A search for diboson resonances at ATLAS using boson-tagged jets

Using the jet substructure thresher on the QCD haystack

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Introduction

- Today I will present searches for narrow **diboson resonances** using **jet-substructure** performed on the full 8 TeV and 13 TeV ATLAS datasets

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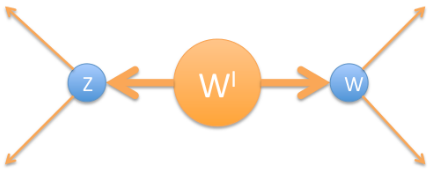
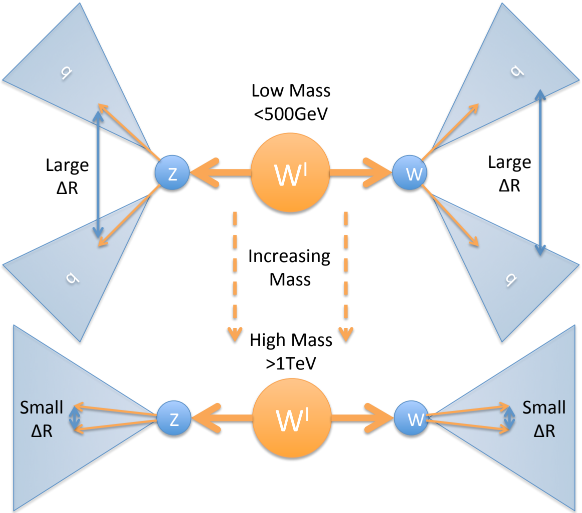
- **Diboson resonances** appear in many extensions to the standard model
- The following analyses concentrate on two **benchmark** models
  - Extended gauge sector models, HVT ($W' \to WZ$)
  - Extra dimensions models ($G_{RS} \to WW/ZZ$)
- **Low branching ratios** hinder the leptonic searches at the highest masses
- Obviously, a **fully hadronic** search has access to these lost events
- The problem, is controlling the **enormous QCD background** that the leptonic searches were avoiding



$W \Downarrow$	Diboson branching ratios		
$l\nu$ (33%)	23%	7%	3%
qq (67%)	47%	13%	7%
$Z \Rightarrow$	qq (70%)	$\nu\nu$ (20%)	ll (10%)

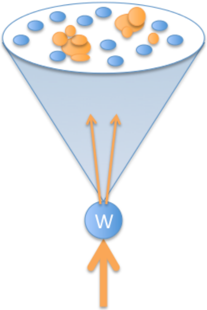
High mass resonances→Boosted Bosons!



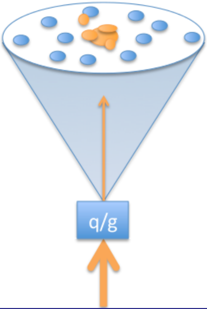
- We are interested in particles of mass $\geq \mathcal{O}(1\text{ TeV})$
- Vector bosons have mass $\mathcal{O}(0.1\text{ TeV})$
- Therefore the decays of the form, $X \rightarrow VV$ with large m_X, lead to vector bosons with **very high** p_{T}
- Boosted decay products become more **collimated**
- **Rule of thumb** for angular separation of decay products:
- $\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2} \approx \frac{2m}{p_{\mathrm{T}}}$
- Use **di-jet mass** spectrum formed from **boson-tagged** fat-jets to search for **resonance**

Bosonic vs QCD Jets

- **Bosonic** jets
  - Form **two** narrow regions with high energy density corresponding to each quark
  - Each quark carries a roughly **equal fraction** of the boson momentum in the lab frame
  - Jet mass originates from the **boson mass**, i.e. peaked

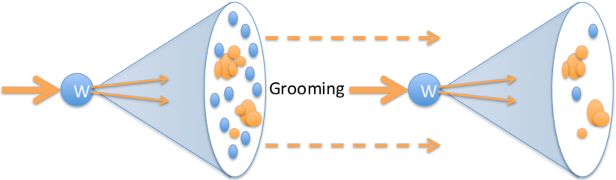


- **QCD** jets
  - **Narrow** region with high energy density corresponding to a single quark/gluon
  - Majority of the jet momentum is **concentrated** in this single region
  - Jet mass originates from the **spread** of the energy deposition by the single parton/any final state radiation, i.e. essentially random

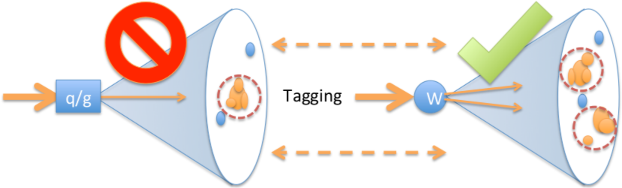


Fat Jet→Grooming→Tagging

1. **Reconstruct** decay as **fat-jet**
   - Use **large-R** parameter jet to collect radiation from the original decay
2. **Groom** the jet
   - Signal: **Remove** unwanted jet constituents not from the signal, e.g. pile-up
   - Background: **Preserve** the background characteristics

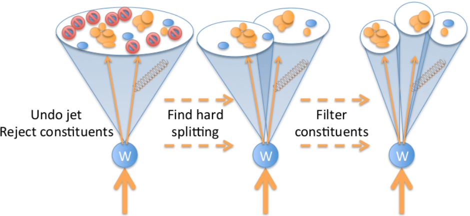


3. **Tag** as boson jet
   - Use **differences** between signal and background jet characteristics to **reject** background jets



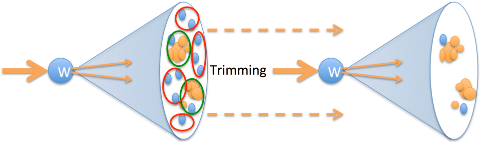
Fat Jet→Grooming→Tagging: Run-1/2

1. Run-1 analysis uses Cambridge-Aarchen 1.2 jets
   - Construction based on jet component separation in detector
2. Split-filtering algorithm used to groom and soft-tag the jet
   - Deconstruct the jet looking for hard splittings
   - Discards soft contributions



3. Cuts on jet mass, split-filter variables and associated tracks to tag jet
   - Distributions offer good discrimination of jets originating from q/g vs W/Z

1. Run-1 analysis uses anti-k_t 1.0 jets
   - Construction based on jet component separation and p_T^{-2}
2. Trim the jet
   - Remove $r = 0.2$ sub-jets that contain $\lesssim 5\%$ of the jet p_T



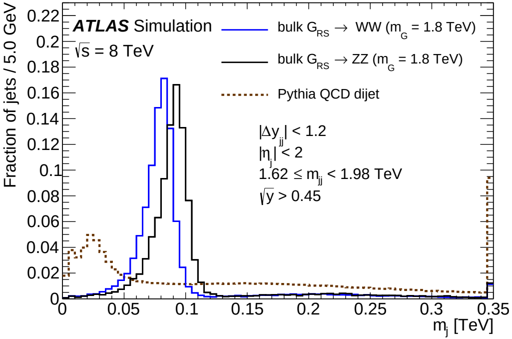
3. Tag using mass and $D_2^{\beta=1}$
   - Energy correlations used to separate 2-pronged jets

$$D_2^{\beta} = \frac{e_3^{\beta}}{(e_2^{\beta})^3}$$

Tools: Jet mass – Run-1 & 2

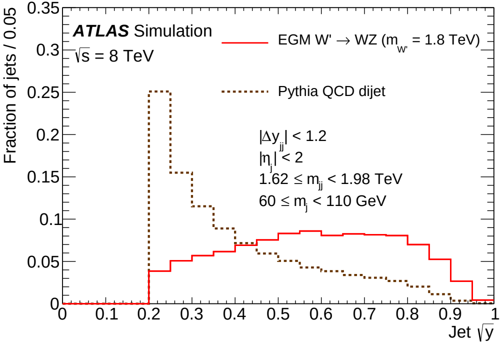
2. **Filtered jet mass**
    - Separates peaked boson mass from falling QCD spectrum

- Apply ± 13 GeV **window cuts** around boson mass from MC simulation peak ($m_W = 82.4$, $m_Z = 92.8$)
- For example, in the *WZ* cut;
    - Leading mass jet $79.8 \text{ GeV} < m_{\text{jet}} < 105.8 \text{ GeV}$
    - Subleading mass jet $69.4 \text{ GeV} < m_{\text{jet}} < 95.4 \text{ GeV}$
- Very **powerful** cut!
    - $\epsilon_{\text{signal}} \approx 80\%$
    - $\epsilon_{\text{background}} \approx 10 - 15\%$
- Cuts optimised using a **data CR**
    - Dijet formed from two tagged/un-tagged regions
- N.B. **Windows overlap!!!**



3 **Subjet momentum balance**
- Boson jets **symmetric**, QCD **unbalanced**

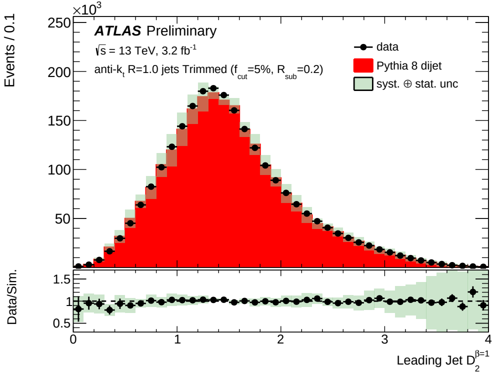
- **Soft gluon** radiation leads to asymmetric splittings
- $W/Z \rightarrow q\bar{q}$ decays tend to share momentum more **equally** between decay products
- Apply a more stringent $\sqrt{y} \geq 0.45$ cut on the subjet momentum balance
- Another **powerful** cut!
  - $\epsilon_{\mathrm{signal}} \approx 70\%$
  - $\epsilon_{\mathrm{background}} \approx 30\%$
- Cuts optimised using **MC**, using a wide mass window, 60 GeV $< m_{\mathrm{jet}} <$ 110 GeV



Tools: $D_2^{\beta 1}$ – Run-2

3. **Subjet momentum balance**
   - Boson jets **lower**, QCD **higher**

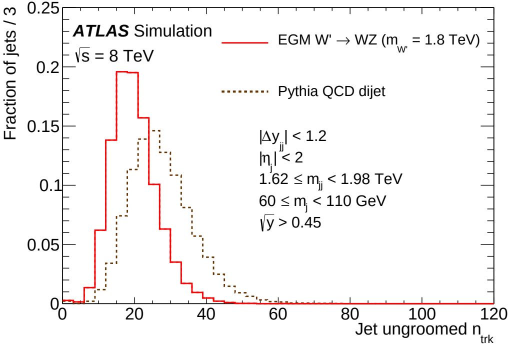
- **Soft gluon** radiation leads to asymmetric splittings
- **Bosonic jets** have more two-pronged structure
- Apply a p_T dependent cut to remove backgrounds
- **Robust** against pile-up
- Another **powerful** cut!
  - $\epsilon_{\rm signal} \approx 50\%$ (Combined with mass window)
  - p_T dependent QCD rejection factor 40-70
- Cuts optimised using **MC**
- Plans to check performance in data CRs



Tools: Ghost matched jets – Run-1 & 2

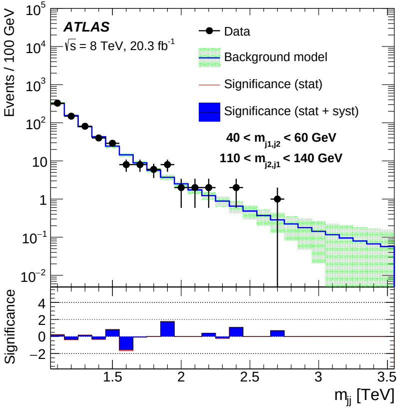
4. **Number of tracks** ghost matched to the unfiltered jet
   - More hadronic activity in QCD jets

- Emission of **hard gluon** dominates after mass/tagger cuts
- Expect increased **hadronic** activity from gluon
- Use the number of **ghost associated** ungroomed tracks, n_{trk}, as a proxy for hadronic activity, [arXiv:0802.1188]
- Apply $n_{\mathrm{trk}} \leq 30$ cut
- Efficiency after mass/tagger
  - $\epsilon_{\mathrm{signal}} = 83 \pm 7\%$
  - $\epsilon_{\mathrm{background}} \approx 65\%$
- Very **hard** to model in MC
- Cuts optimised using V+jets enriched **data CR**
- Efficiency **calibrated** in this CR



Modelling the Background – Run-1 & 2

- After trying to **kill** the background we now arrive at the point of **modelling** it
- **MC statistics** needed to properly model the high m_{JJ} tail are **prohibitively** large



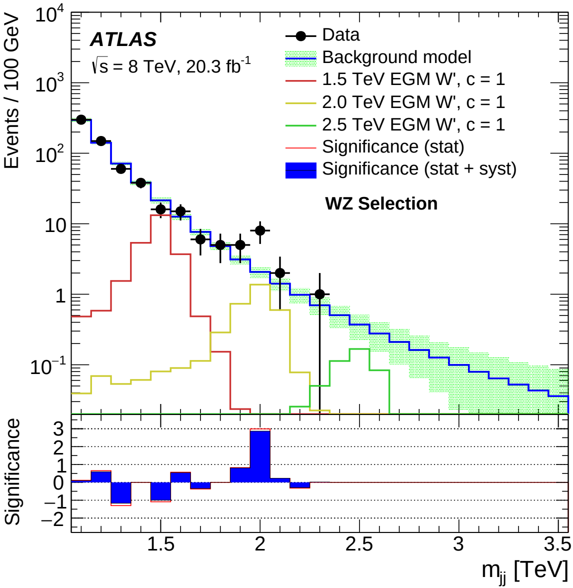
Sample	χ^2/nDOF	Probability
PYTHIA dijet events	24.6/22	0.31
HERWIG++ dijet events	15.9/22	0.82
Data with 110 $< m_{j1} \leq$ 140 GeV and 40 $< m_{j2} \leq$ 60 GeV	12.1/11	0.79
Data with 40 $< m_j \leq$ 60 GeV for both jets	19.8/13	0.56
Data with 110 $< m_j \leq$ 140 GeV for both jets	5.0/6	0.91

- Assume a **steeply** and **smoothly falling** distribution models the background
- Any resonance should be **narrow**, thus only affect a few bins
- Use a **parametric function** to model the background from the data

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

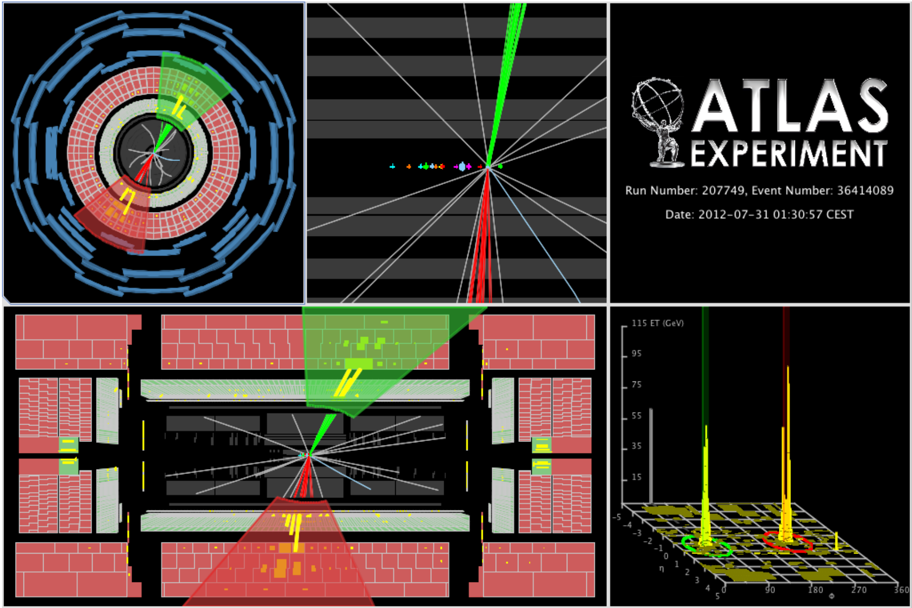
- Error taken from errors on **functional parameters**
- Fit tested on,
  - Raw data
  - PYTHIA/HERWIG MC
  - Mass **sideband** data CRs
- Alternate fit functions give **similar** results

$X \to WZ$ selection – Run-1

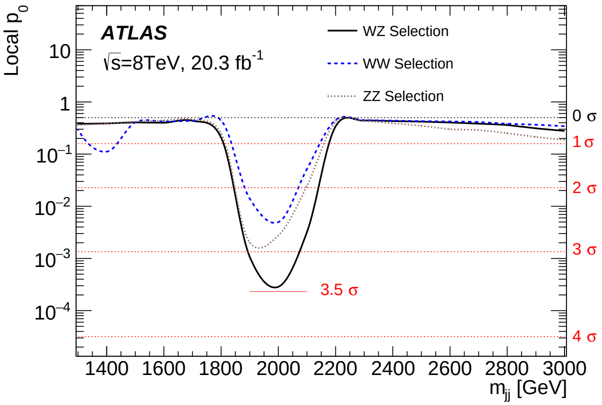


- Full **WZ** selection applied to the data
  - Z mass window applied to **leading** mass jet
  - W mass window applied to **sub-leading** mass jet
- **Good agreement** seen with steeply, smoothly falling background model in the low/high mass regions
- **Deviation** from the background observed at around 2 TeV
- **Benchmark** extended gauge model W' signal MC shown for **comparison** purposes

What do these events look like? Dramatic!



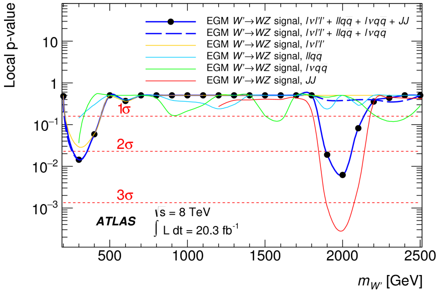
Observed p_0 value – Run-1

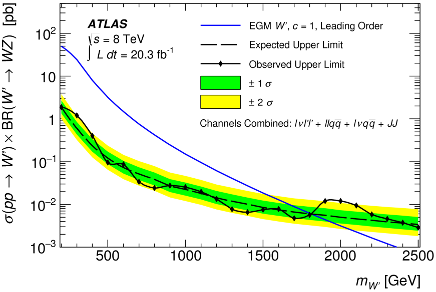


- Therefore, no **statistically significant deviation** from the background has been observed

- A **discrepancy** was seen with respect to the expected background distribution
- Once suitably confident it is not an error, its significance should be **quantified**
- In the *WZ* channel:
- **Local** $p_0 = 3.4\sigma$
- **Global** $p_0 = 2.5\sigma$
  - Global σ takes into account the **look elsewhere effect**
  - LEE includes **weighted contribution** from *WW*/*ZZ* channels due to the overlap

Are we alone? ATLAS combination

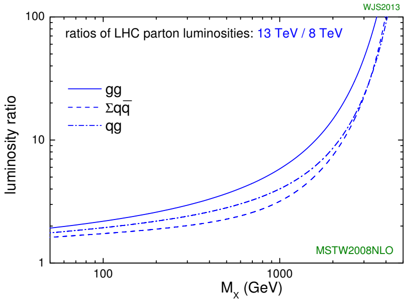




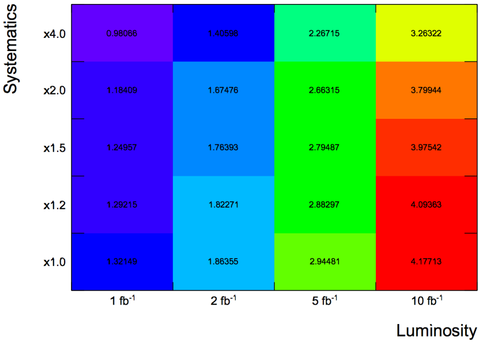
- ATLAS diboson combination [arXiv:1512.05099] (in journal yesterday!)
- In the full combination discrepancy is reduced to a 2.5σ local excess
- Limits increased to 1.81TeV in the W' search channels
- Fully hadronic channel in (significant) tension with the leptonic channels
  - Pointing to statistical fluctuation in fully hadronic channel?
  - Run-2 will sort this out!

How much data is needed?

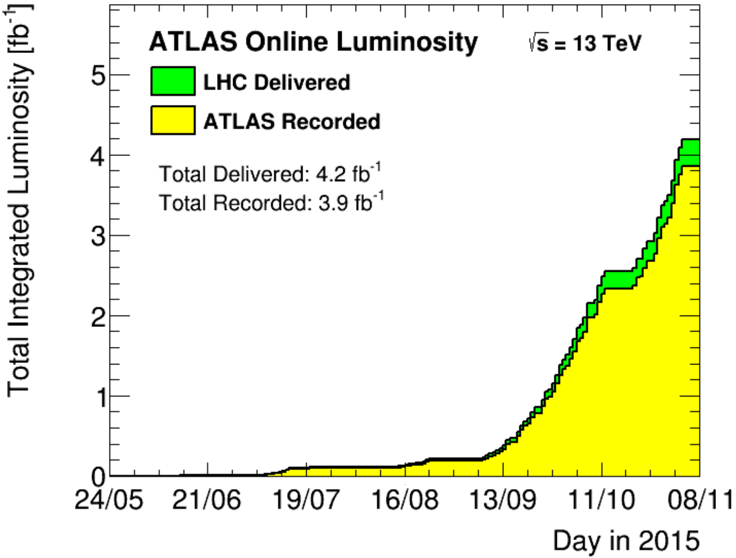
- So question one is **how much** Run-2 13 TeV data do we need to **surpass** the Run-1 result?
- At 2 TeV production cross-sections grow **considerably**
- So a **smaller** amount of Run-2 data roughly equivalent to the 8 TeV dataset



- What local σ values can we see **assuming**
  - Different 13 TeV recorded luminosity
  - Systematics size w.r.t. Run-1
  - Injecting a Run-1 'signal'
- **If realised** in nature, observation should be possible with the 2015 data

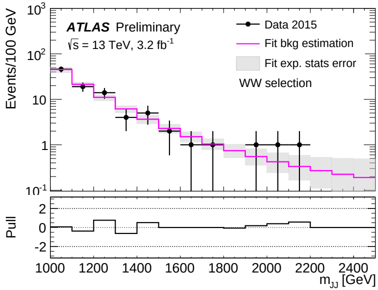


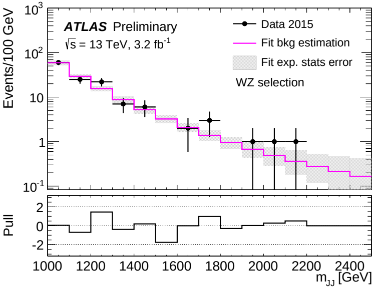
Run-2: Data is here!

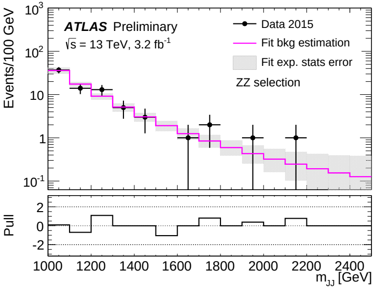


Results - 3.2fb $^{-1}$ – [CDS:2114845]

- Full **WZ** selection applied to the 3.2fb $^{-1}$ of 13TeV data (data lost to GRL/IBL off)
- **Good fit** agreement seen for all mass window combinations
- Poor statistics in the **tails**
- No **significant** discrepancies seen in any signal region
- **More data** needed to conclude (the final nail)

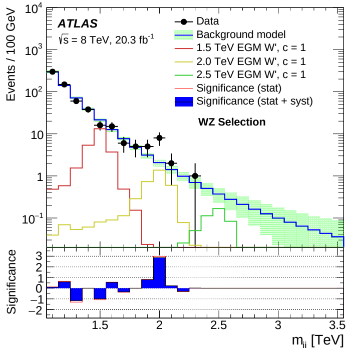


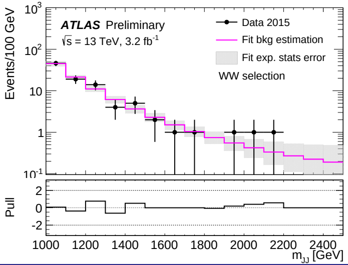




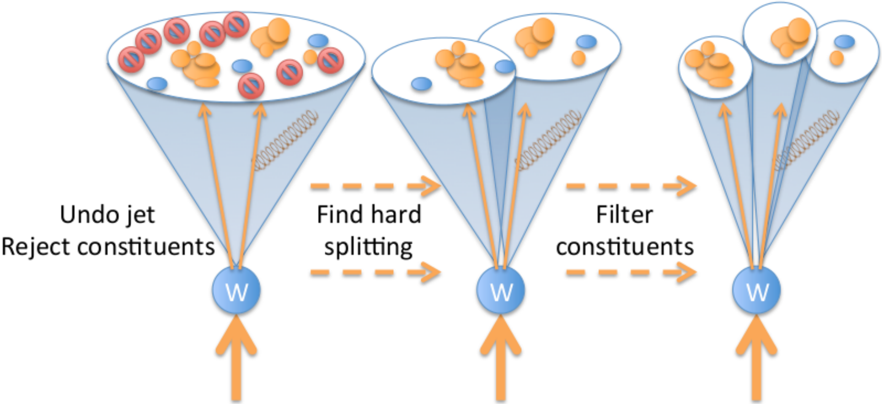
Conclusions

- Presented searches for a **high mass diboson resonance**, [arXiv:1506.00962], [CDS:2114845]
  - Used 20.3fb^{-1}(3.2fb^{-1}) 8(13)TeV ATLAS data
  - Jet substructure used to separate signal from background
  - QCD dominated background modelled by parametric function
- **Deviation** from expected steeply, smoothly falling background seen at **2 TeV**
- Cross-checks performed, **no major issues** discovered
- **Excess** $p_0 = 3.4\sigma$ local, 2.5σ global
- **Nothing** seen in Run-2...
- Statistics are **too low** for a definite conclusion... but looking like a **fluctuation**





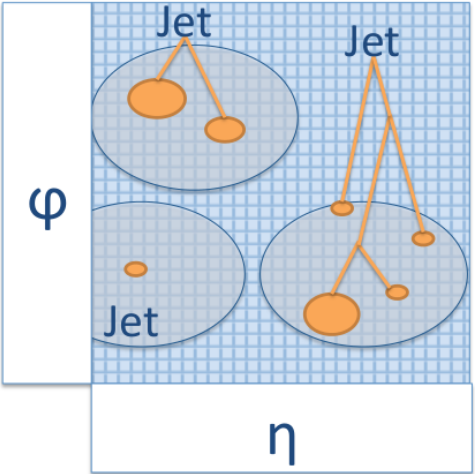
Backup



Undo jet
Reject constituents
Find hard
splitting
Filter
constituents
W
W
W

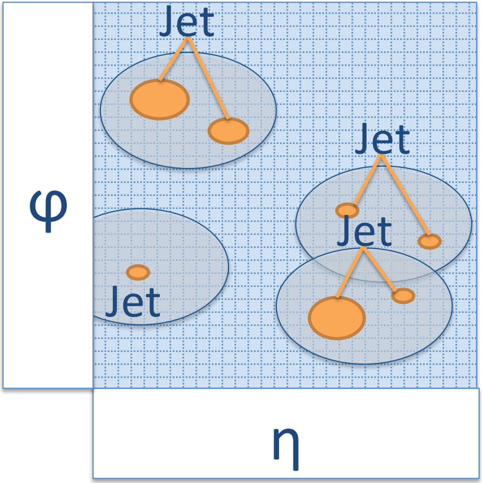
Jet Algorithms – Run-1 Analysis

- **Cambridge-Aachen** 1.2 jets (CA jets) used in Run-1
  - [arXiv:9707323] or [arXiv:0802.2470]
- Part of the **sequential recombination** family of jet reconstruction algorithms
  - Calculate the $d_{ij} = \frac{\Delta R_{ij}^2}{R^2}$ between all jet constituents
  - Combine **closest constituents** first
  - Merge while $R_{ij} \leq 1.2$ (in this analysis)
  - If there are no components within 1.2, **redefine as a jet** and remove from the collection of constituents
  - Merge until there are **no components** left
- CA jets have **NO** p_{T} dependence!
- Therefore can look into the history and use the p_{T} splitting information



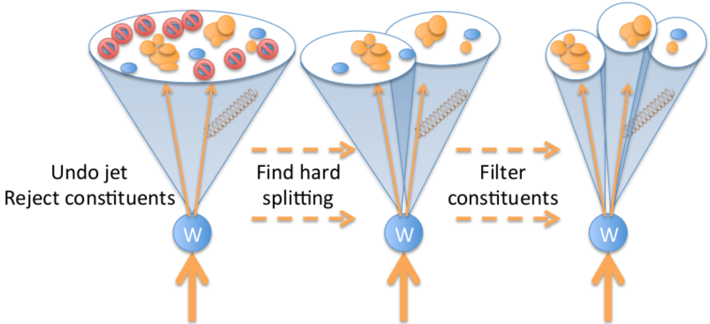
Jet Algorithms – Run-2 Analysis

- **anti-k_t** 1.0 jets used in Run-2
  - [arXiv:9707323] or [arXiv:0802.2470]
- Part of the **sequential recombination** family of jet reconstruction algorithms
  - Calculate the $d_{ij} = \min(k_{ti}^{-2}, k_{tj}^{-2}) \frac{\Delta R_{ij}^2}{R^2}$ between all jet constituents
  - Combine **closest constituents** first
  - Merge while $R_{ij} \leq 1.0$ (in this analysis)
  - If there are no components within 1.0, **redefine as a jet** and remove from the collection of constituents
  - Merge until there are **no components** left
- Anti-kt jets have **have** p_{T} dependence!
- Form more "conical" jets, history less informative



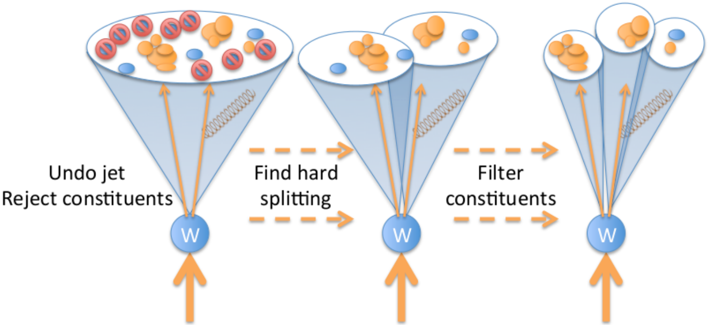
BDRS Split-Filter – Run-1 Analysis

- The **BDRS split filtering** algorithm, [arXiv:0802.2470], decomposes CA jets sequential clustering to find **hard substructure** within
- Originally defined to find **boosted** $H \to bb$ decays



- The **decomposition** follows some simple steps
  - For jet j, undo the **last step** of clustering forming jets j_1 and j_2 ($m_{j_1} > m_{j_2}$)
  - If there was a **large mass drop**, $m_{j_1} < \mu_{\text{max}} m_j$ and the p_{T} balance is not **too asymmetric**, $\frac{min(p_{T_{j_1}}^2, p_{T_{j_2}}^2)}{m_{j_0}^2} \Delta R_{j_1,j_2}^2 \geq y_{\text{min}}$, define j as from a **hard** splitting and stop
  - Otherwise redefine j as j_1, discard j_2, and continue
- Filter the resulting jet by **re-clustering** as $n_{\text{r}} \times R_{\text{r}}$ sized subjets

BDRS-A Split-Filter – Run-1 Analysis



- In this analysis a **modified BDRS-A** split filtering algorithm is used
- Starts from $R = 1.2$ CA jets seeded from local cluster weighted (LCW) topological clusters
- Loose BDRS tagger, with **no mass drop** requirement

Iterative parameter	Value
$\sqrt{y_{\mathrm{min}}}$	0.20
μ_{max}	1.00
Filtering parameter	**Value**
n_{r}	3
R_{r}	0.3

BDRS-A CA $R = 1.2$ Jet Calibration

- Particle level jet **energy and mass calibrations** were derived and applied to the BDRS-A CA $R = 1.2$ jets used in the analysis
- Effectively **restores** jet energy/mass response over the **full** jet E and η range

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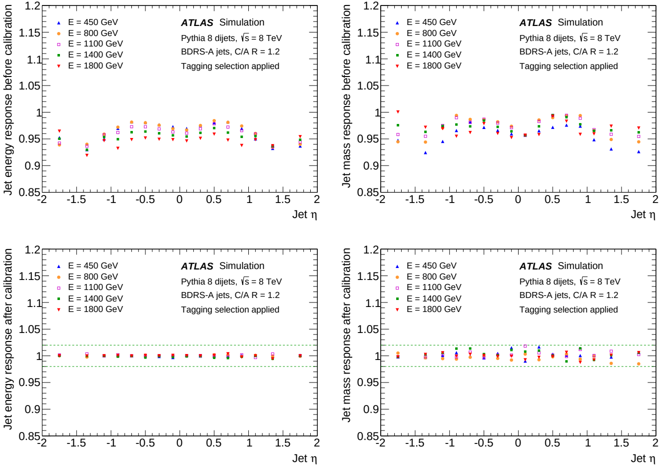
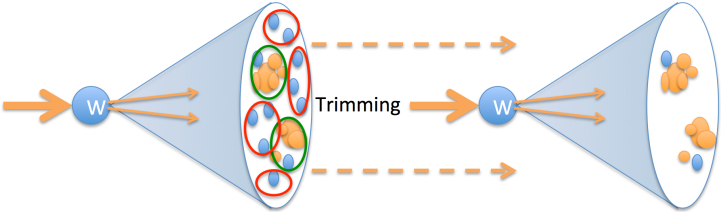
- Calculate the **jet energy response** in bins of η_{det} and E_{truth}
- Fit the responses with a Gaussian fit, to gain **mean response** in each bin, $< \mathrm{R}_{\mathrm{E}}^{\mathrm{jet}} >$
- Derive the mean reconstructed jet energy, $< \mathrm{E}_{\mathrm{reco}}^{\mathrm{jet}} >$
- Fit the $< \mathrm{R}_{\mathrm{E}}^{\mathrm{jet}} >$ vs $< \mathrm{E}_{\mathrm{reco}}^{\mathrm{jet}} >$ distribution to gain a **calibration function**
- Repeat process for **mass calibration** using the LCW+JES jets



Anti-k_t Trimming – Run-2 Analysis

- The **trimming** algorithm, [arXiv:0912.1342], does what it says on the tin
- Aims to identify **soft** contamination from **pile-up/underlying event** and remove them from the jet



- The method is a few simple steps
  - For jet j, **re-cluster** the constituents into smaller-R **sub-jets** ($R = 0.2$)
  - If a sub-jet's $p_T^{\mathrm{sub}} < 0.05 \times p_T^{\mathrm{jet}}$ **discard** this sub-jet as a soft contribution
  - Otherwise keep the sub-jets constituents in the **final jet**

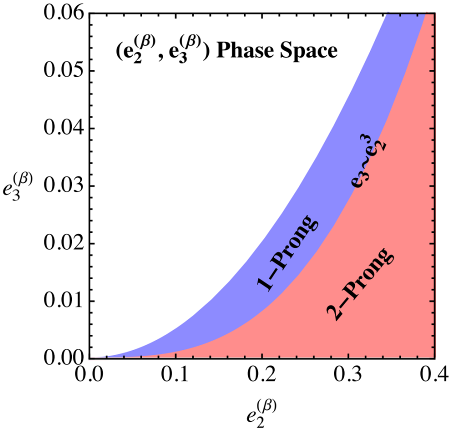
$D_2^{\beta=1}$ – Run-2 Analysis

- $D_2^{\beta=1}$ is a tagging variable based on **2/3 point energy correlation functions**, [arXiv:1409.6298]
- Analogous to **n-subjettiness**, i.e. it tries to quantify how much a jet looks like a collection of n-sub-jets

$$e_2^\beta = \frac{1}{p_{TJ}^2} \sum_{1\leq i\leq j\leq n_J} p_{T_i} p_{T_j} \Delta R_{ij}^\beta$$

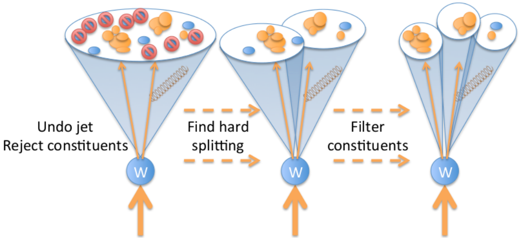
$$e_3^\beta = \frac{1}{p_{TJ}^3} \sum_{1\leq i\leq j\leq k\leq n_J} p_{T_i} p_{T_j} p_{T_k} \Delta R_{ij}^\beta \Delta R_{ik}^\beta \Delta R_{jk}^\beta$$

$$D_2^\beta = \frac{e_3^\beta}{(e_2^\beta)^3}$$

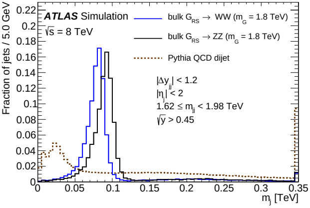


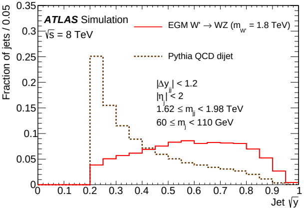
Tools at our disposal – Run-1

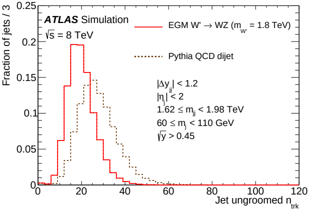
- What do we have to remove the QCD background?



1. The BDRS-A filtered CA $R = 1.2$ jets
   - Selects two (three) pronged decays within jets







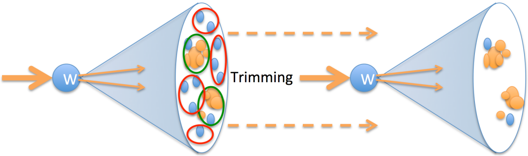
2. Filtered jet mass
   - Separates peaked boson mass from falling QCD spectrum

3. Subjet momentum balance
   - Boson jets symmetric, QCD unbalanced

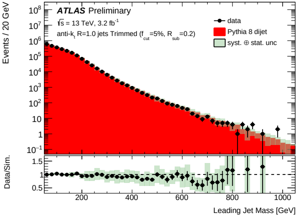
4. Number of tracks ghost matched to the unfiltered jet
   - More hadronic activity in QCD jets

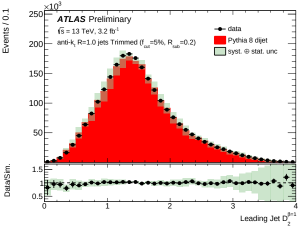
Tools at our disposal – Run-2

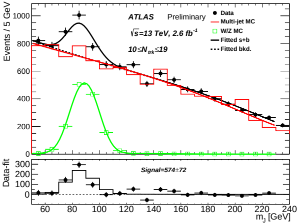
- What do we have to remove the QCD background?



1. The anti-k_T $R = 1.0$ jets
   - Removes pile-up contributions







2. Filtered jet mass
   - Separates peaked boson mass from falling QCD spectrum

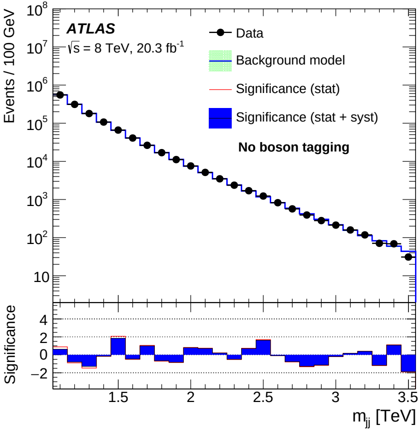
3. $D_2^{\beta^1}$
   - Boson jets **lower**, QCD **higher**

4. Number of tracks ghost matched to the unfiltered jet
   - More hadronic activity in QCD jets

Event selection: Run-1 all together

1. **Trigger:** $p_T > 360$ GeV anti-kt 1.0
2. Apply **BDRS-A** split-filter
3. Require $m_{JJ} > 1.05$ TeV
   - Ensures on **trigger plateau**
4. **Rapidity gap** between leading jets, $|\Delta y_{12}| < 1.2$
   - s-channel signal more **central** than t-channel QCD
5. Leading jets p_T **asymmetry** $A_{p_T} < 0.15$
   - Used as proxy for large-R **jet cleaning**
6. Leading jets $|\eta| < 2.0$
   - Ensures a good **overlap** with tracker
7. Correction for jets on **calorimetry holes**
8. **Boson tagging** cuts
   - Jet mass (WZ, WW, ZZ), momentum balance, n_{trk}

- Background efficiencies
  - **Topological** $\epsilon \approx 48\%$
  - **Tagger** $\epsilon \approx 1.2 - 0.6\%$



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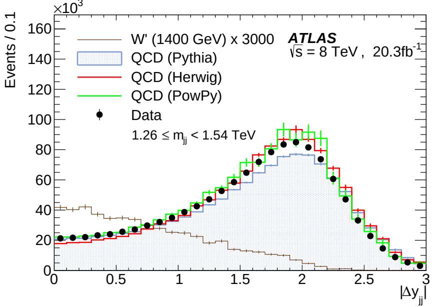

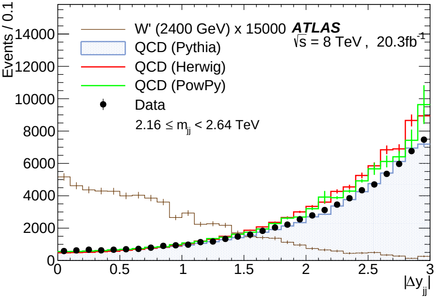

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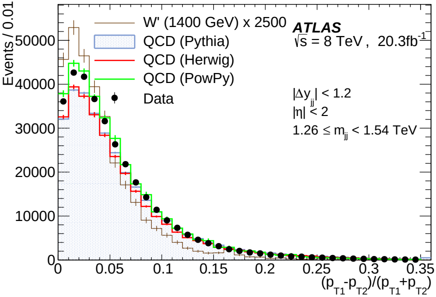

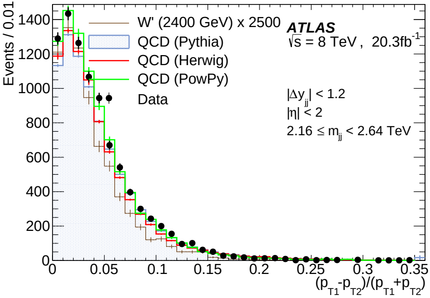

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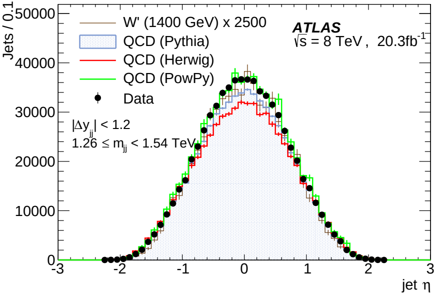

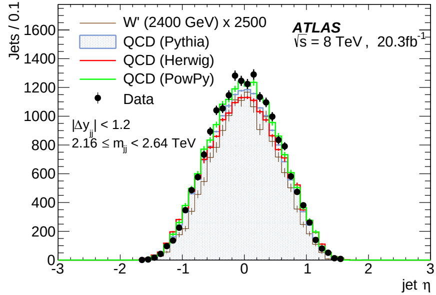

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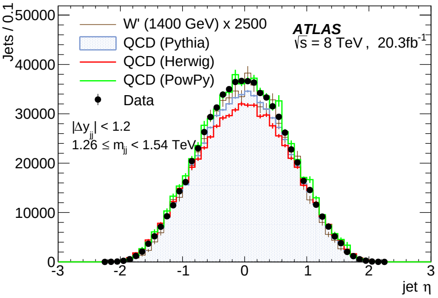

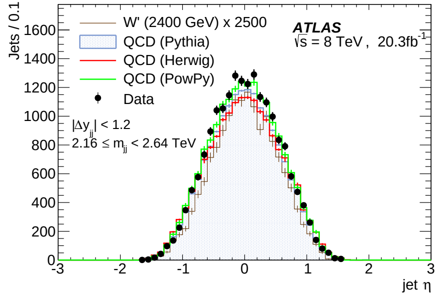

Event selection: Run-1 all together

1. **Trigger:** $p_T > 360$ GeV anti-kt 1.0
2. Apply **BDRS-A** split-filter
3. Require $m_{JJ} > 1.05$ TeV
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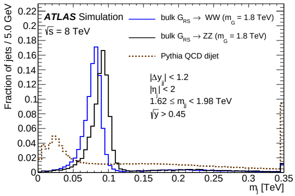
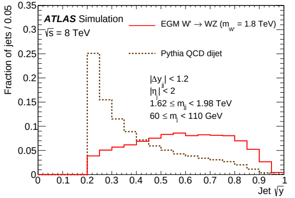
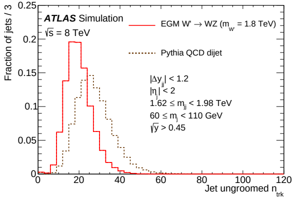
7. Correction for jets on **calorimetry holes**
8. **Boson tagging** cuts
   - Jet mass (WZ, WW, ZZ), momentum balance, n_{trk}

- Background efficiencies
  - **Topological** $\epsilon \approx 48\%$
  - **Tagger** $\epsilon \approx 1.2 - 0.6\%$







Event selection: Run-1 all together

1. **Trigger:** $p_{\mathrm{T}} > 360$ GeV anti-kt 1.0
2. Apply **BDRS-A** split-filter
3. Require $m_{JJ} > 1.05$ TeV
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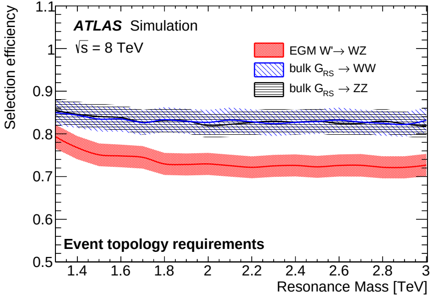
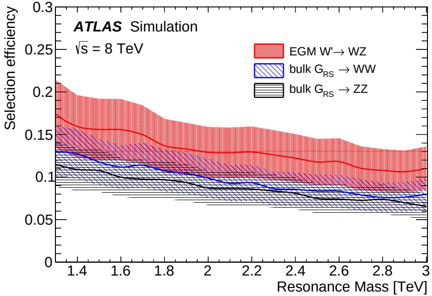
8. **Boson tagging** cuts
   - Jet mass (WZ, WW, ZZ), momentum balance, n_{trk}

- Background efficiencies
  - **Topological** $\epsilon \approx 48\%$
  - **Tagger** $\epsilon \approx 1.2 - 0.6\%$

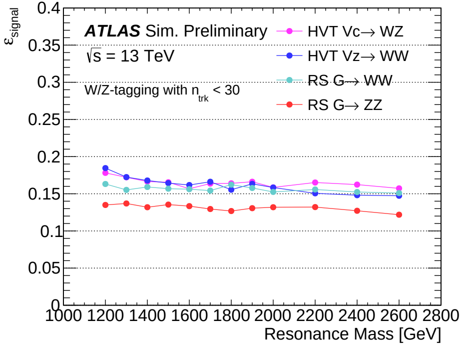




Event selection: Run-2 all together

1. **Trigger:** $p_T > 360$ GeV anti-kt 1.0
2. Apply trimming proceedure
3. Require $m_{JJ} > 1.0$ TeV
   - Ensures on **trigger plateau**
4. **Rapidity gap** between leading jets, $|\Delta y_{12}| < 1.2$
   - s-channel signal more **central** than t-channel QCD
5. Leading jets p_T **asymmetry** $A_{p_T} < 0.15$
   - Used as proxy for large-R **jet cleaning**
6. Leading jets $|\eta| < 2.0$
   - Ensures a good **overlap** with tracker
7. **Boson tagging** cuts
   - Jet mass (WZ, WW, ZZ), $D_2^{\beta^1}$, n_{trk}

- Background efficiencies
  - **Topological** $\epsilon \approx 30\%$
  - **Tagger** $\epsilon \approx 2\%$



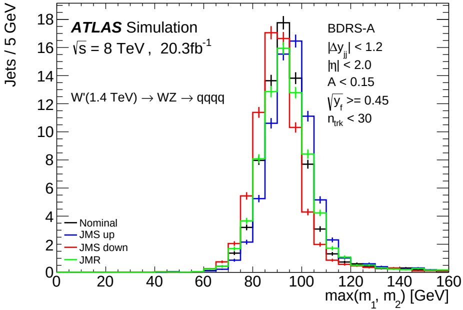
Systematics: Shape – Run-1 & 2

- **Background:** Taken from the uncertainties on the **fit parameters**
- **Signal:** Various systematics affect the signal **reconstruction** and **selection efficiency**

- **Shape systematics:**
- The jet p_T and jet mass scale uncertainties determined by the **track/calo double ratio** technique
- For example for a variable x,

$$\frac{x_{\text{track}}^{\text{data}} / x_{\text{calo}}^{\text{data}}}{x_{\text{track}}^{\text{MC}} / x_{\text{calo}}^{\text{MC}}}$$

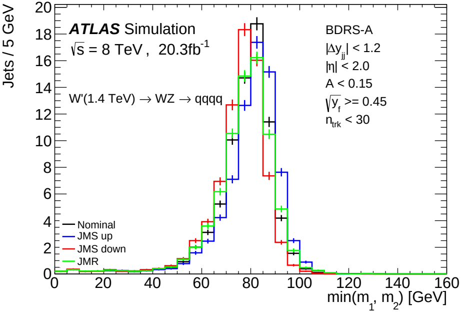
- Applied as a Gaussian with $\mu = 1$ and σ equal to the **observed uncertainty**
  - jet p_T scale: 2%
  - jet mass scale: 3%
- An uncertainty on the jet p_T resolution of 20% is applied as an additional **smearing** on top of the nominal 5%



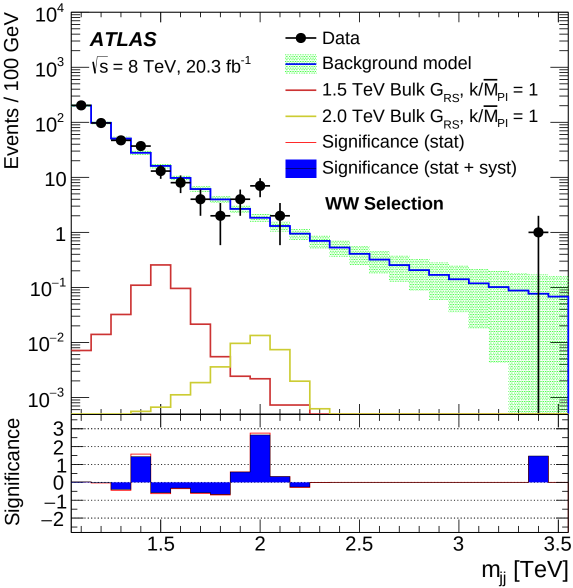
Source	Uncertainty	Constraining pdf
Jet p_T scale	2%	$G(\alpha_{PT}\|1, 0.02)$
Jet p_T resolution	20%	$G(\sigma_{r_E}\|0, 0.05 \times \sqrt{1.2^2 - 1^2})$
Jet mass scale	3%	$G(\alpha_m\|1, 0.03)$

- **Background:** Taken from the uncertainties on the **fit parameters**
- **Signal:** Various systematics affect the signal **reconstruction** and **selection efficiency**

- **Normalisation systematics:**
- **Large uncertainty** on the n_{trk} cut evaluated in the data driven V+jets study used to define the efficiency of the cut
- Jet mass scale affects **both** shape and normalisation strongly
- $\sqrt{y}$ scale evaluated using the **double ratio** method
- Resolutions taken as 20% **smearings**
- **Shower model** evaluated by comparing MC showered by PYTHIA or HERWIG
- **PDF4LHC** method used to evaluate PDF uncertainties
- ATLAS **luminosity** uncertainty assumed

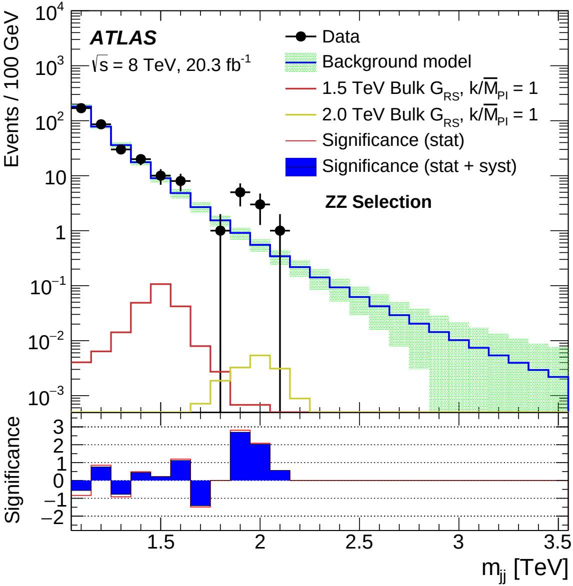


Source	Uncertainty
Efficiency of the track-multiplicity cut	20.0%
Jet mass scale	5.0%
Jet mass resolution	5.5%
Subjet momentum-balance scale	3.5%
Subjet momentum-balance resolution	2.0%
Parton shower model	5.0%
Parton distribution functions	3.5%
Luminosity	2.8%



- Full **WW** selection applied to the data
  - *W* mass window applied to **both** jets
- **Good agreement** again seen with steeply, smoothly falling background model
- **Deviation** from the background still observed at around 2 TeV
- **Remember:** There is an **overlap** between the *W*/*Z* mass windows
- **Benchmark** Bulk Randall-Sundrum graviton signal MC shown for **comparison** purposes

$X \to ZZ$ selection – Run-1



- Full **ZZ** selection applied to the data
  - *Z* mass window applied to **both** jets
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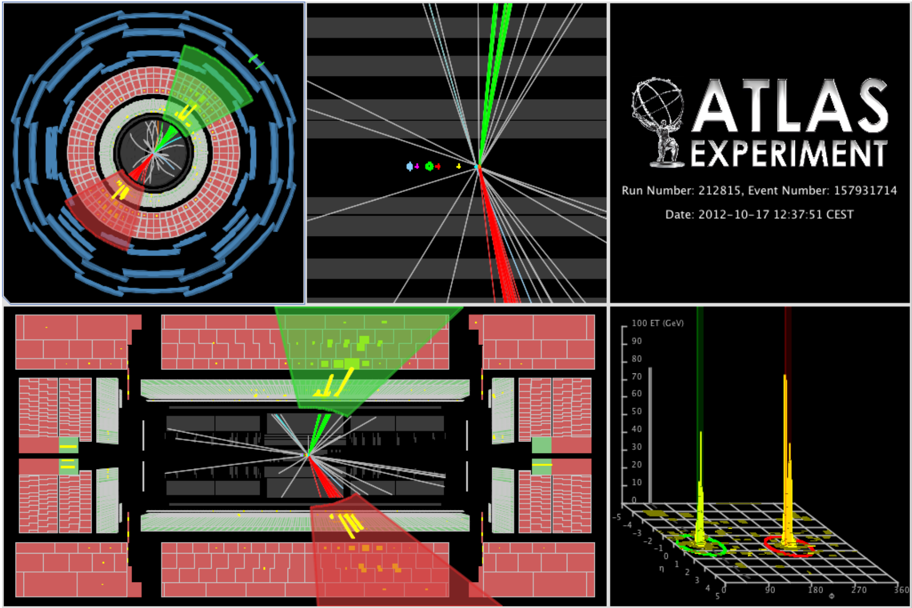
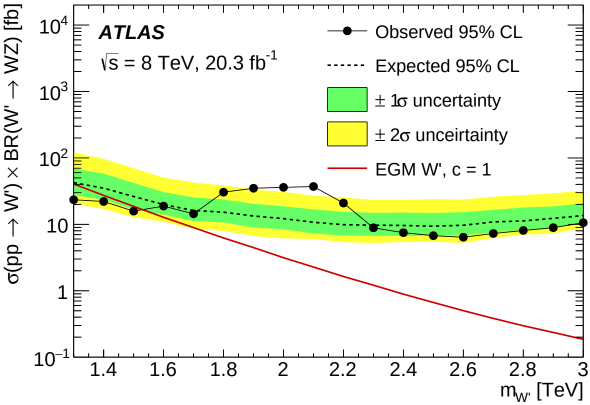
- **Deviation** from the background still observed at around 2 TeV
- **Remember:** There is an **overlap** between the *W*/*Z* mass windows
- **Benchmark** Bulk Randall-Sundrum graviton signal MC shown for **comparison** purposes

What do these events look like? Energetic!



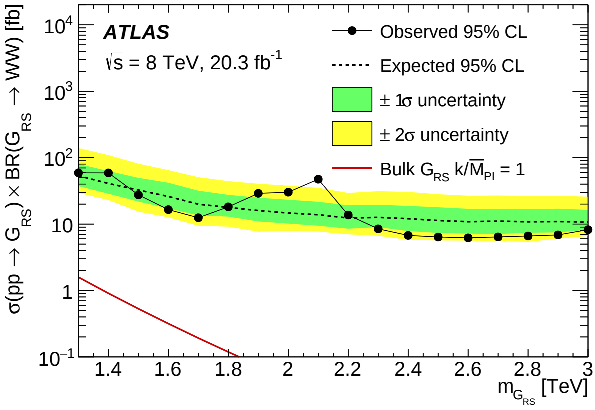
- As no **significant deviation** was observed, we continue to set limits on the observed distributions
- 95% confidence limits set on $\sigma \times \mathcal{B}$ using the $\mathrm{CL_S}$ prescription taking into account the **systematic uncertainties** and **background fit**



- **Expected** limits broadly agree with the observed limits
- **Exclusion** of EGM W' from 1.3 – 1.5 TeV
- **Broad deviation** from the background observable at around 2 TeV
- **Benchmark** extended gauge model W' $\sigma \times \mathcal{B}$ shown for **comparison** purposes

$X \rightarrow WW$ limits – Run-1

- As no significant deviation was observed, we continue to set limits on the observed distributions
- 95% confidence limits set on $\sigma \times \mathcal{B}$ using the $\mathrm{CL_S}$ prescription taking into account the systematic uncertainties and background fit

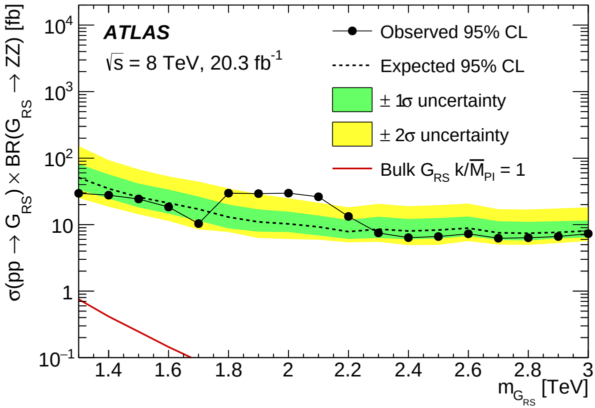


- **Expected** limits broadly agree with the observed limits
- **Exclusion** of graviton production at no masses
- **Deviation** from the background observable at around 2.1 TeV
- **Benchmark** Bulk Randall-Sundrum graviton $\sigma \times \mathcal{B}$ shown for **comparison** purposes

$X \to ZZ$ limits -Run-1

UCL

- As no significant deviation was observed, we continue to set limits on the observed distributions
- 95% confidence limits set on $\sigma \times \mathcal{B}$ using the $\mathrm{CL_S}$ prescription taking into account the systematic uncertainties and background fit

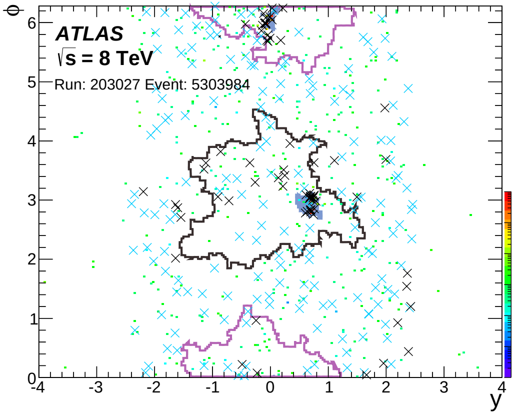


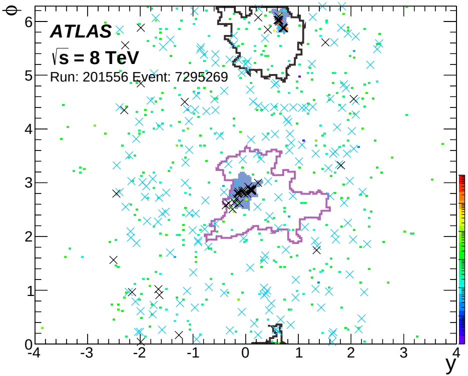
- **Expected** limits broadly agree with the observed limits
- **Exclusion** of graviton production at no masses
- **Broad deviation** from the background observable at around 2 TeV
- **Benchmark** Bulk Randall-Sundrum graviton $\sigma \times \mathcal{B}$ shown for **comparison** purposes

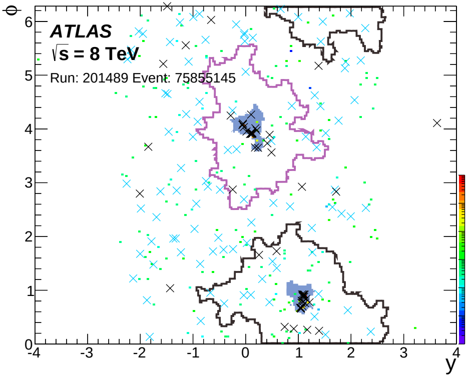
Digging deeper into the jets.... – Run-1

These jet event displays take a bit more explanation, but offer a powerful insight into the analysis jets

- The ATLAS detector volume is shown unfolded in y and ϕ
- Inner detector track positions are shown as crosses
  - Black Tracks: From primary vertex
  - Blue Tracks: From secondary vertices
- Calorimeter deposits are displayed on the rainbow scale
- The outlines of the CA 1.2 jets are shown
  - Black: Leading p_T jet
  - Mauve: Sub-leading jet
- Grey area: Sub-jets after filtering



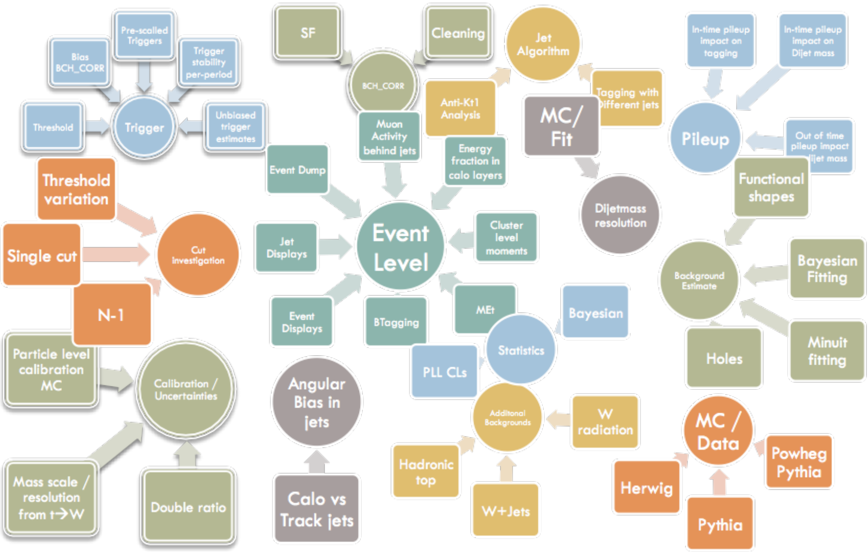




What do we see here?

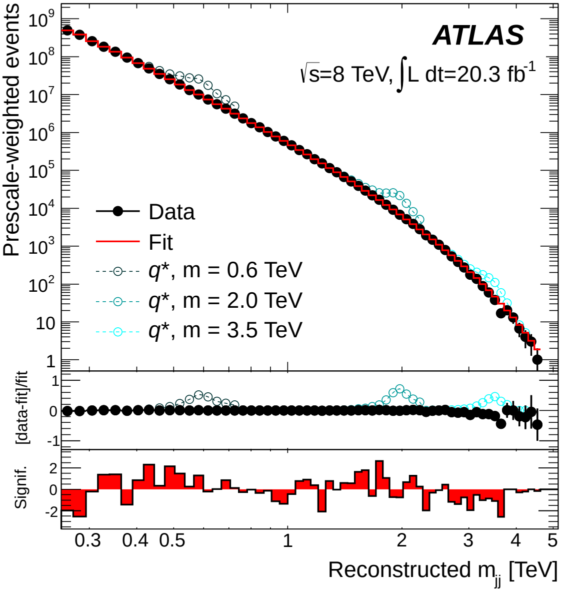
- Subjets are highly collimated
- PV tracks are highly correlated with the selected sub-jets
- Energy deposits concentrated in the sub-jet
- Pile-up tracks/deposits sparsely distributed over the events
- Successfully picked the boson out of the pileup?

Time to cross-check..... – Run-1



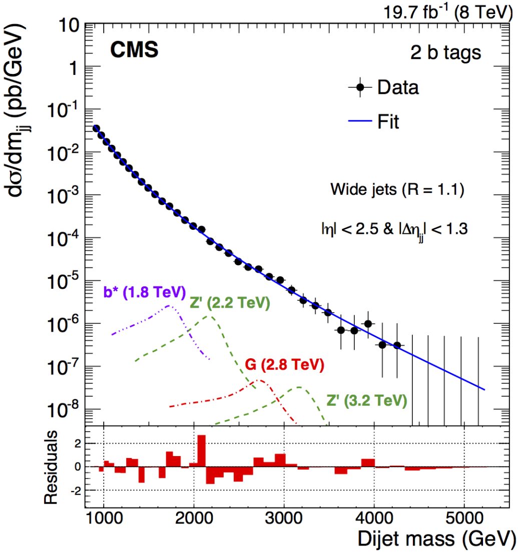
From E. Kajomovitz

Are we alone? ATLAS searches

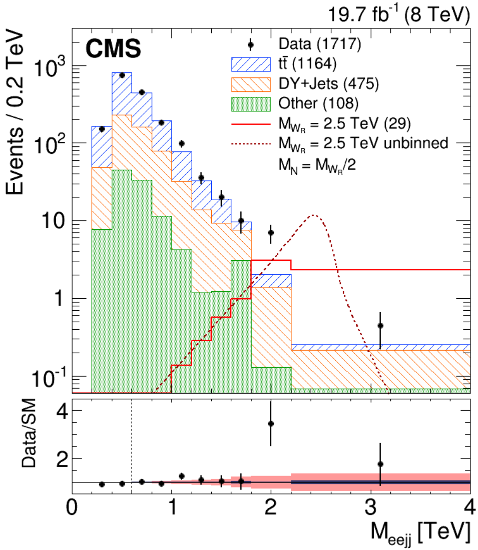


- ATLAS resolved dijet search [arXiv:1407.1376], nothing seen ⊠
- ATLAS resolved Run-2 dijet search ATLAS-CONF-2015-042, nothing seen ⊠
- ATLAS semi-leptonic search $W(l\nu)Z(jj)$ [arXiv:http://1503.04677], using similar BDRS-A CA 1.2 reconstruction, in tail/nothing seen ⊠
- ATLAS semi-leptonic search $W(jj)Z(ll)$ [arXiv:1409.6190], using similar BDRS-A CA 1.2 reconstruction, in tail/nothing seen ⊠

Are we alone? Across the ring....CMS



- CMS dijet search [arXiv:1501.04198], blip in 2-btag at 2 TeV? Trick of the eye? ☒
- CMS W_R search [arXiv:1407.3683], excess at 2 TeV in *eejj* channel only ☒☑
- CMS $WW/WZ/ZZ$ semi-leptonic search [arXiv:1405.3447], in tails/nothing seen ☒
- CMS $WW/WZ/ZZ$ fully hadronic search [arXiv:1405.3447], uses n-subjettiness, broad blip at ≈ 1.8TeV ☒☑



- CMS dijet search [arXiv:1501.04198], blip in 2-btag at 2 TeV? Trick of the eye? ⊠
- CMS W_R search [arXiv:1407.3683], excess at 2 TeV in *eejj* channel only ⊠☑
- CMS *WW*/*WZ*/*ZZ* semi-leptonic search [arXiv:1405.3447], in tails/nothing seen ⊠
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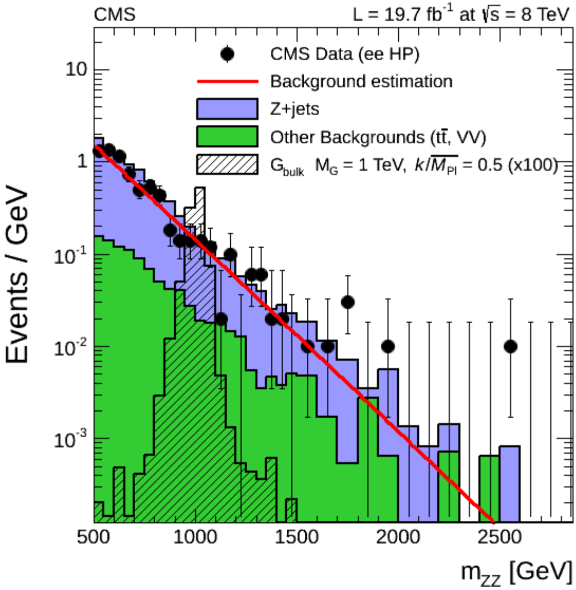
Are we alone? Across the ring....CMS



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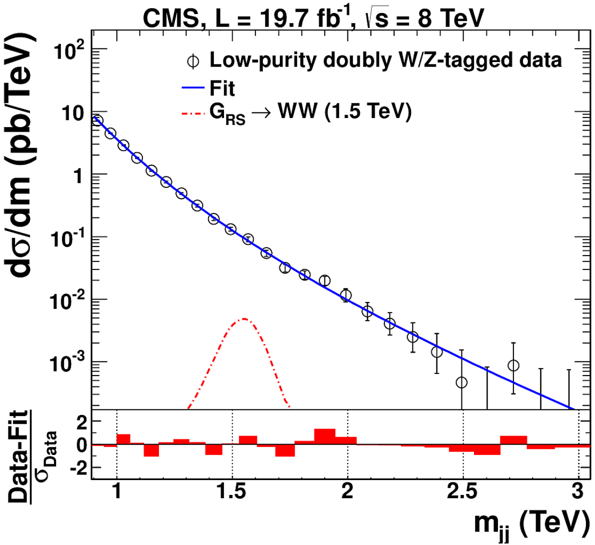

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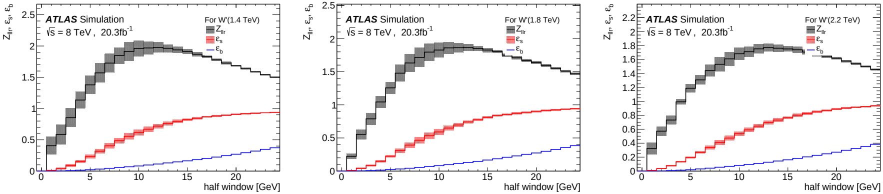
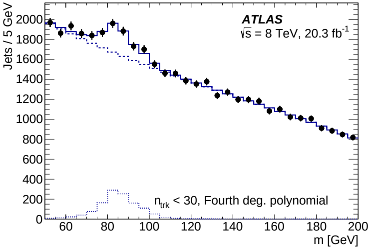
Mass window optimisation

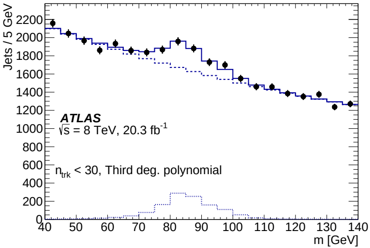
- A data CR was formed from two tagged/untagged samples
- A wide mass window ($40 < m_J < 400$ GeV) used
  1. CR A: Leading jet tagged, sub-leading fails tag
  2. CR B: Leading jet fails tag, sub-leading passes tag
- Forms dijet sample by taking one jet from CR A and one from CR B
- Use this as a high stats QCD region for comparison with signal MC
- Compute mass window efficiencies as function of window width for different W' masses



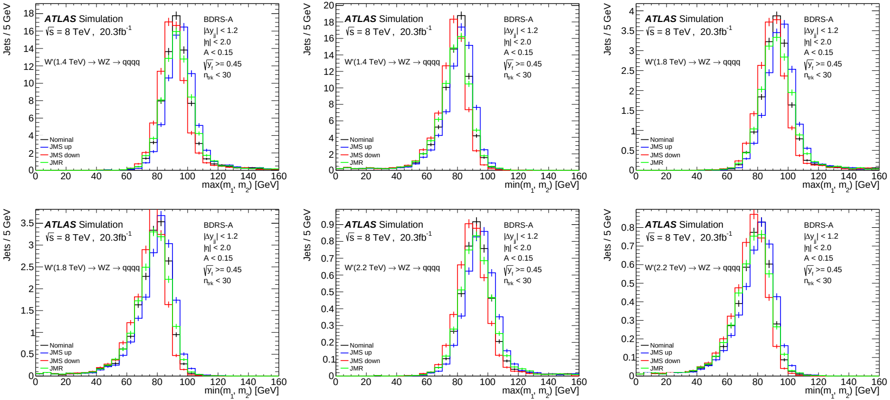
n_{trk} optimisation

- n_{trk} is poorly modelled in MC
- Cannot trust it to optimise cut or measure its efficiency
- Select V+jets enriched data sample
  1. Optimise the cut by fitting QCD background vs selected signal peak
  2. Measure the efficiency of selected cut in data sample
- Two models used to fit background in this region
- Both fit well, efficiency error taken from a combined PDF of both fits



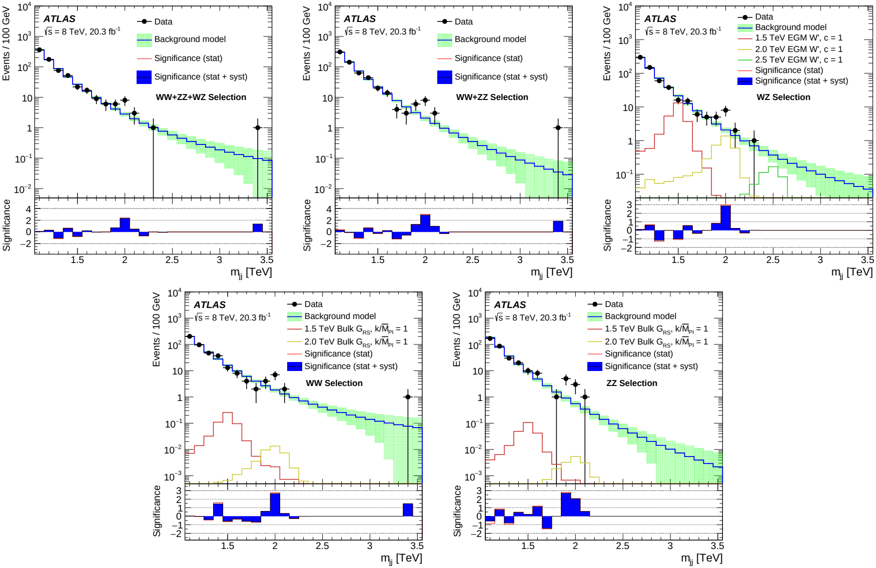


Systematic variations



Selection overlaps

- Comparing the effect of applying all signal selections at once, and the same flavour selections at once



Signal properties

- The resonance width (Γ) and the product of cross sections and branching ratios (BR) to four-quark final states used in modelling $W? \to WZ$, $G_{RS} \to WW$, and $G_{RS} \to ZZ$, for several values of resonance pole masses (m). The fraction of events in which the invariant mass of the $W?$ or G_{RS} decay products lies within 10% of the nominal resonance mass ($f_{10\%}$) is also displayed.

m [TeV]	$\Gamma_{W'}$ [GeV]	$\Gamma_{G_{\mathrm{RS}}}$ [GeV]	$W' \to WZ$ $\sigma \times$BR [fb]	$W' \to WZ$ $f_{10\%}$	$G_{\mathrm{RS}} \to WW$ $\sigma \times$BR [fb]	$G_{\mathrm{RS}} \to WW$ $f_{10\%}$	$G_{\mathrm{RS}} \to ZZ$ $\sigma \times$BR [fb]	$G_{\mathrm{RS}} \to ZZ$ $f_{10\%}$
1.3	47	76	19.1	0.83	0.73	0.85	0.37	0.84
1.6	58	96	6.04	0.79	0.14	0.83	0.071	0.84
2.0	72	123	1.50	0.72	0.022	0.83	0.010	0.82
2.5	91	155	0.31	0.54	0.0025	0.78	0.0011	0.78
3.0	109	187	0.088	0.31	0.00034	0.72	0.00017	0.71

Observed and expected numbers

- Number of events observed in the WZ, WW, and ZZ selected samples in each dijet mass bin used in the analysis, compared to the prediction of the background-only fit.

m_{jj} bin [GeV]	WZ selection (Events)				WW selection (Events)				ZZ selection (Events)			
	obs	exp	$+1\sigma$	-1σ	obs	exp	$+1\sigma$	-1σ	obs	exp	$+1\sigma$	-1σ
1050–1150	299	296.65	312.60	280.90	203	202.39	215.30	189.33	169	180.83	194.82	166.70
1150–1250	149	140.82	146.83	134.68	97	97.98	102.93	92.97	86	78.04	82.65	73.32
1250–1350	60	71.37	75.30	67.21	47	50.79	54.10	47.42	30	36.01	39.53	32.51
1350–1450	38	38.24	40.98	35.40	37	27.91	30.28	25.52	20	17.59	20.02	15.26
1450–1550	16	21.50	23.36	19.64	13	16.13	17.78	14.49	10	9.02	10.55	7.58
1550–1650	15	12.61	13.88	11.39	8	9.75	10.87	8.62	8	4.83	5.76	3.96
1650–1750	6	7.67	8.56	6.86	4	6.12	6.90	5.35	0	2.68	3.25	2.16
1750–1850	5	4.82	5.47	4.25	2	3.98	4.54	3.43	1	1.54	1.90	1.22
1850–1950	5	3.12	3.62	2.70	4	2.67	3.09	2.27	5	0.91	1.14	0.71
1950–2050	8	2.08	2.47	1.75	7	1.84	2.18	1.53	3	0.55	0.71	0.42
2050–2150	2	1.41	1.74	1.15	2	1.30	1.58	1.06	1	0.34	0.46	0.25
2150–2250	0	0.98	1.26	0.77	0	0.95	1.18	0.74	0	0.22	0.30	0.15
2250–2350	1	0.70	0.94	0.52	0	0.70	0.91	0.52	0	0.14	0.20	0.09
2350–2450	0	0.50	0.71	0.35	0	0.53	0.71	0.37	0	0.09	0.14	0.06
2450–2550	0	0.37	0.55	0.24	0	0.41	0.58	0.27	0	0.06	0.10	0.03
2550–2650	0	0.28	0.44	0.17	0	0.32	0.48	0.20	0	0.04	0.07	0.02
2650–2750	0	0.21	0.36	0.12	0	0.25	0.40	0.15	0	0.03	0.06	0.01
2750–2850	0	0.16	0.29	0.08	0	0.21	0.35	0.11	0	0.02	0.04	0.01
2850–2950	0	0.13	0.25	0.06	0	0.17	0.30	0.08	0	0.01	0.03	0.00
2950–3050	0	0.10	0.21	0.04	0	0.14	0.27	0.06	0	0.01	0.03	0.00
3050–3150	0	0.08	0.18	0.03	0	0.12	0.25	0.05	0	0.01	0.02	0.00
3150–3250	0	0.06	0.16	0.02	0	0.10	0.23	0.03	0	0.01	0.02	0.00
3250–3350	0	0.05	0.15	0.02	0	0.09	0.22	0.03	0	0.00	0.01	0.00
3350–3450	0	0.04	0.13	0.01	1	0.08	0.21	0.02	0	0.00	0.01	0.00
3450–3550	0	0.04	0.12	0.01	0	0.07	0.20	0.01	0	0.00	0.01	0.00

Observed and expected limits

- Observed and expected limits on the EGM *W*? models in the *WZ* selection

	$W' \to WZ$		95% CL Limits [fb]					
m [GeV]	$\sigma\mathrm{BR}_{WZ}$ [fb]	Γ [GeV]	obs	exp	-2σ	-1σ	$+1\sigma$	$+2\sigma$
1300	40.5	46.66	23.47	42.43	20.51	27.61	69.49	120.84
1400	27.3	50.30	22.08	35.01	16.96	23.41	58.15	96.95
1500	18.7	53.99	15.79	26.28	12.82	16.81	41.96	70.12
1600	12.8	57.60	18.82	19.84	10.97	13.99	30.62	50.61
1700	8.93	61.32	14.40	16.19	8.55	11.18	25.36	42.78
1800	6.23	65.00	30.47	15.22	7.95	10.67	23.64	38.51
1900	4.46	68.66	34.96	13.35	6.69	8.96	20.40	33.37
2000	3.14	72.30	36.04	12.18	6.12	8.39	18.71	30.84
2100	2.28	76.00	37.12	10.74	6.02	7.31	16.77	27.06
2200	1.64	79.60	20.92	9.88	5.36	6.73	15.40	25.36
2300	1.21	83.34	8.87	9.72	5.24	6.70	14.89	23.30
2400	0.889	87.00	7.49	9.61	5.40	6.68	15.05	23.37
2500	0.666	90.68	6.75	9.37	5.47	6.76	14.83	23.97
2600	0.502	94.30	6.40	9.69	5.25	6.80	15.22	23.60
2700	0.383	98.03	7.28	10.88	6.24	7.49	16.53	26.11
2800	0.297	101.70	8.08	11.26	6.96	8.24	17.88	27.75
2900	0.236	105.40	8.91	12.32	7.27	8.86	18.61	29.37
3000	0.186	109.00	10.58	13.54	8.86	10.12	20.71	32.11

Observed and expected limits

- Observed and expected limits on the bulk G_{RS} models in the WW selection

m [GeV]	$G_{\mathrm{RS}} \to WW$ $\sigma \mathrm{BR}_{WW}$ [fb]	Γ [GeV]	95% CL Limits [fb] obs	exp	-2σ	-1σ	$+1\sigma$	$+2\sigma$
1300	1.59	76.0	59.16	53.46	29.46	37.36	80.36	139.90
1400	0.908	82.8	59.00	40.90	23.03	28.67	62.92	109.16
1500	0.532	89.5	27.57	32.60	15.39	21.85	49.69	81.17
1600	0.317	96.2	16.53	26.04	12.63	17.18	41.93	64.89
1700	0.192	103	12.47	19.92	9.44	13.56	31.84	50.82
1800	0.119	109	18.18	17.83	9.15	12.96	27.57	44.35
1900	0.0744	116	29.01	15.99	7.68	10.97	24.93	40.50
2000	0.0470	123	30.23	14.68	7.87	10.18	23.25	37.90
2100	0.0300	129	47.39	13.83	7.72	9.46	21.67	35.14
2200	0.0194	136	13.70	12.34	7.02	8.53	19.19	29.46
2300	0.0136	142	8.48	12.63	6.67	9.01	19.53	31.31
2400	0.0083	149	6.76	12.06	5.78	7.86	18.78	30.54
2500	0.0055	155	6.39	11.32	5.68	7.36	17.92	28.18
2600	0.0036	161	6.21	10.87	5.64	7.19	16.99	26.76
2700	0.0024	168	6.41	11.07	5.58	7.10	16.94	26.91
2800	0.0016	174	6.62	10.84	5.41	7.41	16.72	26.60
2900	0.0011	181	6.87	10.93	6.02	7.50	17.07	26.76
3000	0.0008	187	8.24	10.76	6.61	8.25	16.39	25.85

Observed and expected limits

- Observed and expected limits on the bulk G_{RS} models in the ZZ selection

m [GeV]	$G_{\mathrm{RS}} \to ZZ$ $\sigma\mathrm{BR}_{ZZ}$ [fb]	Γ [GeV]	95% CL Limits [fb] obs	exp	-2σ	-1σ	$+1\sigma$	$+2\sigma$
1300	0.753	76.0	29.55	50.91	25.19	33.72	81.26	152.30
1400	0.415	82.8	27.71	34.78	18.59	24.56	56.97	93.29
1500	0.245	89.5	24.30	25.93	14.29	18.15	41.45	67.91
1600	0.144	96.2	18.39	21.13	11.35	14.58	33.67	53.01
1700	0.0888	103	10.36	17.07	8.46	11.42	26.44	44.35
1800	0.0557	109	29.71	12.98	7.74	8.78	20.04	34.98
1900	0.0338	116	29.24	10.98	6.28	7.83	16.94	28.79
2000	0.0213	123	29.73	10.26	6.07	7.72	15.68	24.91
2100	0.0137	129	26.23	9.25	5.93	6.87	13.70	21.35
2200	0.0088	136	13.27	7.84	5.41	6.09	11.76	18.20
2300	0.0058	142	7.50	8.55	5.51	6.30	13.15	20.57
2400	0.0037	149	6.37	8.02	4.91	6.01	12.16	18.93
2500	0.0025	155	6.61	8.30	4.96	6.15	12.57	19.61
2600	0.0019	161	7.27	8.85	5.64	6.73	13.23	20.72
2700	0.0011	168	6.24	7.53	5.00	5.88	11.26	17.05
2800	0.0008	174	6.34	7.41	4.96	5.75	11.00	16.88
2900	0.0005	181	6.62	7.66	5.28	6.22	11.27	17.50
3000	0.0003	187	7.31	8.05	5.69	6.42	11.52	18.21