Searches for diboson resonances using boosted W/Z boson tagging with the ATLAS detector at LHC Run 1

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On behalf of the ATLAS Collaboration

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Overview

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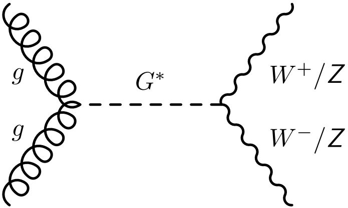
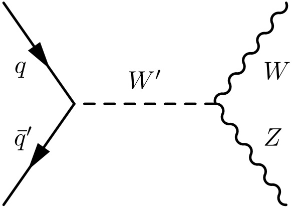
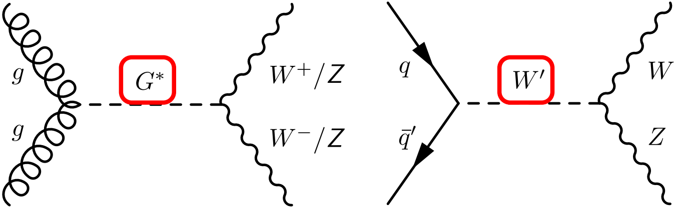
- Extensions of the Standard Model predict the existence of new particles decaying into vector-boson pairs





Overview

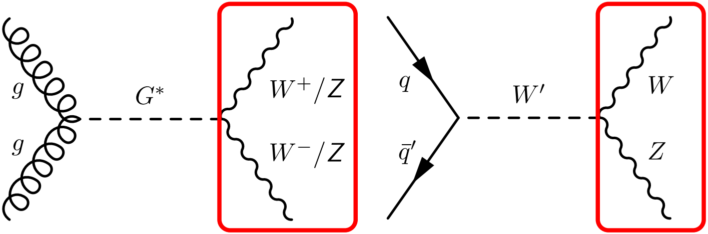
- Extensions of the Standard Model predict the existence of new particles decaying into vector-boson pairs



1. What can these extensions of the Standard Model be? (Selected examples)
   - Grand Unified Theories
   - Warped extra dimensions
   - Technicolor

Overview

- Extensions of the Standard Model predict the existence of new particles decaying into vector-boson pairs

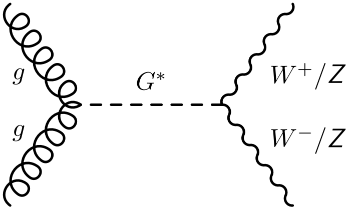


1. What can these extensions of the Standard Model be? (Selected examples)
   - Grand Unified Theories
   - Warped extra dimensions
   - Technicolor
2. How can we detect these new resonances?
   - For high-mass resonances ($m_X > 1000$ GeV), the W/Z-bosons are highly boosted $\rightarrow$ need special reconstruction techniques

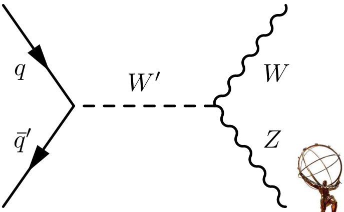
Benchmark Models for Run-1 Analysis

- Two **benchmark** models were chosen in ATLAS to search for **narrow** diboson resonances

1. **Bulk Randall-Sundrum model**
   - Model of warped extra dimensions
   - Spin-2 Kaluza-Klein graviton (G*)
   - Gluon-gluon production
   - Decays into WW, ZZ
   - $m_{G*} = 1$ TeV:
     BR(G* $\rightarrow WW$) $\approx$ 20%
     BR(G* $\rightarrow ZZ$) $\approx$ 10%



2. **Extended gauge model (EGM)**
   - Sequential Standard Model (modified WZ couplings)
   - Spin-1 gauge boson (W')
   - $q\bar{q}$ production
   - Decays into WZ
   - $m_{W'} = 1$ TeV:
     BR(W' $\rightarrow WZ$) $\approx$ 1.3%



Diboson Analysis in a Nutshell

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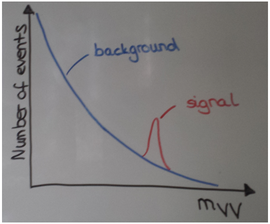
How to search for diboson resonances

- Observable:
  invariant mass of diboson system m_{VV}
- Here: search for narrow resonance on top of smoothly falling background distribution



Decay modes:

- **Semi-leptonic final state**
- **Full-hadronic final state:**
  - Large branching ratio:

$$\mathrm{BR}(W \to qq) \approx 3 \times \sum_{\ell=e,\mu} \mathrm{BR}(W \to \ell\nu)$$

$$\mathrm{BR}(Z \to qq) \approx 10 \times \sum_{\ell=e,\mu} \mathrm{BR}(Z \to \ell\ell)$$

  - No MET
  - large dijet background

- **Full-leptonic final state**
  - Clean signature and low background
  - Small branching ratio
  - (Not considered here)

Run-1 Analyses in ATLAS

Analyses presented in this talk *

1. $ZW/ZZ \to \ell\ell q\bar{q}$ Eur. Phys. J. C (2015) 75:69
2. $WZ/WW \to \ell\nu q\bar{q}$ Eur. Phys. J. C (2015) 75:209
3. $WW/WZ/ZZ \to qqqq$ (submitted to JHEP) arXiv:1506.00962

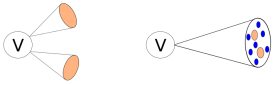
Further diboson resonance searches in ATLAS (not shown here)

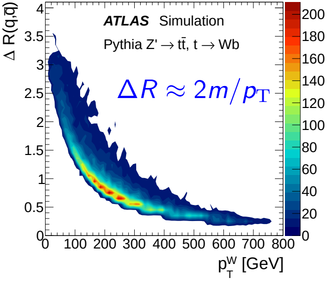
- $WH/ZH \to \ell\nu bb, \ell\ell bb, \nu\nu bb$ Eur. Phys. J. C (2015) 75: 263
  (no substructure information used in Run-1)
- $HH \to bbbb$ (submitted to EPJC) arXiv:1506.00285
  resolved and boosted regime using trimmed jets, see Michael Kagan's talk
- $HH \to \gamma\gamma b\bar{b}$ Phys. Rev. Lett. 144, 081802

*using the full 2012 dataset of $\mathcal{L} = 20.3$ fb^{-1}

Boosted Boson Jets

- Especially interesting in high p_T regime:
  $\rightarrow$ larger signal over background ratio
- For resonance masses above O(1 TeV) the vector-boson decay products are boosted
  $\rightarrow$ reconstruction as one single large-radius jet





JHEP09 (2013) 076

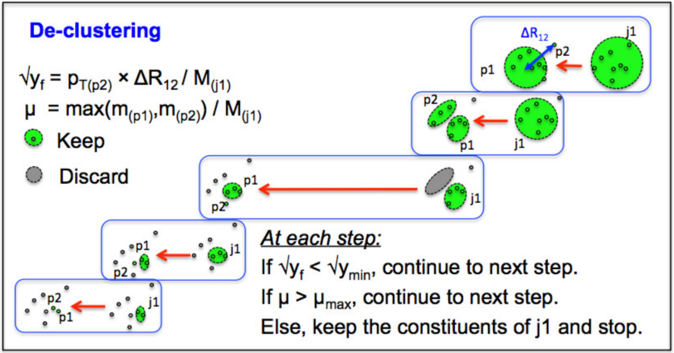
Need to distinguish between large-R jets from boosted bosons and quarks/gluons

1. **Grooming techniques**
   - Clean the large-R jet from soft gluon radiation and pile-up effects that diminish jet mass resolution
   - Techniques: BDRS* (mass-drop/filtering), trimming, pruning
2. **Substructure information (tagging)**
   - Use hard substructure of jet (not present in e.g. gluon jet) to improve signal efficiency and background rejection

* Butterworth, Davison, Rubin, Salam

1 Jet reconstruction:
All diboson searches presented here use C/A $R = 1.2$ jets groomed with the BDRS (split-filtering) algorithm

- **Splitting**:
  - Require symmetric splitting $\sqrt{y_\mathrm{f}} = \frac{\min(p_{\mathrm{T}1}, p_{\mathrm{T}2})}{m_{12}} \times \Delta R_{12}$ with $\sqrt{y_\mathrm{min}} = 0.2$
  - No mass drop-criterion is used in ATLAS ($\mu = 100\%$)
  - Slightly modified version of BDRS using a fixed reclustering distance parameter
- **Filtering**: remove soft radiation



Boson Tagging in ATLAS Run-1 Diboson Analyses

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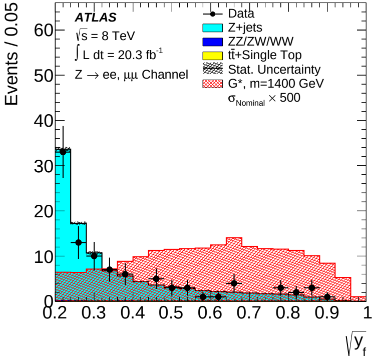
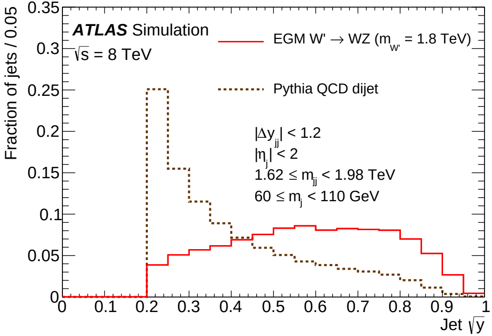
2 Boson tagging:

All diboson searches presented here use as tagging variable

- the large-R jet mass m_J (mass window around boson)
- y_{f} as tagging variable: $\sqrt{y_{\mathrm{f}}} = \frac{\min(p_{\mathrm{T}1}, p_{\mathrm{T}2})}{m_{12}} \times \Delta R_{12}$, $\sqrt{y_{\mathrm{f}}} > 0.45$
  QCD dijet events have unbalanced subjet momenta compared to signal jets due to soft gluon radiation





$ZV \to \ell\ell qq$ - Overview

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Event selection

$Z \to \ell\ell$

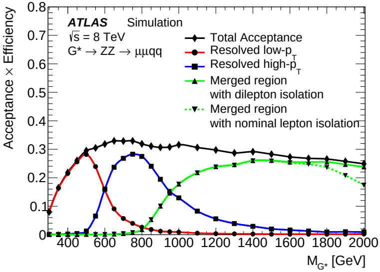
- 2 isolated leptons with same flavor, $m_{\ell\ell}$ compatible with Z-boson mass
- Improved isolation requirement for boosted dilepton system ($p_{\mathrm{T}}^{Z} > 800$ GeV)

$V \to qq$

- Low-p_{T} resolved region
- High-p_{T} resolved region

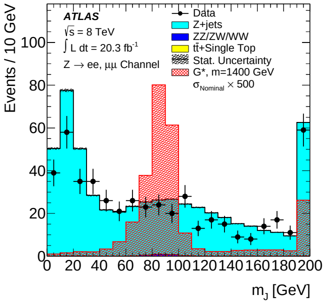
} two small-R jets

- Merged-region (MR) $\to$ one large-R C/A jet
  $p_{\mathrm{T}}^{\ell\ell} > 400$ GeV, $p_{\mathrm{T}}^{J} > 400$ GeV



Merged region:

- Using substructure to improve sensitivity (optimized for longitudinally polarized vector-bosons):
  $70 < m_{\mathrm{J}} < 110$ GeV, $\sqrt{y_{\mathrm{f}}} > 0.45$



$ZV \rightarrow \ell\ell qq$ - $m_{\ell\ell J}$ Spectrum

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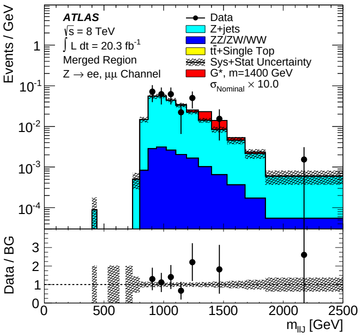
Dominating background: Z+jets

- Normalization and shape correction for $m_{\ell\ell J}$ determined in data using control regions
- Control regions: $m_J < 70$ GeV or $m_J > 110$ GeV
- Corrections up to 22%

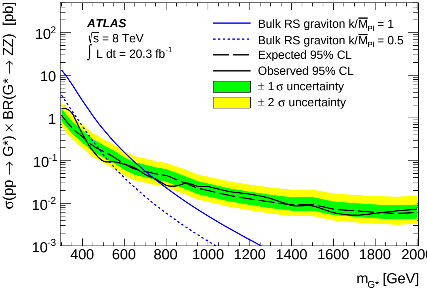
Dominating systematic uncertainties:

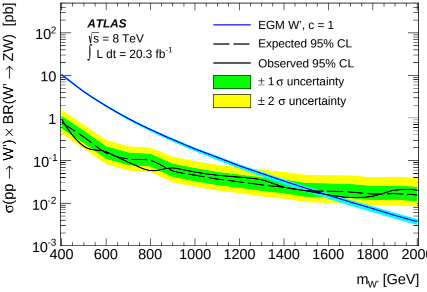
- Normalization and shape uncertainties from Z+jets background: 11% – 47%



$ZV \rightarrow \ell\ell qq$ - Limits

- No significant deviations from the Standard Model are observed
- 95% CL upper limits on cross-section times BR
- Exclude M(G*) $<$ 740 GeV and M(W') $<$ 1590 GeV
- The MR is the most powerful search region for signal masses above 850 GeV



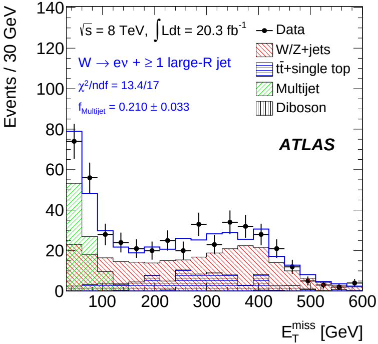


$WV \rightarrow \ell\nu qq$ - Overview

Event selection

$W \rightarrow \ell\nu$

- Exactly one electron or muon with $p_{\mathrm{T}} > 25$ GeV
- $E_{\mathrm{T}}^{\mathrm{miss}} > 30$ GeV
- Reject events with b-tagged small-R jets



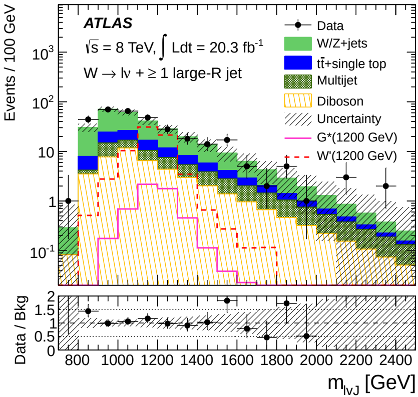
$V \rightarrow qq$

- Similar to $ZV \rightarrow \ell\ell qq$ selection: three regions
- Events are assigned exclusively to one region only
- Merged region:
  - $p_{\mathrm{T}}^{\ell\nu} > 400$ GeV
  - $65 < m_J < 105$ GeV, $\sqrt{y_{\mathrm{f}}} > 0.45$
  - $\Delta\Phi(J, E_{\mathrm{T}}^{\mathrm{miss}}) > 1$

Background estimation:

- W/Z+jets and multijet normalization determined from control regions in data (inverted m_J requirement) by fitting the $E_{\mathrm{T}}^{\mathrm{miss}}$ distribution
- Multijet bkg shape from looser identification criterion data sample

$WV \to \ell\nu qq$ - $m_{\ell\nu J}$ Spectrum

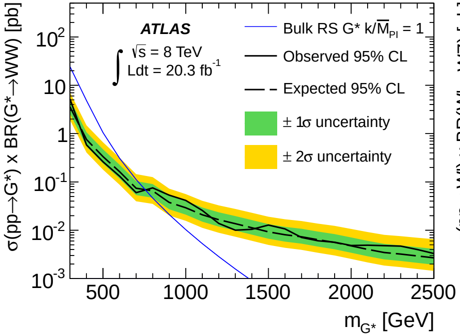


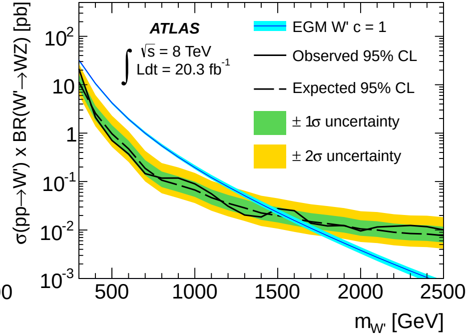
Sample	LRR	HRR	MR
W/Z + jets	104800 ± 1600	415 ± 10	180 ± 20
$t\bar{t}$ + single top	37700 ± 1600	271 ± 13	42 ± 7
Multijet	13500 ± 500	84 ± 9	29.3 ± 2.9
Diboson	5500 ± 270	96 ± 6	43 ± 7
Total	161500 ± 2300	870 ± 40	295 ± 22
Data	157837	801	323
G^* signal	7000 ± 500	36 ± 6	5.5 ± 2.3
W' signal	6800 ± 600	318 ± 21	70 ± 4

- No significant deviations from the Standard Model are observed in $m_{\ell\nu J}$ spectrum → 95% CL upper limits on cross-section times BR
- Maximum likelihood fits to $m_{\ell\nu J}$ distribution taking systematic uncertainties into accounts as nuisance parameters
- Merged region: signal pole masses between 800–2000 GeV

$WV \to \ell\nu qq$ - Limits

- Exclude M(G*) $<$ 760 GeV and M(W') $<$ 1490 GeV
- $\sigma(pp \to W') \times \mathrm{BR}(W' \to WZ)$ of 9.6 fb excluded for W' masses around 2 TeV

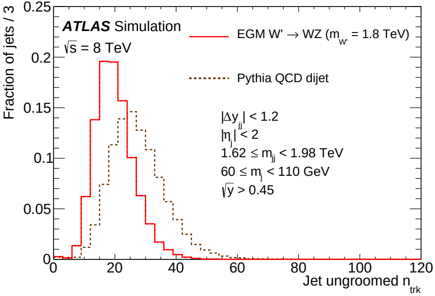




$VV \rightarrow qqqq$ - Overview

Boson tagging:

- Jet mass (26 GeV window around m_{V})
- $\sqrt{y_f} > 0.45$
- Number of charged-particle tracks associated to the ungroomed jet:
  - $n_{\mathrm{trk}} < 30$: expect QCD jet to be composed of more hadrons
  - Efficiency is measured in data



Event Selection

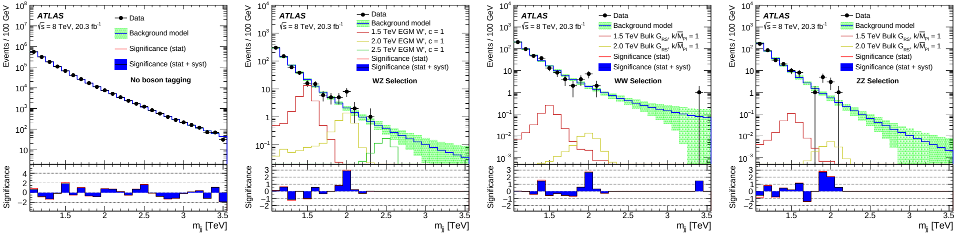
- Compared to semileptonic analysis only boosted regime is considered
- Reject events with electron or muon candidate or $E_{\mathrm{T}}^{\mathrm{miss}} > 350$ GeV (orthogonal to other diboson resonance searches)
- Overlap between WW, WZ, ZZ selection due to chosen mass window
- Rapidity difference: $|y_1 - y_2| < 1.2$
- p_{T} asymmetry: $|(p_{\mathrm{T}_1} - p_{\mathrm{T}_2})|/(p_{\mathrm{T}_1} + p_{\mathrm{T}_2}) < 0.15$
- $m_{\mathrm{JJ}} > 1.05$ TeV: trigger plateau of large-R jet trigger

$VV \rightarrow qqqq$ - m_{JJ} Spectrum

- Background invariant dijet mass spectrum assumed to be smoothly falling distribution, characterized by:

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

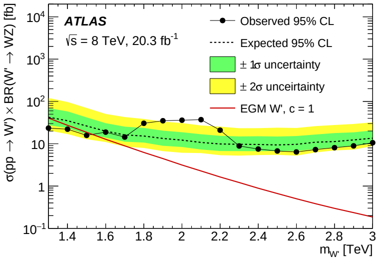
- Maximum-likelihood fit performed to data to estimate background

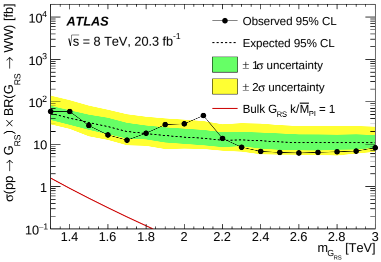


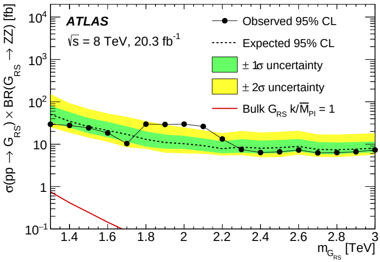
- Good agreement between data and background model over full dijet mass range except for region around $m_{\mathrm{jj}} = 2$ TeV
- Frequentist approach used to interpret data:
  - Local significance: $WZ : 3.4\sigma$, $WW : 2.6\sigma$, $ZZ : 2.9\sigma$
  - Global significance: $WZ : 2.5\sigma$

$VV \to qqqq$ - Limits

- Exclude $1300 < \mathrm{M}(W') < 1500$ GeV
- Cross-section times branching ratio for excited graviton production with chosen model parameters too low to be excluded







Conclusion

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- The diboson final state provides a direct key to new physics models beyond the Standard Model
- Several searches have been performed with the full 2012 dataset in the semi-leptonic and full-hadronic decay channel
- Boosted boson tagging techniques were used to increase the sensitivity for high-mass resonances
- Small excess around 2 TeV observed in the $VV \rightarrow JJ$ analysis

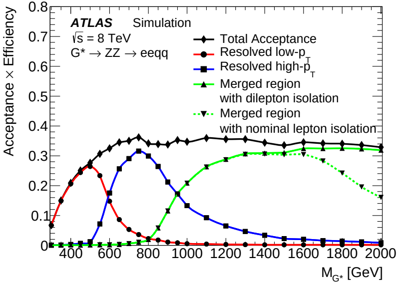
Stay tuned for $\sqrt{s} = 13$ TeV data!!!

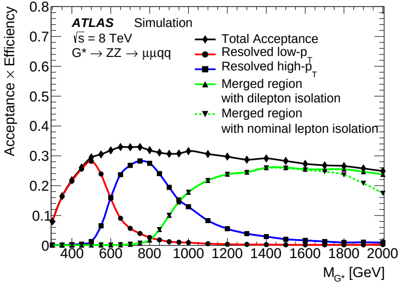
- Large effort on-going to optimize the identification of boosted bosons using tagging techniques and hence to increase the signal sensitivity
  See Matt Leblanc and Julien Caudron's talk

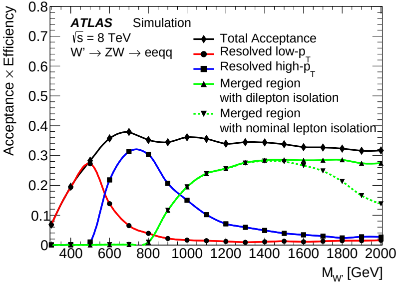
ATLAS

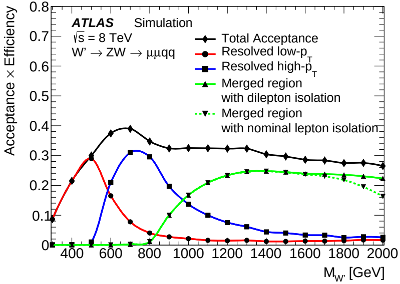
Backup

Acceptance - $ZV \to \ell\ell qq$









Acceptance - $WV \to \ell\nu qq$

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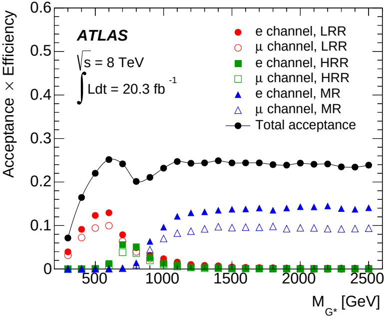

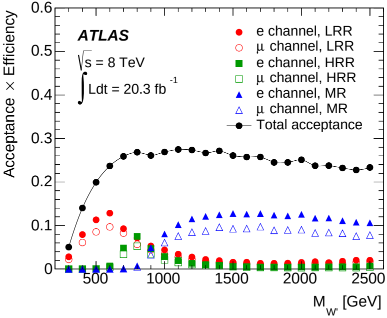

Selection Efficiency - $VV \to qqqq$

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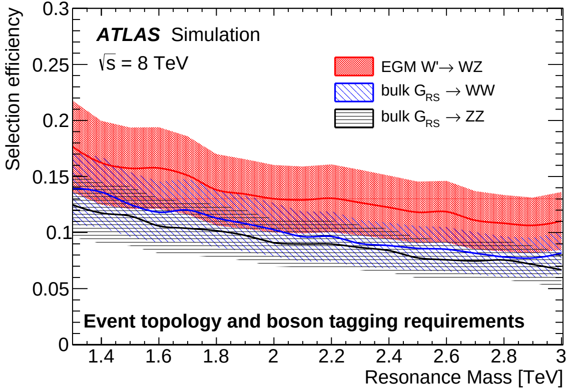
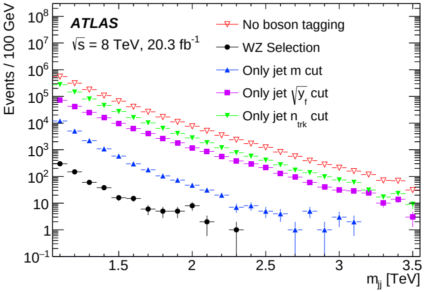
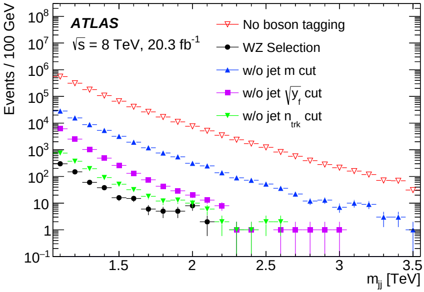
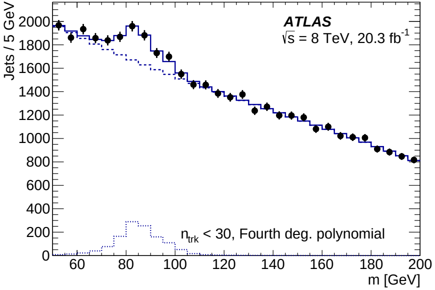


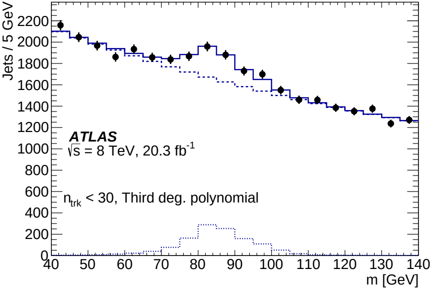
Tagging Criteria - $VV \to qqqq$





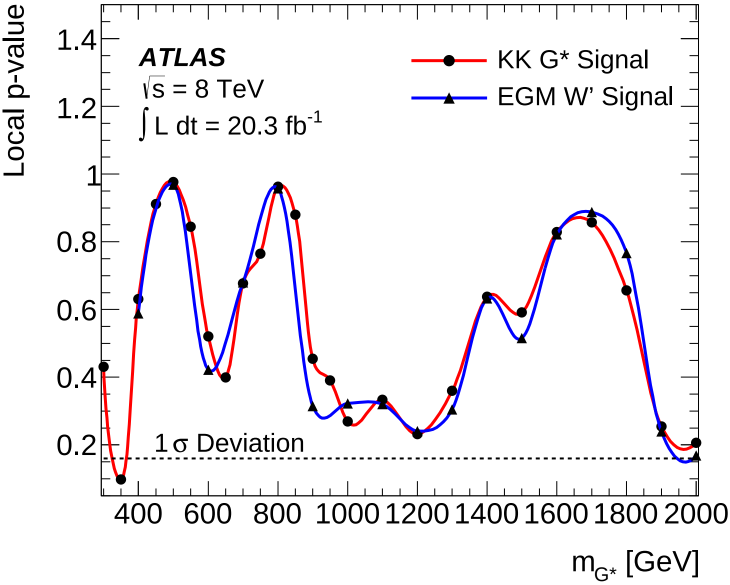
- Left: Comparison of no tagging criterion and only one boson tagging requirement applied to each jet
- Right: The effect of applying all tagging requirements except one is displayed.



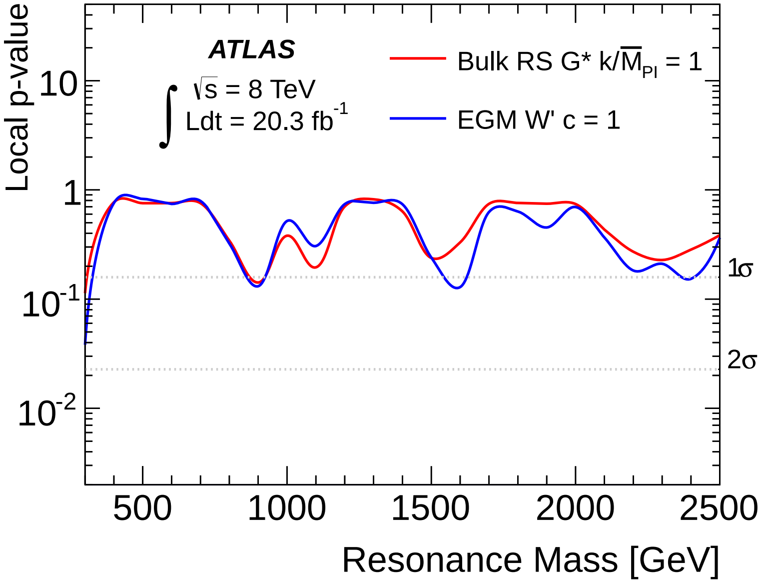


- Plots show the fit to the mass spectrum in data after $n_{trk} < 30$ cut
- Efficiency of track-multiplicity cut measured in V+jets events in data
- V+jets contribution evaluated in data with a fit over the mass range shown, using a polynomial function to describe the bkg and a pair of crystal-ball functions for the W and Z contributions

p-Value - $ZV \to \ell\ell qq$



p-Value - $WV \to \ell\ell qq$



p-Value - $VV \to qqqq$

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