Boosted vector-boson reconstruction and searches for diboson resonances in ATLAS

Chris Malena Delitzsch
Université de Genève

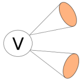
On behalf of the ATLAS Collaboration

Multi-Boson Interactions Workshop - DESY Hamburg

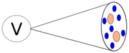
September, 2-4 2015

Motivation

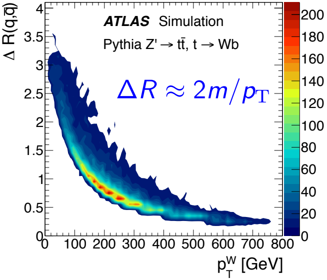
- W-bosons produced in Standard Model processes and decay of exotic particles (technicolor, extra dimensions ...)
- Hadronic decay modes have large branching ratio
- At high p_{T}, signal over bkg ratio generally increases
  $\rightarrow$ the W-boson decay products are boosted
  $\rightarrow$ reconstruction as one single large-radius jet



low-pT



high-pT



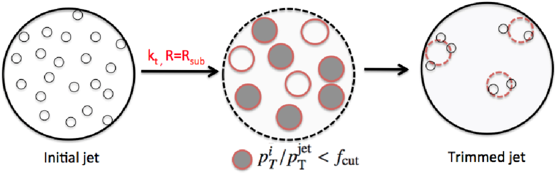
JHEP09 (2013) 076

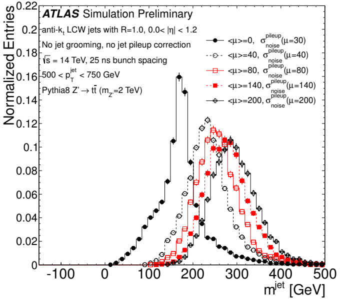
Need to distinguish between large-R jets from boosted bosons and quarks/gluons

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

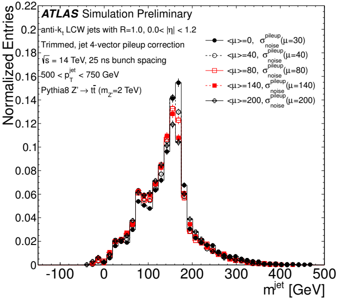
Grooming Techniques - Trimming

- Removes **soft** constituents from pile-up, ISR and multiple parton interaction
- Reclustering of constituents of large-R jet into small-R jets with size R_{sub}
- Remove subjet i if $p_{\mathrm{T}}^{i} < f_{\mathrm{cut}} \times p_{\mathrm{T}}^{\mathrm{jet}}$ arXiv:0912.1342





trimming →

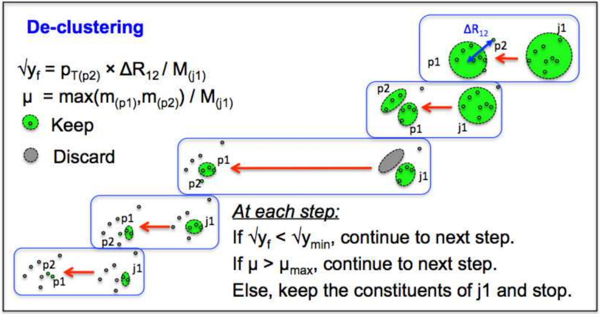


ATLAS public substructure plots

Grooming Techniques - Split-filtering

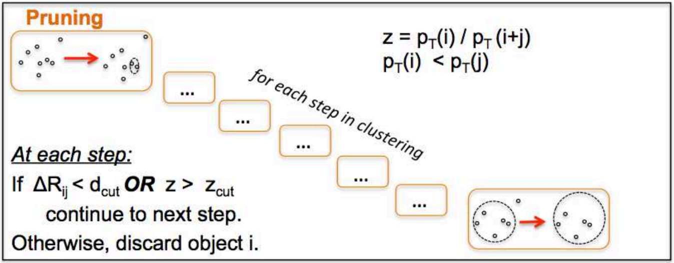
UNIVERSITÉ DE GENÈVE

- Also referred to as BDRS algorithm (arXiv:0802.2470)
- **Splitting** (based on substructure of jet)
  - Large-R jets are de-clustered following the clustering history of the jets
  - Require symmetric splitting $\sqrt{y_\mathrm{f}} = \frac{\min(p_{\mathrm{T}1}, p_{\mathrm{T}2})}{m_{12}} \times \Delta R_{12}$
  - 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)
  - Keep only the three highest p_T subjets



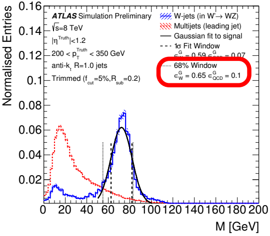
ATLAS

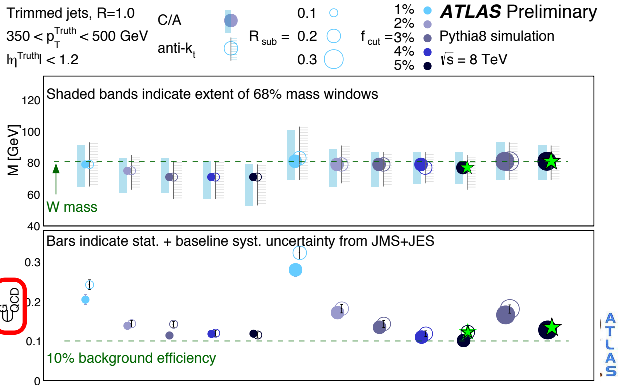
- arXiv:0912.0033
- Constituents of large-R jet are reclustered with either C/A or k_t algorithm
- In each pairwise clustering step, the softer constituent is removed if:
  - wide-angled: $\mathrm{R}_{12} > \mathrm{R}_{\mathrm{cut}} \cdot 2\mathrm{m}/\mathrm{p}_{\mathrm{T}}$ or
  - soft: $\frac{\min(\mathrm{p}_{\mathrm{T},1},\mathrm{p}_{\mathrm{T},2})}{\mathrm{p}_{\mathrm{T},1}+\mathrm{p}_{\mathrm{T},2}} < Z_{cut}$



1. Optimization based on the uncalibrated jet mass
   - Consider different jet algorithm, grooming techniques and configurations (approx. 500 different combinations)
   - Determine smallest mass window containing 68% of the signal
   - Sort algorithms based on **bkg efficiency** ϵ^{G}_{QCD} in **68% signal mass window**

ATL-PERF-2015-03





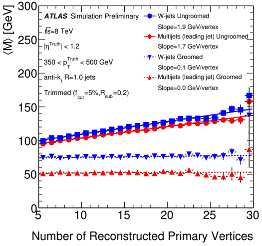
Comprehensive Studies of W-tagging in Run 1 - Overview

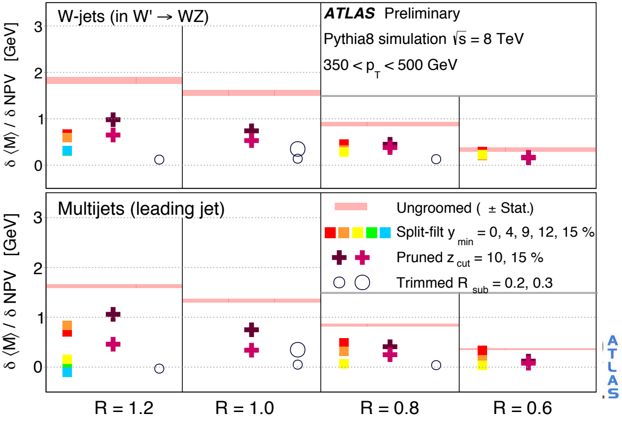
UNIVERSITÉ DE GENÈVE

1 Optimization based on the uncalibrated jet mass

- Consider different jet algorithm, grooming techniques and configurations (approx. 500 different combinations)
- Determine smallest mass window containing 68% of the signal
- Sort algorithms based on **bkg efficiency** ϵ^{G}_{QCD} in **68% signal mass window**
- Remove groomers with large pile-up dependence

ATL-PERF-2015-03





Second Step: Jet Substructure

2. Combination of jet mass and substructure variables
   - Improve bkg. rejection by combining mass window cut with one-sided cut on **tagging variable**
   - Reduce to four different groomers and three tagging variables based on bkg eff. $\epsilon_{QCD}^{G\&T}$ at $\epsilon_{W}^{G\&T} = 50\%$

Considered 22 substructure variables:

- Angularity a_3
- Aplanarity A
- Dipolarity D
- $C_2^{(\beta=1)}$, $C_2^{(\beta=2)}$
- $D_2^{(\beta=1)}$, $D_2^{(\beta=2)}$
- FoxWolfram20 $\mathrm{R}_2^{\mathrm{FW}}$
- PlanarFlow P
- $\sqrt{d_{12}}$
- Sphericity S
- Softdrop
- τ_2, τ_{21}
- τ_2^{wta}, τ_{21}^{wta}
- ThrustMin, ThrustMaj (T_{min}, T_{max})
- Volatility
- $z_{\mathrm{cut},12}$
- μ_{12}
- $\sqrt{y_{12}}$

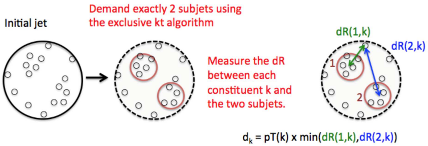
N-subjettiness

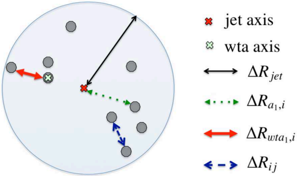
JHEP 03 (2011) 015

- Describes how likely it is that a jet is composed out of N subjets:

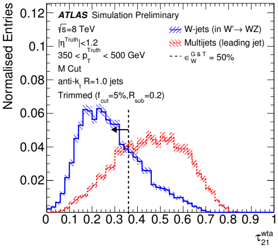
$$\tau_N = \frac{\sum_k p_{\mathrm{T,k}} (\min(\Delta R_{1,k}, R_{2,k}, \ldots, R_{N,k}))^\beta}{\sum_k p_{\mathrm{T}} (R_0)^\beta}$$

- Powerful discrimination using the ratio: τ_2 / τ_1



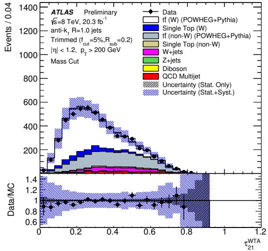


Simulation



ATL-PERF-2015-03

$t\bar{t} \to$ lep+jets events in data



Energy Correlation

Energy Correlation C_2 and D_2 http://arxiv.org/abs/1305.0007

$$C_2^{\beta} = \frac{E_{CF}1(\beta)}{E_{CF}2(\beta)} \times \frac{E_{CF}3(\beta)}{E_{CF}2(\beta)}, \qquad D_2^{\beta} = \frac{E_{CF}^3 1(\beta)}{E_{CF}^3 2(\beta)} \times E_{CF}3(\beta)$$

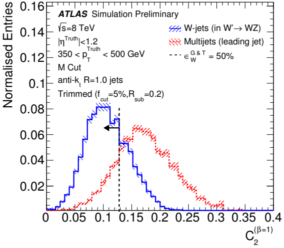
N-point energy correlation function

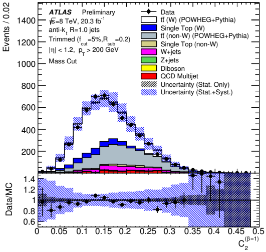
$$E_{CF}1(\beta) = \sum_{i\in J} p_{\mathrm{T}_i}, \qquad E_{CF}2(\beta) = \sum_{i<j\in J} p_{\mathrm{T}_i} p_{\mathrm{T}_j} \left(\Delta R_{ij}\right)^{\beta},$$

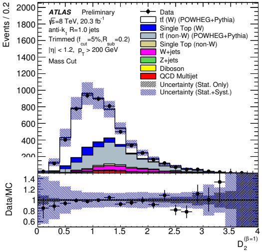
$$E_{CF}3(\beta) = \sum_{i<j<k\in J} p_{\mathrm{T}_i} p_{\mathrm{T}_j} p_{\mathrm{T}_k} \left(\Delta R_{ij} \Delta R_{ik} \Delta R_{jk}\right)^{\beta},$$

ATL-PERF-2015-03

Simulation | $t\bar{t} \to$ **lep+jets events in data**





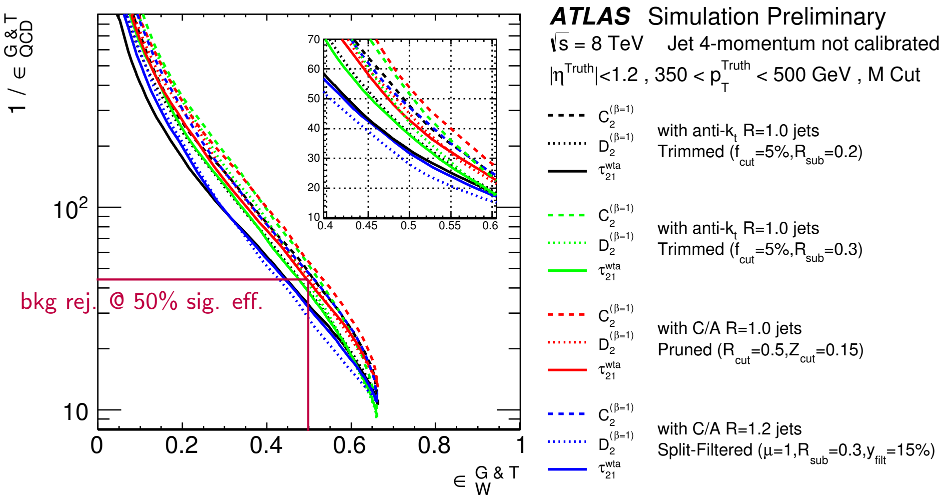


ROC Curves

UNIVERSITÉ DE GENÈVE

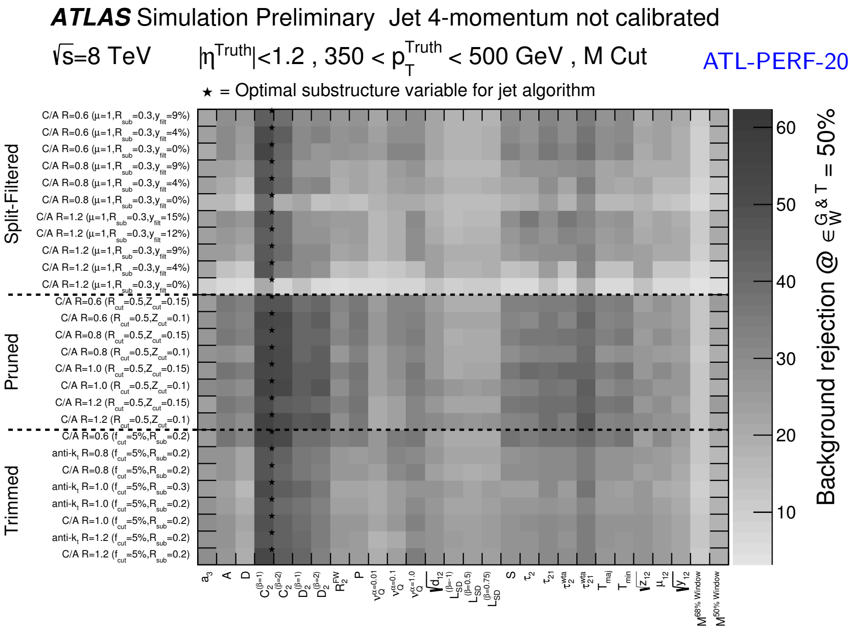
- Scan through substructure distributions and determine signal vs. bkg. efficiency curves
- Determine bkg. rejection at 50% signal efficiency

ATL-PERF-2015-03



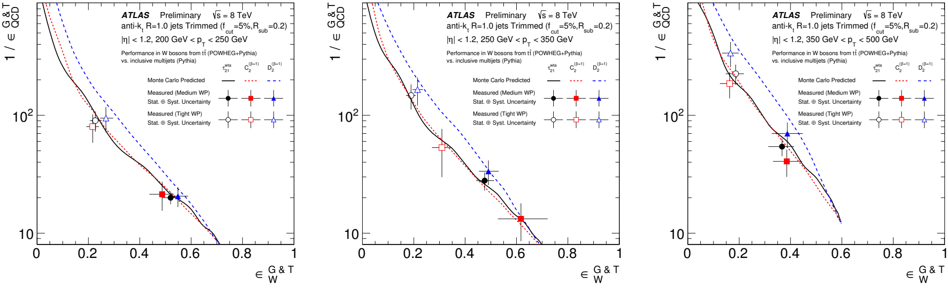
Background Rejection Matrix

UNIVERSITÉ DE GENÈVE



Measurement in Data

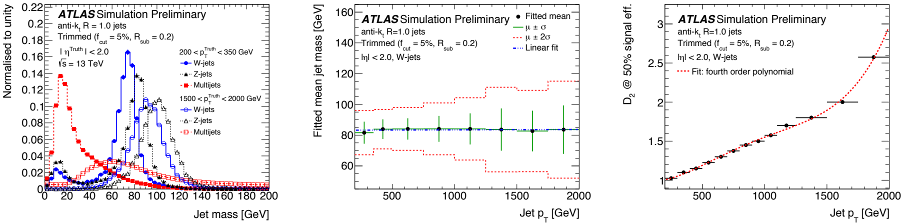
- Based on the pile-up dependence and bkg. rejection anti-k_t $R = 1.0$ trimmed jets with $R_{\mathrm{sub}} = 0.2$ and $f_{\mathrm{cut}} = 5\%$ were chosen for further studies
- **Calibrations** and **systematic uncertainties** (in-situ) were derived
- Two **working points** based on mass + substructure: medium (50%) and tight (25%)
- Signal ($t\bar{t}$ events) and multijet bkg. efficiencies measured in **data**
- Signal efficiency measured using template fits to the jet mass distribution



- Differences between MC and data expected: ATL-PERF-2015-03
  - data measurement from $t\bar{t}$ topology, working points optimized with W' sample
  - different MC generators give different results (Pythia+Powheg vs. MC@NLO)

ATLAS W/Z-tagger for Run 2

- Based on the results obtained in Run-1
- Started with reduced set of grooming algorithms and substructure variables
- **Run 2 tagger**: anti-k_t trimmed jets with $R_{sub} = 0.2$, $f_{cut} = 5\% +$ mass $+ D_2$



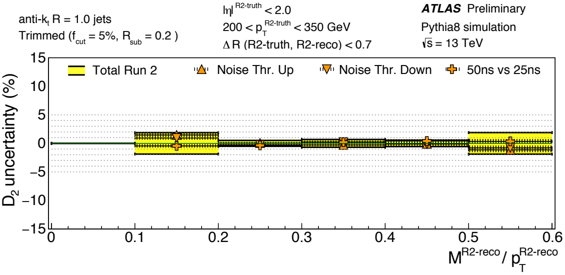
ATL-PHYS-PUB-2015-033

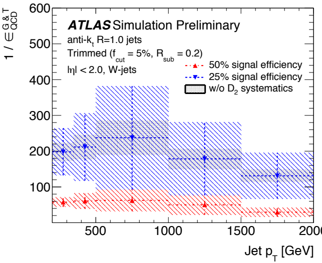
- Strong dependence of jet mass with jet p_T for trimming algorithm
  $\rightarrow$ mass calibration
- Define 50% and 25% signal efficiency working points using smooth parametrizations of the jet mass and D_2
- 15 GeV mass window around mean W/Z-mass and p_T dependent D_2 cut

ATLAS W/Z-tagger for Run 2 - Systematics

UNIVERSITÉ DE GENÈVE

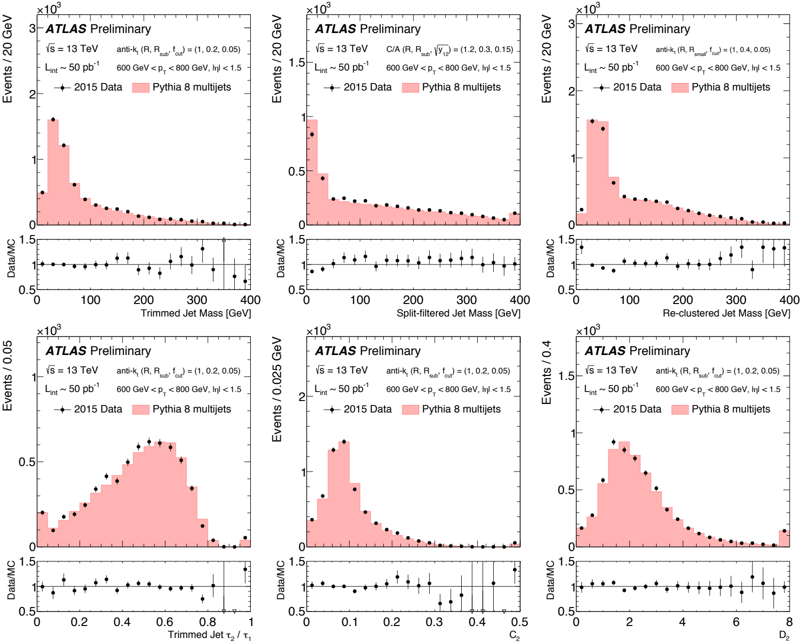
- Derived systematic uncertainties for JES, JMS and D_2 scale
- (Jet mass and energy are calibrated)
- Baseline uncertainties are taken from Run-1: track-jet double-ratio method
- Additional uncertainties are added based on our best knowledge of the detector conditions for Run 2
    - Noise threshold variations
    - 50 vs. 25 ns bunch spacing
- Above 1 TeV, lack of jets for Run 1 $\rightarrow$ different physics lists tested





ATL-PHYS-PUB-2015-033

Fist Look at the Data - ATLAS-CONF-2015-035

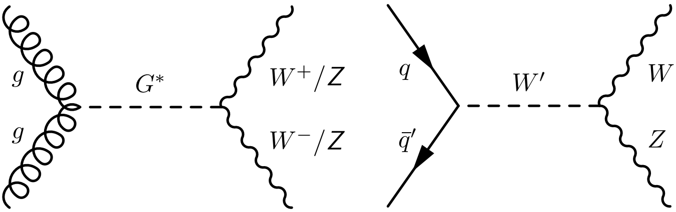


Using diboson resonance searches as an example for boosted boson tagging

Overview

UNIVERSITÉ DE GENÈVE

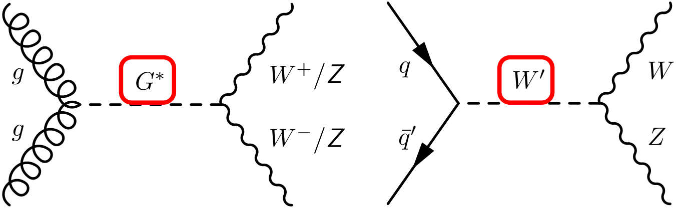
- Extensions of the Standard Model predict the existence of new particles decaying into vector-boson pairs



Overview

UNIVERSITÉ DE GENÈVE

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

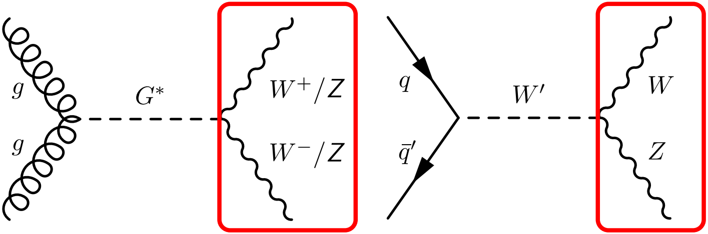


1. What can these extensions of the Standard Model be? (Selected examples)
   - Grand Unified Theories
   - Warped extra dimensions
   - Technicolor

ATLAS

Overview

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

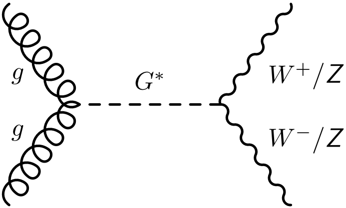


1. What can these extensions of the Standard Model be? (Selected examples)
   - Grand Unified Theories
   - Warped extra dimensions
   - Technicolor
2. How can we detect these new resonances?
   - For high-mass resonances ($m_X > 1000$ GeV), the W/Z-bosons are highly boosted → need special reconstruction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

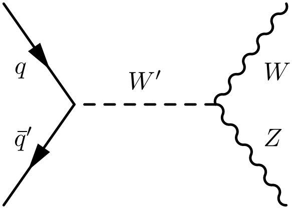
Benchmark Models for Run 1 Analysis

Two **benchmark** models were chosen 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* $\to WW$) $\approx$ 20%
     BR(G* $\to ZZ$) $\approx$ 10%



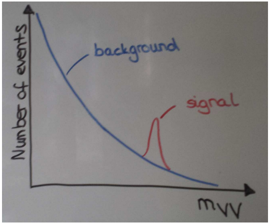
2. **Extended gauge model (EGM)**
   - Sequential Standard Model (modified WZ couplings)
   - Spin-1 gauge boson (W')
   - $q\bar{q}$ production
   - Decays into WZ
   - $m_{W'} = 1$ TeV:
     BR(W' $\to WZ$) $\approx$ 1.3%



Diboson Analysis in a Nutshell

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**
  - Analysis: VV $\rightarrow \ell\nu qq$, $\ell\ell qq$
- **Full-hadronic final state:**
  - Large branching ratio:

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

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

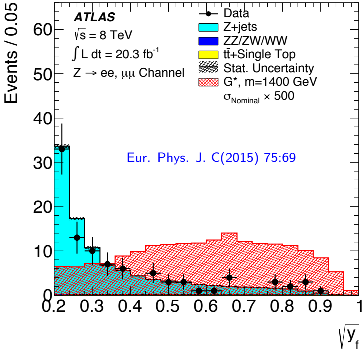
  - No MET
  - large dijet background
- **Full-leptonic final state**
  - Clean signature and low background
  - Small branching ratio
  - Analysis: VV $\rightarrow \ell\nu\ell\ell$

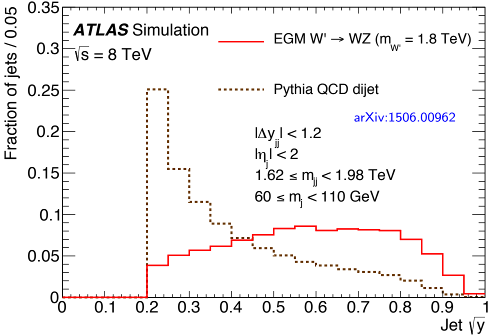
Boson Tagging in ATLAS Run 1 Diboson Analyses

UNIVERSITÉ DE GENÈVE

*used for all boosted diboson resonance searches in ATLAS, semi-leptonic and all-hadronic

1. **Jet reconstruction:**
   C/A $R = 1.2$ jets groomed with the BDRS algorithm, $\sqrt{y_{\rm filt}} = 0.2$
2. **Boson tagging:**
   - the large-R jet mass m_J (mass window around boson)
   - $y_{\rm f}$ as tagging variable: $\sqrt{y_{\rm f}} = \frac{\min(p_{\rm T1}, p_{\rm T2})}{m_{12}} \times \Delta R_{12}$, $\sqrt{y_{\rm f}} > 0.45$
     QCD dijet events have unbalanced subjet momenta compared to signal jets due to soft gluon radiation



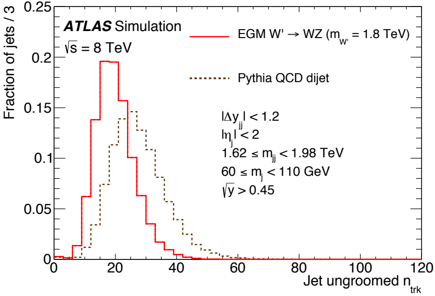


$VV \to qqqq$ - Overview

UNIVERSITÉ DE GENÈVE

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



arXiv:1506.00962

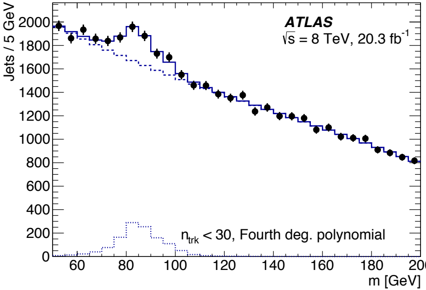
Event Selection

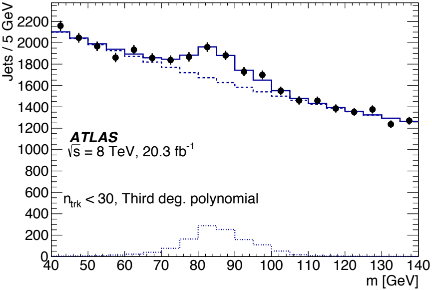
- Compared to semileptonic analysis only boosted regime is considered
- Reject events with electron or muon candidate or $E_{\mathrm{T}}^{\mathrm{miss}} > 350$ GeV (orthogonal to other diboson resonance searches)
- Overlap between WW, WZ, ZZ selection due to chosen mass window
- Rapidity difference: $|y_1 - y_2| < 1.2$
- 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

n_{trk}

UNIVERSITÉ DE GENÈVE

arXiv:1506.00962





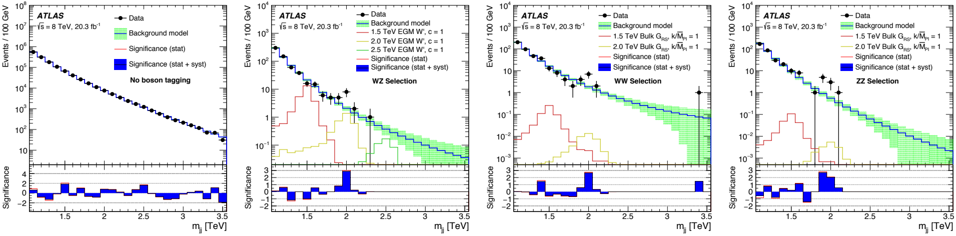
- Plots show the fit to the mass spectrum in data after $n_{trk} < 30$ cut
- Efficiency of track-multiplicity cut measured in V+jets events in data
- V+jets contribution evaluated in data with a fit over the mass range shown, using a polynomial function to describe the bkg and a pair of crystal-ball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

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

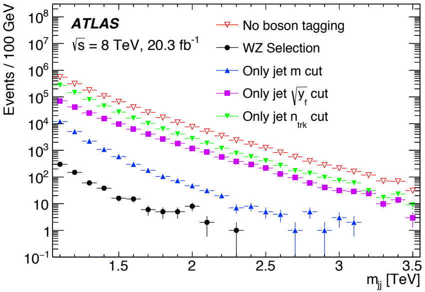


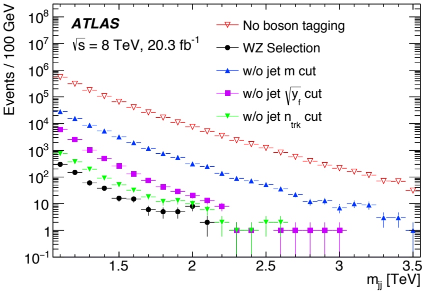
arXiv:1506.00962

- 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: $WZ : 2.5\sigma$

Shaping of Background?

arXiv:1506.00962

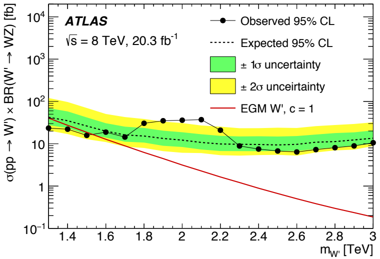


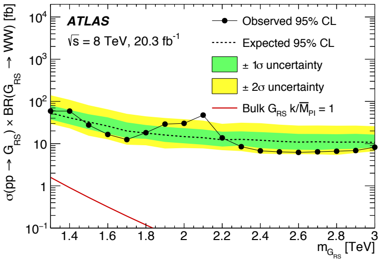


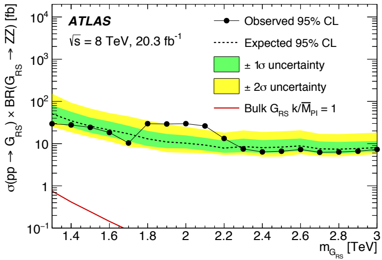
- Left: Comparison of no tagging criterion and only one boson tagging requirement applied to each jet
- Right: The effect of applying all tagging requirements except one is displayed.

$VV \rightarrow qqqq$ - 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 arXiv:1506.00962







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

Event selection

Eur. Phys. J. C (2015) 75:69

$Z \to \ell\ell$

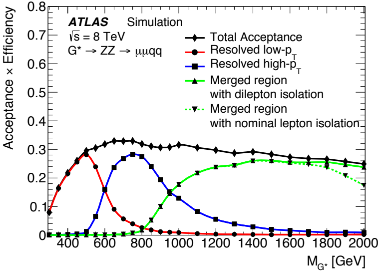
- 2 isolated leptons with same flavor, $m_{\ell\ell}$ compatible with Z-boson mass
- Improved isolation requirement for boosted dilepton system ($p_{\mathrm{T}}^{Z} > 800$ GeV)

$V \to qq$

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

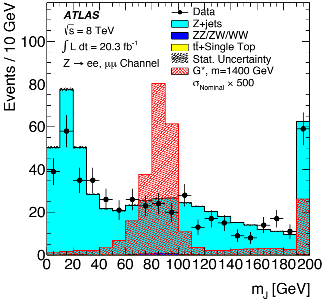
} two small-R jets

- Merged-region (MR) → 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, $\sqrt{y_{\mathrm{f}}} > 0.45$



$m_{\ell\ell J}$ Spectrum

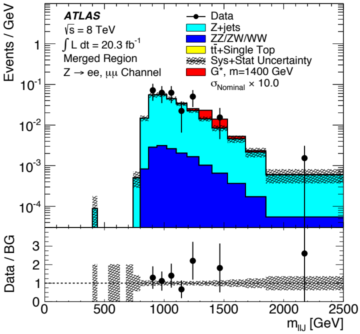
UNIVERSITÉ DE GENÈVE

Dominating background: Z+jets

- Data driven normalization and shape correction for $m_{\ell\ell J}$ in control regions
- Control regions: $m_J < 70$ GeV or $m_J > 110$ GeV

Dominating systematic uncertainties:

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

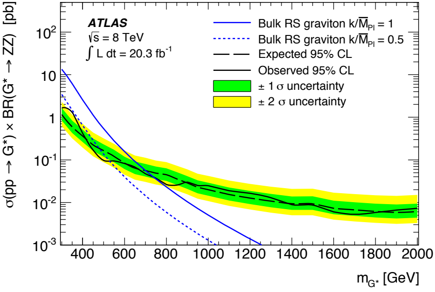


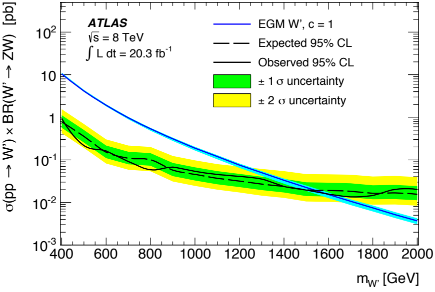
Eur. Phys. J. C (2015) 75:69

- No significant deviations from the Standard Model are observed
- → Set 95% CL upper limits on the cross-section × BR

$ZV \to \ell\ell qq$ - Limits

- Exclude M(G*) $<$ 740 GeV and M(W') $<$ 1590 GeV
- The MR is the most powerful search region for signal masses above 850 GeV





Eur. Phys. J. C (2015) 75:69

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

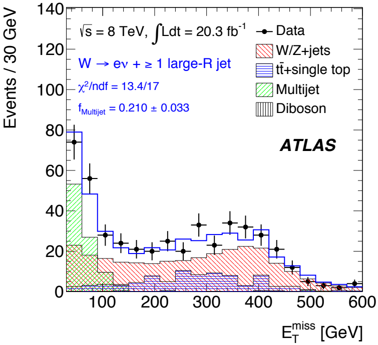
UNIVERSITÉ DE GENÈVE

Event selection

Eur. Phys. J. C (2015) 75:209

$W \to \ell\nu$

- 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



$V \to qq$

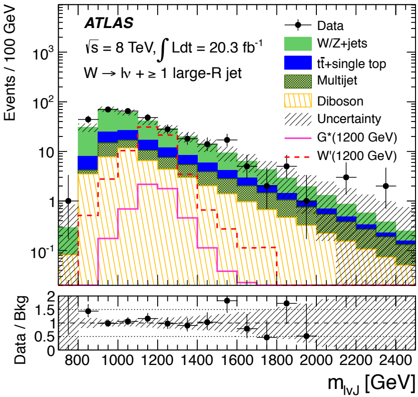
- Similar to $ZV \to \ell\ell qq$ selection: three regions
- Events are assigned exclusively to one region only
- Merged region:
  - $p_{\mathrm{T}}^{\ell\nu} > 400$ GeV
  - $65 < m_J < 105$ GeV, $\sqrt{y_{\mathrm{f}}} > 0.45$
  - $\Delta\Phi(J, E_{\mathrm{T}}^{\mathrm{miss}}) > 1$

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

$m_{\ell\nu J}$ Spectrum

UNIVERSITÉ DE GENÈVE



Eur. Phys. J. C (2015) 75:209

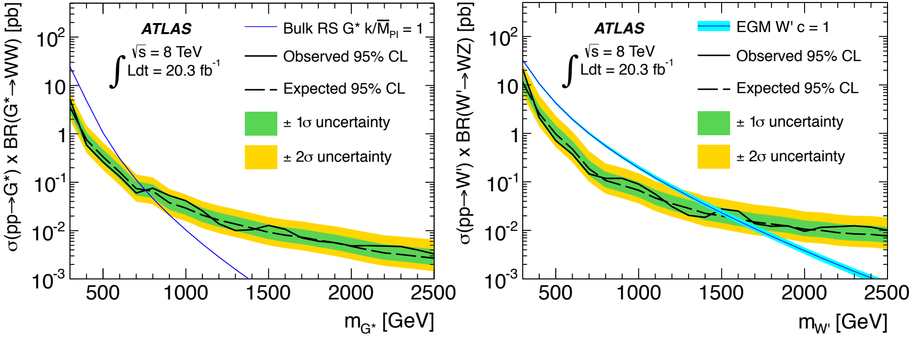
Sample	LRR	HRR	MR
$W/Z+$jets	104800 ± 1600	415 ± 10	180 ± 20
$t\bar{t}+$single top	37700 ± 1600	271 ± 13	42 ± 7
Multijet	13500 ± 500	84 ± 9	29.3 ± 2.9
Diboson	5500 ± 270	96 ± 6	43 ± 7
Total	161500 ± 2300	870 ± 40	295 ± 22
Data	157837	801	323
G^* signal	7000 ± 500	36 ± 6	5.5 ± 2.3
W' signal	6800 ± 600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

UNIVERSITÉ DE GENÈVE

- 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



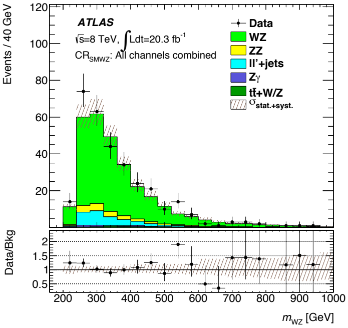
Eur. Phys. J. C (2015) 75:209

Event selection

Phys. Lett. B (2014) 737

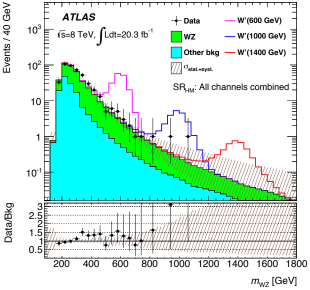
- Three charged leptons with $p_T > 25$ GeV
- $E_T^{miss} > 25$ GeV
- $|m_{\ell^+\ell^-} - m_Z| < 20$ GeV
- $\Delta y(W, Z) < 1.5$

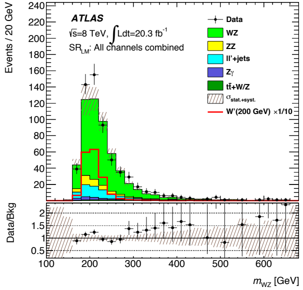
- Two regions for high/low W' masses:
  - $\Delta\Phi(\ell, E_T^{miss}) < 1.5$ (ℓ: lepton from W-decay)
  - $\Delta\Phi(\ell, E_T^{miss}) > 1.5$



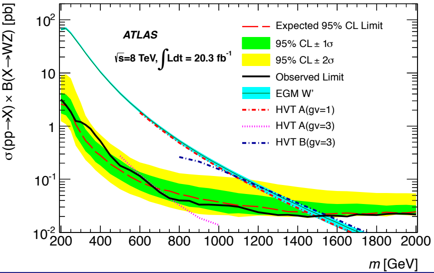
Background estimation:

- Dominant bkg: WZ, ZZ, $t\bar{t} + W/Z$
- WZ control region to check modelling of the bkg in MC (reversed Δy cut and removed $\Delta\Phi$ criteria)
- Mis-reconstruction rate of leptons is determined with data driven methods





- No deviation from SM prediction observed in invariant mass spectrum
- Exclude M(W') $<$ 1520 GeV and in addition limits are set on HVT models



Phys. Lett. B (2014) 737

Conclusion

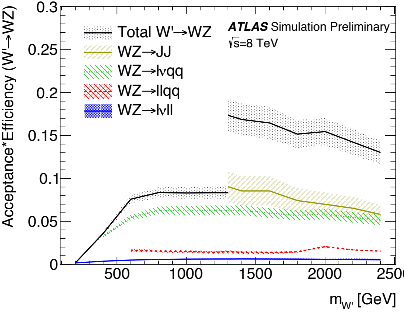
UNIVERSITÉ DE GENÈVE

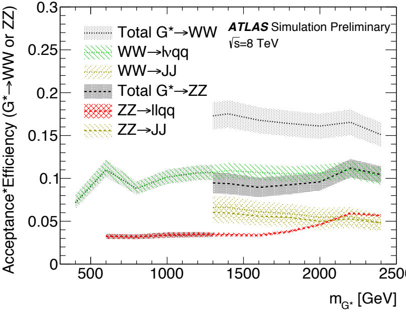
- W/Z-boson tagging studied for Run 1 and for early Run 2 analysis using 13 TeV simulation
- Different grooming and tagging techniques were compared and best performing one chosen
- The diboson final state provides a direct key to new physics beyond the SM
- Sensitivity in high mass region can be increased using tagging techniques
- Several searches have been performed with the full 2012 dataset in the semi-leptonic and full-hadronic decay channel using boosted techniques
- Combination of Run 1 diboson resonance searches has been just published
- Small excess around 2 TeV observed in the $VV \rightarrow JJ$ analysis

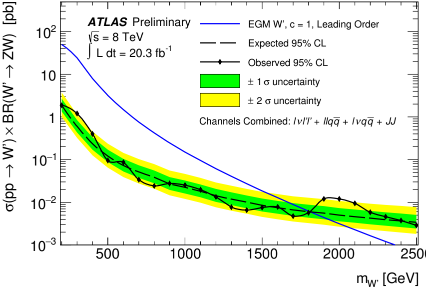
Stay tuned for $\sqrt{s} = 13$ TeV data!!!

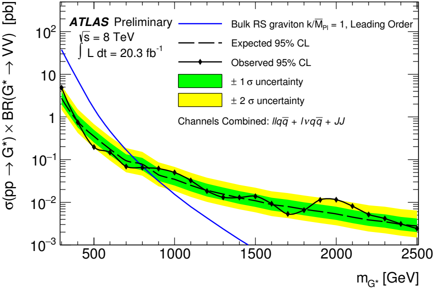
- Approx. 5 fb^{-1} of 13 TeV data will tell us if this is a statistical fluctuation or something "real"

Combination - ATLAS-CONF-2015-045









Backup

Useful Links

UNIVERSITÉ DE GENÈVE

Boosted boson tagging:

- Identification of boosted, hadronically decaying W bosons and comparison with ATLAS data taken at $\sqrt{s} = 8$ TeV, to be published soon, ATL-PERF-2015-03
- Identification of Boosted, Hadronically-Decaying W and Z Bosons in $\sqrt{s} = 13$ TeV Monte Carlo Simulations for ATLAS ATL-PHYS-PUB-2015-033
- Identifying the type of a Hadronically Decaying W or Z Boson with the ATLAS Detector, to be published soon, ATL-PERF-2015-02

Diboson Analysis with boosted vector-boson tagging

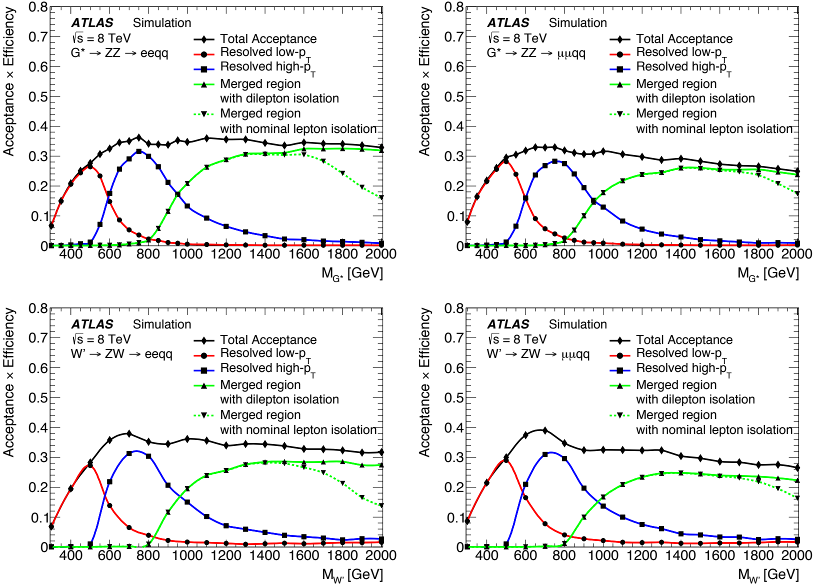
1. $ZW/ZZ \to \ell\ell q\bar{q}$ Eur. Phys. J. C (2015) 75:69
2. $WZ/WW \to \ell\nu q\bar{q}$ Eur. Phys. J. C (2015) 75:209
3. $WW/WZ/ZZ \to qqqq$ (submitted to JHEP) arXiv:1506.00962
4. $WZ \to \ell\nu\ell\ell$ Phys. Lett. B (2014) 737

Further diboson resonance searches in ATLAS

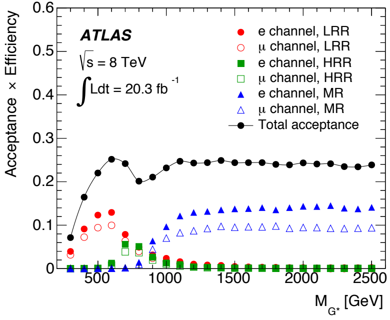
- $WH/ZH \to \ell\nu bb, \ell\ell bb, \nu\nu bb$ Eur. Phys. J. C (2015) 75: 263 (no substructure information used in Run-1)
- $HH \to bbbb$ (submitted to EPJC) arXiv:1506.00285 resolved and boosted regime using trimmed jets
- $HH \to \gamma\gamma b\bar{b}$ Phys. Rev. Lett. 144, 081802

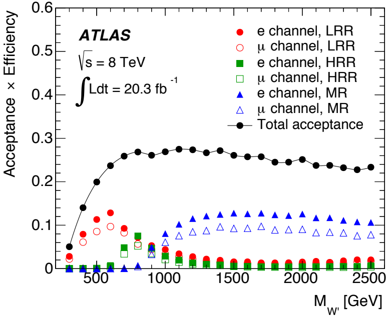
Acceptance - $ZV \rightarrow \ell\ell qq$ - Eur. Phys. J. C (2015) 75:69

UNIVERSITÉ DE GENÈVE

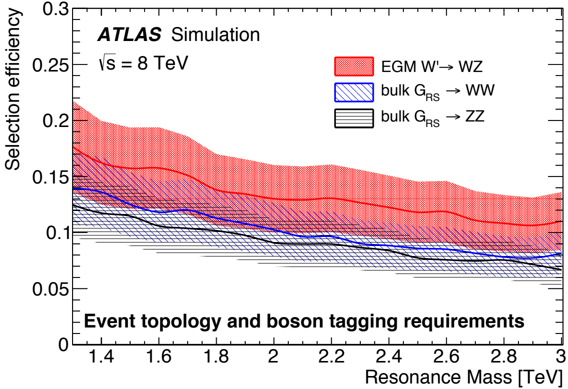


UNIVERSITÉ DE GENÈVE



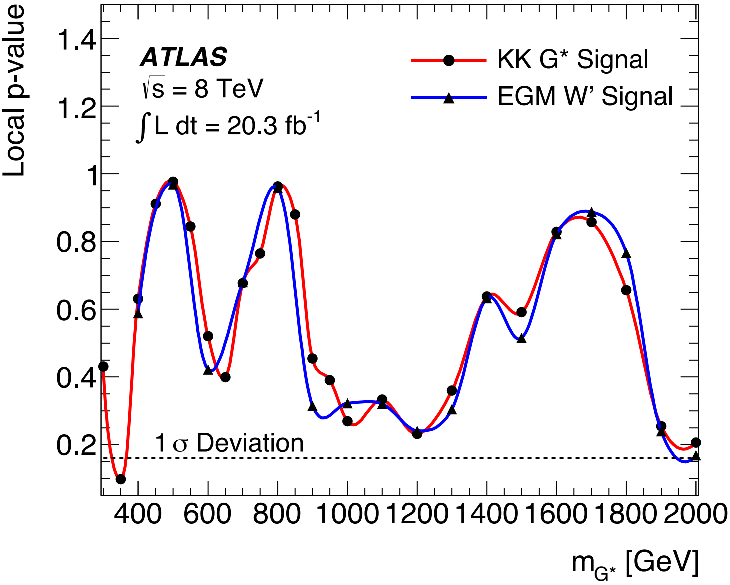


Selection Efficiency - $VV \to qqqq$ - arXiv:1506.00962



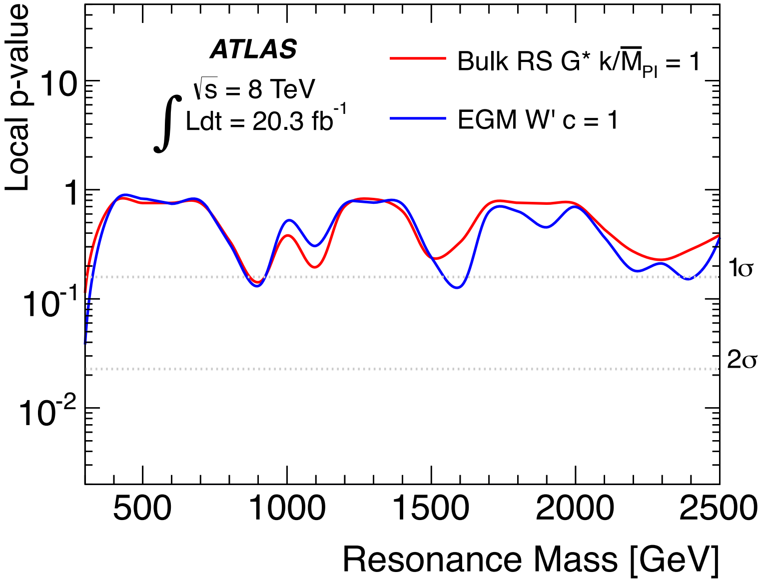
p-Value - $ZV \to \ell\ell qq$ - Eur. Phys. J. C (2015) 75:69

UNIVERSITÉ DE GENÈVE



p-Value - $WV \to \ell\nu qq$ - Eur. Phys. J. C (2015) 75:209

UNIVERSITÉ DE GENÈVE



p-Value - $VV \rightarrow qqqq$ - arXiv:1506.00962

UNIVERSITÉ DE GENÈVE