Search For High Mass Resonances With Boson-Tagged Jets At ATLAS In Run-2

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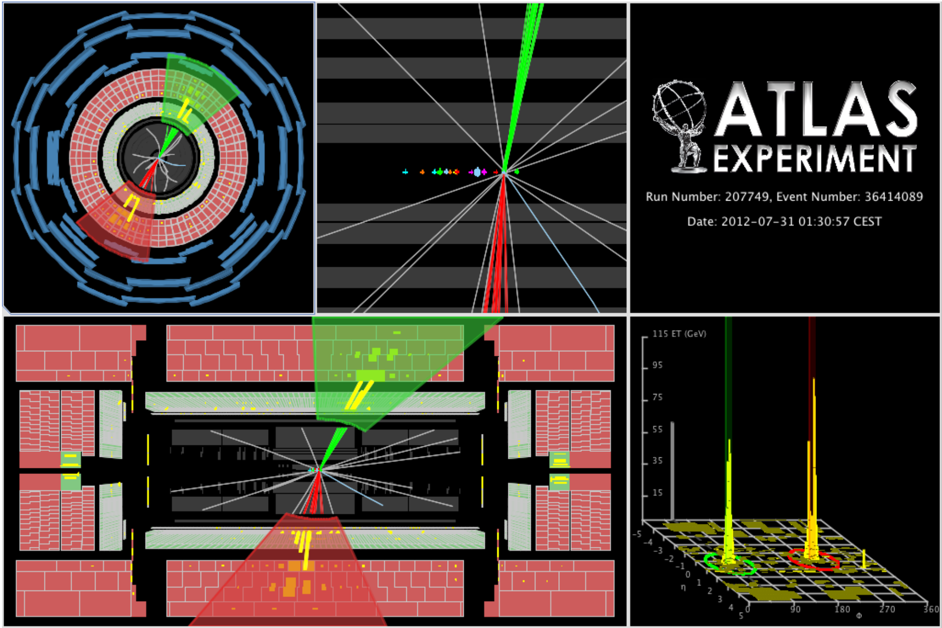
Introduction


ATLAS
EXPERIMENT
Run Number: 207749, Event Number: 36414089
Date: 2012-07-31 01:30:57 CEST
115 ET (GeV)
95
75
55
35
15
-5
-4
-3
-2
-1
0
η
1
2
3
4
5
0
90
180
270
360
φ

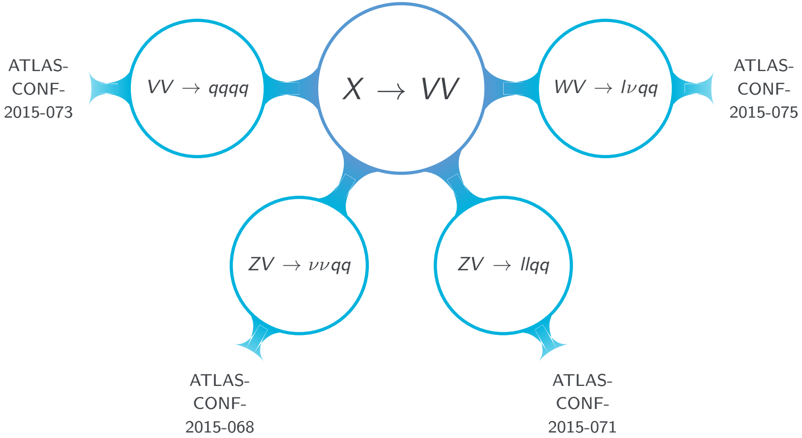
Introduction

- Many extensions to the standard model predict new particles which couple to the electroweak bosons.
- For a high-mass resonance the child bosons are highly boosted so their decay products are highly collimated.
- For hadronic decays the branching ratios are large but so is the background!
  - 67% of W and 70% of Z decays are hadronic.
- To see anything at all we need at least on of the bosons to decay hadronically.
  - We use jet substructure techniques to tag large-radius jets consistent with hadronically decaying bosons and reject the QCD background.

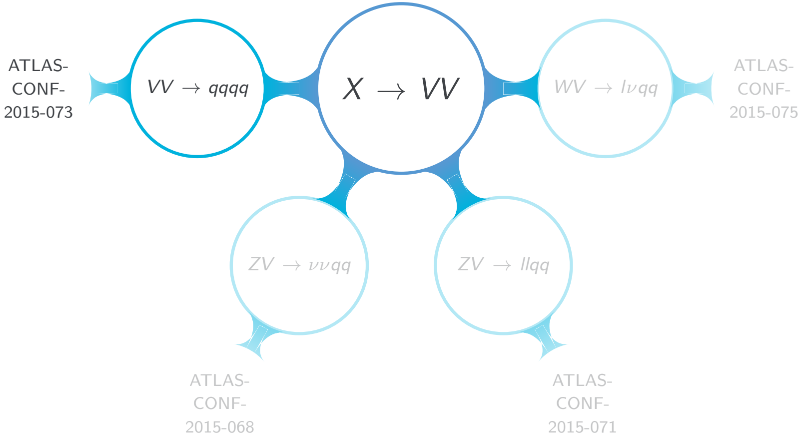
Signature: Highly collimated, high-p_T, boson decays produced back-to-back in the detector

Strategy: Search for a bump in a smoothly falling invariant mass distribution distribution of

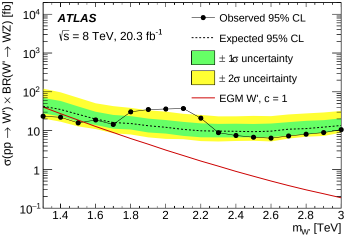
Decay Channels

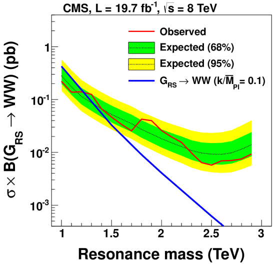


Decay Channels



Dibosons in Run-1

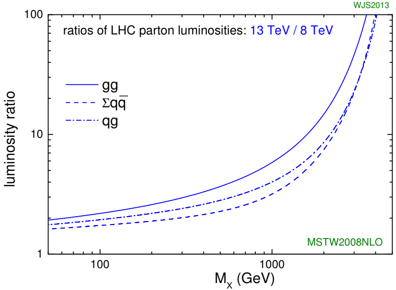


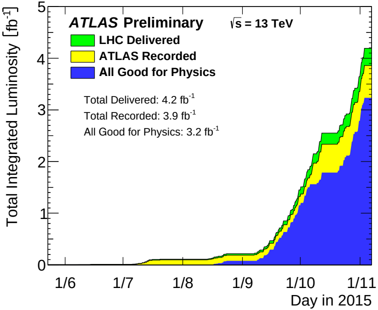


- ATLAS search excluded Extended Gauge Model (EGM) W' with $1.3 < m_{W'} < 1.5$ TeV (JHEP12(2015)055).
- No limit was set on Randall-Sundrum (RS) Graviton model.
- Largest discrepancy was seen in the WZ at 2 TeV - global significance was 2.5σ.
- Smaller discrepancy also seen in the same place at CMS!
- Search was an obvious candidate to be followed up quickly in run-2.

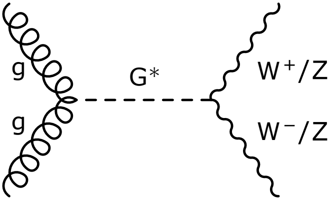
What's New?

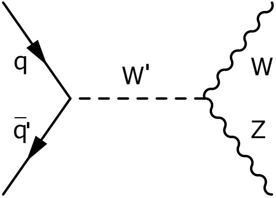
- $3.2fb^{-1}$ of data.
  - Down from $20fb^{-1}$ but...
- 13TeV!
  - Factor of 3-10 growth for 2 TeV signal, depending on signal model.
  - Already more sensitive than run-1 to *gg* production modes.
- New signal model - EGM replaced with HVT.
- Improved techniques for identifying EW bosons.





Theoretical Models





Bulk Randall-Sundrum Model

- A (4+1)-d universe with the SM particles localized near one 3-brane and the graviton localized around a second.
- Signature is a tower of Spin-2 gravitons with TeV scale masses.
- Main production mode is gg.

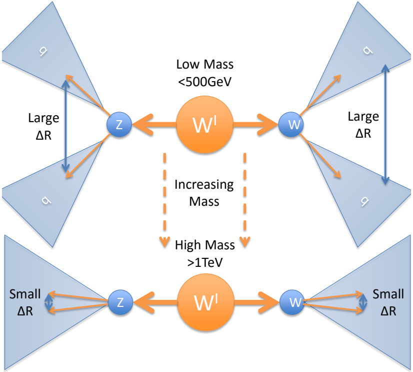
Heavy Vector Triplet

- Adds a new set of mass-degenerate Spin-1 gauge bosons $W'^{\pm}$,Z'.
- Parameterized couplings to describe a large class of models
- Main production mode is $q\bar{q}$.

Boson Tagging

Boosted Vector Bosons

- Reconstruct both decay products of a boosted W or Z as a single large-R jet.
- Use a combination of jet 'grooming' algorithms and substructure information to identify jets which are consistent with a hadronically decaying W or Z - a boson tag.
- NB. All jets used for this analysis are clustered with the anti-k_T algorithm with radius $R = 1.0$.



[Image: A. Martyniuk]

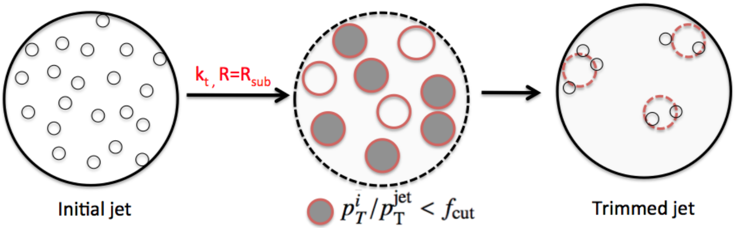
Large-R Jet Trimming

The large-R jets are groomed using the trimming algorithm to remove contributions from pileup whilst leaving as much of the hard decay process as possible.

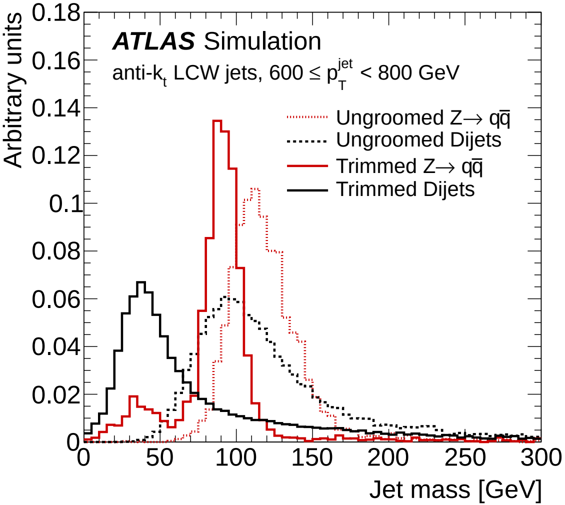
The trimming algorithm takes two parameters, R_{small} and f_{cut}. The algorithm is:

(1) Re-cluster consituents into several small jets using the k_t algorithm with radius R_{small}.

(2) Discard any small-jet where $\frac{p_T^{\text{small-jet}}}{p_T^{\text{fatjet}}} < f_{\text{cut}}$.



Extracting a Mass Peak

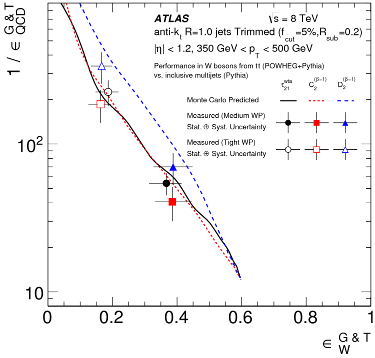


This analysis used $R_{\text{small}} = 0.2$, $f_{\text{cut}} = 5\%$.

Boson Tagging

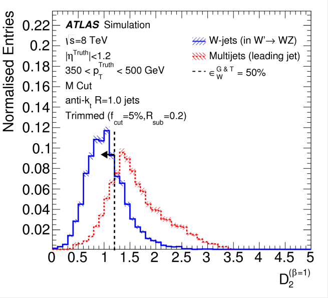
There are two requirements for the standard ATLAS boson tag:

- $|m_J - m_V| < 15\text{GeV}$
- p_T-dependent cut on $D_2^{\beta=1}$



D_2^β

D_2 is a ratio of energy correlation functions and contains information about the angular spread of energy within a jet

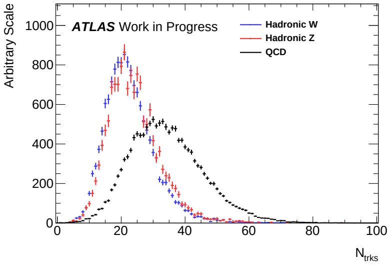


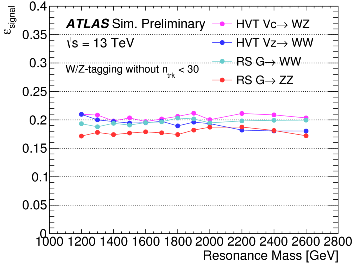
Taking the "medium" working point and requiring two bosons, this tagging gives a signal acceptance of 25% with a background acceptance of 0.0002%.

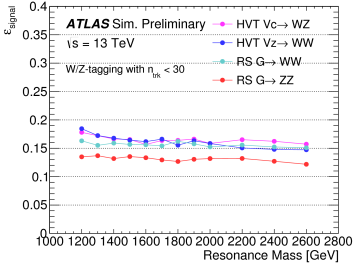
Boson Tagging - Ntrk Cut

For the fully-hadronic search the sensitivity was found to increase by applying a further boson identification requirement.

Required $N_{trk} < 30$ - where N_{trk} is the number of tracks with $p_T > 0.5$ GeV associated with the original ungroomed jet.



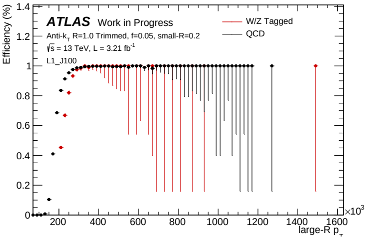


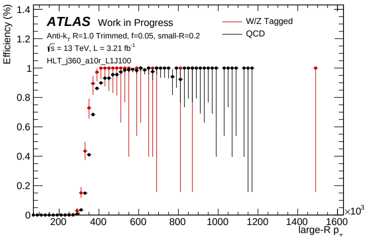


Event Selection & Background Fit

Trigger Efficiency

- Trigger is one of the main limitations on the analysis.
- Inefficiencies would lead to a distorted m_{JJ} spectrum so lower limit of the analysis is set by trigger plateau.
- The analysis uses a *reclustering* fatjet trigger with E_T threshold of 360 GeV
  - Seeded by 100 GeV L1 jet trigger.
  - Input objects to the jet algorithm are calibrated anti-k_t4 jets.
  - Slow turn-on for QCD jets but much faster for boson-like jets.
- Trigger plateau was measured in data to be 400 GeV $\rightarrow$ the analyis requires $m_{JJ} > 1.0$ TeV





Event Selection

Trigger Selection:

- Pass 360 GeV large-R jet trigger
- Leading jet $p_T > 450$ GeV
- $1.0 < m_{JJ} < 2.5$TeV[1]

Topology:

- Two large-R jets with $p_T > 200$ GeV, $m_J > 50$ GeV and $|\eta| < 2.0$
- No leptons (e or μ) with $p_T > 25$ GeV and $|\eta| < 2.5$
- $E_T^{\text{miss}} < 250$ GeV

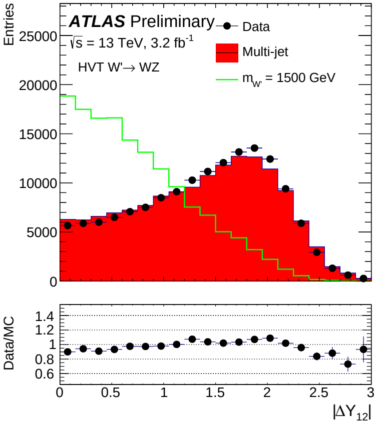
Our primary background is SM multijet. How do we reduce this?

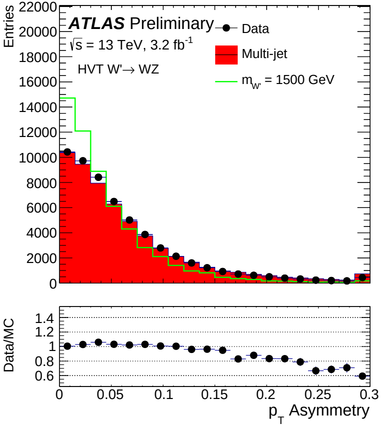
Event Shape & Boson Tag:

- $|\Delta y_{J_1,J_2}| < 1.2$
- $A_{p_T} = \frac{p_{T,J_1} - p_{T,J_2}}{p_{T,J_1} + p_{T,J_2}} < 0.15$
- Two leading jets pass boson tagging criteria.
- Events are divided into (overlapping) WW, ZZ and WZ signal regions

[1]Upper limit is to keep analysis within the region-of-validity for the large-R jet mass calibration

Event Variables



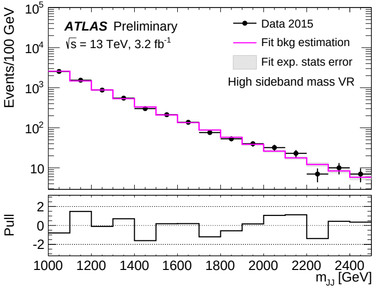


Background Modelling

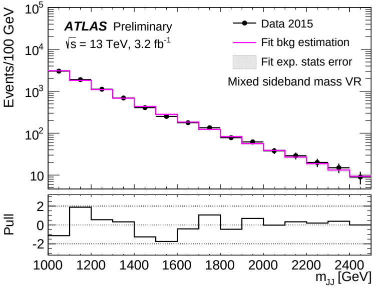
Dijet background can be modelled as smoothly falling distribution in m_{JJ}

$$\frac{dn}{dx} = p_1(1-x)^{p_2+\varepsilon p_3} x^{p_3}$$

Which was fit to data in each signal region in the range $1.0 < m_{JJ} < 2.5$ TeV using a maximum-likelihood fit. The fitting method was checked in mass sidebands.



$110 < m_J < 140$ GeV

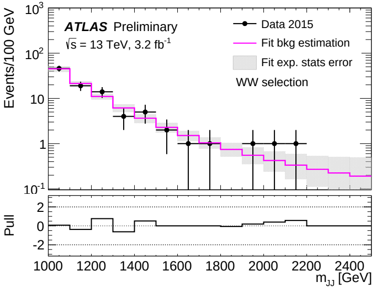


$110 < m_{J_1} < 140\text{GeV}, 50 < m_{J_2} < 60\text{GeV}$

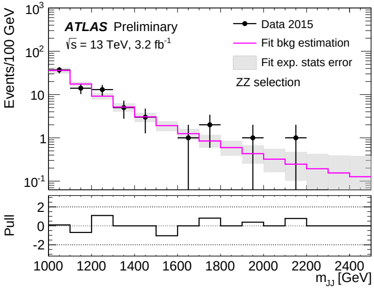
Results

Results

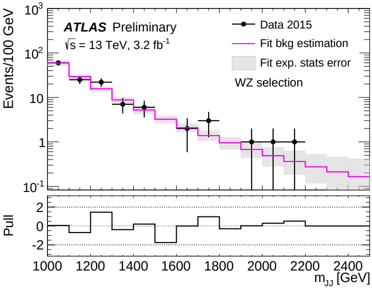
WW



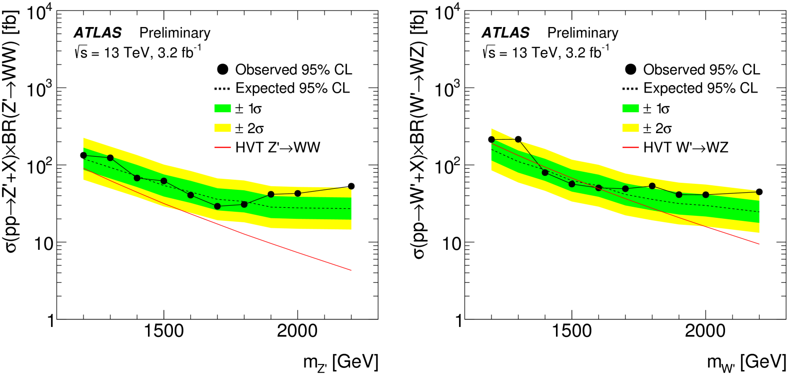
ZZ



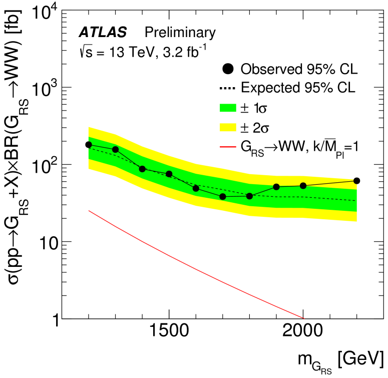
WZ

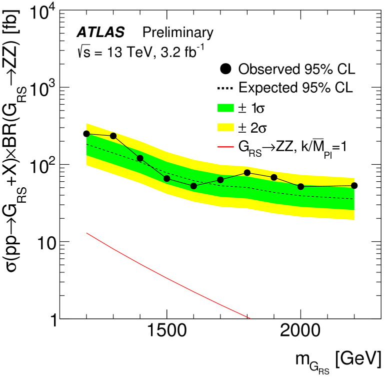


Heavy Vector Triplet Model



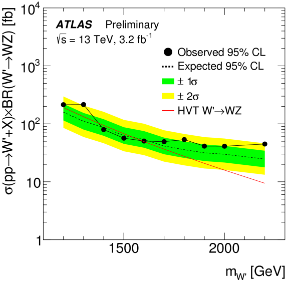
Randall-Sundrum Graviton Model



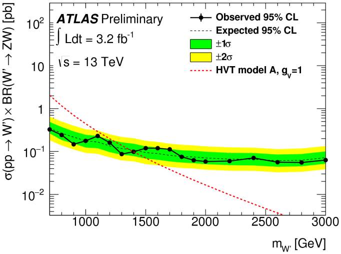


Cross-channel Limits

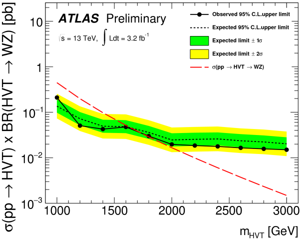
$WZ \to qqqq$



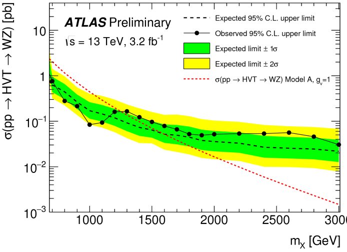
$WZ \to llqq$



$WZ \to \nu\nu qq$



$WZ \to l\nu qq$



Conclusion

Conclusion

- ATLAS placed updated limits on heavy masses decaying to vector bosons.
- Exclude $W' \to WZ$ between $1.38 < m_{W'} < 1.6$ TeV
- Discrepancy from run-1 is not seen in any channel
- Channel is competitive with the semi-leptonic channels but still needs more data
- Combination is on it's way!

Questions?

Backup

Run-1 Boson Tagging

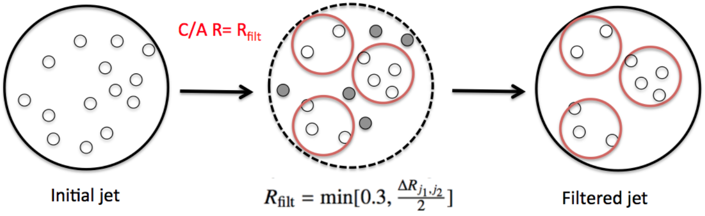
	Run-1	Run-2
Algorithm	Cambridge-Aachen $R = 1.2$	Anti-k_t $R = 1.0$
Grooming	Mass-drop Filter	Trimming
Mass	$\lvert m_J - m_V \rvert < 13$ GeV	$\lvert m_J - m_V \rvert < 15$ GeV
Substructure	$\sqrt{y} < 0.45$	p_T-dependent $D_2^{\beta=1}$
Tracks	$N_{\text{trks}} < 30$	$N_{\text{trks}} < 30$

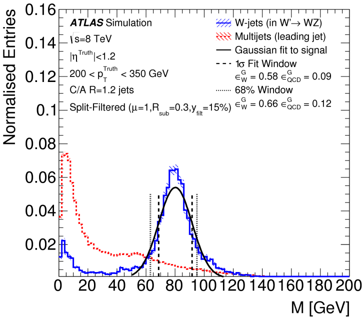
Mass-drop Algorithm

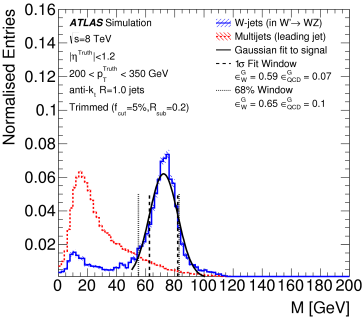
Momentum-balance criteria : $\sqrt{y} = \min(p_{T,J_1}, p_{T,J_2}) \frac{\Delta R_{J_1,J_2}}{m_0} \geq \sqrt{y_f}$
Mass-drop criteria : $\mu = m_i/m_0 \geq mu_f$
For run-1 - $\sqrt{y_f} = 0.2, \mu_f = 1$

- Examine pairwise combinations performed by clustering algorithm in reverse order
- If the pair satisfies the momentum-balance condition stop, else discard the lowest mass subjet of the pair and iterate on the other
- Once stopped, recluster the remaining subjet pair with a small-R (0.3) C/A algorithm and cluster the three highest-p_T jets to form the filtered jet.

Run-1 Boson Tagging (II)







D_2^β

D_2 [1] is a jet substructure variable optimised to discriminate between jets initiated by 1 or 2 hard (LO) objects. Unlike similar variables (such as n-subjettiness) It does not require any reclustering into smaller subjets, instead it uses a ratio of a jet's energy correlation functions (ECFs) which describe the angular distribution of energy within a jet.

$$D_2^\beta = \frac{\mathrm{ECF}(3,\beta) \times \mathrm{ECF}(1,\beta)^3}{\mathrm{ECF}(2,\beta)^3}$$

$$\mathrm{ECF}(N,\beta) = \sum_{i_1<i_2<\ldots<i_N \in J} \left(\prod_{a=1}^{N} p_{T,i_a} \right) \left(\prod_{b=1}^{N-1} \prod_{c=b+1}^{N} \Delta R_{i_b i_c} \right)^\beta$$

For a jet containing N hard subjet, $\mathrm{ECF}(\beta, N+1) \ll \mathrm{ECF}(\beta, N)$ so for a two-prong jet (such as those from a vector boson) D_2 will be small.

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[1] See *Power Counting to Better Jet Observables, A. Larkoski et. al., 10.1007/JHEP12(2014)009*

Statistical Intepretation

Signal templates were created from MC in steps of 0.1 (0.2) TeV from 1.2-2.0 (2.0-2.2) TeV. A background + signal fit was performed at each mass point.

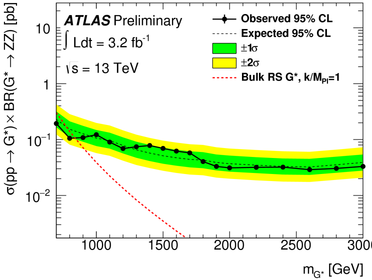
To set limits a test statistic was used:

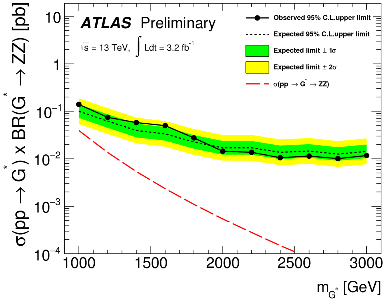
$$\Lambda \equiv -2\ln\mathcal{L} = -2\sum_i\left(\ln\frac{\lambda_i^{n_i}}{n_i!} - \lambda_i\right) + \sum_j \mathcal{C}(j)$$

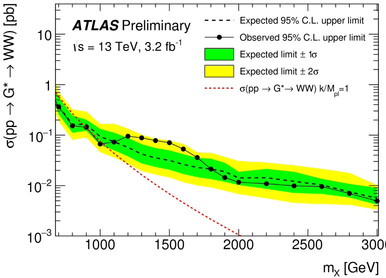
Where n_i is the number of events in the i^{th} m_{JJ} bin, λ_i is the expectation in that bin and each $\mathcal{C}(j)$ term is the χ^2 constraint on nuisance parameter j

Upper limits on $\sigma \times BR$ is set using a modified-frequentist CL_s prescription where the probability of observing a particular Λ or larger is calculated using a one-sided profile-likelihood.

Graviton Results for Other Channels







CMS Results

The combined-channel CMS analysis has also been made public. (CMS-PAS-EXO-15-002)