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

Using the jet substructure thresher on the QCD haystack

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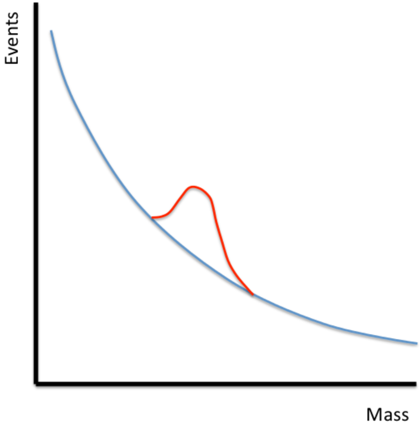
Introduction

- Resonance searches are the **classic methodology** to search for new particles and their excitations
- In essence they boil down to, 'Look for a **peak** on a **smooth background**'
- Used in searches ranging from **quarkonia** to the **Higgs**



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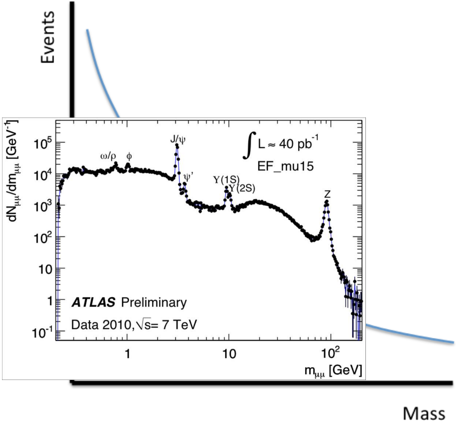
    - Rediscovering the SM



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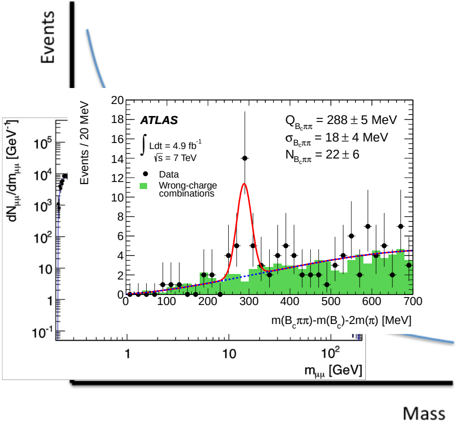
    - New meson states



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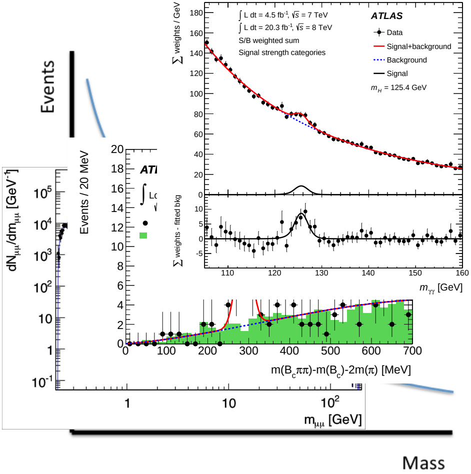
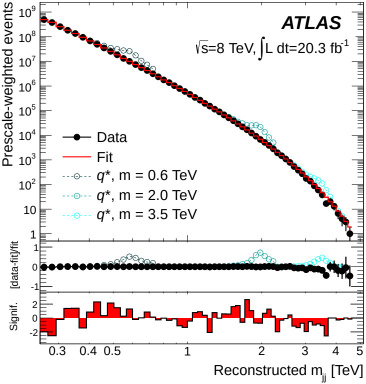
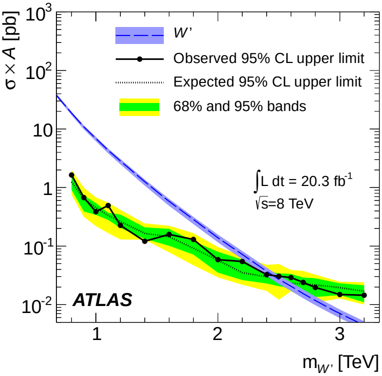
    - New bosons!



Introduction

- In searches for exotic models at ATLAS they are used to probe the **very highest** mass ranges
- An example from Run-1 is the ATLAS dijet resonance search, [arXiv:1407.1376]
  - Uses pairs of **high** p_{T} anti-kt 0.6 jets
  - Searches for **narrow** mass resonances
  - **Data driven** background model
- (Additional nice search using the angular distributions of dijets, [arXiv:1504.00357])





Introduction

- Today I will present a complementary analysis to the dijet, a search for **diboson resonances** using **jet-substructure** performed on the full 8 TeV dataset from ATLAS.
- Which can be found here [arXiv:1506.00962], for those with no patience

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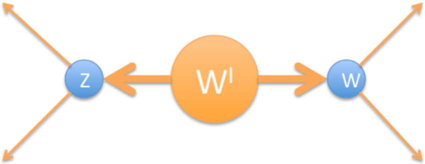
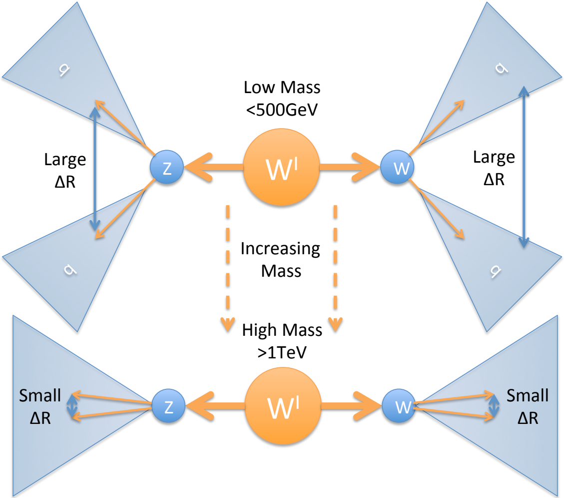
- Diboson resonances appear in many extensions to the standard model
- The following analysis concentrates on two **benchmark** models
  - Extended gauge sector models ($W' \rightarrow WZ$)
  - Extra dimensions models ($G_{RS} \rightarrow WW/ZZ$)
- **Low branching ratios** hinder the leptonic searches 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%)

Boosted Bosons



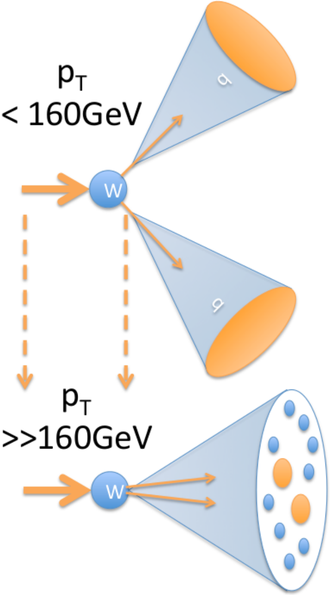
- Vector bosons have mass $\mathcal{O}(0.1\text{ TeV})$
- We are interested in particles of mass $\geq \mathcal{O}(1\text{ TeV})$
- Therefore the decays of the form, $X \rightarrow VV$ with large m_X, lead to vector bosons with **very high p_T**
- Therefore, boosted decay products become more **collimated**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

Boosted Bosons

- Can roughly separate hadronic boson decays into **two** regimes

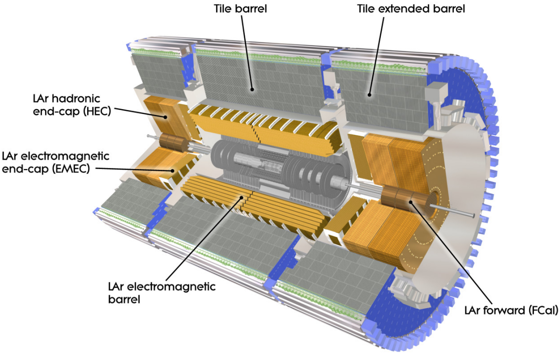
1. **Resolved**
   - Lower momentum W, $p_{\mathrm{T}} < 160$ GeV
   - W decay resolved in **two distinct** anti-kt 0.4 jets
2. **Boosted**
   - Higher momentum W, $p_{\mathrm{T}} \gg 160$ GeV
   - W decay products can be captured within a **single large-R** jets ($R \geq 1.0$)

- Some overlap in between for **partially** resolved systems
- So, how can we use this information to our **advantage**?



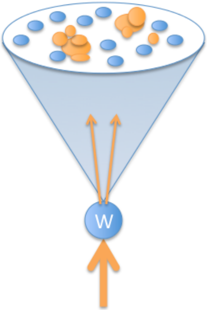
A quick aside: ATLAS calorimetry

- Jets in ATLAS are formed from **topoclusters**
  - Logical combinations of adjacent energy deposits in the calorimeter cells
- The hadronic calorimeters in ATLAS have a **fine** granularity
  - Tile: $\Delta R \approx 0.1$
  - LAr: $\Delta R \approx 0.025$
- We have the resolution to pick apart **large-R** jets and look at the **substructure**
- Therefore we can use the **guts** of boosted jets to our advantage

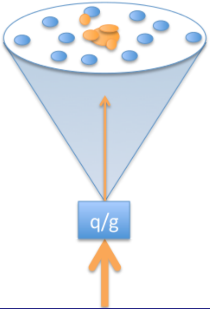


Bosonic vs QCD Jets

- **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

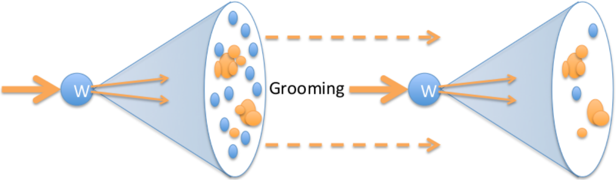


- **QCD** jets
  - **Narrow** region with high energy density corresponding to a single quark/gluon
  - Majority of the jet momentum is **concentrated** in this single region
  - Jet mass originates from the **spread** of the energy deposition by the single parton/any final state radiation, i.e. essentially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

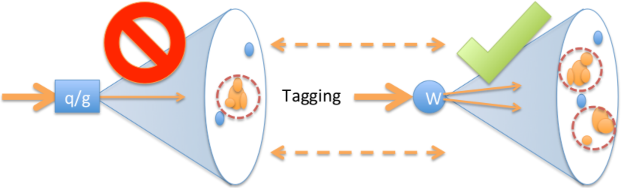


Fat Jet→Grooming→Tagging

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

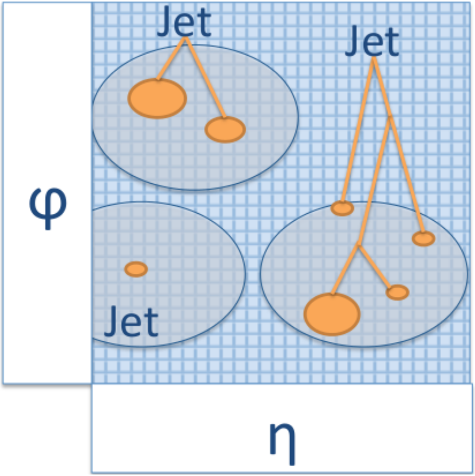


3. Tag as boson jet
    - Use differences between signal and background jet characteristics to reject background jets



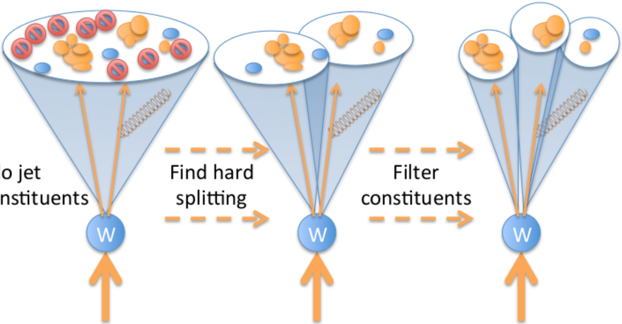
Cambridge-Aachen Jets

- **Cambridge-Aachen** jets (CA jets)
  - [arXiv:9707323] or [arXiv:0802.2470]
- Part of the **sequential recombination** family of jet reconstruction algorithms
  - Calculate the ΔR_{ij} between all jet constituents
  - Combine **closest constituents** first
  - Merge while $R \leq 1.2$ (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
- **NO** p_{T} dependence!
- Therefore can look into the history and use the p_{T} splitting information



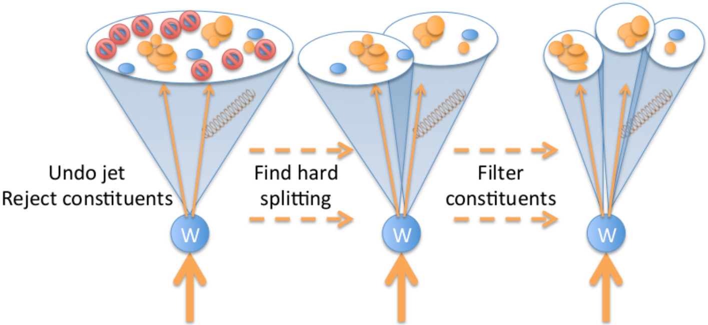
BDRS Split-Filter

- The **BDRS split filtering** algorithm, [arXiv:0802.2470], decomposes CA jets sequential clustering to find **hard substructure** within
- Originally defined to find **boosted** $H \rightarrow bb$ 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**, $m_{j_1} < \mu_{\max} m_j$ and the p_{T} balance is not **too asymmetric**, $\frac{min(p^2_{T_{j_1}}, p^2_{T_{j_2}})}{m^2_{j_0}} \Delta R^2_{j_1,j_2} \geq y_{\min}$, 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 $n_{\mathrm{r}} \times R_{\mathrm{r}}$ sized subjets

BDRS-A Split-Filter



- In this analysis a **modified BDRS-A** split filtering algorithm is used
- Starts from $R = 1.2$ CA jets seeded from locally 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
Iterative 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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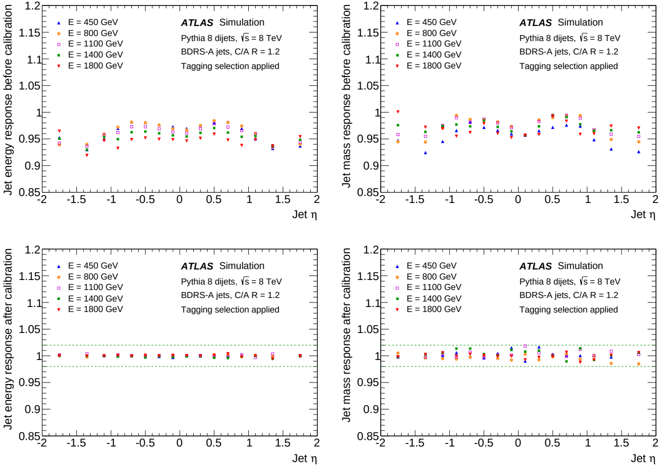
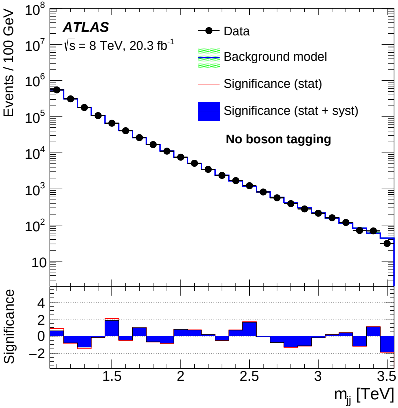
- Calculate the **jet energy response** in bins of η_{det} and E_{truth}
- Fit the responses with a Gaussian fit, to gain **mean response** in each bin, $< \mathrm{R}_{\mathrm{E}}^{\mathrm{jet}} >$
- Derive the mean reconstructed jet energy, $< \mathrm{E}_{\mathrm{reco}}^{\mathrm{jet}} >$
- Fit the $< \mathrm{R}_{\mathrm{E}}^{\mathrm{jet}} >$ vs $< \mathrm{E}_{\mathrm{reco}}^{\mathrm{jet}} >$ distribution to gain a **calibration function**
- Repeat process for **mass calibration** using the LCW+JES jets



Killing the Background

- Let me briefly try to quantify the level of the dominant **QCD background** the analysis will encounter
    - Other backgrounds contribute, at a significantly lower rates
    - All modelled to be smoothly falling
- It is a lot.... an **awful** lot



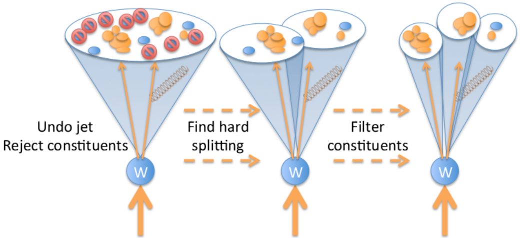
Leading jet p_T	QCD $\frac{d\sigma}{dp_T}$	W' $\frac{d\sigma}{dp_T}$	S/B
[TeV]	[fb/GeV]	[fb/GeV]	[−]
0.5	10^3	10^{-1}	10^{-4}
1.0	10	10^{-3}	10^{-4}

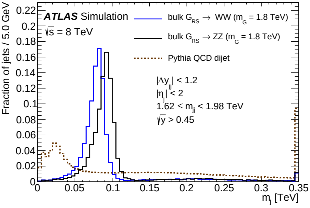
- Rough order of magnitude differential cross sections taken from MC show the extent of the problem, **1 signal in 10k** background events
- **Obvious problem** when you look at the raw events selected by the jet trigger used in the analysis
- Our **jet substructure thresher** has quite the **haystack** against it

Tools at our disposal

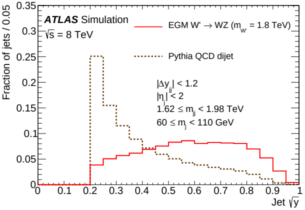
- What do we have to remove the QCD background?

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

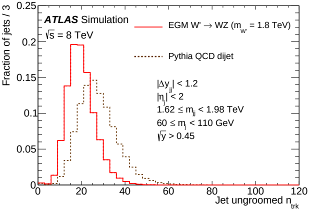




2. Filtered jet mass
    - Separates peaked boson mass from falling QCD spectrum



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

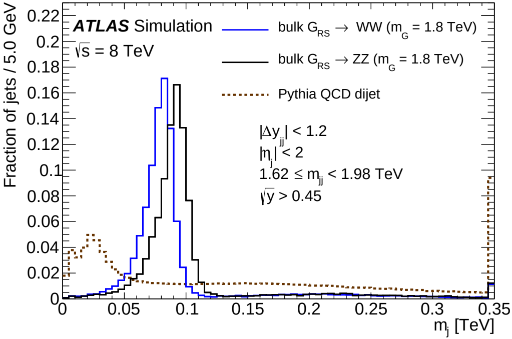


4. Number of tracks ghost matched to the unfiltered jet
    - More hadronic activity in QCD jets

Tools: Jet mass

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

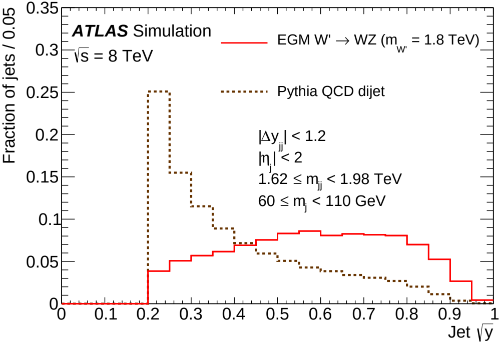
- Apply ±13 GeV **window cuts** around boson mass from MC simulation peak ($m_W = 82.4$, $m_Z = 92.8$)
- For example, in the *WZ* cut;
    - Leading mass jet $79.8 \text{ GeV} < m_{\text{jet}} < 105.8 \text{ GeV}$
    - Subleading mass jet $69.4 \text{ GeV} < m_{\text{jet}} < 95.4 \text{ GeV}$
- Very **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!!!**



Tools: Subjet momentum balance

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

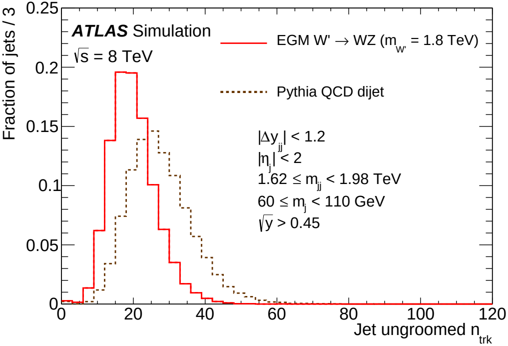
- $W/Z \to q\bar{q}$ decays tend to share momentum **equally** between decay products
- **Soft gluon** radiation leads to asymmetric splittings
- Apply a more stringent $\sqrt{y} \geq 0.45$ cut on the subjet momentum balance
- Another **powerful** cut!
  - $\epsilon_{\text{signal}} \approx 70\%$
  -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



Tools: Ghost matched jets

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

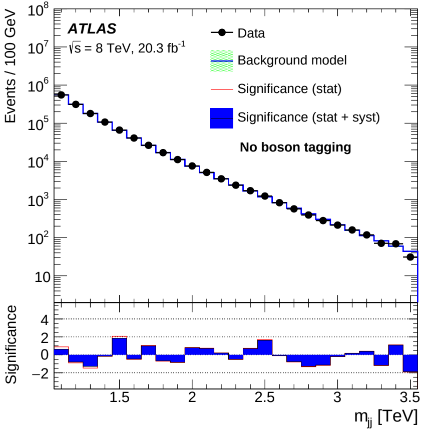
- Emission of **hard gluon** dominates after mass/asymmetry cuts
- Expect increased **hadronic** activity from gluon
- Use the number of **ghost associated** ungroomed tracks, n_{trk}, as a proxy for hadronic activity, [arXiv:0802.1188]
- Apply $n_{\mathrm{trk}} \leq 30$ cut
- Efficiency after mass/asymmetry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



Event selection: Putting it 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
    - 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** $A_{p_\mathrm{T}} < 0.15$
    - 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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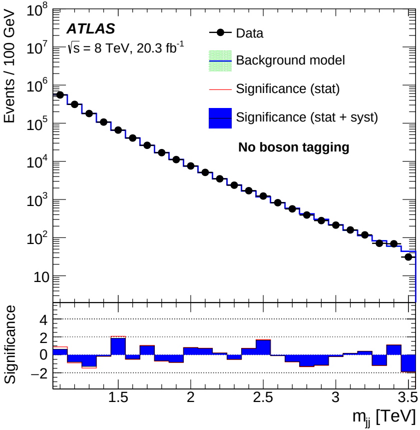

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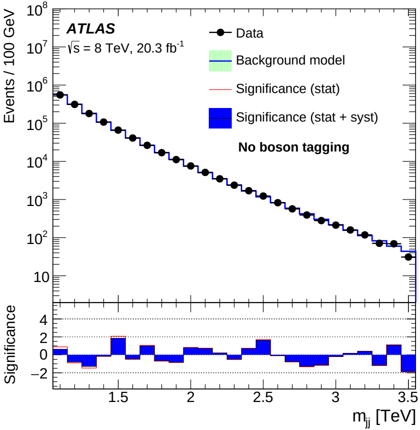

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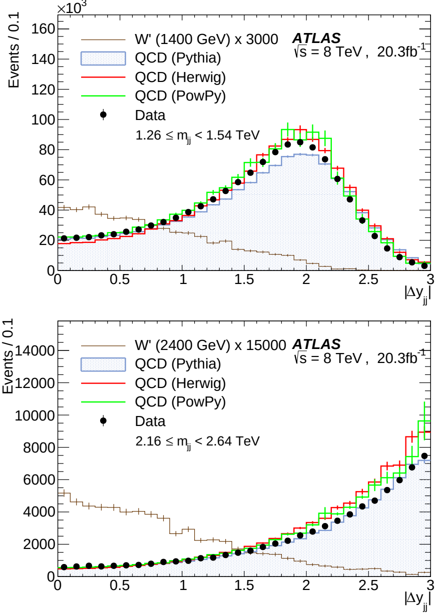

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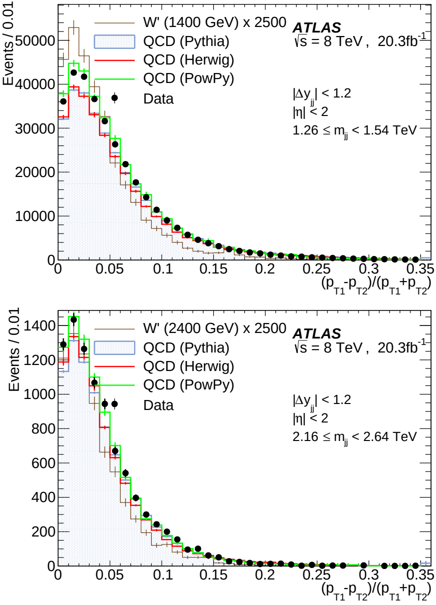

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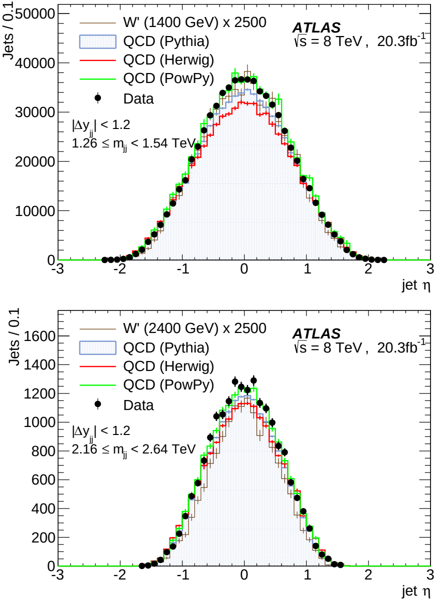

Event selection: Putting it all together

1. **Trigger:** $p_{\mathrm{T}} > 360$ GeV anti-kt 1.0
2. Apply **BDRS-A** split-filter
3. Require $m_{JJ} > 1.05$ TeV
   - 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** $A_{p_{\mathrm{T}}} < 0.15$
   - Used as proxy for large-R **jet cleaning**
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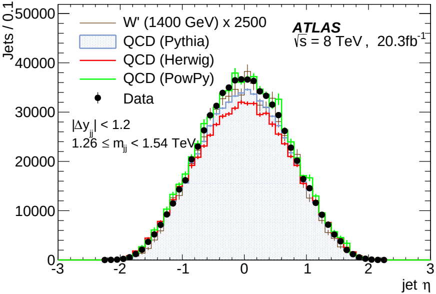

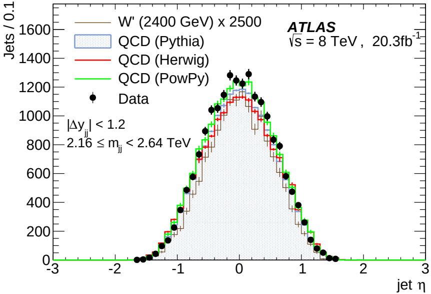

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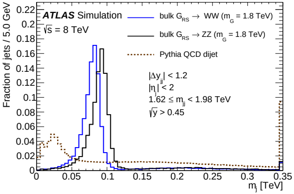

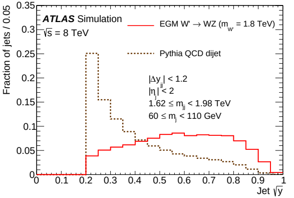

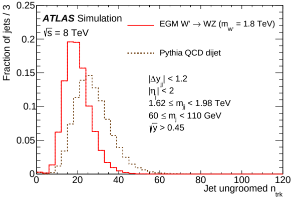

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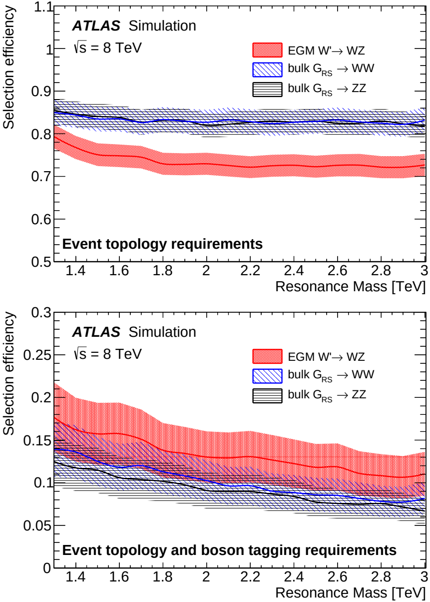
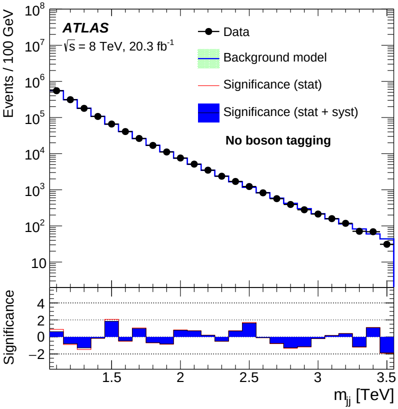


Modelling the Background

- 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



- 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

$$\frac{\mathrm{d}n}{\mathrm{d}x} = p_1(1 - x)^{p_2 - \xi p_3} x^{p_3}$$

- Where,
  - $x = m_{JJ}/\sqrt{s}$
  - m_{JJ} is the dijet invariant mass,
  - p_1 is a normalisation factor,
  - p_2 and p_3 are dimensionless shape parameters
  - ξ is a dimensionless constant chosen after fitting to minimise the correlations between p_2 and p_3

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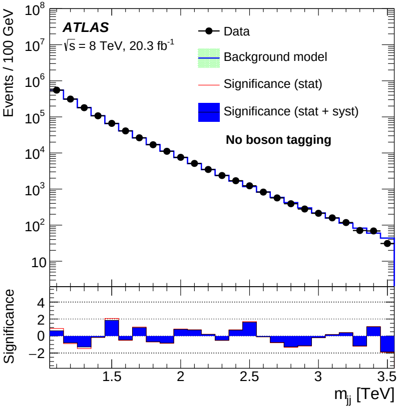

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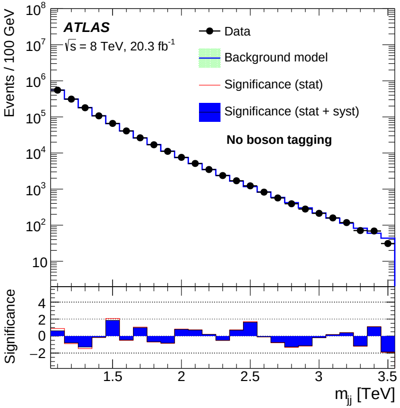

Sample	χ^2/nDOF	Probability
PYTHIA dijet events	24.6/22	0.31
HERWIG++ dijet events	15.9/22	0.82
Data with $110 < m_{j1} \leq 140$ GeV and $40 < m_{j2} \leq 60$ GeV	12.1/11	0.79
Data with $40 < m_j \leq 60$ GeV for both jets	19.8/13	0.56
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- Alternate fit functions give **similar** results
- Error taken from errors on **functional parameters**
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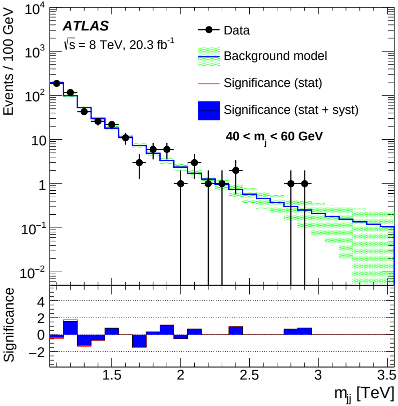

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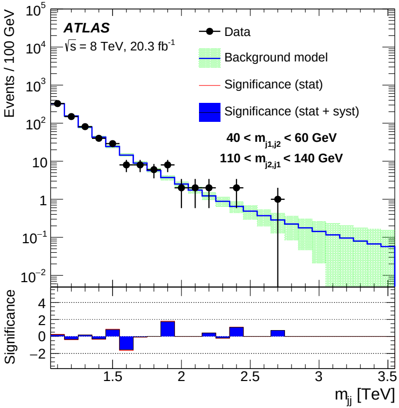

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$$\frac{dn}{dx} = p_1(1-x)^{p_2-\xi p_3}x^{p_3}$$

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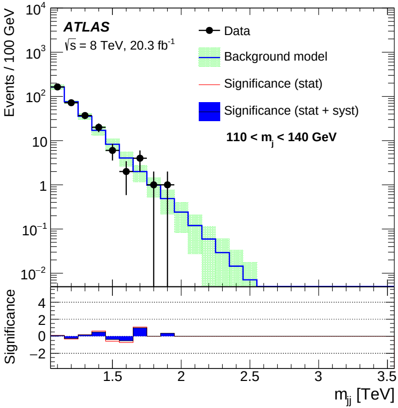

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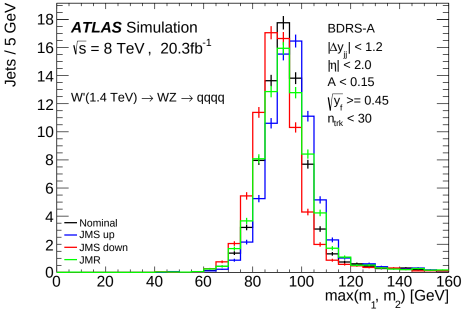
Systematic uncertainties: Shape

- **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,

$$\frac{X^{\mathrm{data}}_{\mathrm{track}} / X^{\mathrm{data}}_{\mathrm{calo}}}{X^{\mathrm{MC}}_{\mathrm{track}} / X^{\mathrm{MC}}_{\mathrm{calo}}}$$

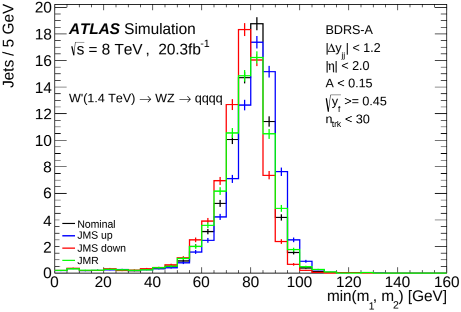
- Applied as a Gaussian with $\mu = 1$ and σ equal to the **observed uncertainty**
  - jet p_{T} scale: 2%
  - jet mass scale: 3%
- An uncertainty on the jet p_{T} resolution of 20% is applied as an additional **smearing** on top of the nominal 5%



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

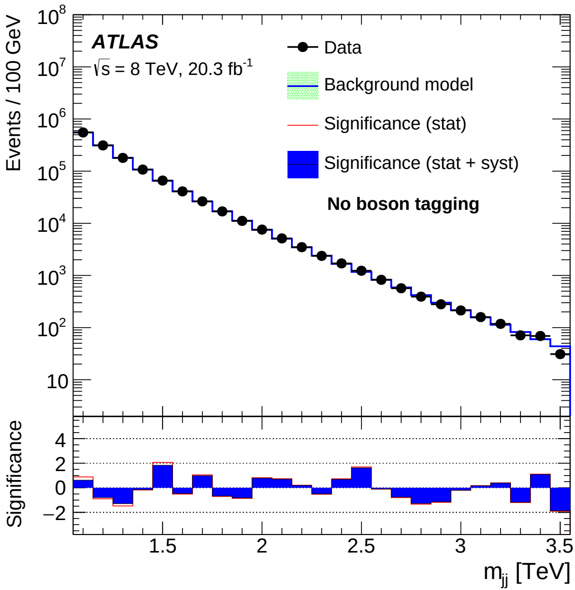
Systematic uncertainties: Normalisation

  - **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



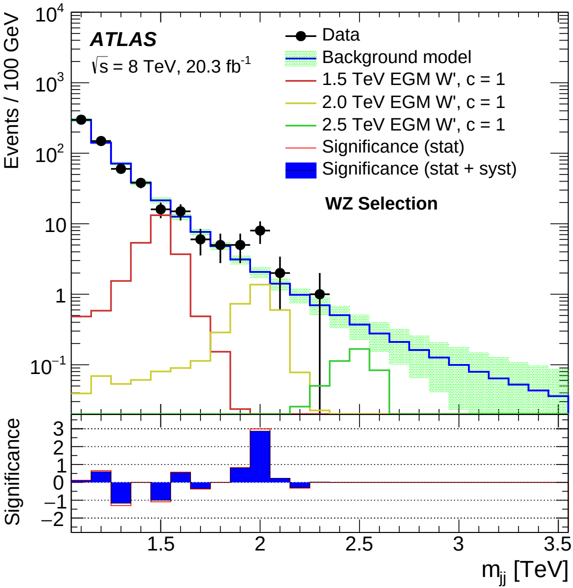
Source	Uncertainty
Efficiency of the track-multiplicity cut	20.0%
Jet mass scale	5.0%
Jet mass resolution	5.5%
Subjet momentum-balance scale	3.5%
Subjet momentum-balance resolution	2.0%
Parton shower model	5.0%
Parton distribution functions	3.5%
Luminosity	2.8%

The long and winding road....



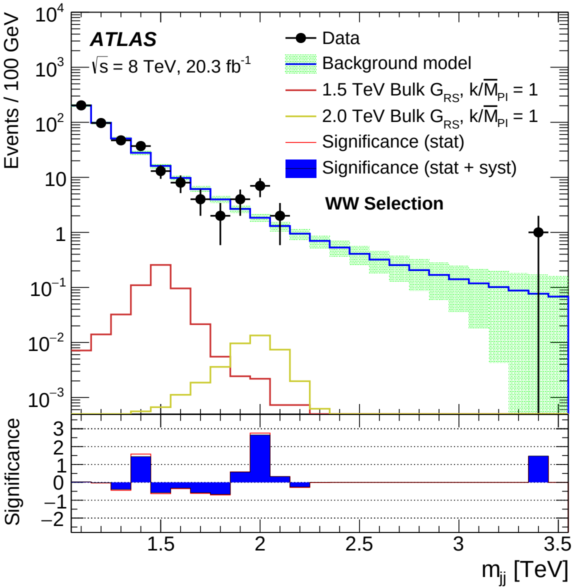
- OK, enough with the build-up.....
- What does the triggered data look like after applying our selection???

$X \rightarrow WZ$ selection



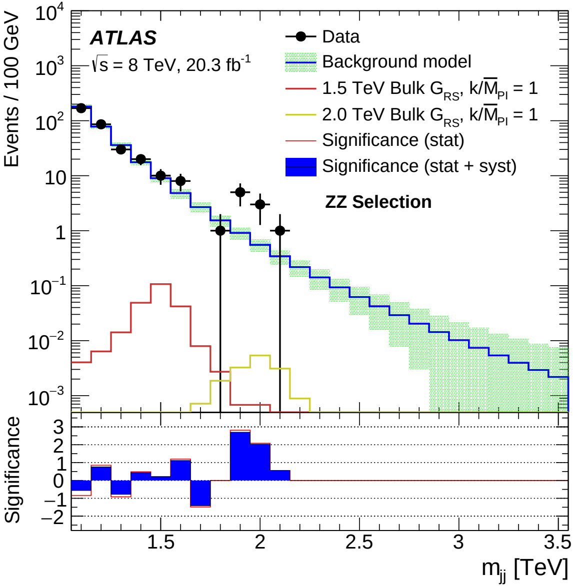
- Full **WZ** selection applied to the data
  - Z mass window applied to **leading** mass jet
  - W mass window applied to **sub-leading** mass jet
- **Good agreement** seen with steeply, smoothly falling background model in the low/high mass regions
- **Deviation** from the background observed at around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

$X \to WW$ selection



- 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 (≈ 20%)
- **Benchmark** Bulk Randall-Sundrum graviton signal MC shown for **comparison** purposes

$X \to ZZ$ selection



- Full **ZZ** selection applied to the data
  - *Z* 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 (≈ 20%)
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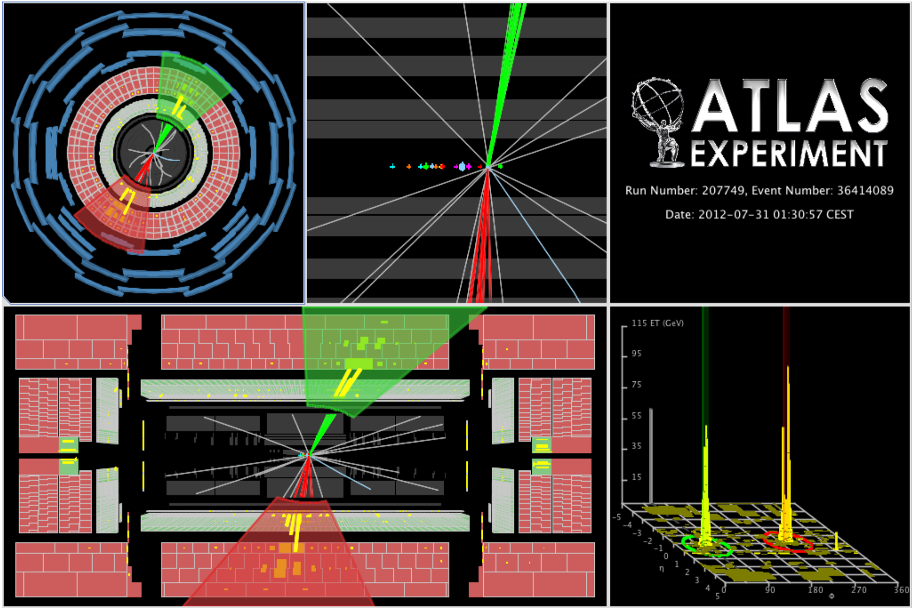
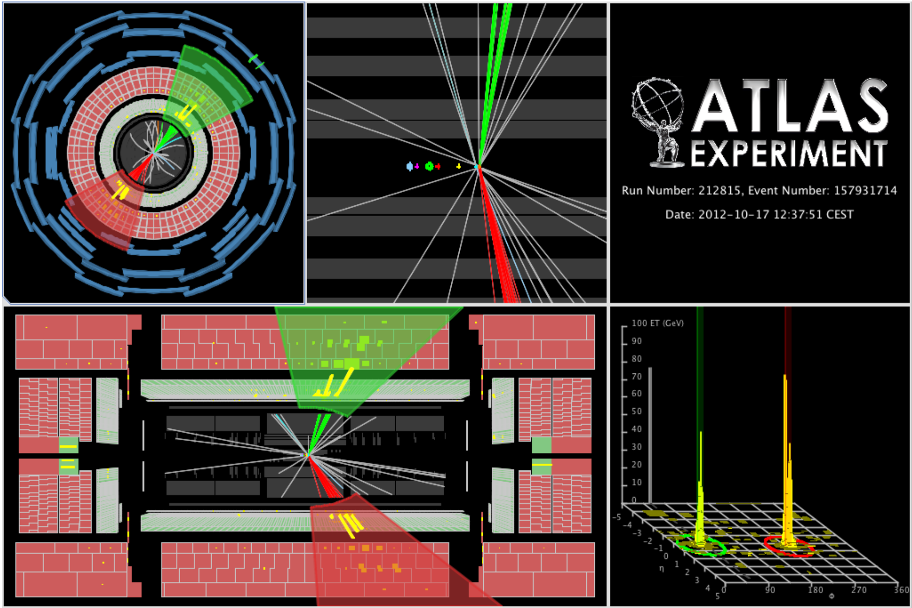
What do these events look like? Dramatic!



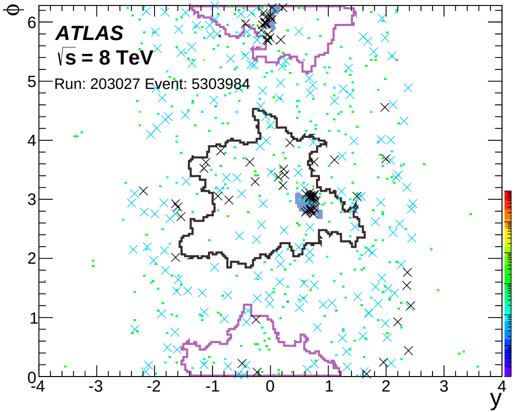
What do these events look like? Energetic!



Digging deeper into the jets....

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 η 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



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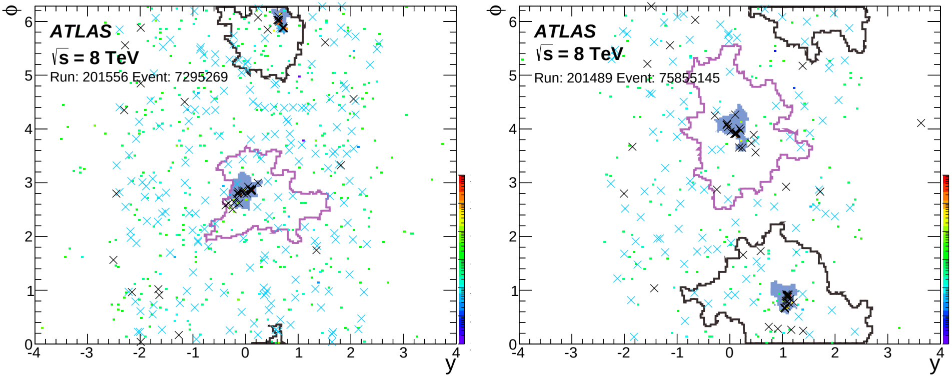
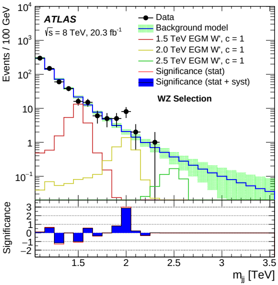


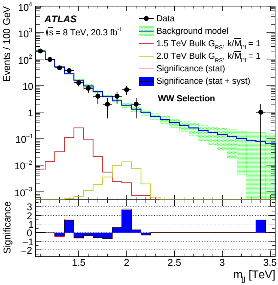
What do we see here?

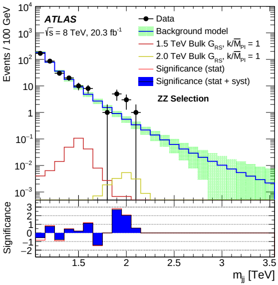
- Subjets are highly collimated
- PV tracks are highly correlated with the selected sub-jets
- Energy deposits concentrated in the sub-jet
- Pile-up tracks/deposits sparsely distributed over the events
- Successfully picked the boson out of the pileup?

Time to cross-check.....

- Deviations from the expected background, especially ones at the tail of the data distribution, mean one thing for physicists....
  - What on Earth did we do wrong?
- Try to evaluate any possible issues with the analysis
- Operation Cross-check begins
- Look for mistakes, bugs or shaping effects in:
  - Detector/data taking effects
  - Jet reconstruction effects
  - Event selection effects







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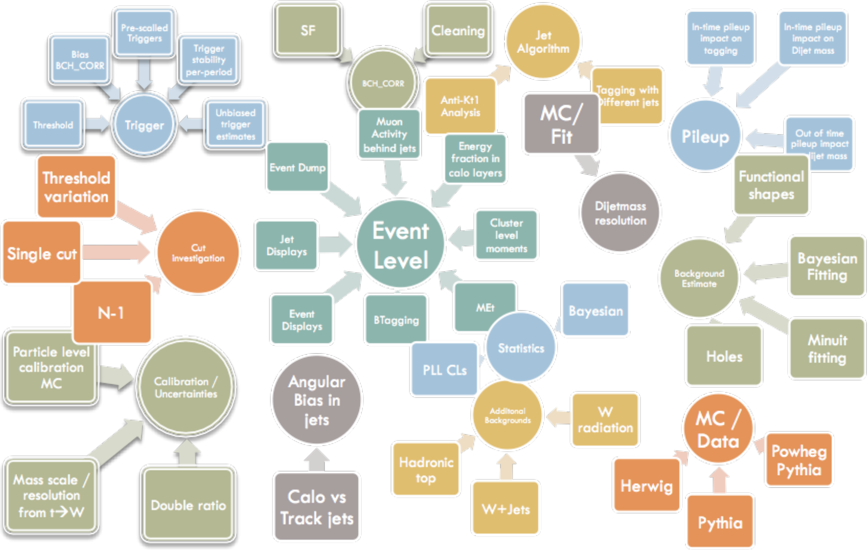


Bias BCH_CORR

Pre-scalled Triggers

Trigger stability per-period

Threshold

Trigger

Unbiased trigger estimates

Threshold variation

Single cut

Cut investigation

N-1

Particle level calibration MC

Calibration / Uncertainties

Mass scale / resolution from t→W

Double ratio

SF

BCH_CORR

Cleaning

Muon Activity behind jets

Anti-Kt1 Analysis

Energy fraction in calo layers

Jet Algorithm

Event Dump

Jet Displays

Event Level

Cluster level moments

Event Displays

BTagging

MEt

Statistics

Bayesian

PLL CLs

Angular Bias in jets

Calo vs Track jets

Additonal Backgrounds

W radiation

Hadronic top

W+Jets

MC/ Fit

Tagging with Different jets

Dijetmass resolution

In-time pileup impact on tagging

In-time pileup impact on Dijet mass

Pileup

Out of time pileup impact ijet mass

Functional shapes

Background Estimate

Bayesian Fitting

Minuit fitting

Holes

MC / Data

Powheg Pythia

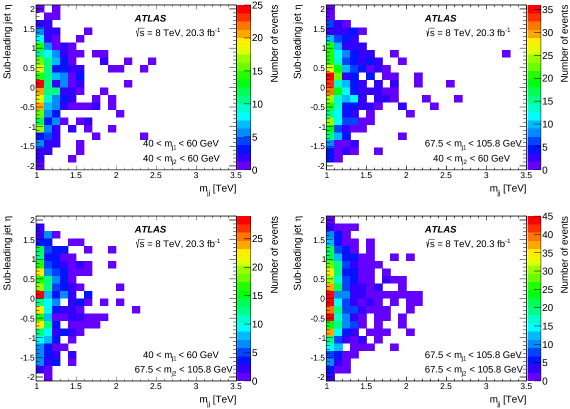
Herwig

Pythia

From E. Kajomovitz

Time to cross-check.....

- Started trawling through SR/CR kinematic distributions, looking for unusual features in the signal regions
- Look at the effect of single cuts on the distribution
- Look at the effect of $N - 1$ cuts on the distribution
  - Is one cut driving all of the deviation?
- Many, many, many..... more, you can only get so much approved...



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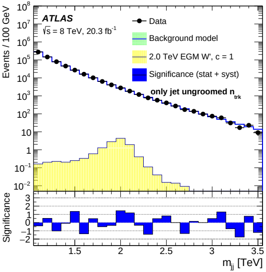

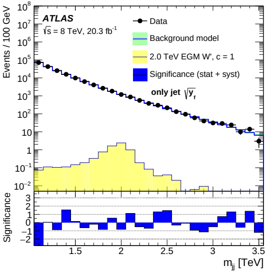

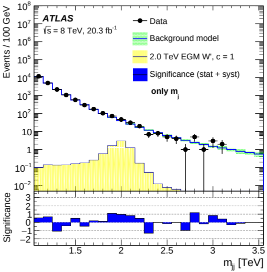

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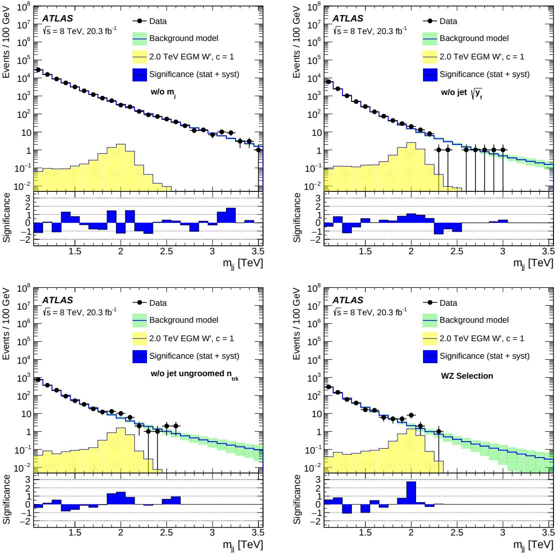
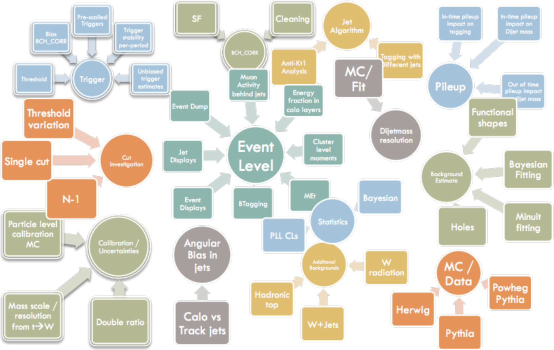
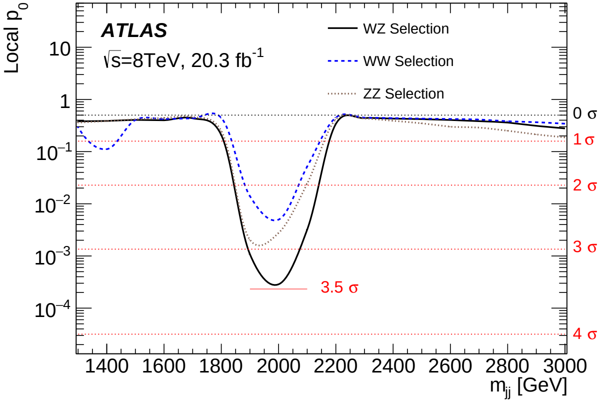


Did we find any errors?

- In so many cross-checks, yes, bugs were found and fixed
- Always attempted to shield the data from any possible biases by using control regions to test
- After almost a year and a half of scrutiny by the analysers/Exotics group/ATLAS we found no major issues
- Therefore we continue to publish the final results
- Run-2 was looming!



Observed p_0 value

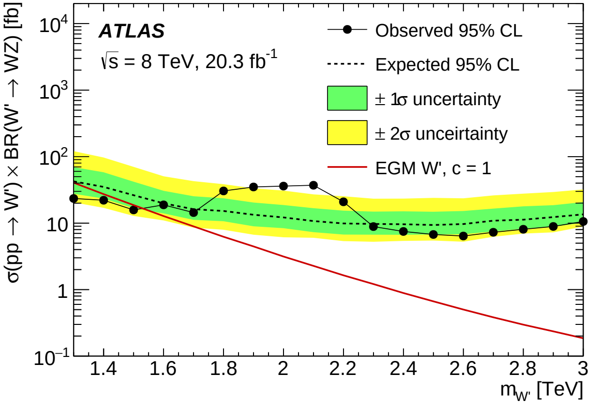


- A **discrepancy** was seen with respect to the expected background distribution
- Once suitably confident it is not an error, its significance should be **quantified**
- In the *WZ* channel:
- **Local** $p_0 = 3.4\sigma$
- **Global** $p_0 = 2.5\sigma$
  - Global σ takes into account the **look elsewhere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

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

$X \to WZ$ limits

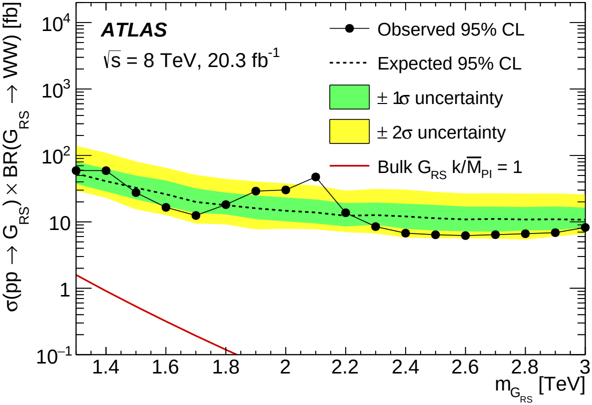
- As no **significant deviation** was observed, we continue to set limits on the observed distributions
- 95% confidence limits set on $\sigma \times \mathcal{B}$ using the $\mathrm{CL_S}$ prescription taking into account the **systematic uncertainties** and **background fit**



- **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

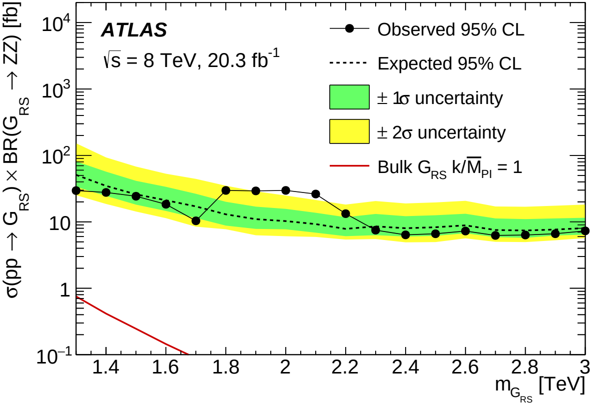
- As no significant deviation was observed, we continue to set limits on the observed distributions
- 95% confidence limits set on $\sigma \times \mathcal{B}$ using the $\mathrm{CL_S}$ prescription taking into account the systematic uncertainties and background fit



- **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

- 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



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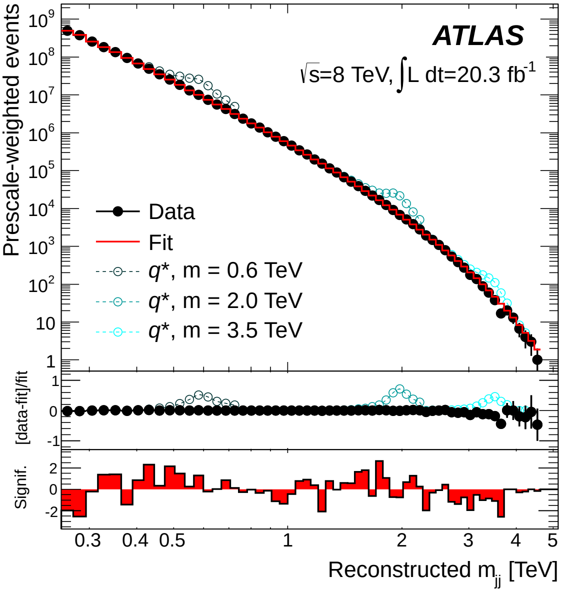
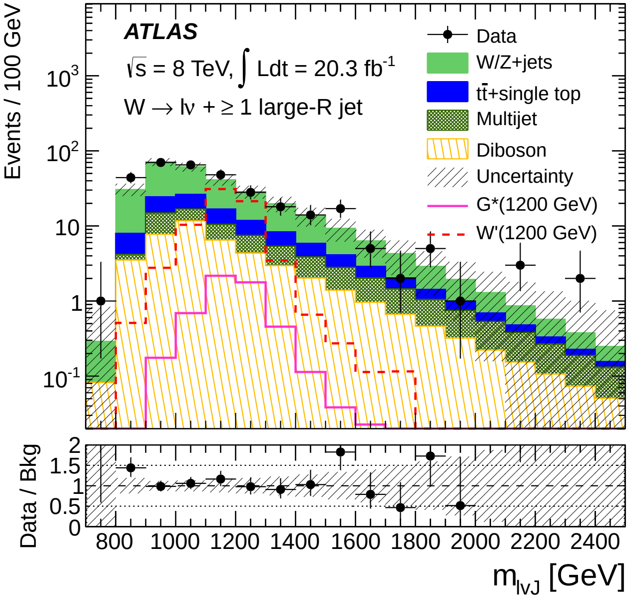
- **Exclusion** of graviton production at no masses
- **Broad deviation** from the background observable at around 2 TeV
- **Benchmark** Bulk Randall-Sundrum graviton $\sigma \times \mathcal{B}$ shown for **comparison** purposes

Are we alone? ATLAS searches



- ATLAS resolved dijet search [arXiv:1407.1376], 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? ATLAS searches



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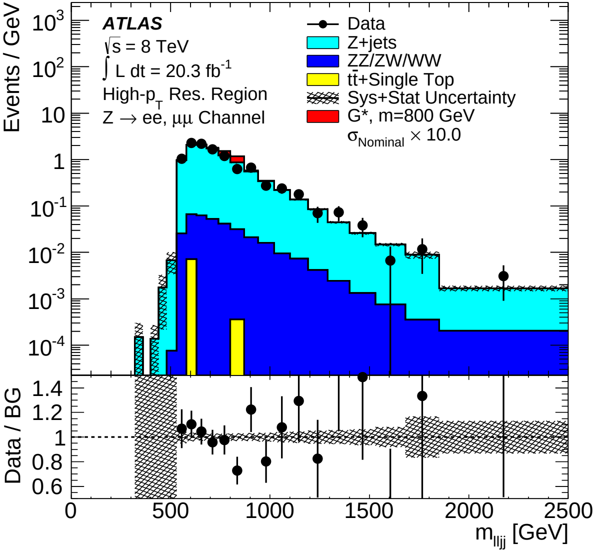

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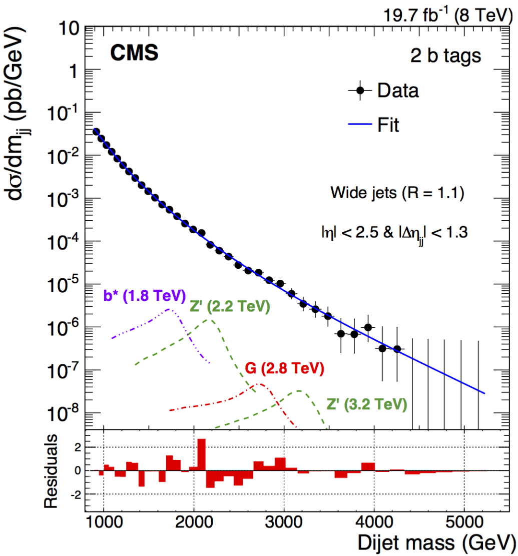
Are we alone? Across the ring....CMS



- 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 hadonric search [arXiv:1405.3447], uses n-subjettiness, broad blip at 2TeV ☒☑

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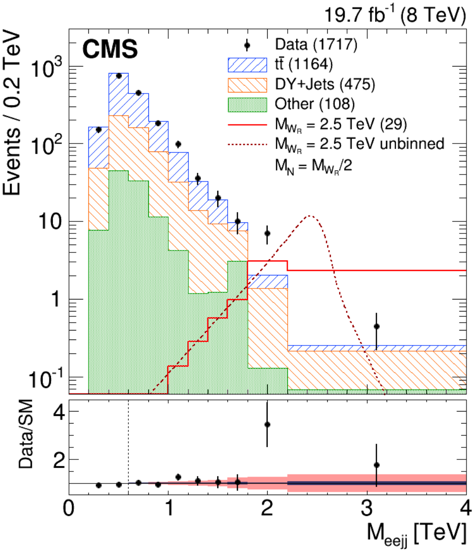

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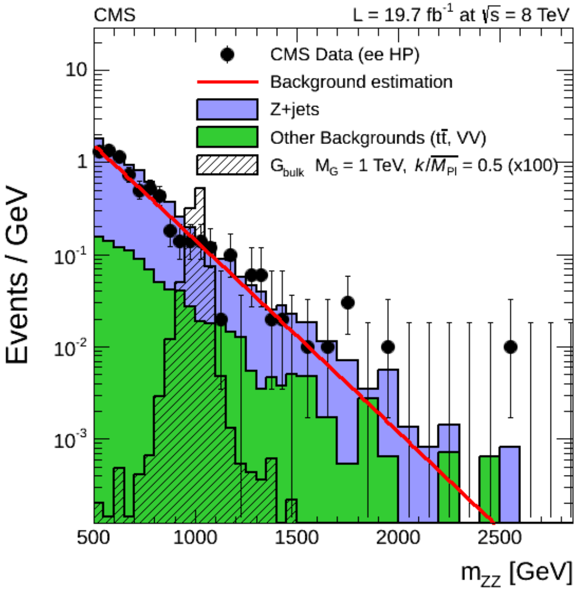

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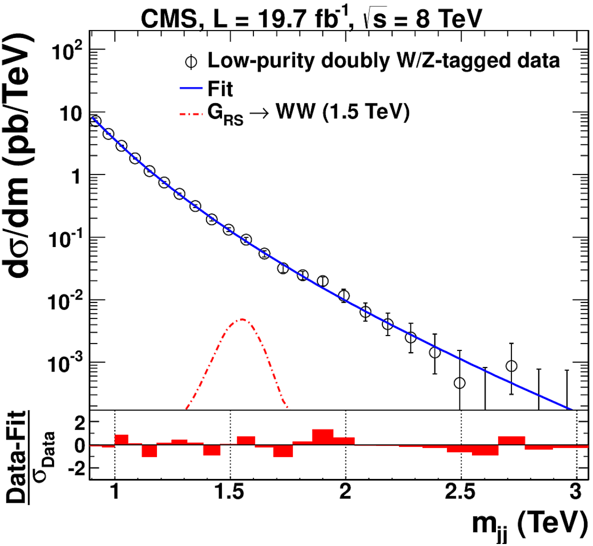

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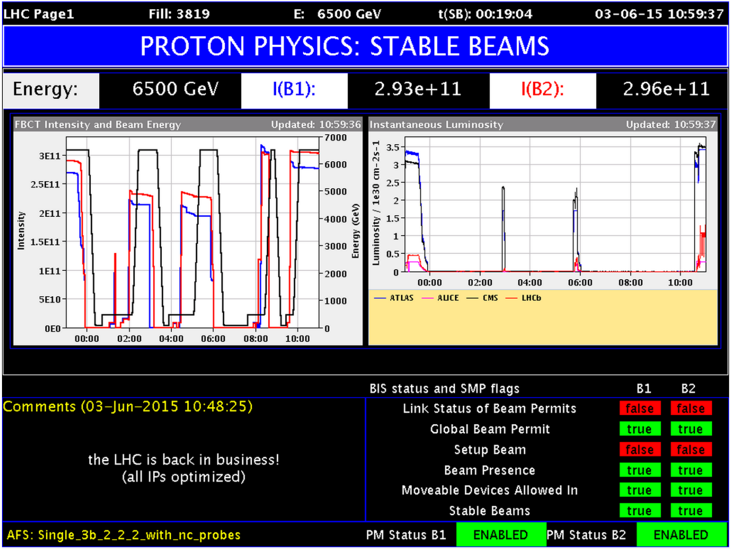
The Future: Run-2

~~The Future~~ Now: Data is here!



LHC Page1 Fill: 3819 E: 6500 GeV t(SB): 00:19:04 03-06-15 10:59:37

PROTON PHYSICS: STABLE BEAMS

Energy:	6500 GeV	I(B1):	2.93e+11	I(B2):	2.96e+11

Comments (03-Jun-2015 10:48:25)

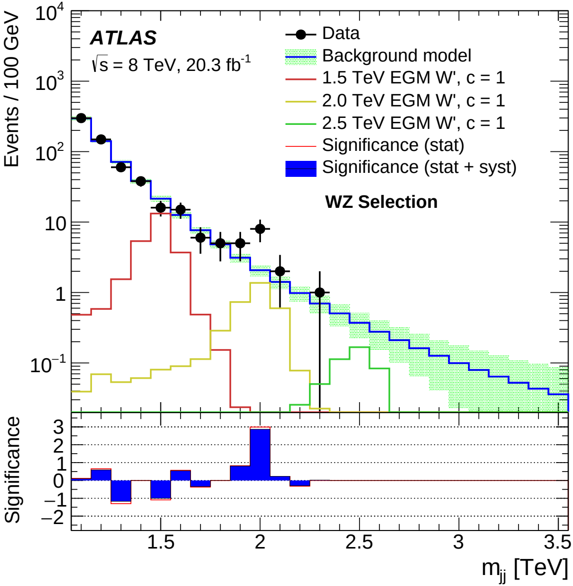
the LHC is back in business!
(all IPs optimized)

BIS status and SMP flags	B1	B2
Link Status of Beam Permits	false	false
Global Beam Permit	true	true
Setup Beam	false	false
Beam Presence	true	true
Moveable Devices Allowed In	true	true
Stable Beams	true	true

AFS: Single_3b_2_2_2_with_nc_probes PM Status B1 ENABLED PM Status B2 ENABLED

Fun fact: The Run-1 paper was submitted around 13 hours before the first collisions of Run-2

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**
  - For gluon-gluon fusion ×15, i.e. for G_{RS} production
  - For $q\bar{q}$ initiated ×8, i.e. for W' production
  - Unfortunately QCD background also increases
- So a **smaller** amount of Run-2 data ($1 - 3 fb^{-1}$) is should be roughly equivalent to the 8 TeV dataset

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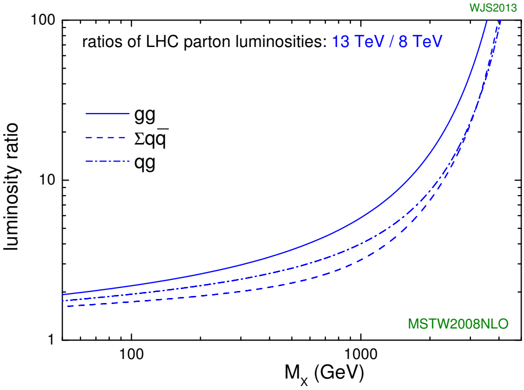

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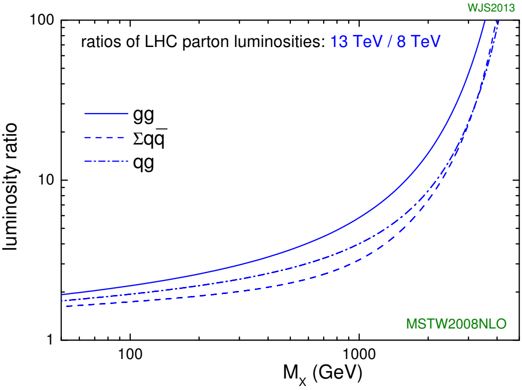

- So question one is **how much** Run-2 13 TeV data do we need to **surpass** the Run-1 result?
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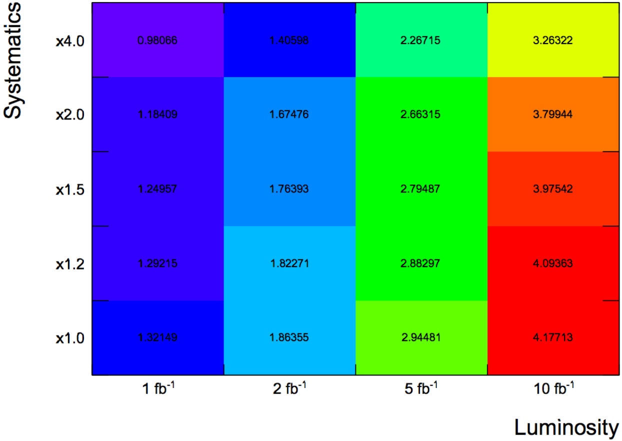


Systematics	1 fb^{-1}	2 fb^{-1}	5 fb^{-1}	10 fb^{-1}
x4.0	0.98066	1.40598	2.26715	3.26322
x2.0	1.18409	1.67476	2.66315	3.79944
x1.5	1.24957	1.76393	2.79487	3.97542
x1.2	1.29215	1.82271	2.88297	4.09363
x1.0	1.32149	1.86355	2.94481	4.17713

- What local σ values can we see **assuming**
  - Different 13 TeV recorded luminosity points
  - Systematics size w.r.t. Run-1
  - Injecting a signal with a cross-section the size of the discrepancy seen in Run-1
- **If realised** in nature, observation should be possible even with the reduced 2015 data expectations

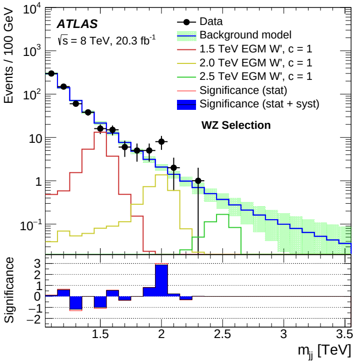
- Semi-leptonic channels can **control backgrounds** more easily (mostly V+jets)
- Should have an **equivalent reach** at 2 TeV to the fully hadronic channel in Run-2!
- Hadronic channel will still be **more competitive** at the highest masses

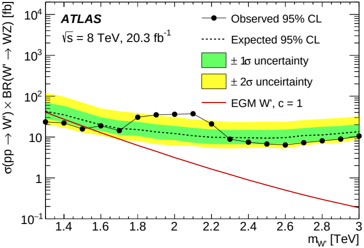
Ready for data?

- New ATLAS data format, **xAOD** working ☑
- Physics derivations, **DxAOD**, running ☑
  - On **MC** ☑
  - On **data** ☑
- **CxAOD** analysis framework in place ☑
- **ResonanceFinder** statistical framework in place ☑
- New **R2D2** boosted boson tagger defined ☑
  - **No really**... $R = 0.2$ subjet, D_2^{β} substructure variable
  - [arXiv:1409.6298]
- Ready, to **improve** the analysis with **new techniques** and **data** **YES!** ☑
- Steady, to **push** search to higher masses **YES!!** ☑
- Go, to **confirm/disprove** excess **YES!!!** ☑

Conclusions

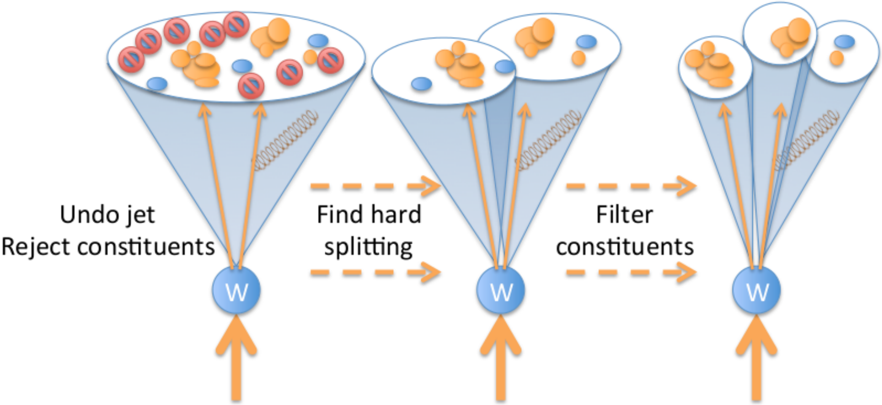
- Presented a search for a **high mass diboson resonance**
    - Used $20.3\mathrm{fb}^{-1}$ 8TeV ATLAS data
    - Jet substructure (BDRS-A CA 1.2 jets) used to separate signal from background
    - QCD dominated background modelled by parametric function
- **Deviation** from expected steeply, smoothly falling background seen at **2 TeV**
- Cross-checks performed, **no major issues** discovered
- **Excess** $p_0 = 3.4\sigma$ local, 2.5σ global
- **Limits** exclude EGM W' models with $1.3 < m_{W'} < 1.5$ TeV
- **Preparations** underway to repeat search in 13TeV data





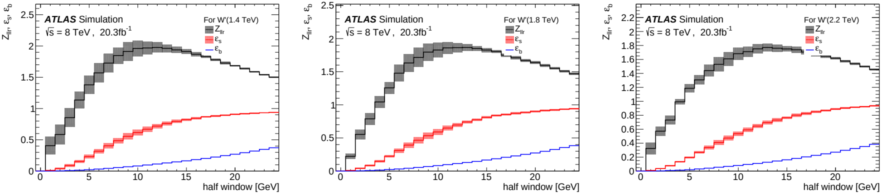
Backup

Backup



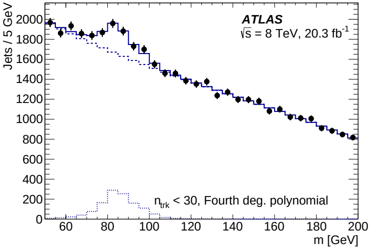
Mass window optimisation

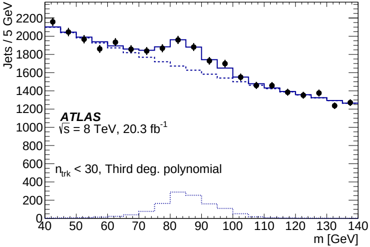
- A data CR was formed from two tagged/untagged samples
- A wide mass window ($40 < m_J < 400$ GeV) used
  1. CR A: Leading jet tagged, sub-leading fails tag
  2. CR B: Leading jet fails tag, sub-leading passes tag
- Forms dijet sample by taking one jet from CR A and one from CR B
- Use this as a high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



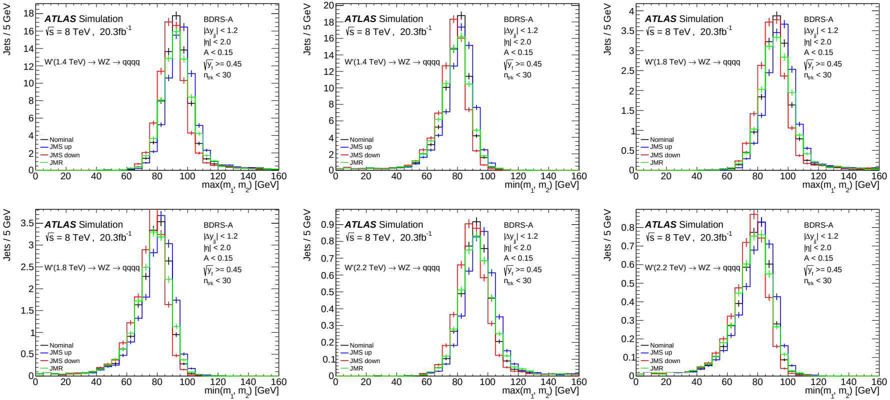
n_{trk} optimisation

- 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



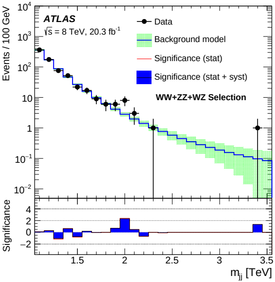


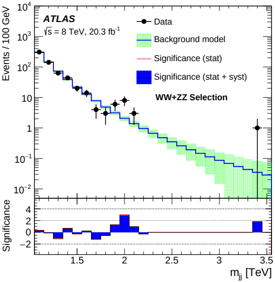
Systematic variations

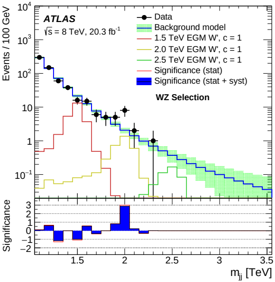


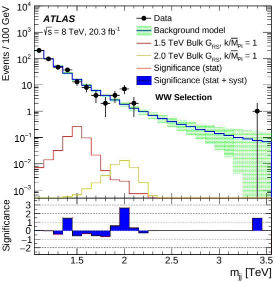
Selection overlaps

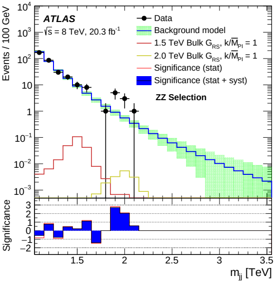
- Comparing the effect of applying all signal selections at once, and the same flavour selections at once











Signal properties

- The resonance width (Γ) and the product of cross sections and branching ratios (BR) to four-quark final states used in modelling $W?\rightarrow WZ$, $G_{RS}\rightarrow WW$, and $G_{RS}\rightarrow ZZ$, 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.

			$W'\rightarrow WZ$		$G_{\mathrm{RS}}\rightarrow WW$		$G_{\mathrm{RS}}\rightarrow ZZ$	
m [TeV]	$\Gamma_{W'}$ [GeV]	$\Gamma_{G_{\mathrm{RS}}}$ [GeV]	$\sigma\times\mathrm{BR}$ [fb]	$f_{10\%}$	$\sigma\times\mathrm{BR}$ [fb]	$f_{10\%}$	$\sigma\times\mathrm{BR}$ [fb]	$f_{10\%}$
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

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m [TeV]	$\Gamma_{W'}$ [GeV]	$\Gamma_{G_{\mathrm{RS}}}$ [GeV]	$\sigma \times \mathrm{BR}$ [fb]	$f_{10\%}$	$\sigma \times \mathrm{BR}$ [fb]	$f_{10\%}$	$\sigma \times \mathrm{BR}$ [fb]	$f_{10\%}$
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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.

	WZ selection (Events)				WW selection (Events)				ZZ selection (Events)			
m_{jj} bin [GeV]	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

	$G_{\mathrm{RS}} \to WW$		95% CL Limits [fb]					
m [GeV]	$\sigma\mathrm{BR}_{WW}$ [fb]	Γ [GeV]	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

	$G_{\mathrm{RS}} \to ZZ$		95% CL Limits [fb]					
m [GeV]	$\sigma\mathrm{BR}_{ZZ}$ [fb]	Γ [GeV]	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