{cut}} \times p_{\mathrm{T}}^{\mathrm{large-R}}$



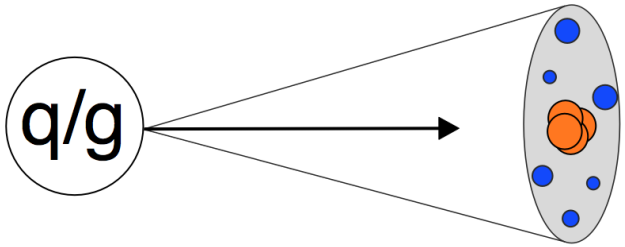
trimming →



Challenges of final states with hadronic decays

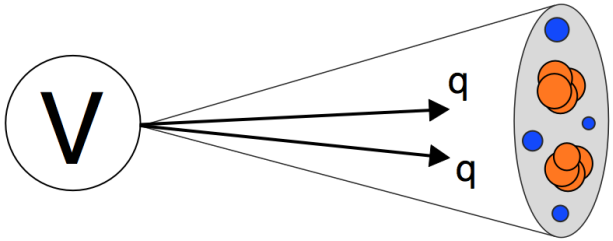
1. How do we handle the high transverse momentum?
2. How can we handle the high pile-up?
   - Jet mass depends on pile-up and mass resolution diminishes with $\langle\mu\rangle$
   - Grooming techniques remove soft gluon radiation and pile-up effects
   - **Trimming:** remove subjets of size R_{subjet} if $p_{\mathrm{T}}^{\mathrm{subjet}} < f_{\mathrm{cut}} \times p_{\mathrm{T}}^{\mathrm{large-R}}$
3. How can we suppress the enormous QCD dijet background?
   - $\sigma_{\mathrm{dijet}} \gg \sigma_{\mathrm{BSM}} \rightarrow$ use **internal structure** of large-R jet

Quark/gluon jet



- One region with high energy density
- Mass from wide-angle radiation

W/Z jet



- Two regions with high energy density
- $m_{\mathrm{jet}} \approx m_{W/Z}$
- Balanced subjet p_{T}

Energy correlation variables

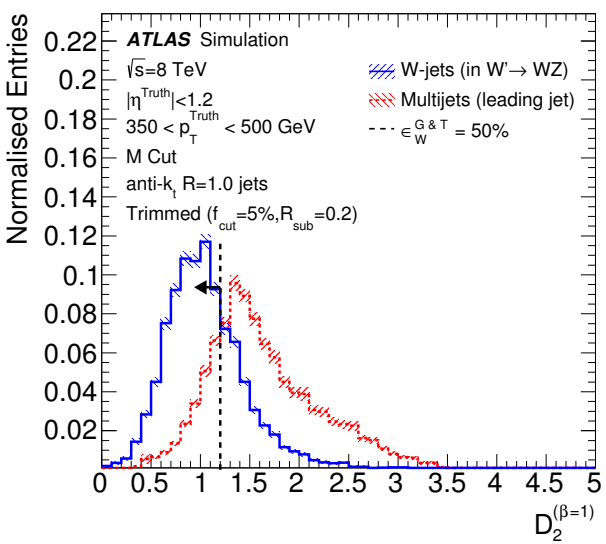
Energy correlation D_2

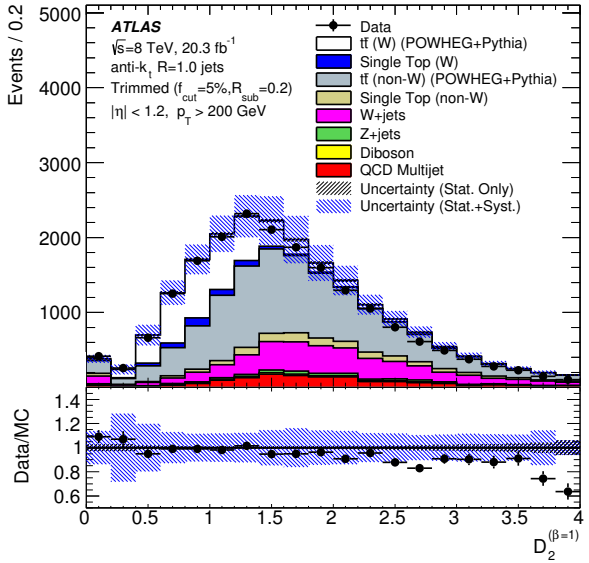
$$D_2^\beta = \frac{E_{CF}^3 1(\beta)}{E_{CF}^3 2(\beta)} \times E_{CF}3(\beta)$$

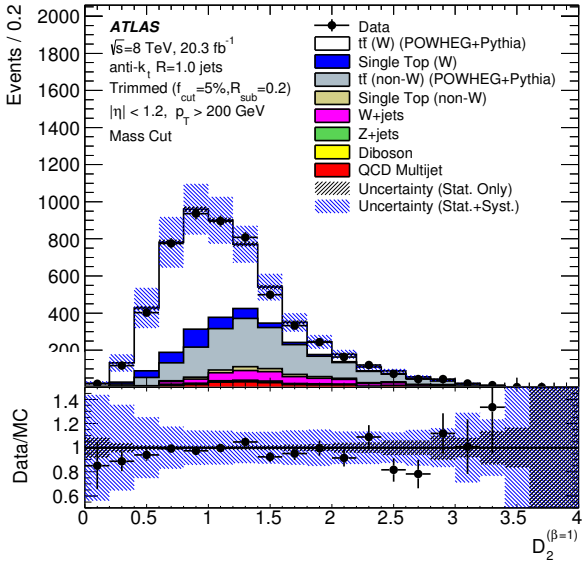
N-point energy correlation function

$$E_{CF}1(\beta) = \sum_{i \in J} p_{\mathrm{T}i}, \qquad E_{CF}2(\beta) = \sum_{i<j \in J} p_{\mathrm{T}i} p_{\mathrm{T}j} \left(\Delta R_{ij}\right)^\beta,$$

$$E_{CF}3(\beta) = \sum_{i<j<k \in J} p_{\mathrm{T}i} p_{\mathrm{T}j} p_{\mathrm{T}k} \left(\Delta R_{ij} \Delta R_{ik} \Delta R_{jk}\right)^\beta,$$

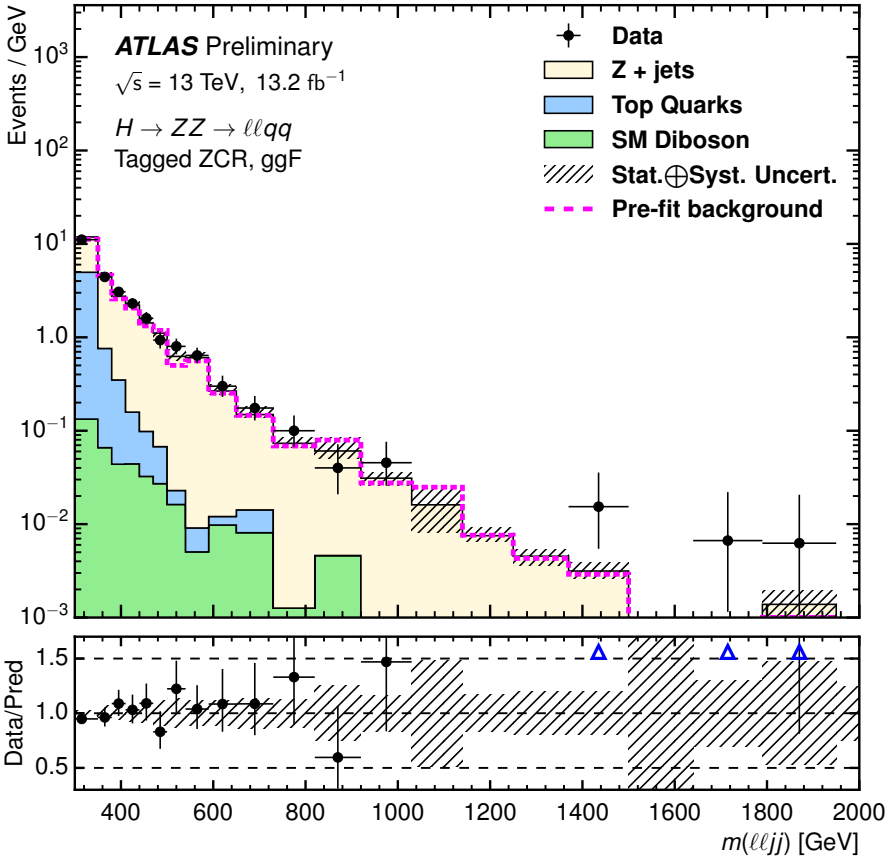


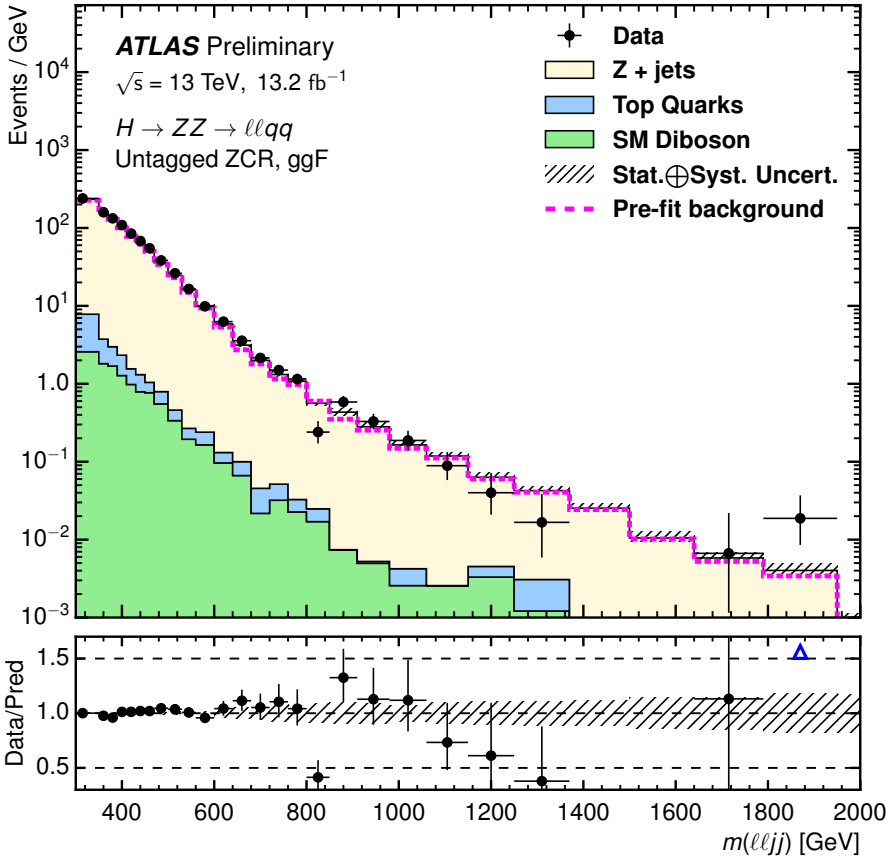




Z+jets CR for resolved $H \to ZZ$ analysis

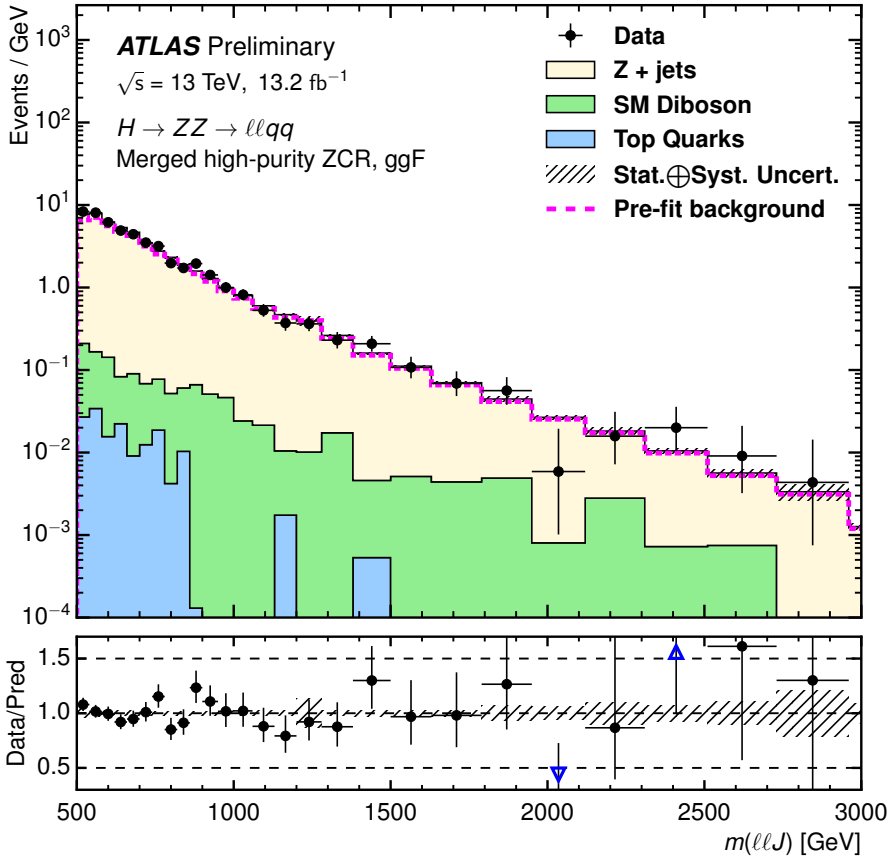
- Z+jets control region for resolved analysis (same event selection apart from Z-boson mass constraint):
  - $50 < m_{jj} < 62$ GeV or $105 < m_{jj} < 150$ GeV
- Resolved analysis is divided in two categories: two b-tagged jets (tagged) and events with fewer than two b-tagged jets (untagged)

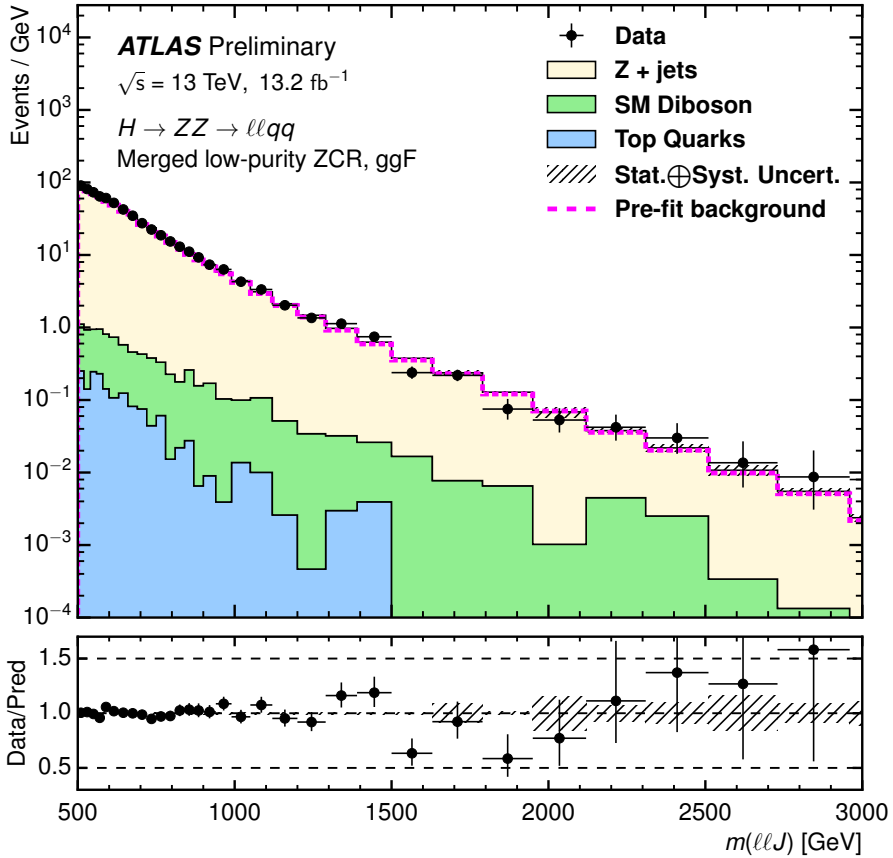




Z+jets CR for merged $H \to ZZ$ analysis

- Z+jets control region for resolved analysis (same event selection apart from Z-boson mass constraint):
  - $m_J < 65$ GeV or $m_J > 106$ GeV
- Merged analysis divided in two categories: events where jet passed/failed the D_2 criteria





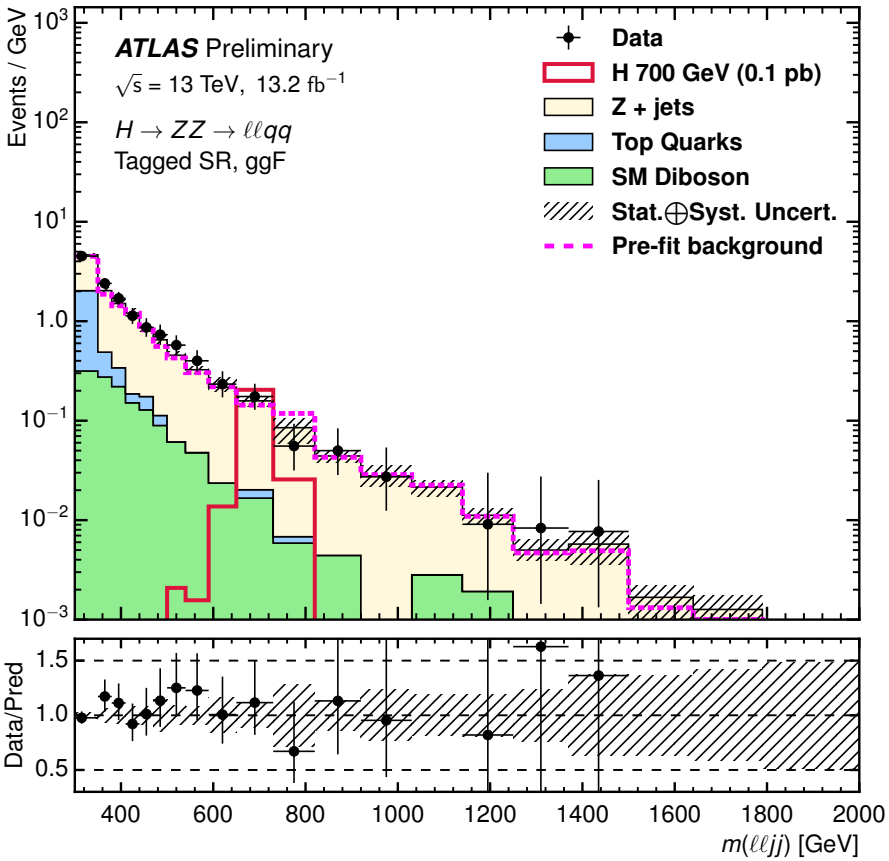
$ZV \to \ell\ell qq$ - data/MC agreement of number of events

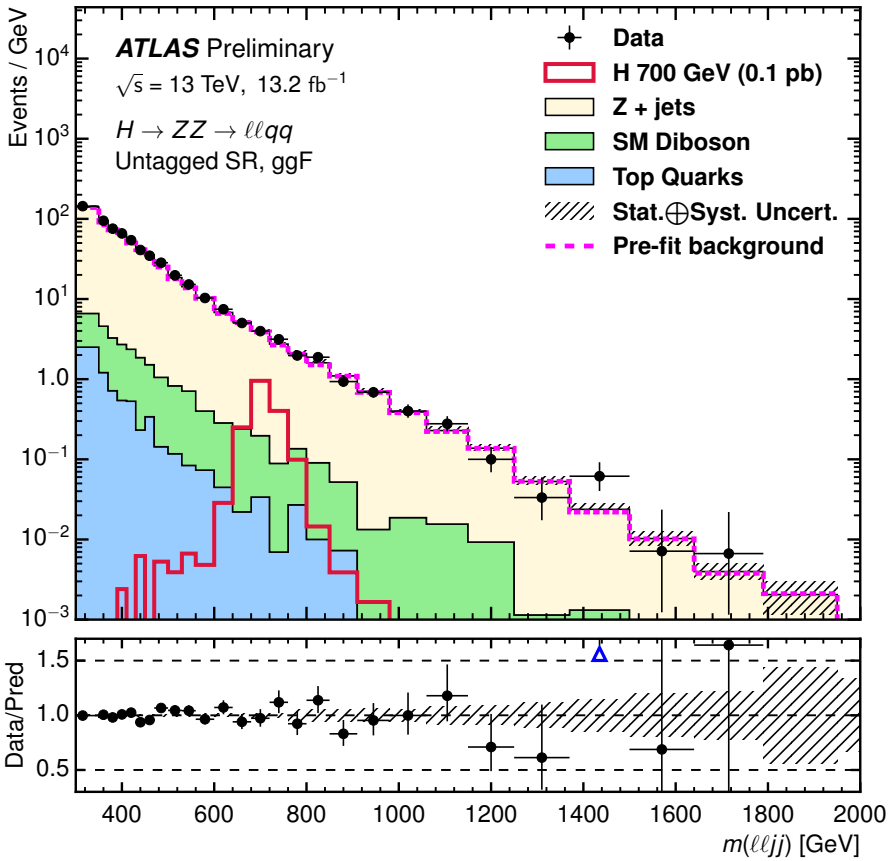
- Comparison of predicted and observed number of events in MC and data for the merged and resolved $\ell\ell qq$ analysis

Process	Merged analysis		Resolved analysis	
	high purity	low purity	tagged	untagged
	Signal regions			
Z+jets	576 ± 22	1230 ± 33	409 ± 18	19900 ± 140
Diboson	49 ± 7	51 ± 5	54 ± 6	670 ± 40
Top quark	4 ± 1	5.9 ± 1.0	131 ± 6	291 ± 28
Total background	629 ± 22	1287 ± 34	594 ± 18	20861 ± 140
Data	606	1270	608	20857
H (400 GeV)	1.6 ± 0.2	4.3 ± 0.7	107 ± 6	626 ± 21
H (700 GeV)	168 ± 4	88.2 ± 2.9	20.0 ± 1.2	71.4 ± 3.3
H (1600 GeV)	35.9 ± 0.8	24.0 ± 0.6	1.00 ± 0.09	1.60 ± 0.08

Resolved $H \to ZZ$ signal region

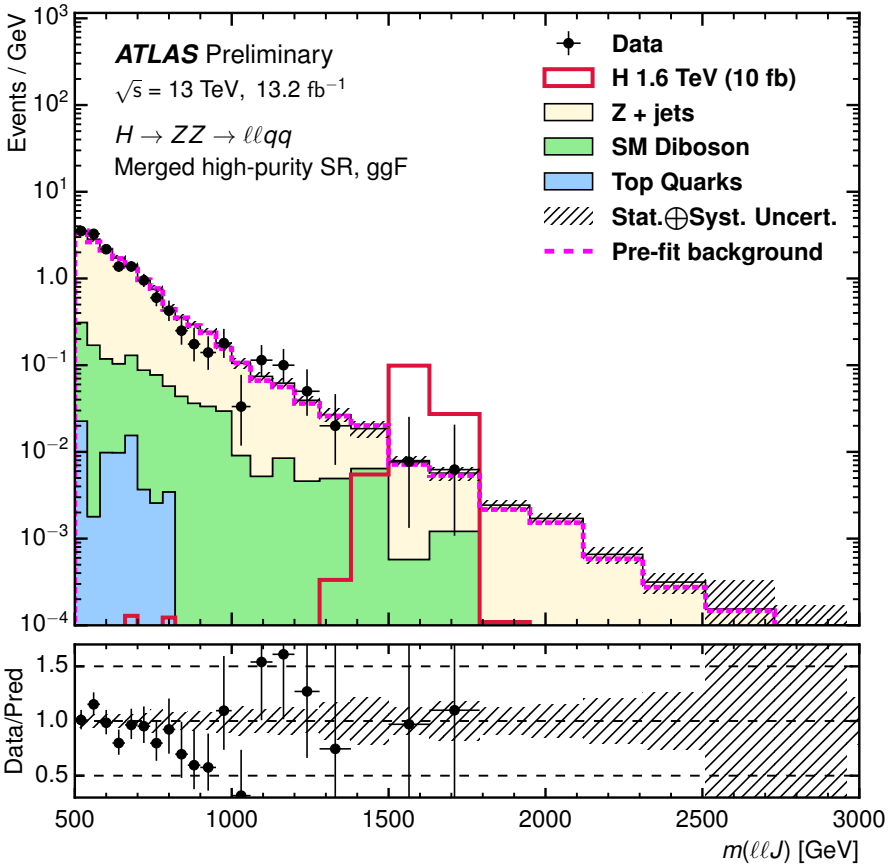
- Resolved analysis is divided in two categories: two b-tagged jets (tagged) and events with fewer than two b-tagged jets (untagged)

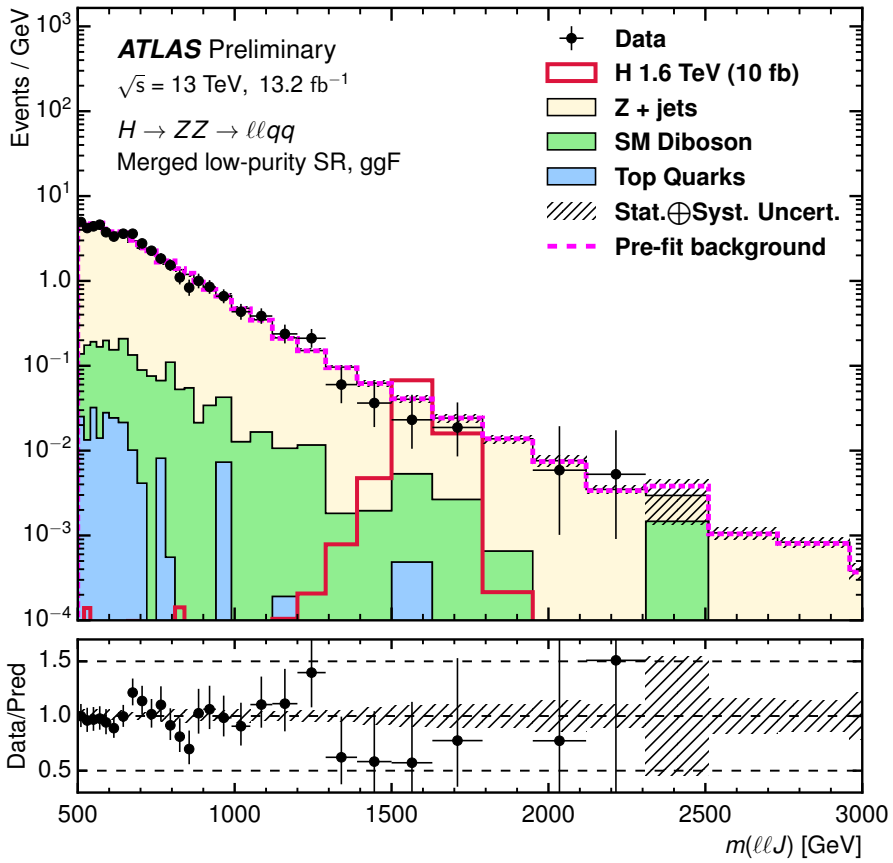




Merged $H \to ZZ$ signal region

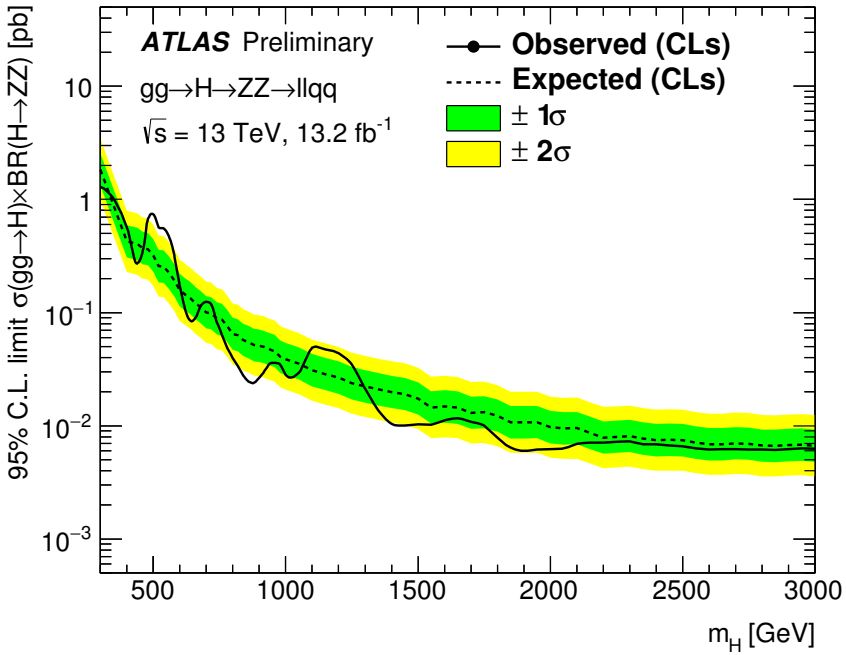
- Merged analysis divided in two categories: events where jet passed/failed the D_2 criteria

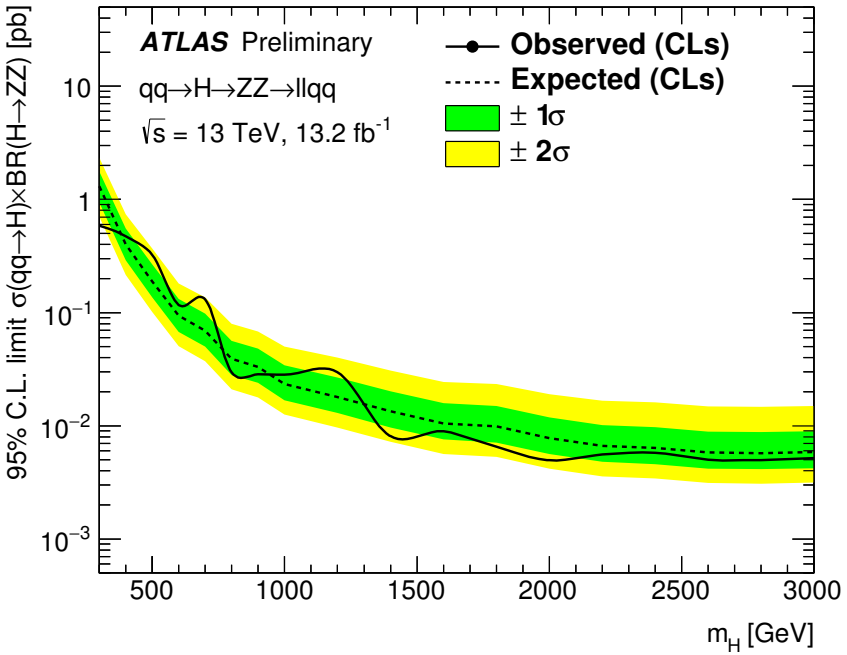




Statistical interpretation of $H \to ZZ$ analysis

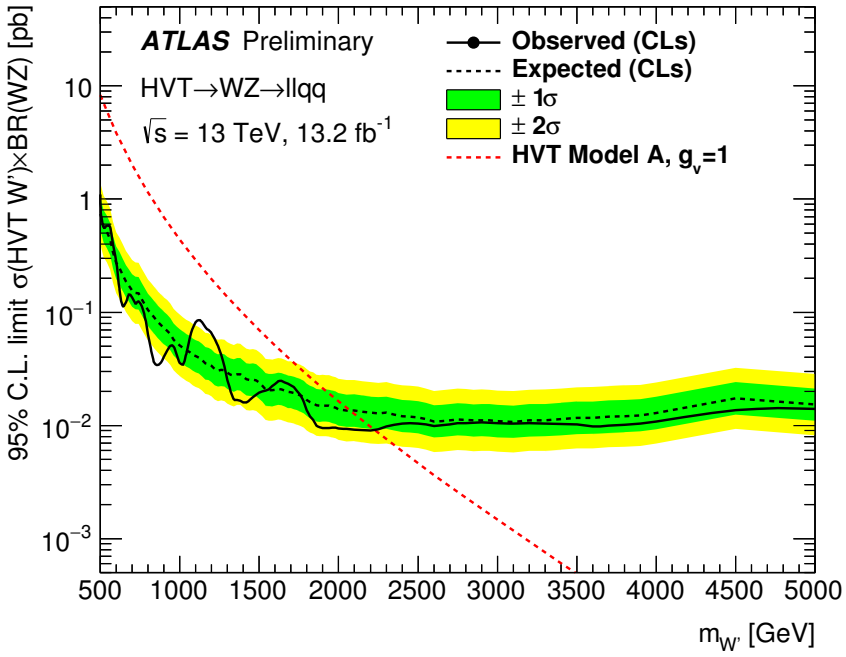
- 95% upper cross-section limits on the $\sigma \times$BR of $H \to ZZ$
- Left: gluon-gluon fusion, Right: VBF
- $\sigma \times$ BR exclusion limits range from 1.28 (0.6) pb at 300 GeV to 6.2 (5.2) fb at 3000 GeV for ggF and VBF

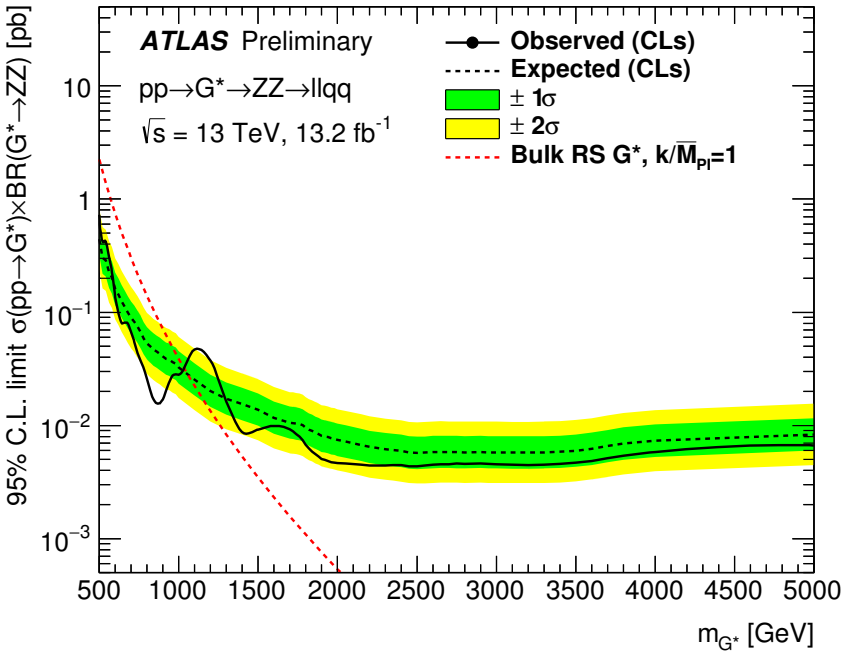




Statistical interpretation of search for W' and G^*

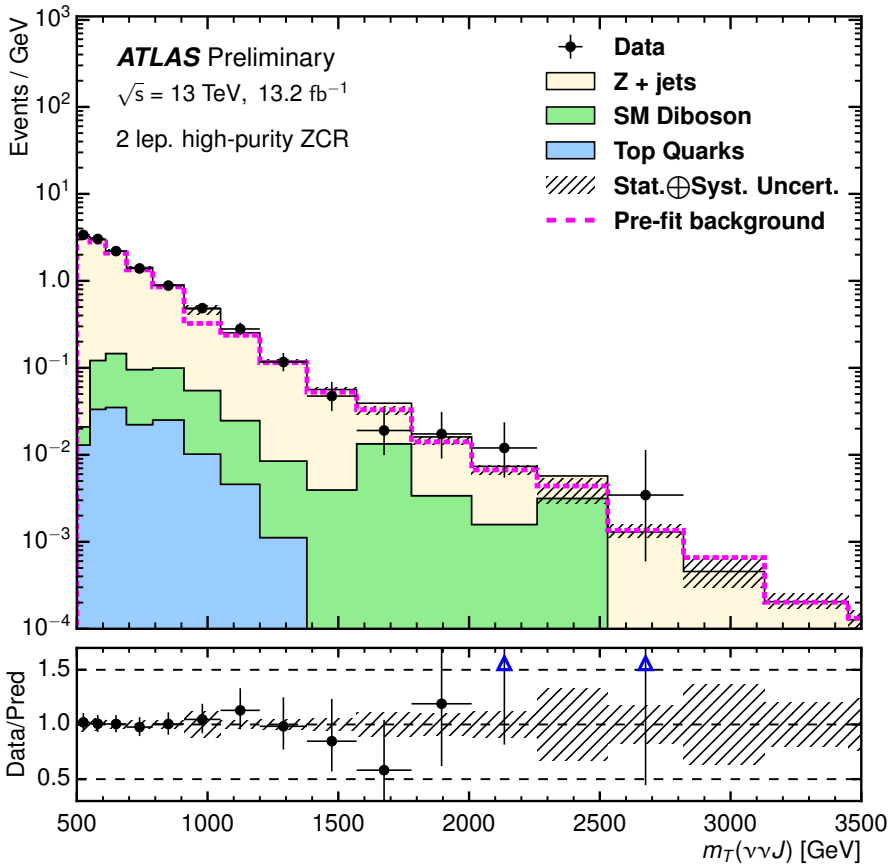
- 95% upper cross-section limits on the $\sigma \times$BR of $H \to ZZ$
- $\sigma \times$ BR exclusion limits range from
  - 1.10 pb at 500 GeV to 13.9 fb at 5000 GeV for HVT
  - 730 fb at 500 GeV to 6.7 fb at 5000 GeV for RS graviton
- Observed (expected) limits exclude $m_{W'} < 2225$ (2075) GeV and $m_{G^*} < 1035$ (1045) GeV

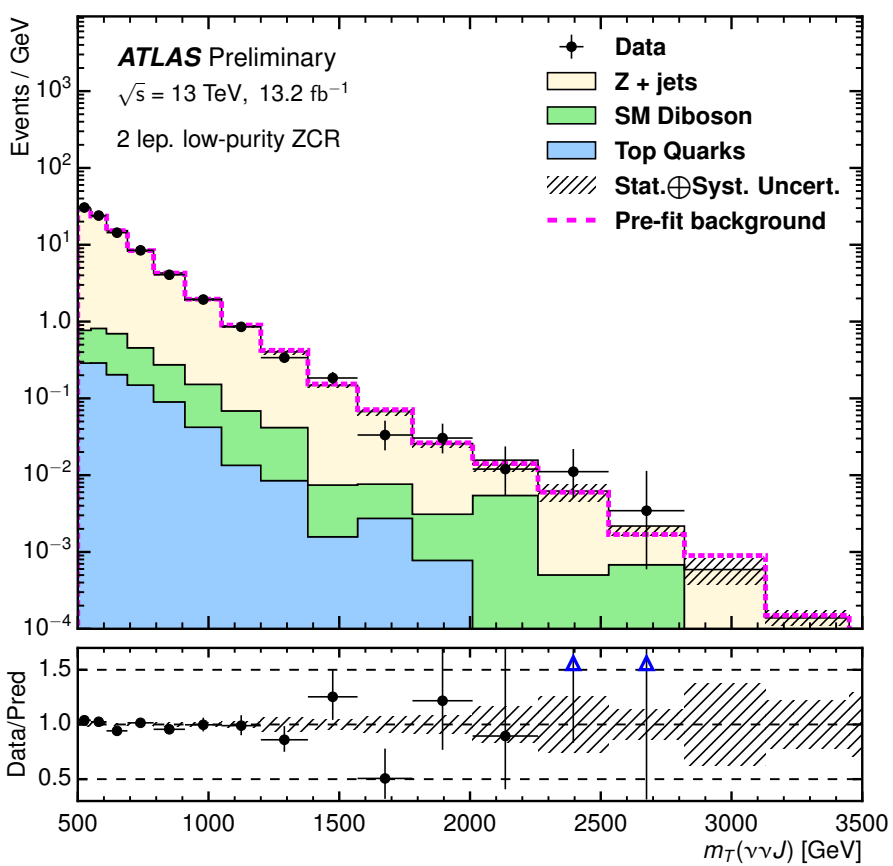




Z+jets CR for $ZV \to \nu\nu qq$ analysis

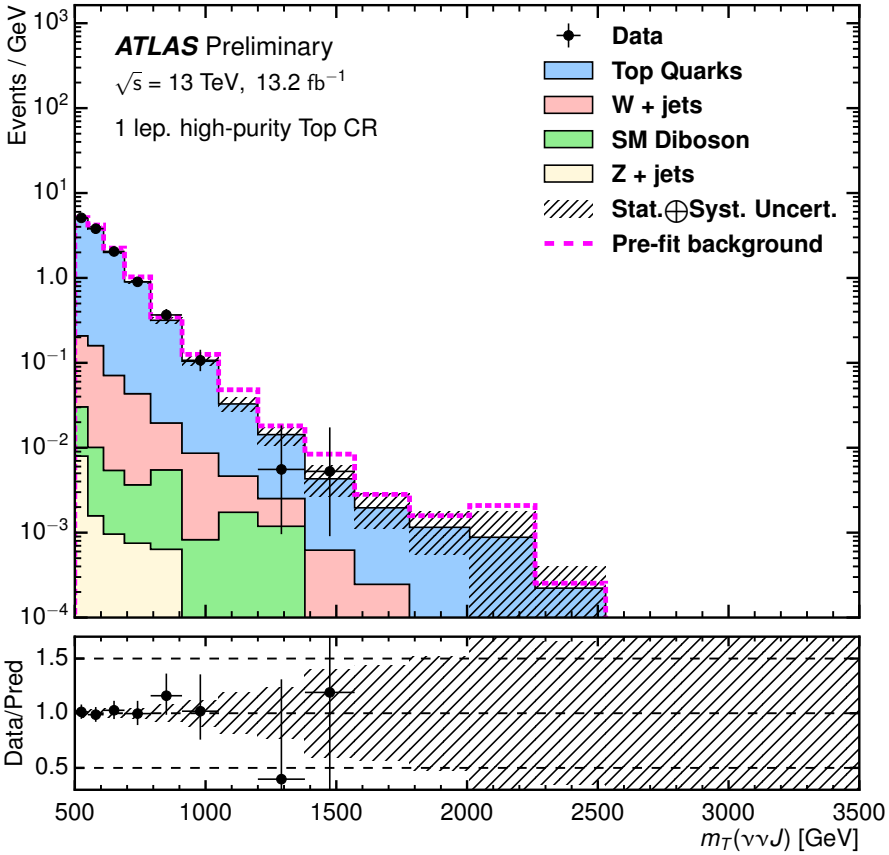
- $Z \to \mu\mu$ + jets events
- Large-R jet required to be outside of Z-mass window ($m_J < 65$ or $m_J > 106$ GeV)
- Merged analysis divided in two categories: events where jet passed/failed the D_2 criteria
- Modified definition of $E_{\mathrm{T}}^{\mathrm{miss}}$ used (without muon contribution)

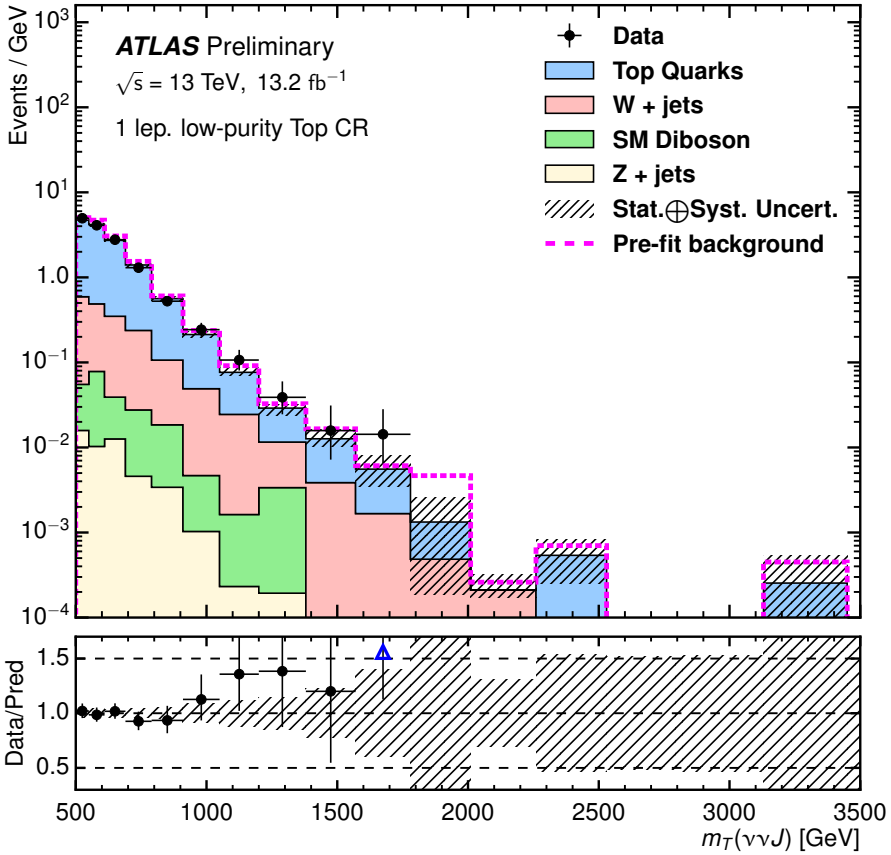




Top control region for $ZV \to \nu\nu qq$ analysis

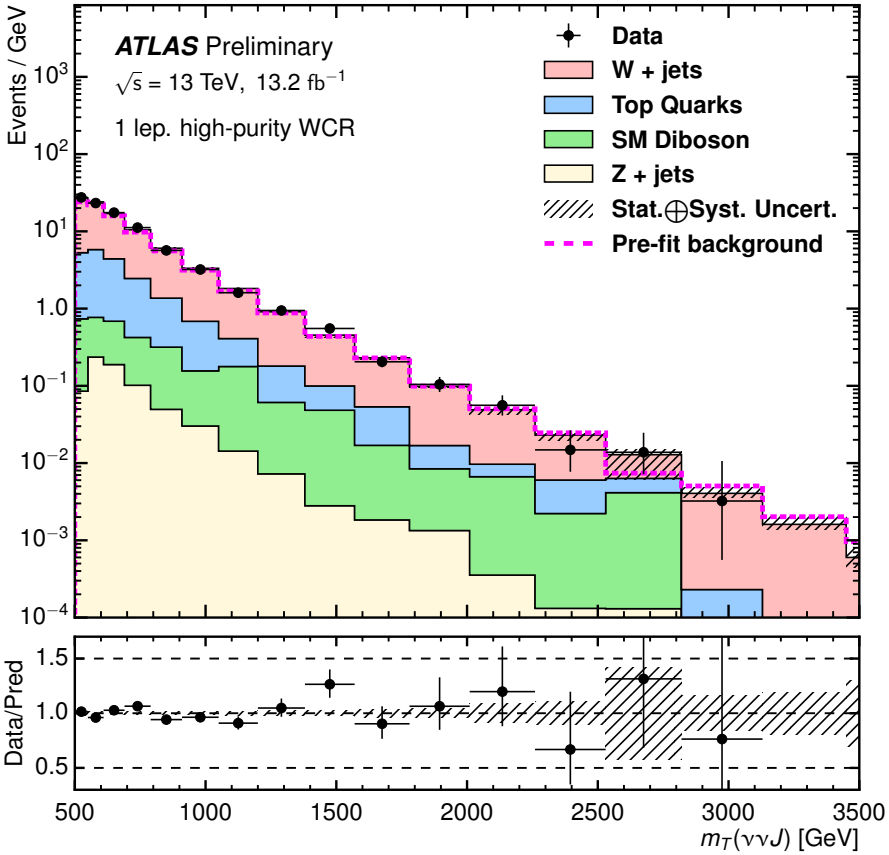
- Exactly one muon candidate and at least one large-R jet
- At least one b-tagged jet is required
- Large-R jet required to be consistent with W boson decay
- Merged analysis divided in two categories: events where jet passed/failed the D_2 criteria

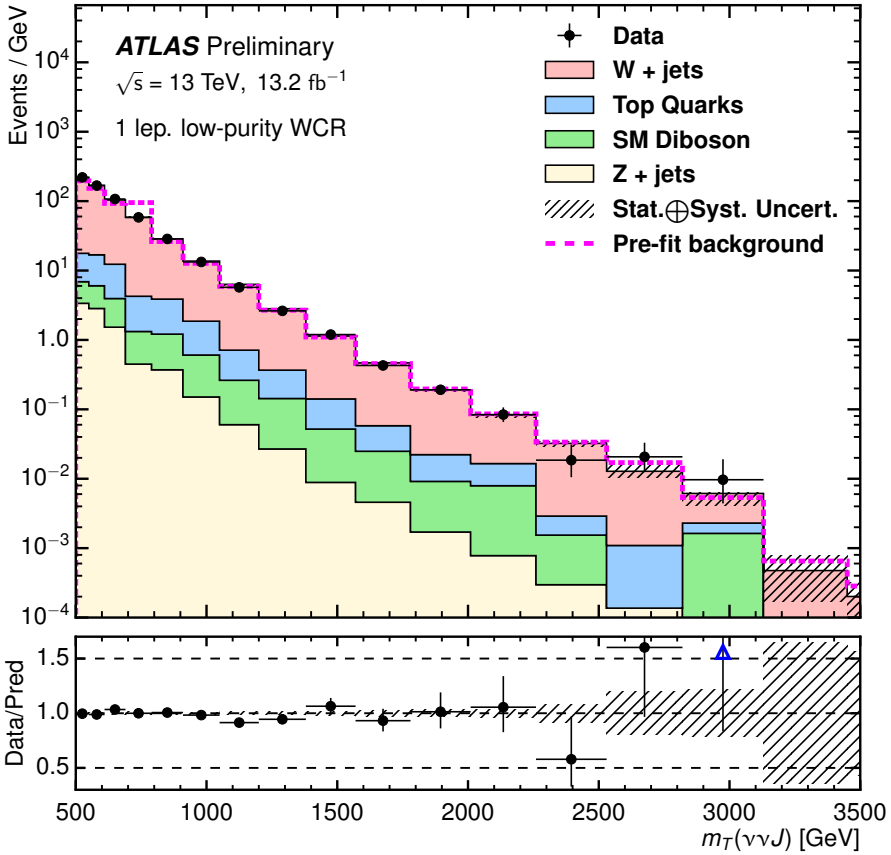




W+jets CR for $ZV \to \nu\nu qq$ analysis

- Exactly one muon candidate and at least one large-R jet
- At least one b-tagged jet is required
- Large-R jet required to be outside of W boson mass window
- Merged analysis divided in two categories: events where jet passed/failed the D_2 criteria





$ZV \to \nu\nu qq$ - data/MC agreement of number of events

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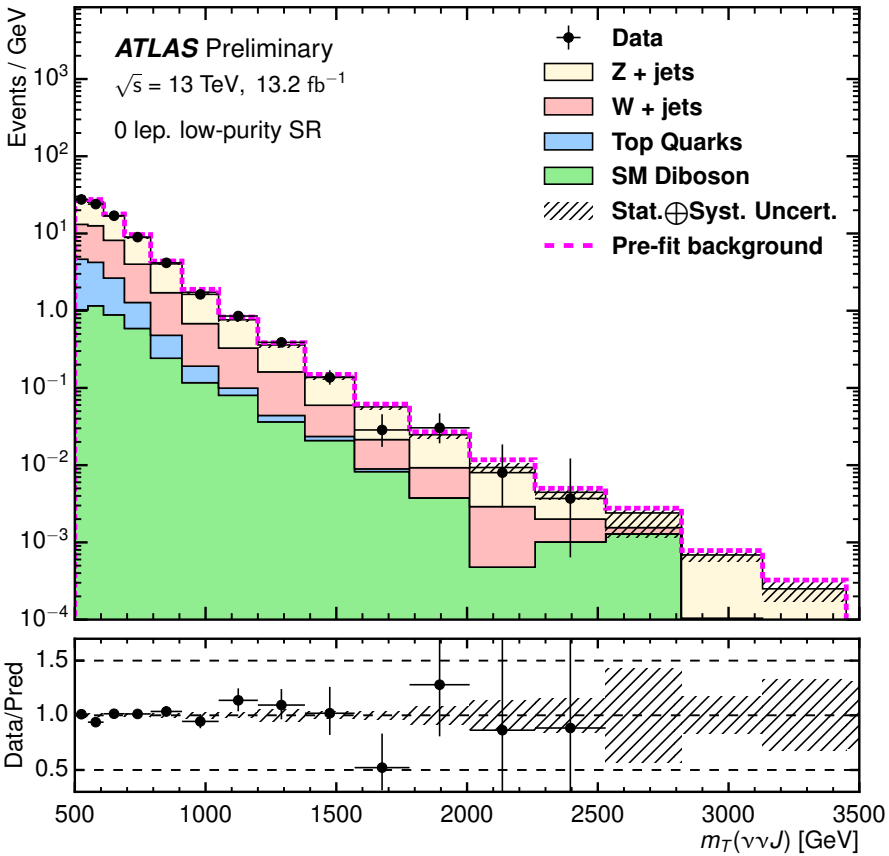
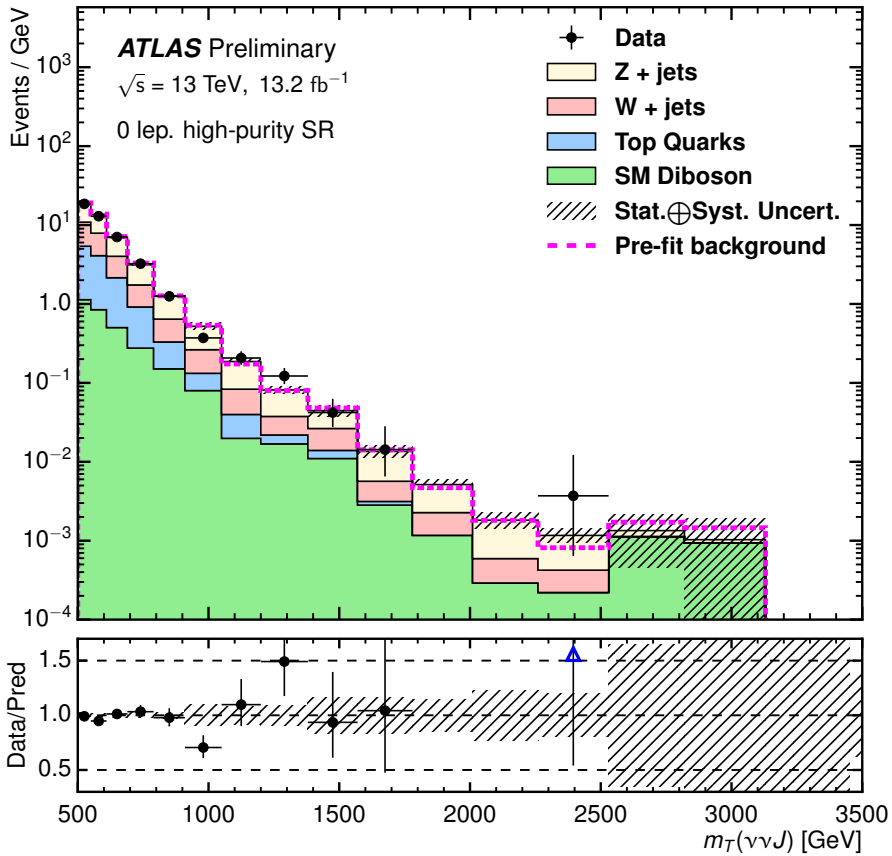
- Comparison of predicted and observed number of events in MC and data for the high and low purity signal region of the $\nu\nu qq$ analysis

Process	Merged analysis	
	high-purity	low-purity
Z+jets	1251 ± 56	3130 ± 79
W+jets	881 ± 45	2092 ± 75
Diboson	202 ± 14	227 ± 10
$t\bar{t}$ + single top	557 ± 85	610 ± 100
Total background	2891 ± 50	6059 ± 76
Data	2859	6044
H (1600 GeV)	63.7 ± 1.9	46.2 ± 1.4

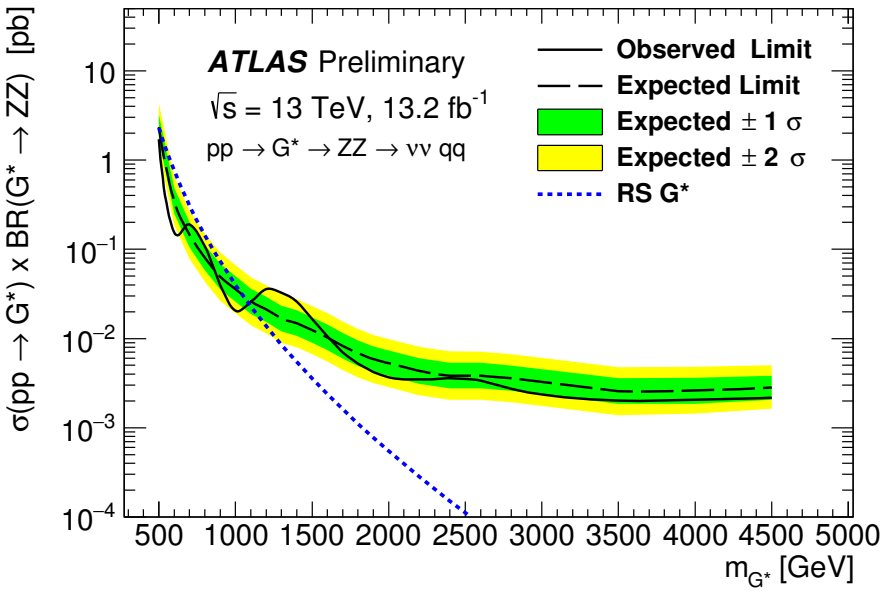
$ZV \to \nu\nu qq$ signal region

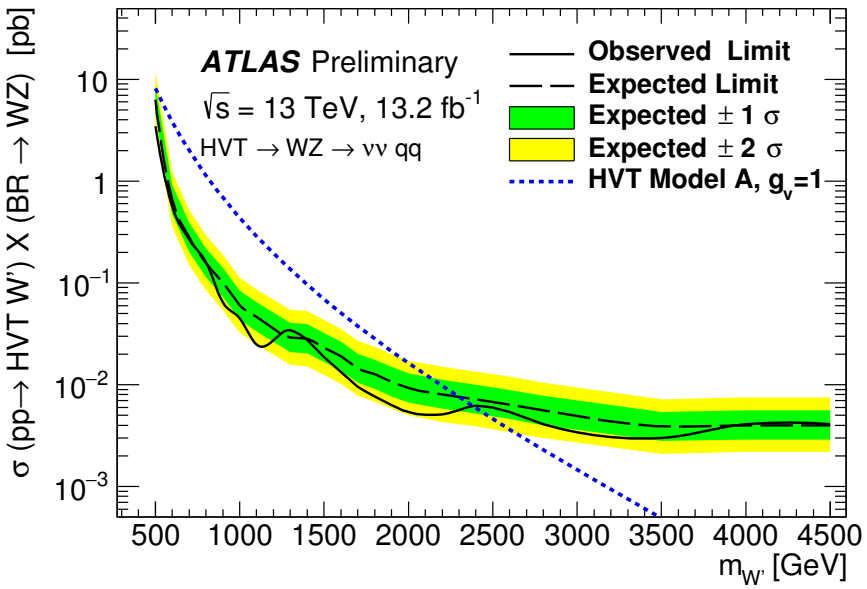
- Merged analysis divided in two categories: events where jet passed (high purity) and failed (low purity) the D_2 criteria

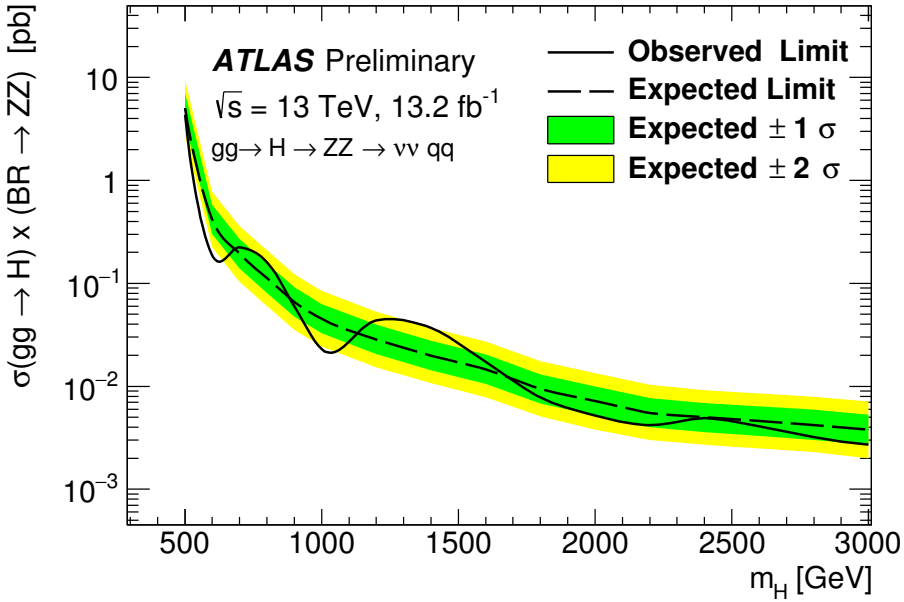




Statistical interpretation of $ZV \to \nu\nu qq$ analysis







- $W' \to WZ$ excluded for $m_{W'} < 2400$ GeV with $g_V = 1$
- $G^* \to ZZ$ excluded for $m_{G^*} < 1100$ GeV

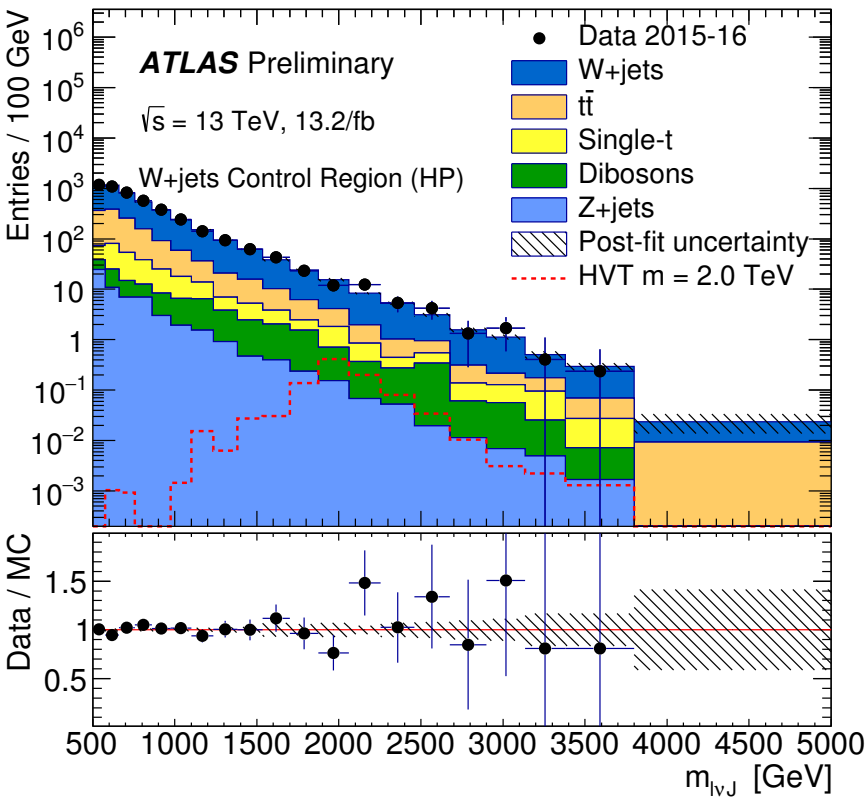
$WV \to \ell\nu qq$ - data/MC agreement of number of events

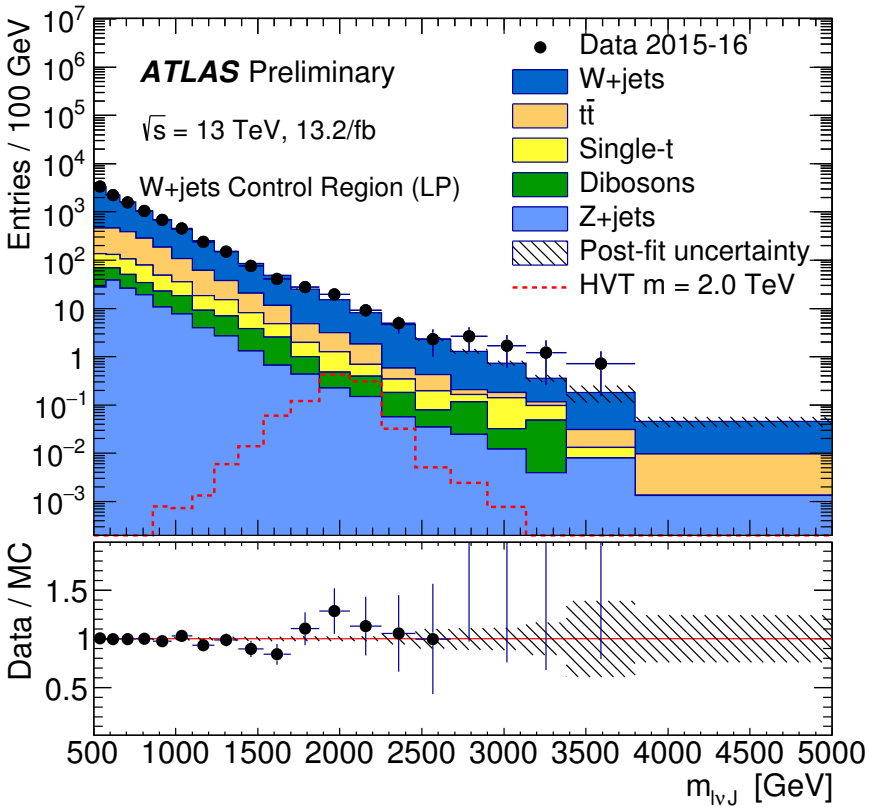
- Event selection criteria for the signal region and W+jets and $t\bar{t}$ control region

Selection		SR: HP (LP)	W CR: HP (LP)	$t\bar{t}$ CR: HP (LP)
$W \to \ell\nu$ selection	Number of signal leptons	1		
	Number of vetoed leptons	0		
	Number of vetoed leptons	0		
	$E_{\mathrm{T}}^{\mathrm{miss}}$	$> 100\,GeV$		
	$p_{\mathrm{T}}(\ell\nu)$	$> 200\,GeV$		
$W/Z \to J$ selection	Number of large-R jets	≥ 1		
	Passing the $D_2^{(\beta=1)}$ cut	yes (no)	yes (no)	yes (no)
	$\lvert m_{W/Z} - m_J \rvert$	< 15 GeV	> 15 GeV	< 15 GeV
Topology cuts	$p_{\mathrm{T}}(\ell\nu)/m_{WV}$ $p_{\mathrm{T}}(J)/m_{WV}$	> 0.4		
Top-quark veto	Number of b-tagged jets	0		≥ 1

W+jets CR for $WV \to \ell\nu qq$ analysis

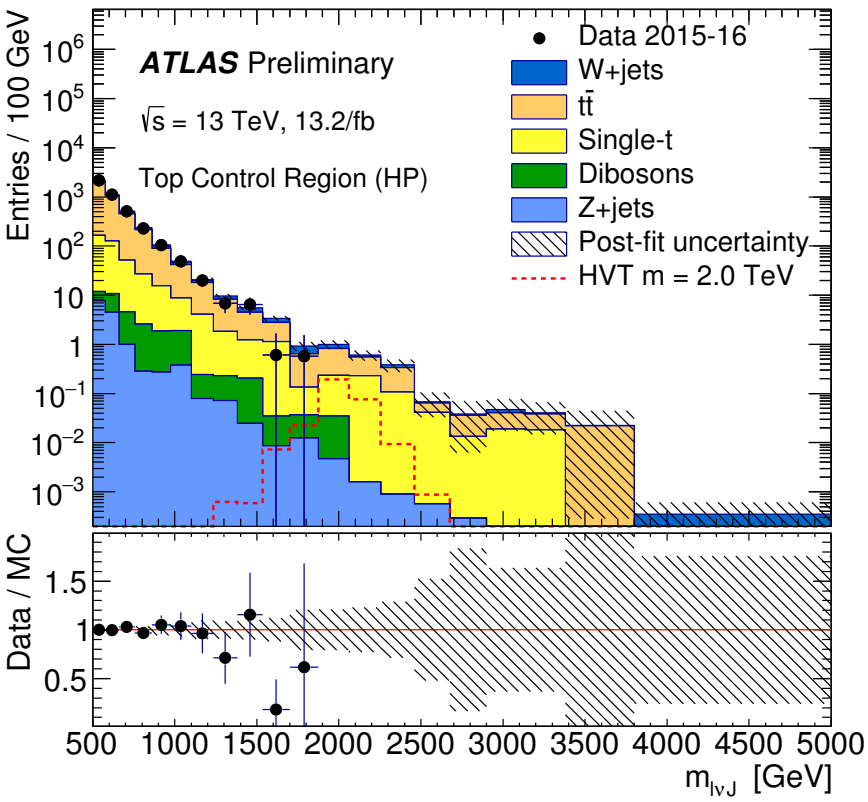
- Mass of large-R jet required to be outside of 15 GeV window around m_W
- Zero b-tagged jets
- Merged analysis divided in two categories: events where jet passed (high purity) and failed (low purity) the D_2 criteria

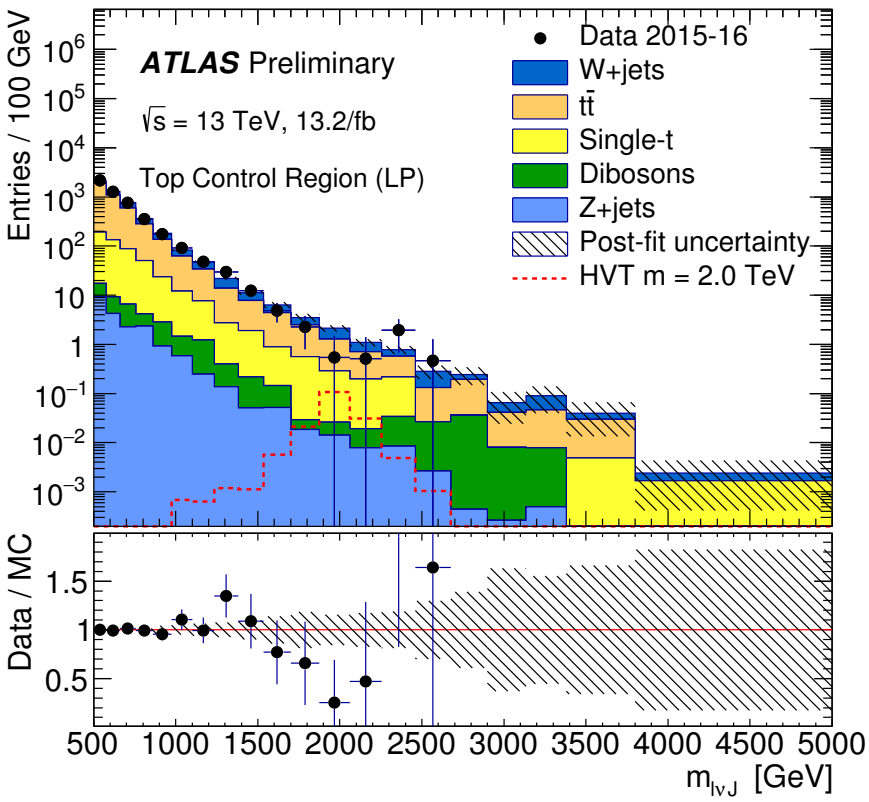




$t\bar{t}$ CR for $WV \to \ell\nu qq$ analysis

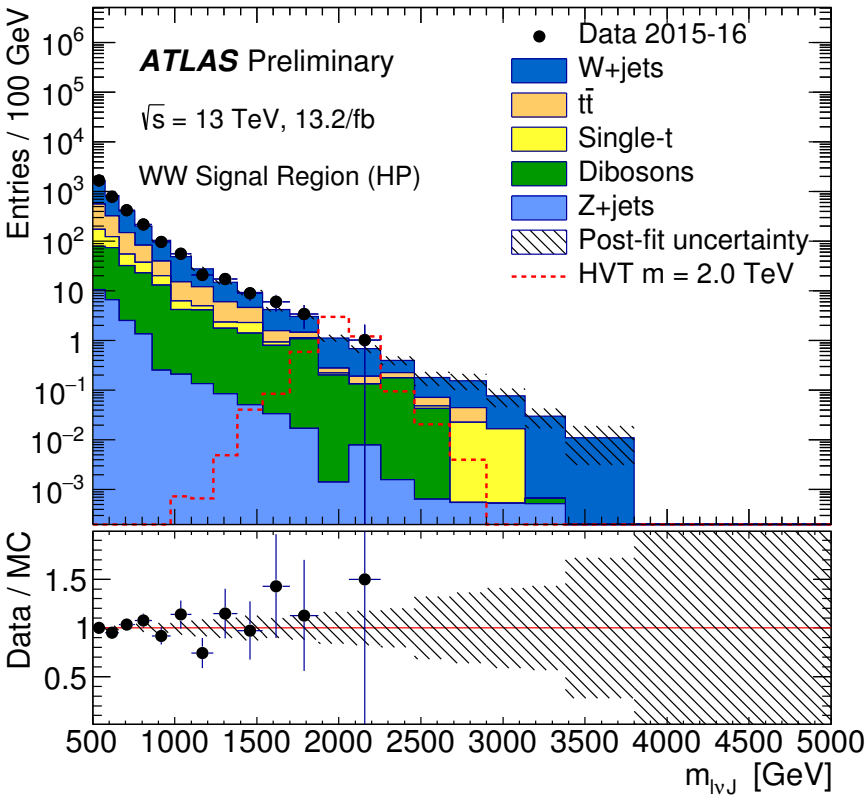
- Large-R jet required to be compatible with W-boson decay
- At least one b-tagged jet
- Merged analysis divided in two categories: events where jet passed (high purity) and failed (low purity) the D_2 criteria

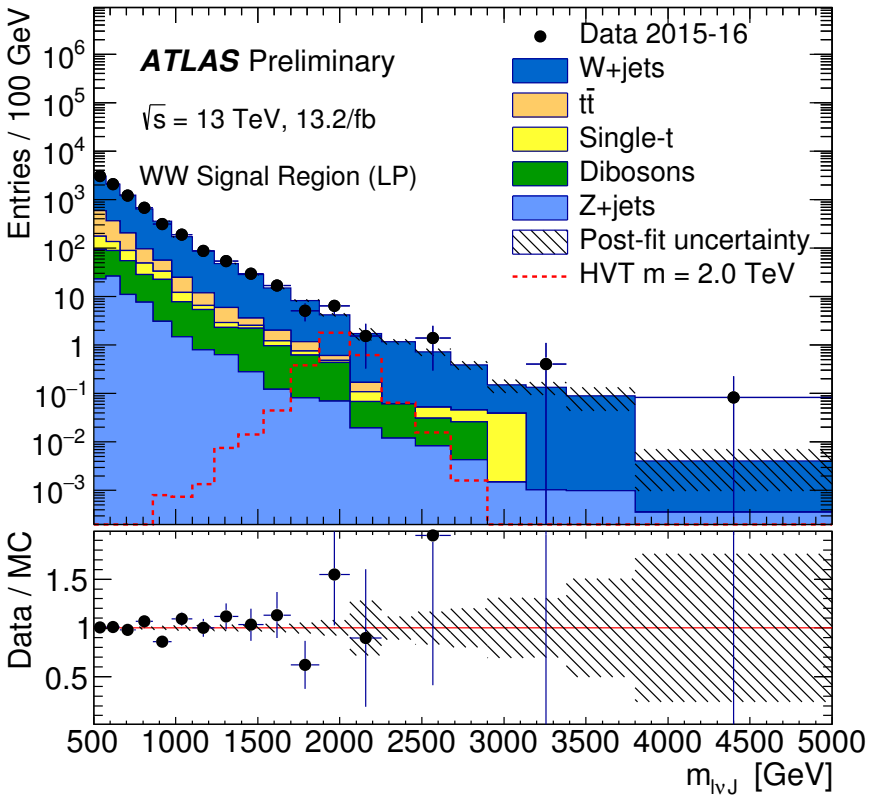




$WW \to \ell\nu qq$ signal region

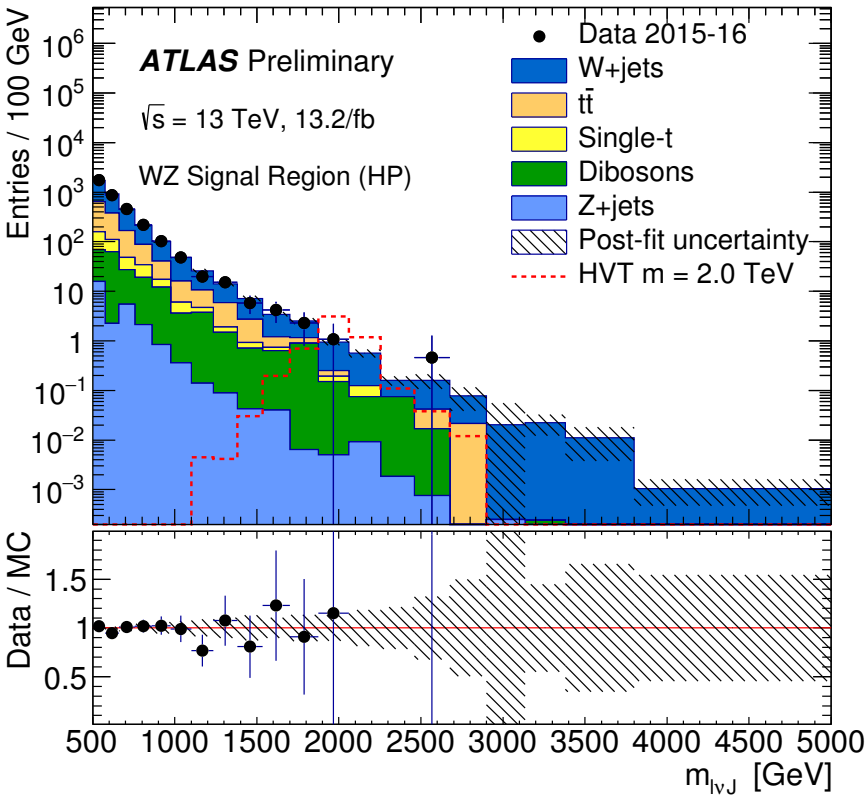
- Merged analysis divided in two categories: events where jet passed (high purity) and failed (low purity) the D_2 criteria

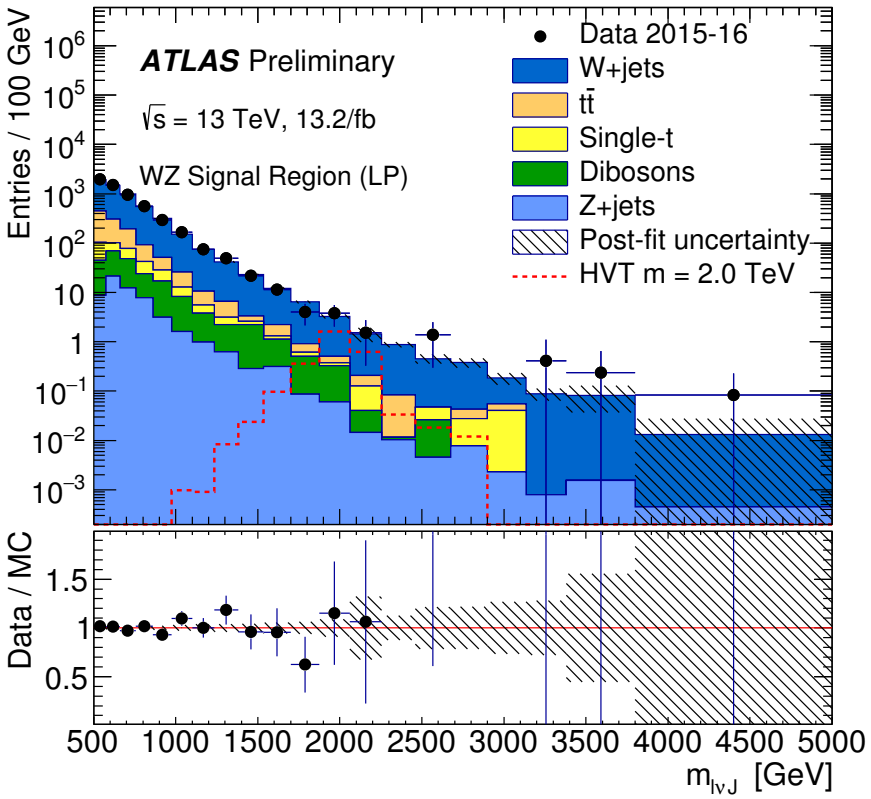




$WZ \to \ell\nu qq$ signal region

- Merged analysis divided in two categories: events where jet passed (high purity) and failed (low purity) the D_2 criteria





$WW \to \ell\nu qq$ - data/MC agreement of number of events

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- Comparison of predicted and observed number of events in MC and data for the WW signal and control regions $\ell\nu qq$ analysis

	WW signal region	W+jets control region	$t\bar{t}$ control region
High-purity category			
W+jets	1810 ± 63	3182 ± 65	215 ± 12
$t\bar{t}$	654 ± 50	1020 ± 33	2940 ± 70
Single-t	163 ± 14	200 ± 15	322 ± 23
Z+jets	18.0 ± 3.8	53 ± 6	12 ± 2
Diboson	192 ± 31	70 ± 11	19.0 ± 3.8
Total SM	2830 ± 80	4530 ± 80	3500 ± 80
Data	2822 ± 53	4534 ± 67	3509 ± 59
Low-purity category			
W+jets	5630 ± 94	7320 ± 110	706 ± 37
$t\bar{t}$	730 ± 50	1410 ± 47	3100 ± 89
Single-t	178 ± 14	290 ± 22	420 ± 31
Z+jets	66.6 ± 4.8	134.1 ± 7.7	17.7 ± 2.8
Dibosons	215 ± 34	150 ± 23	22 ± 4
Total SM	6820 ± 80	9310 ± 125	4260 ± 120
Data	6849 ± 83	9276 ± 96	4270 ± 65

$WZ \to \ell\nu qq$ - data/MC agreement of number of events

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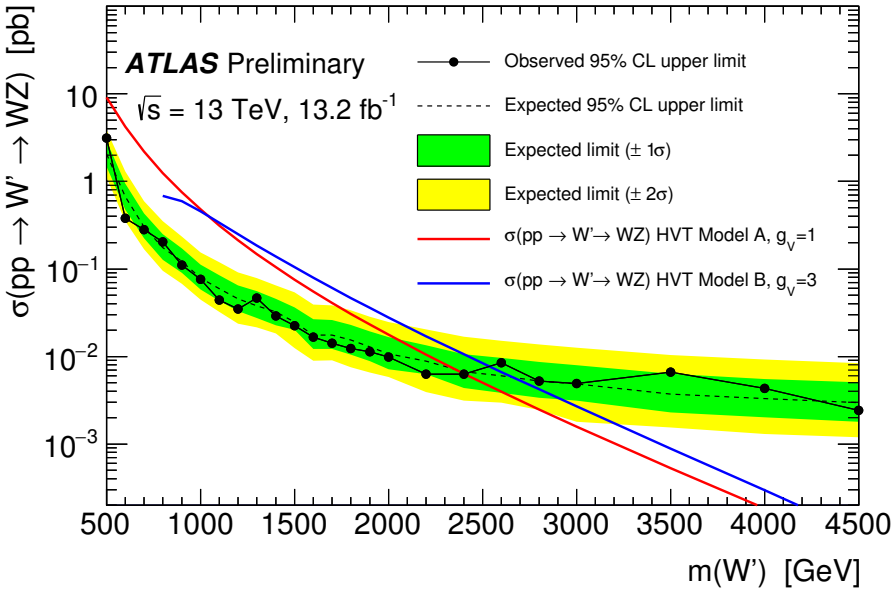
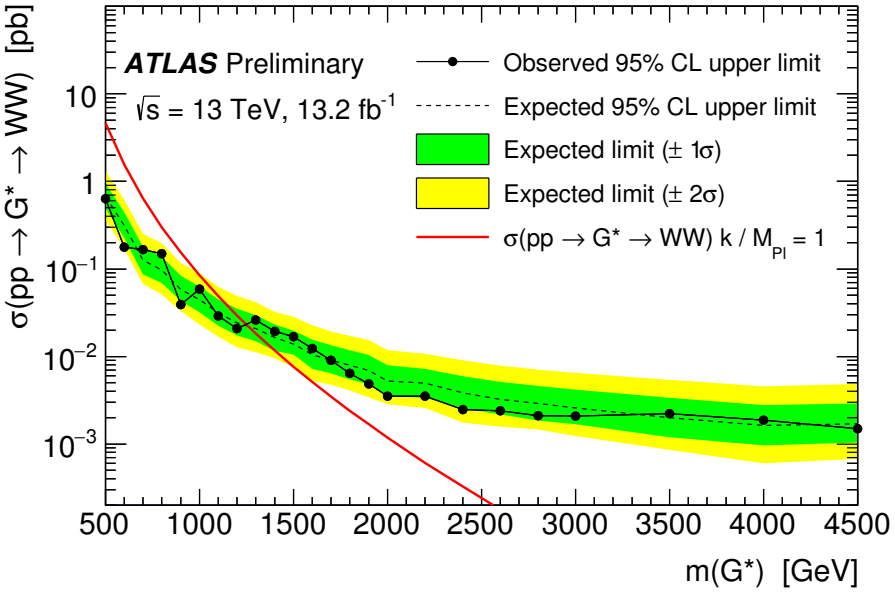
- Comparison of predicted and observed number of events in MC and data for the WZ signal and control regions $\ell\nu qq$ analysis

	WZ signal region	W+jets control region	$t\bar{t}$ control region
High-purity category			
W+jets	1810 ± 92	3050 ± 120	194 ± 28
$t\bar{t}$	830 ± 87	1130 ± 82	2300 ± 100
Single-t	160 ± 23	221 ± 26	312 ± 38
Z+jets	18.1 ± 5.1	50.7 ± 8.4	11.5 ± 2.6
Dibosons	165 ± 43	68 ± 18	19.8 ± 5.5
Total SM	2990 ± 70	4520 ± 97	3510 ± 94
Data	2972 ± 55	4534 ± 67	3509 ± 59
Low-purity category			
W+jets	4003 ± 130	7250 ± 196	670 ± 85
$t\bar{t}$	670 ± 72	1505 ± 120	3150 ± 125
Single-t	153 ± 21	284 ± 33	409 ± 46
Z+jets	54.1 ± 4.0	126 ± 12	16.7 ± 3.3
Dibosons	155 ± 40	135 ± 34	19.2 ± 6.1
Total SM	5035 ± 100	9300 ± 180	4260 ± 95
Data	5059 ± 71	9276 ± 96	4270 ± 65

Statistical interpretation of $WV \to \ell\nu qq$ analysis

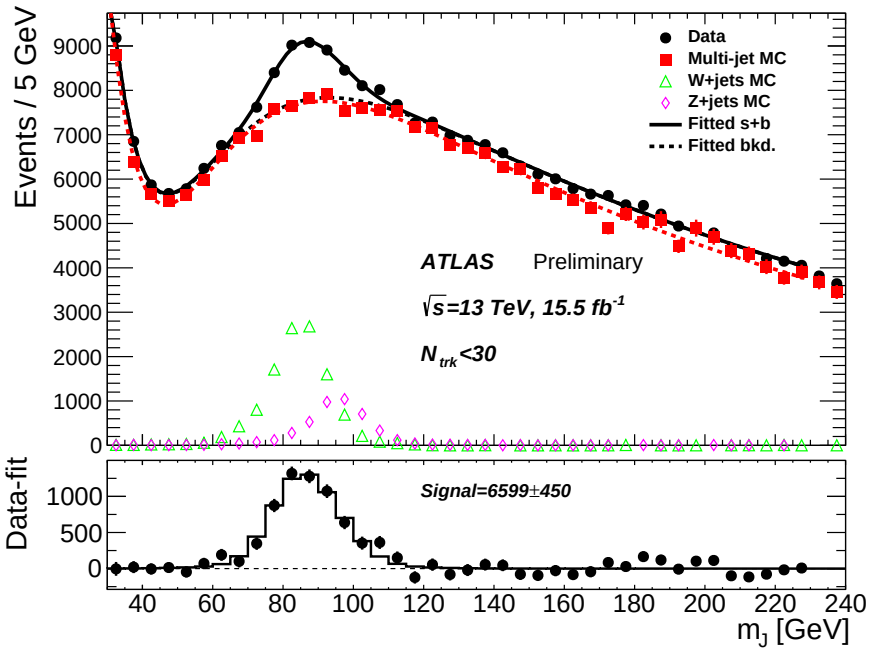
- Resonance masses below 2400 GeV are excluded for model-A
- Resonance masses below 2540 GeV are excluded for model-B
- Graviton masses below 1240 GeV are excluded

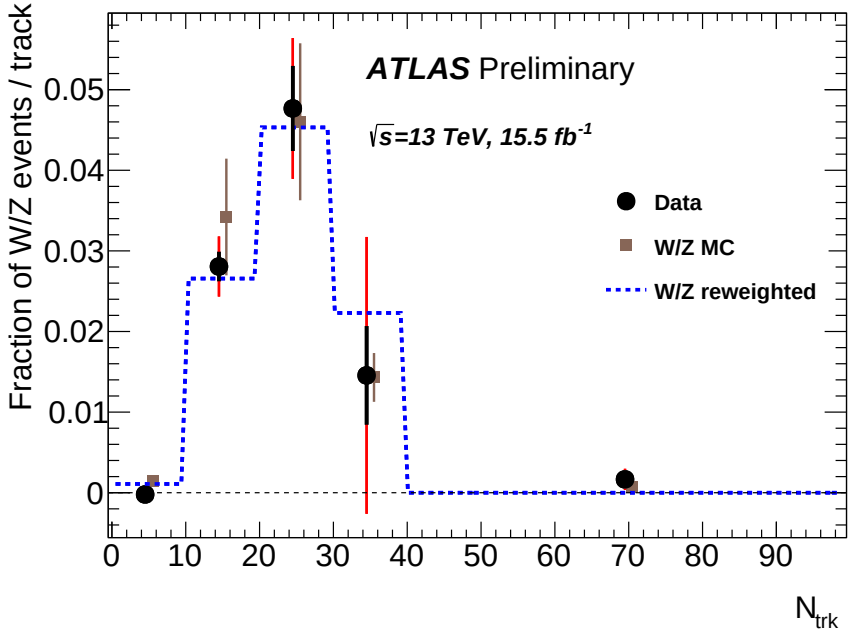




Number of ghost-associated tracks n_{trk}

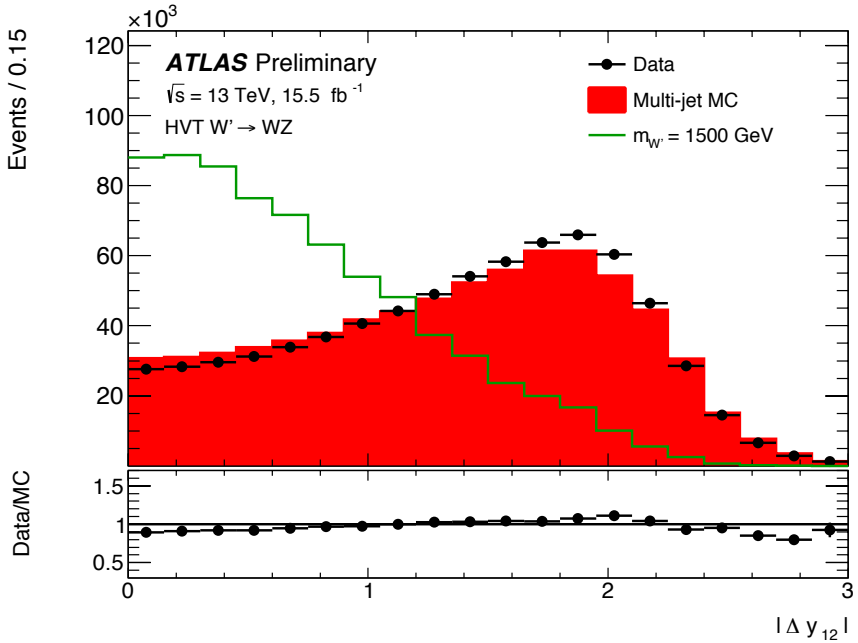
- Study the jet mass distribution in enriched W/Z+jets events
- D_2 criteria applied to select jets and n_{trk} varied
- Scale factor of 1.06 $\rightarrow$ 6% systematic uncertainty on n_{trk}
- Improvement of 20-30% of expected sensitivity

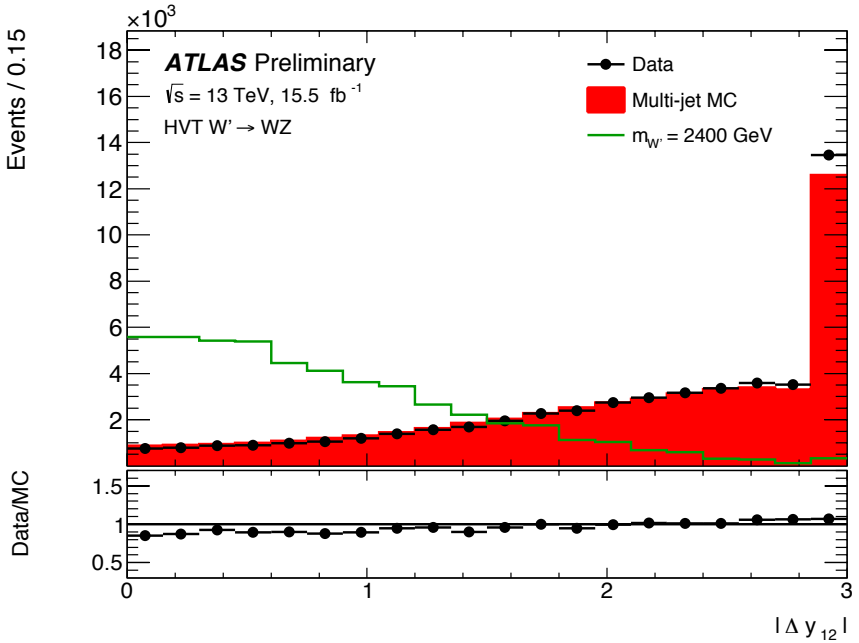




Rapidity difference

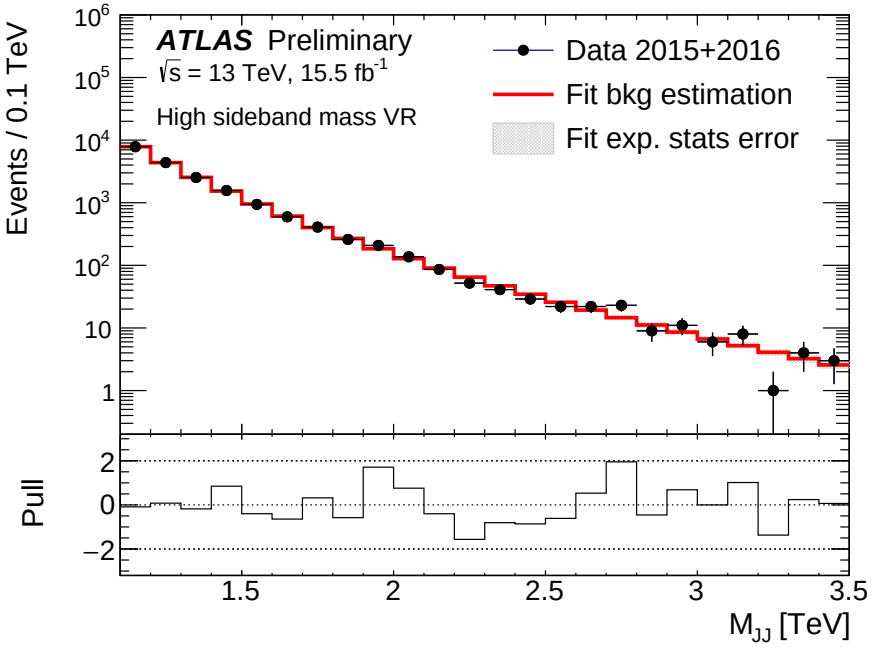
- Rapidity difference is used to suppress QCD dijet background (t-channel production)
- Discriminating power changes with p_{T}
- 10% window around $m_{W'}$ mass

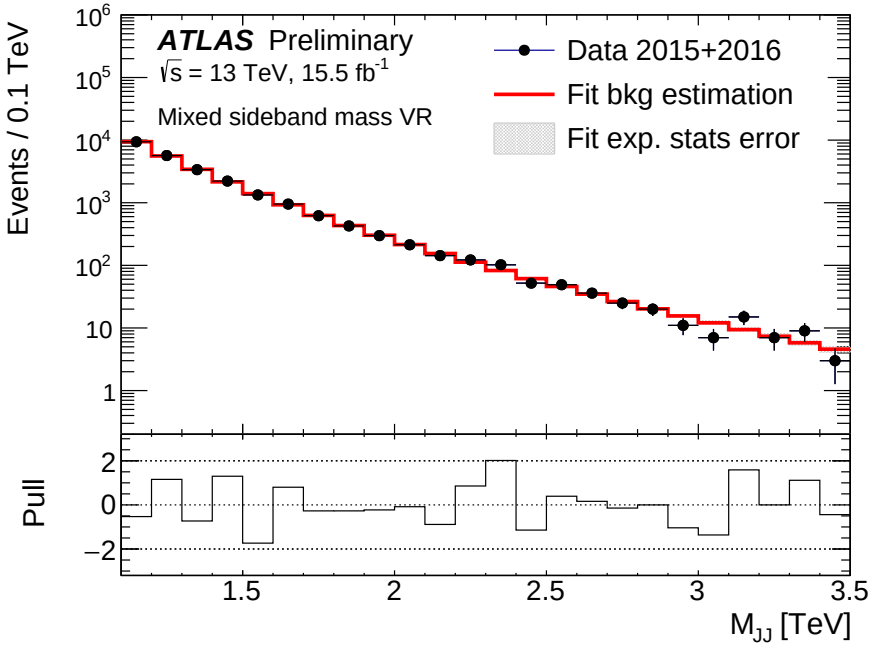




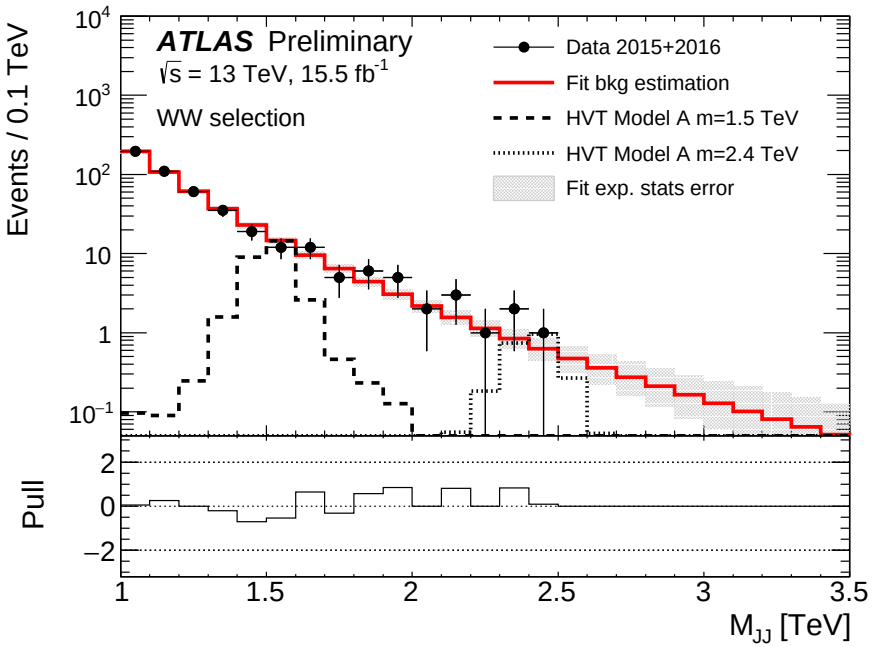
Control regions for $VV \rightarrow JJ$ search

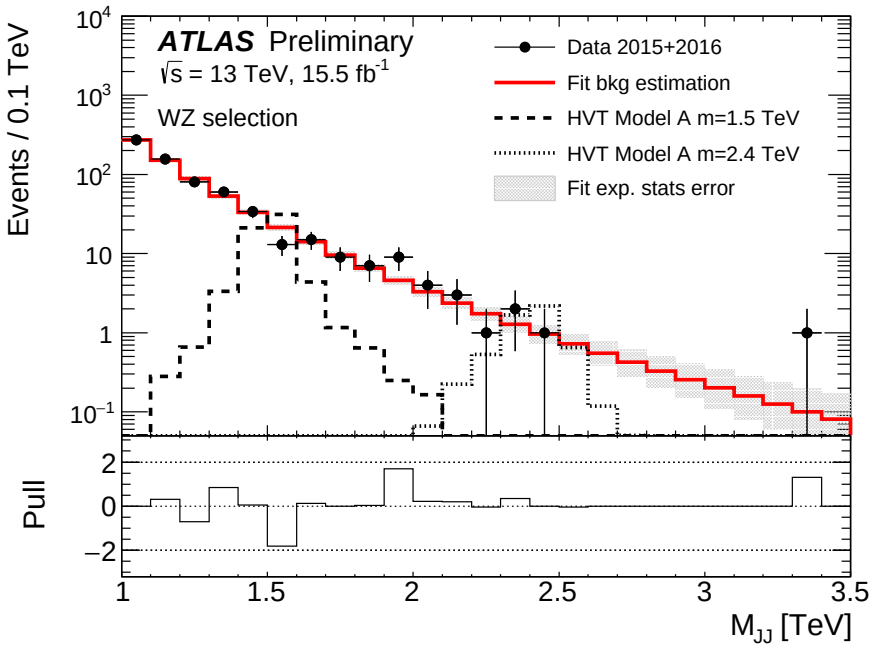
- Background parameterisation is tested in different control regions
- large-R jets required to be outside of W/Z boson mass window

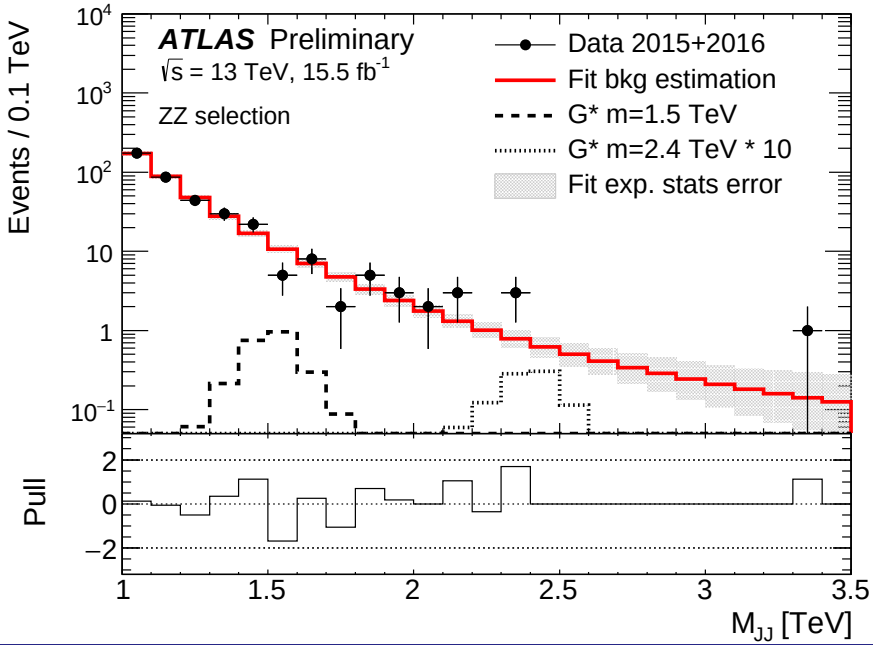




Signal regions for $VV \rightarrow JJ$ search

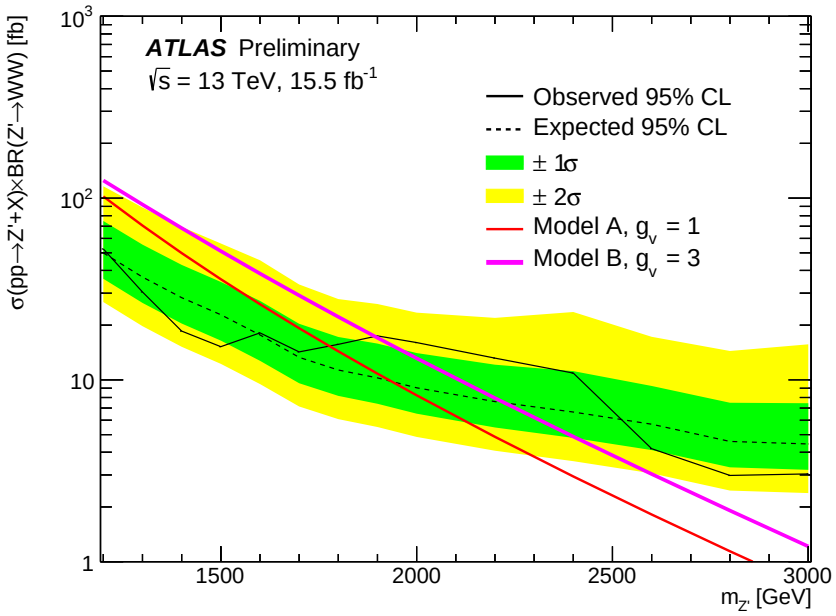


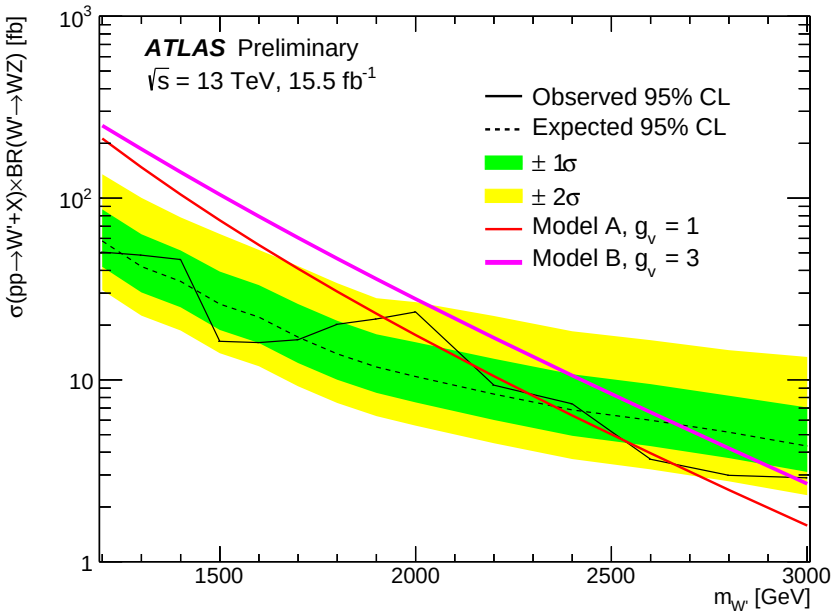




Statistical interpretation of $VV \to JJ$ results

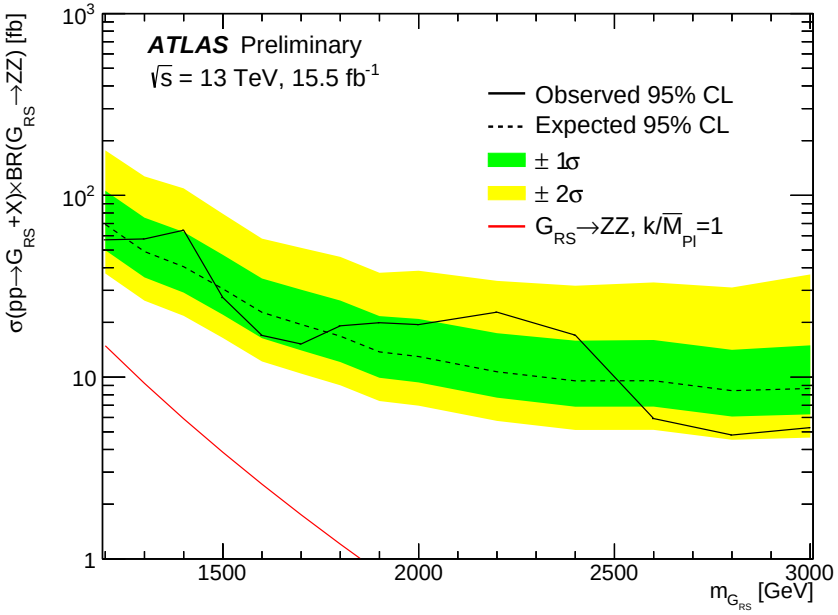
- 95% upper cross-section times Branching ratio limits on the HVT model
- $Z' \to WW$ excluded for masses 1.2 - 1.8 (1.2-1.9) TeV for HVT model A (B)
- $W' \to WZ$ excluded for masses 1.2 - 1.9 (1.2 - 3.0) TeV for HVT model A (B)

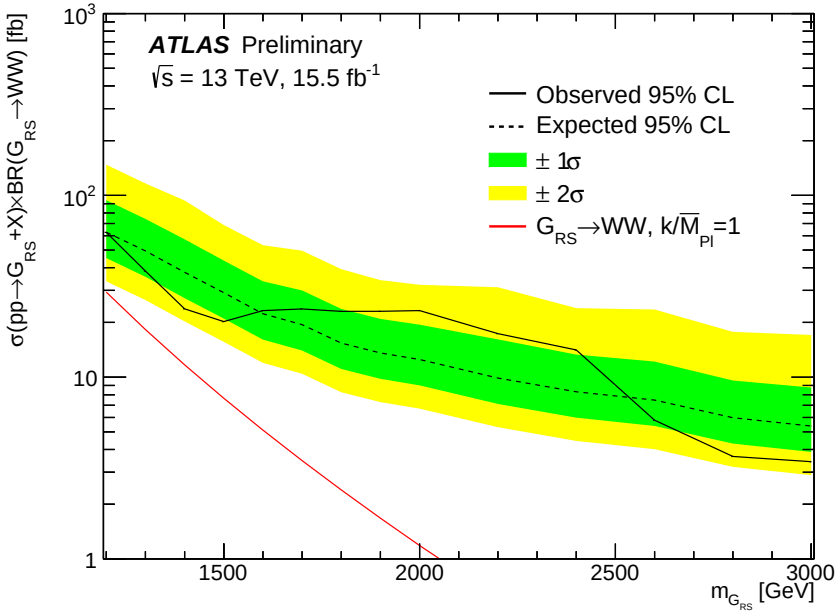




Statistical interpretation of $VV \rightarrow JJ$ results

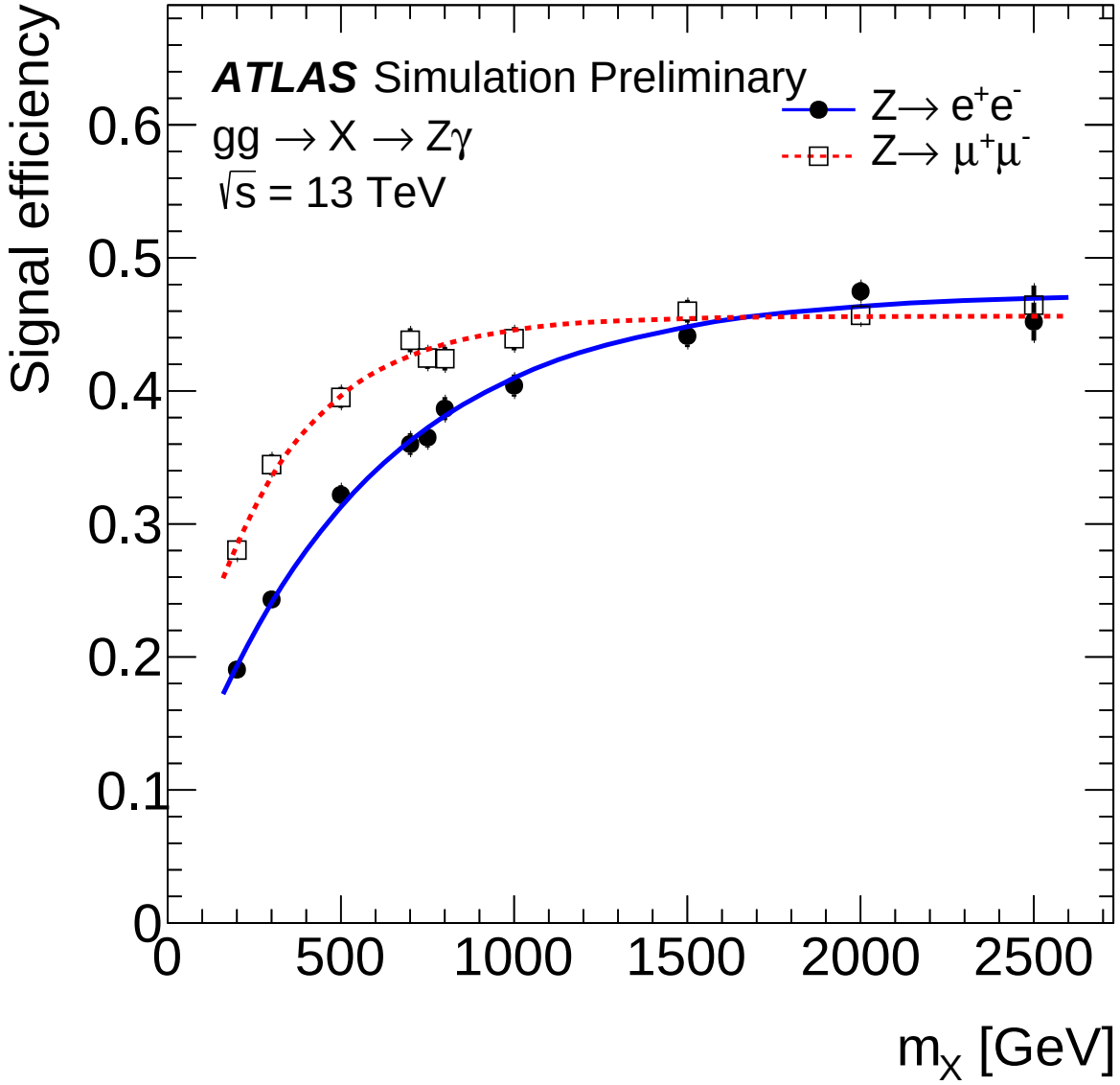
- Analyses not sensitive enough to RS gravitons with the studied parameters here





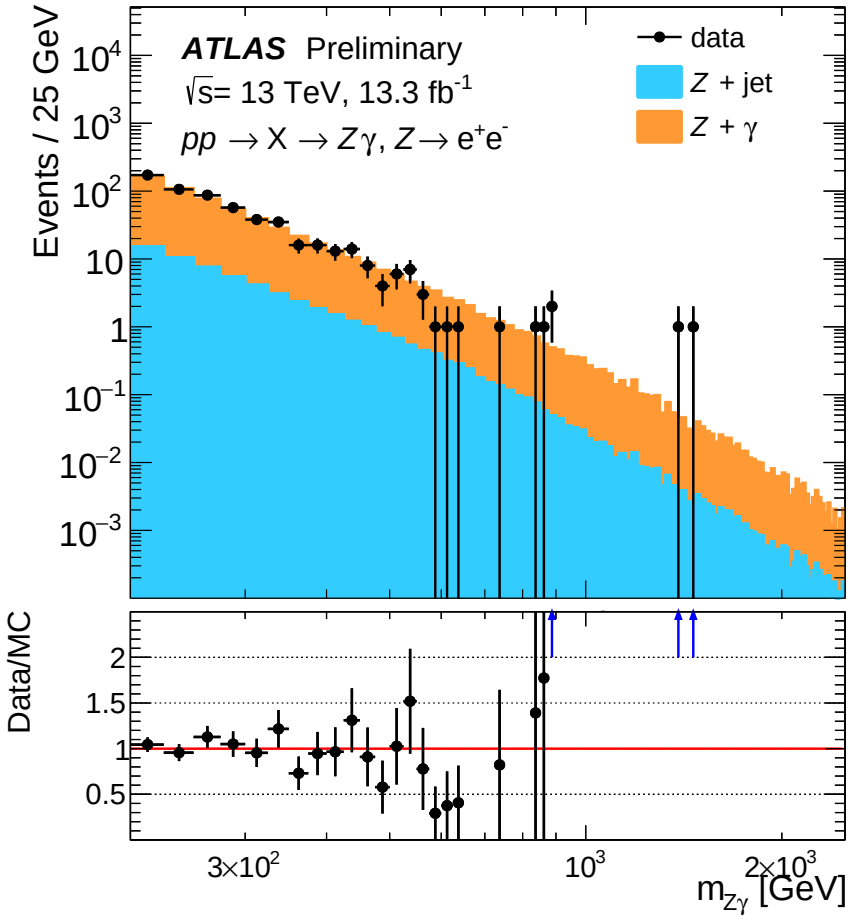
Signal efficiency for $Z\gamma$ search

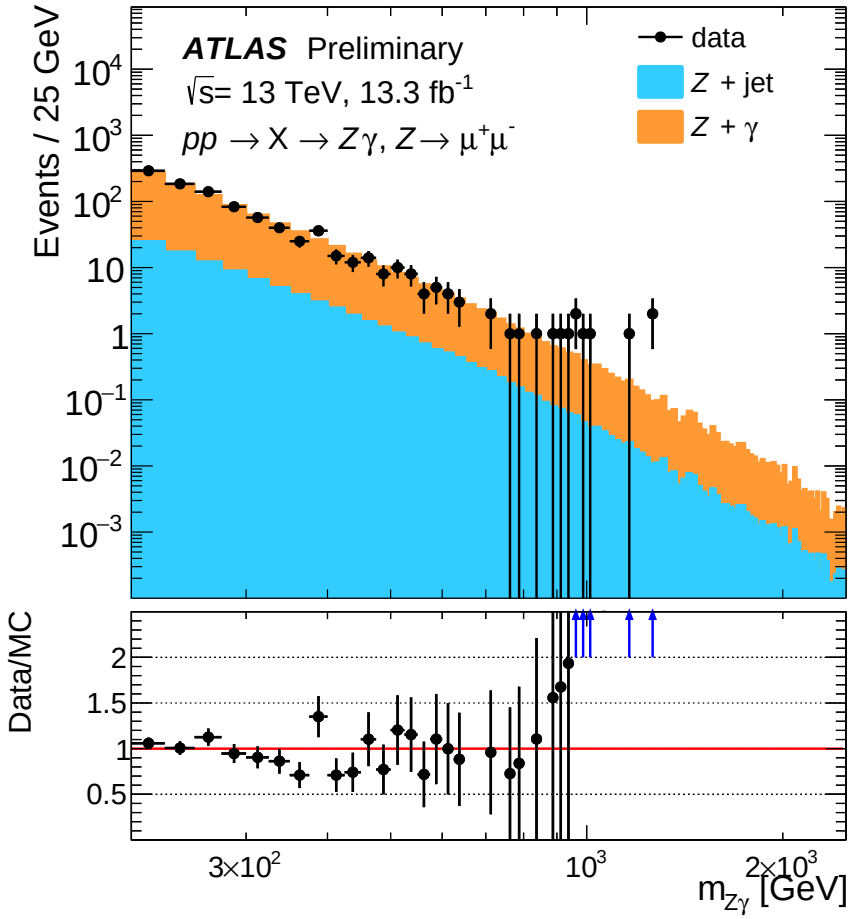
- Signal efficiency as a function of the resonance mass for $Z \to \mu\mu$ and $Z \to ee$ channel separately



Data/MC comparison for the $Z\gamma$ signal region

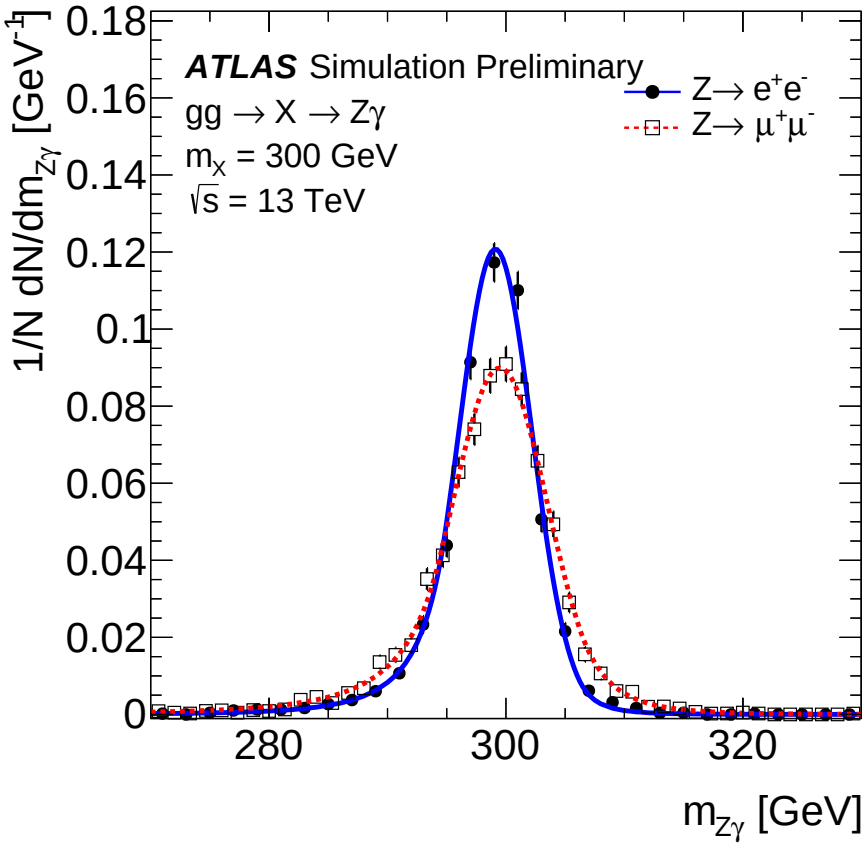
- Data/MC comparison of invariant $Z\gamma$ mass for the $Z \to ee$ and $Z \to \mu\mu$ channel

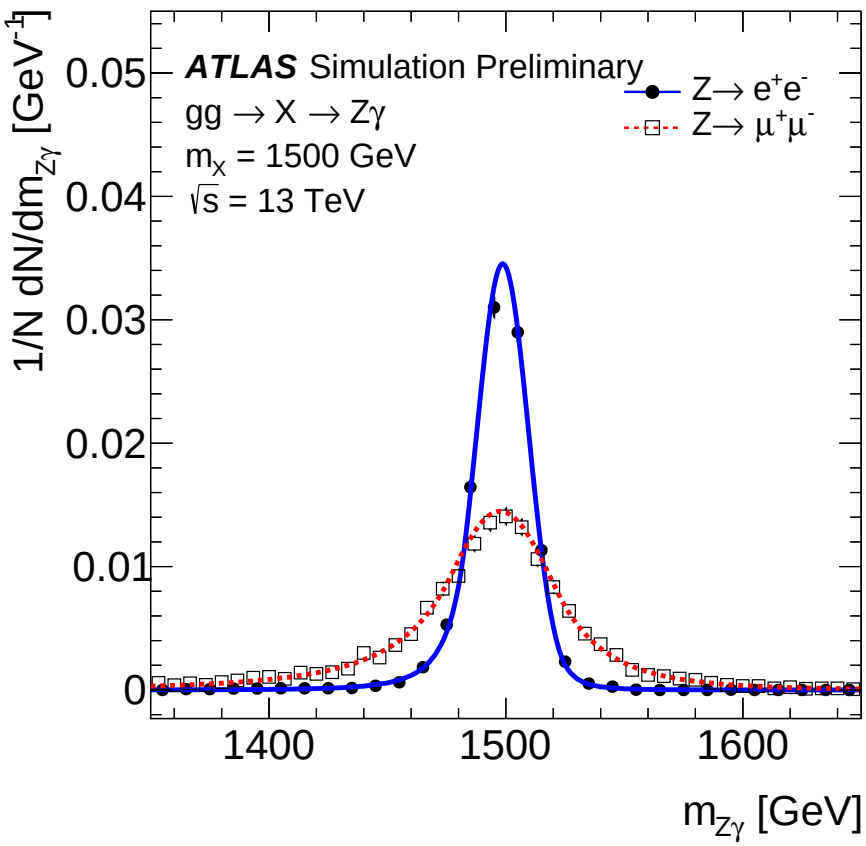




Invariant $Z\gamma$ mass distributions

- Comparison of invariant $Z\gamma$ mass distribution for two different resonance masses
- Width of X mass distributions degrades significantly in muon channel for higher resonance masses





Background parameterisation

- Background parameterisation for the $Z \to ee$ and $Z \to \mu\mu$ channel separately