

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

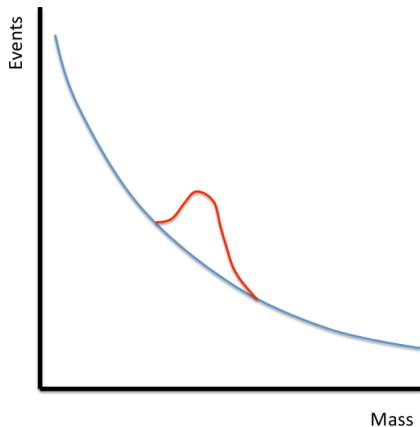
Using the jet substructure thresher on the QCD haystack

Alex Martyniuk, UCL

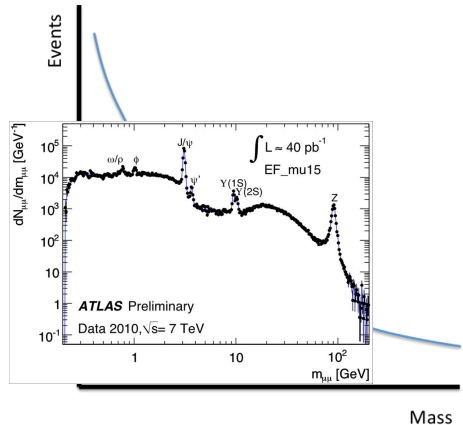
February 10, 2016



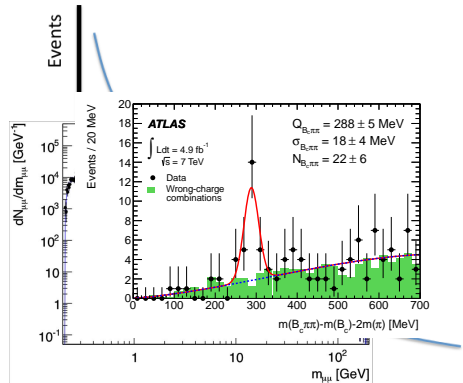
- Resonance searches are the **classic methodology** to search for new particles and their excitations
- In essence they boil down to, 'Look for a **peak** on a **smooth background**'
- Used in searches ranging from **quarkonia** to the **Higgs**



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 - Rediscovering the SM

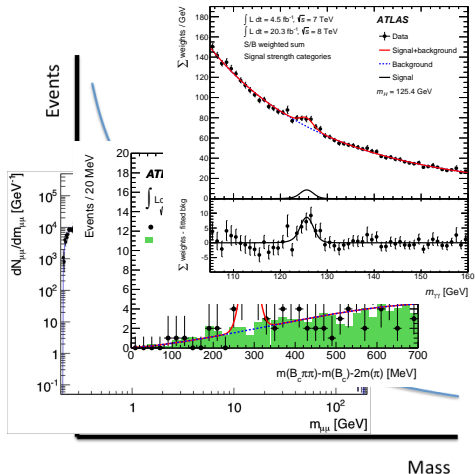


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 - Rediscovering the SM
 - New meson states

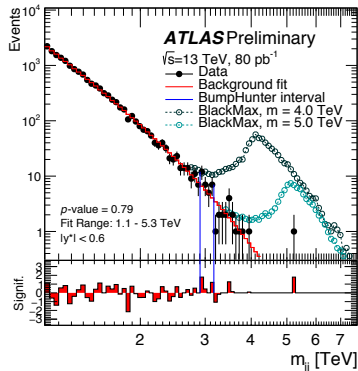
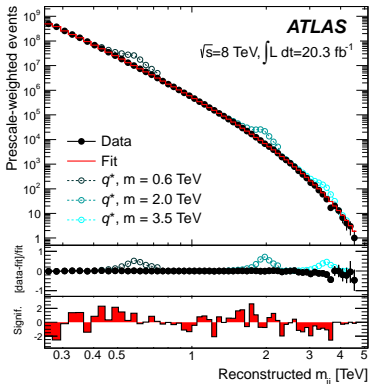


Mass

- 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**
 - Rediscovering the SM
 - New meson states
 - New bosons!

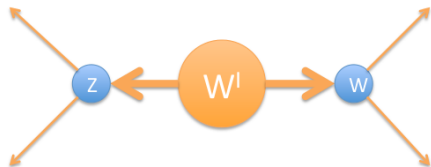


- Searches for exotic models at ATLAS use resonances to probe the **very highest** mass ranges, and are competitive in **very early** data
- Examples from Run-1/2 are the ATLAS dijet resonance searches, [\[arXiv:1407.1376\]](https://arxiv.org/abs/1407.1376) and [ATLAS-CONF-2015-042](https://arxiv.org/abs/1505.04201)
 - Uses pairs of **high** p_T anti-kt 0.6 jets
 - Searches for **narrow** mass resonances, alongside broader signals
 - **Data driven** background model

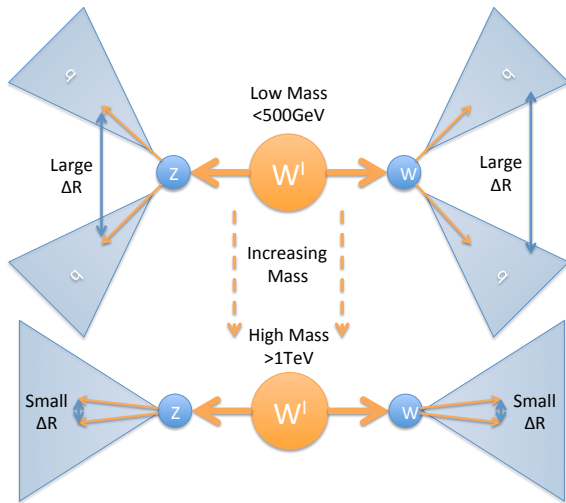


- Today I will present a pair of complementary analyses to the dijet, searches for narrow **diboson resonances** using **jet-structure** performed on the full 8 TeV and current 13 TeV datasets from ATLAS.
- Which can be found here [[arXiv:1506.00962](https://arxiv.org/abs/1506.00962)] and here [[CDS:2114845](https://cds.cern.ch/record/2114845)]

- 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%)



- 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**
- Boosted decay products become more **collimated**
- **Rule of thumb** for angular separation of decay products:
- $\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2} \approx \frac{2m}{p_T}$

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

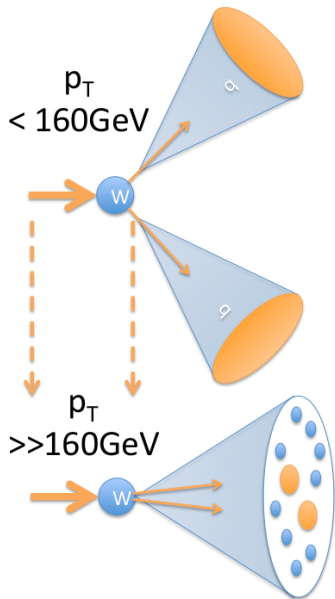
1 Resolved

- Lower momentum W , $p_T < 160$ GeV
- W decay resolved in **two distinct** anti-kt 0.4 jets

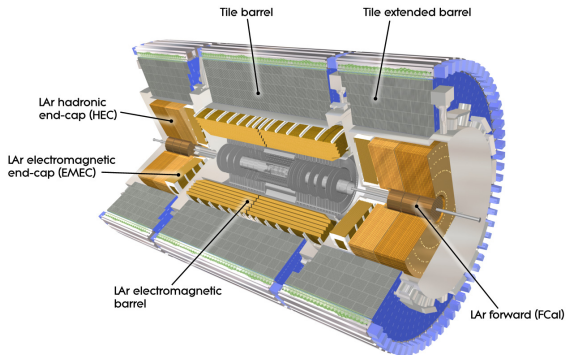
2 Boosted

- Higher momentum W , $p_T \gg 160$ 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?**

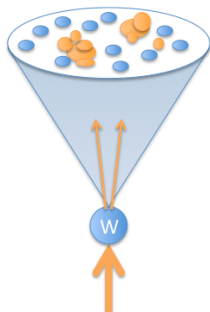


- Jets in ATLAS are formed from **topoclusters**
 - Logical combinations of adjacent energy deposits in the calorimeter cells
- The calorimeters in ATLAS have a **fine** granularity
 - Tile: $\Delta R \approx 0.1$
 - EM LAr: $\Delta R \approx 0.025$
- We have the resolution to pick apart **large-R**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



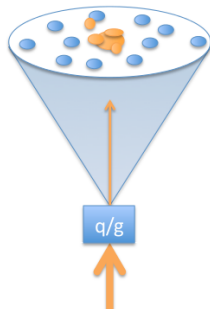
• Bosonic jets

- 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

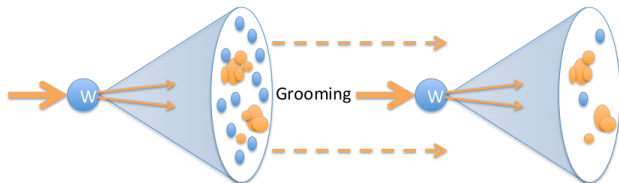


• QCD jets

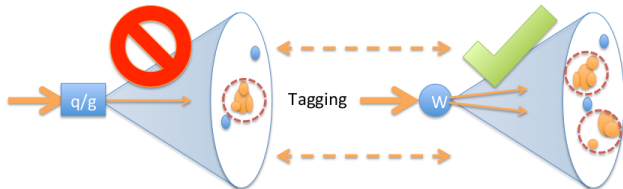
- **Narrow** region with high energy density corresponding to a single quark/gluon
- Majority of the jet momentum is **concentrated** in this single region
- Jet mass originates from the **spread** of the energy deposition by the single parton/any final state radiation, i.e. essentially random



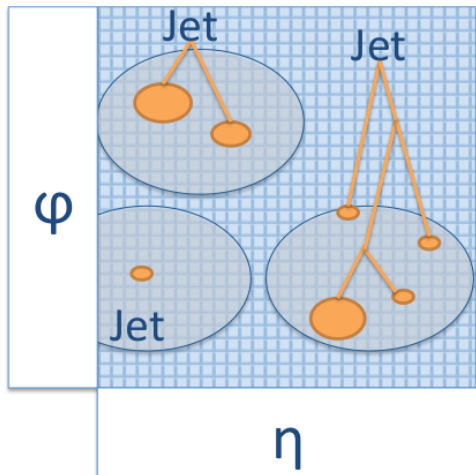
- 1 Reconstruct decay as fat-jet
 - Use large-R parameter jet to collect radiation from the original decay
- 2 Groom the jet
 - Signal: Remove unwanted jet constituents not from the signal, e.g. pile-up
 - Background: Preserve the background characteristics



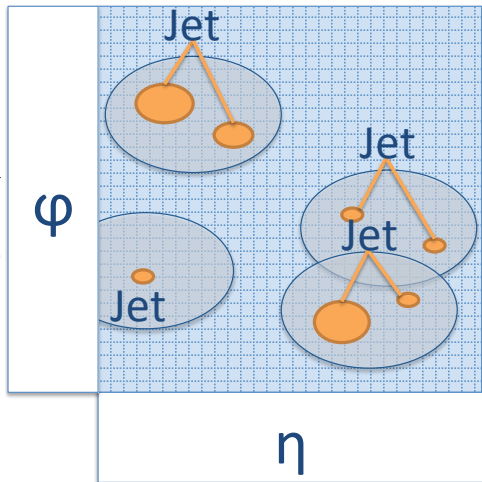
- 3 Tag as boson jet
 - Use differences between signal and background jet characteristics to reject background jets



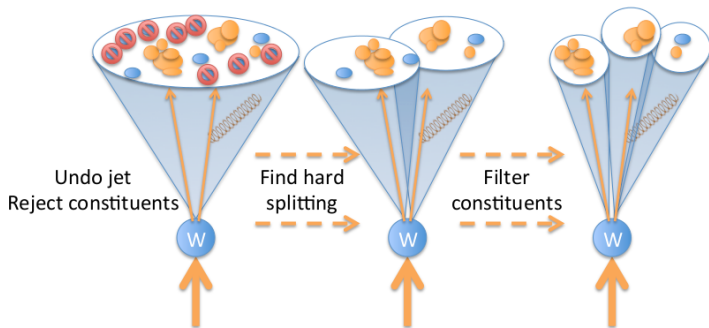
- **Cambridge-Aachen** 1.2 jets (CA jets) used in Run-1
 - [[arXiv:9707323](https://arxiv.org/abs/9707323)] or [[arXiv:0802.2470](https://arxiv.org/abs/0802.2470)]
- Part of the **sequential recombination** family of jet reconstruction algorithms
 - Calculate the $d_{ij} = \frac{\Delta R_{ij}^2}{R^2}$ 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



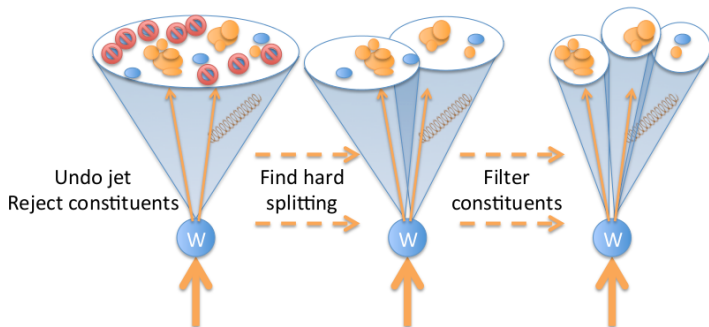
- **anti- k_t** 1.0 jets used in Run-2
 - [[arXiv:9707323](#)] or [[arXiv:0802.2470](#)]
- Part of the **sequential recombination** family of jet reconstruction algorithms
 - Calculate the $d_{ij} = \min(k_{ti}^{-2}, k_{tj}^{-2}) \frac{\Delta R_{ij}^2}{R^2}$ between all jet constituents
 - Combine **closest 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



- 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**, $\frac{\min(p_{T,j_1}^2, p_{T,j_2}^2)}{m_{j_0}^2} \Delta R_{j_1,j_2}^2 \geq y_{\min}$, 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 $n_r \times R_r$ sized subjets

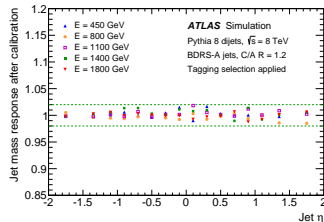
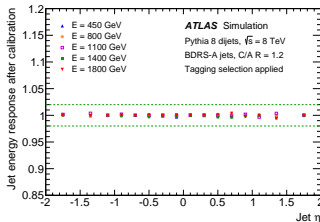
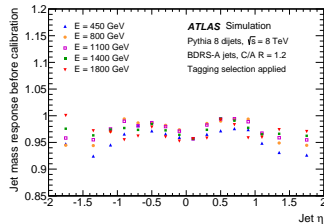
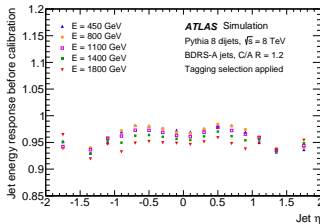


- In this analysis a **modified BDRS-A** split filtering algorithm is used
- Starts from $R = 1.2$ CA jets seeded from local cluster weighted (LCW) topological clusters
- Loose BDRS tagger, with **no mass drop** requirement

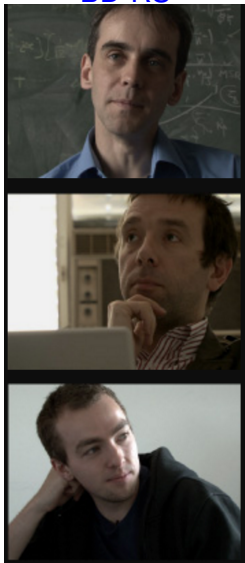
Iterative parameter	Value
$\sqrt{y_{\min}}$	0.20
μ_{\max}	1.00
Filtering parameter	Value
n_r	3
R_r	0.3

- 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**

- 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, $\langle R_E^{\text{jet}} \rangle$
- Derive the mean reconstructed jet energy, $\langle E_{\text{reco}}^{\text{jet}} \rangle$
- Fit the $\langle R_E^{\text{jet}} \rangle$ vs $\langle E_{\text{reco}}^{\text{jet}} \rangle$ distribution to gain a **calibration function**
- Repeat process for **mass calibration** using the LCW+JES jets



BD-RS

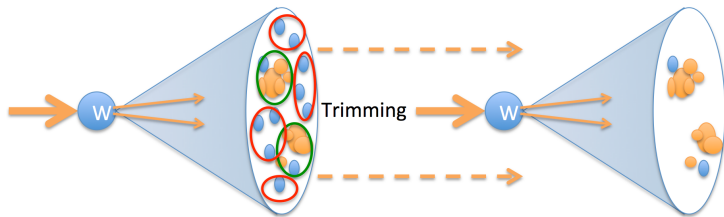


R2-D2



Replaced by.....

- The **trimming** algorithm, [[arXiv:0912.1342](https://arxiv.org/abs/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



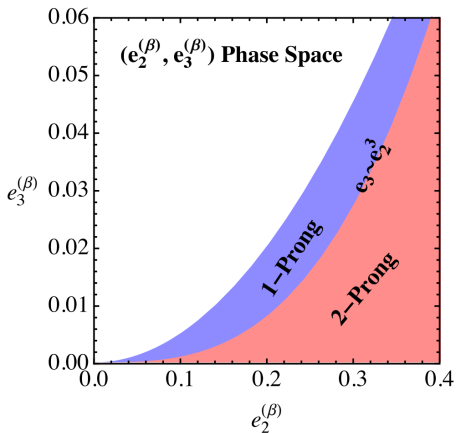
- The method is a few simple steps
 - For jet j , **re-cluster** the constituents into smaller- R **sub-jets** ($R = 0.2$)
 - If a sub-jet's $p_T^{\text{sub}} < 0.05 \times p_T^{\text{jet}}$ **discard** this sub-jet as a soft contribution
 - Otherwise keep the sub-jets constituents in the **final jet**

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

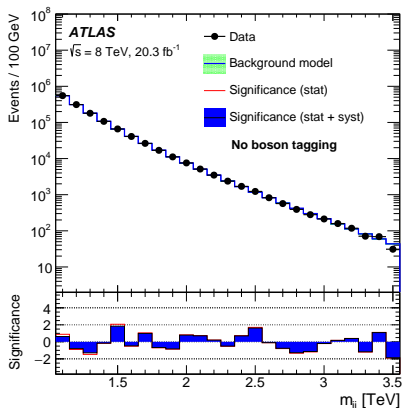
$$e_2^\beta = \frac{1}{p_{TJ}^2} \sum_{1 \leq i < j \leq n_J} p_{T_i} p_{T_j} \Delta R_{ij}^\beta$$

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

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



- 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



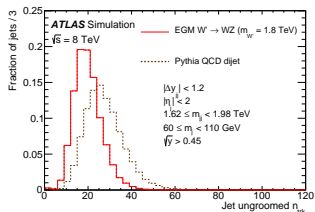
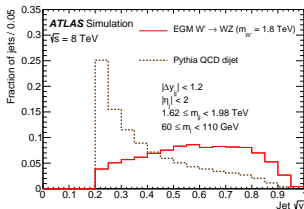
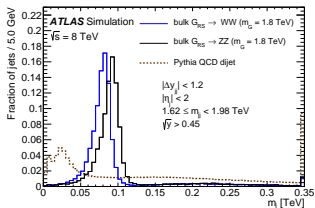
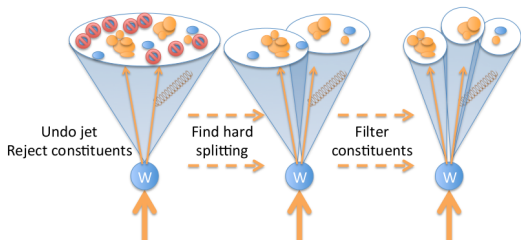
Leading jet p_T	QCD $\frac{d\sigma}{dp_T}$	W' $\frac{d\sigma}{dp_T}$	S/B
[TeV]	[fb/GeV]	[fb/GeV]	[–]
0.5	10^3	10^{-1}	10^{-4}
1.0	10	10^{-3}	10^{-4}

- 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

- 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

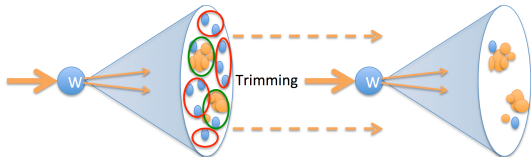
3 Subjet momentum balance

- Boson jets symmetric, QCD unbalanced

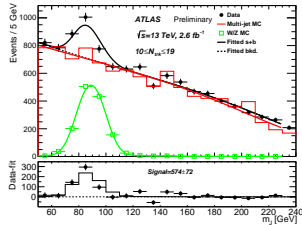
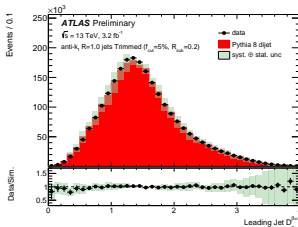
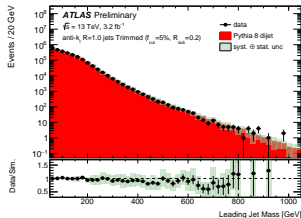
4 Number of tracks ghost

- matched to the unfiltered jet
- More hadronic activity in QCD jets

- What do we have to remove the QCD background?



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



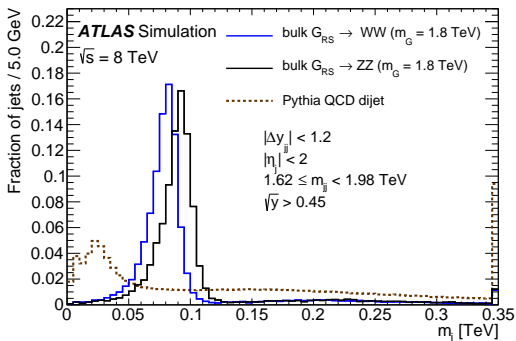
- 2 Filtered jet mass
 - Separates peaked boson mass from falling QCD spectrum

- 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

2 Filtered jet mass

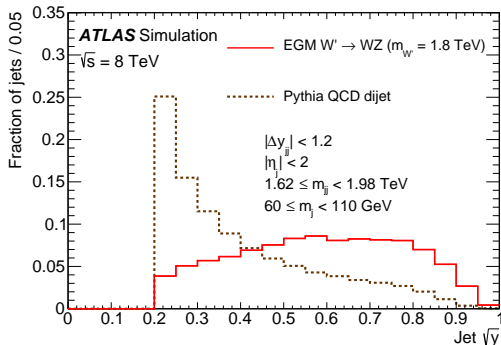
- Separates peaked boson mass from falling QCD spectrum
- Apply ± 13 GeV **window cuts** around boson mass from MC simulation peak ($m_W = 82.4$, $m_Z = 92.8$)
- For example, in the WZ cut;
 - Leading mass jet
 $79.8 \text{ GeV} < m_{\text{jet}} < 105.8 \text{ GeV}$
 - Subleading mass jet
 $69.4 \text{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

- Boson jets **symmetric**, QCD **unbalanced**

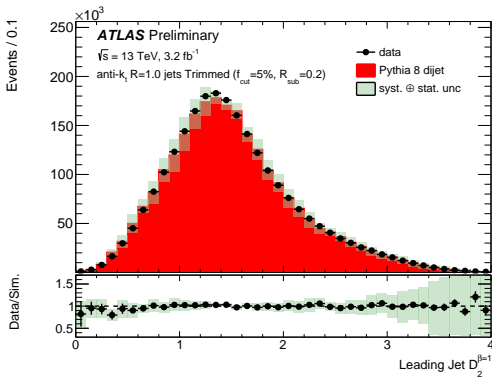
- Soft gluon** radiation leads to asymmetric splittings
- $W/Z \rightarrow q\bar{q}$ decays tend to share momentum more **equally** between decay products
- Apply a more stringent $\sqrt{y} \geq 0.45$ cut on the subjet momentum balance
- Another **powerful** cut!
 - $\epsilon_{\text{signal}} \approx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



3 Subject momentum balance

- Boson jets **lower**, QCD **higher**

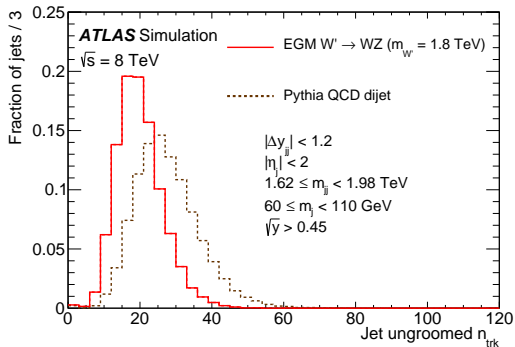
- **Soft gluon** radiation leads to asymmetric splittings
- **Bosonic jets** have more two-pronged structure
- Apply a p_T dependent cut to remove backgrounds
- **Robust** against pile-up
- Another **powerful** cut!
 - $\epsilon_{\text{signal}} \approx 50\%$ (Combined with mass window)
 - p_T dependent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



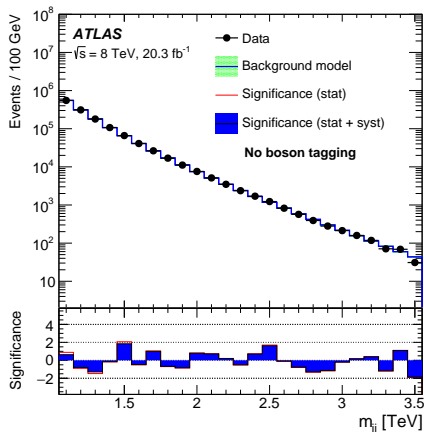
4 Number of tracks ghost matched to the unfiltered jet

- 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](https://arxiv.org/abs/0802.1188)]
- Apply $n_{\text{trk}} \leq 30$ cut
- Efficiency after mass/tagger
 - $\epsilon_{\text{signal}} = 83 \pm 7\%$
 - $\epsilon_{\text{background}} \approx 65\%$
- Very **hard** to model in MC
- Cuts optimised using V +jets enriched **data CR**
- Efficiency **calibrated** in this CR

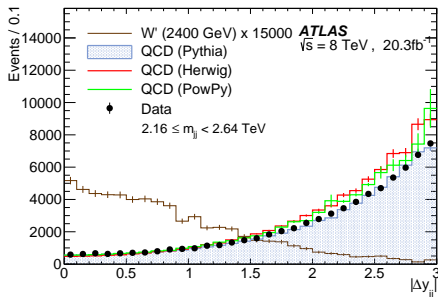
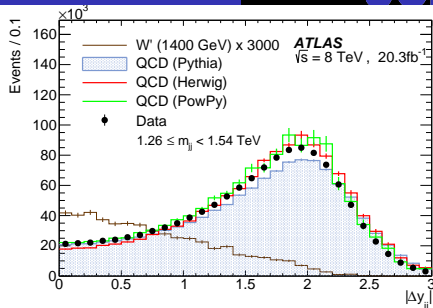


- 1 **Trigger:** $p_T > 360$ GeV anti-kt 1.0
- 2 Apply **BDRS-A** split-filter
- 3 Require $m_{JJ} > 1.05$ TeV
 - Ensures on **trigger plateau**
- 4 **Rapidity gap** between leading jets, $|\Delta y_{12}| < 1.2$
 - s-channel signal more **central** than t-channel QCD
- 5 Leading jets p_T **asymmetry** $A_{p_T} < 0.15$
 - 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** $\epsilon \approx 1.2 - 0.6\%$



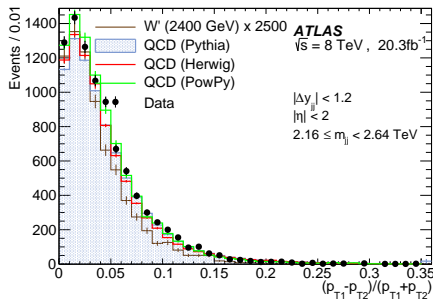
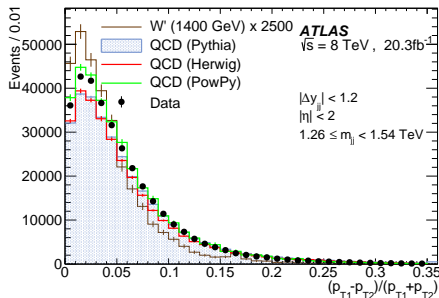
Event selection: Run-1 all together

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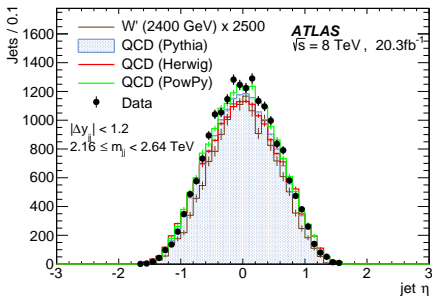
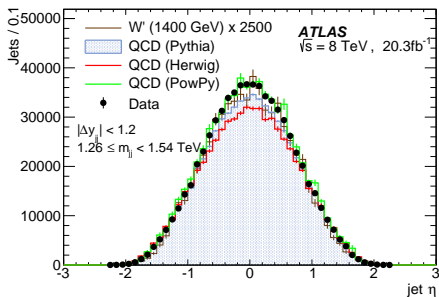
Event selection: Run-1 all together

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 - Ensures on **trigger plateau**
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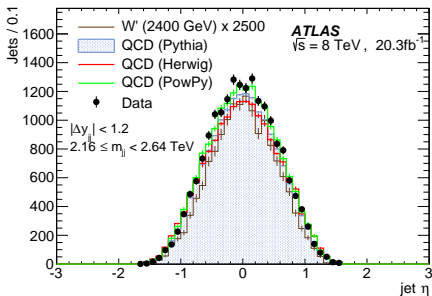
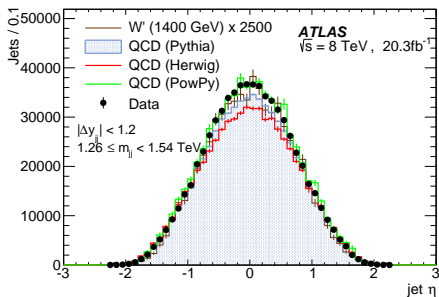
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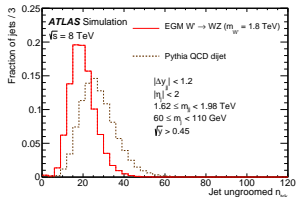
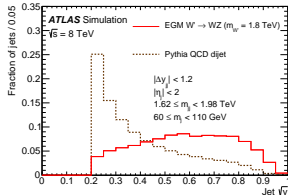
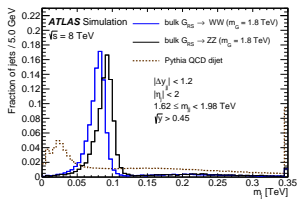
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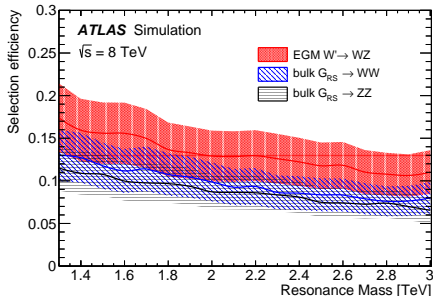
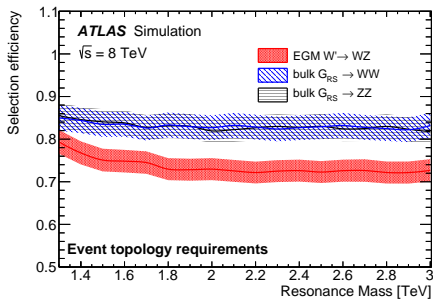


Event selection: Run-1 all together

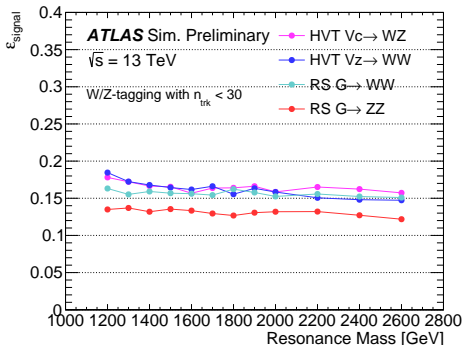
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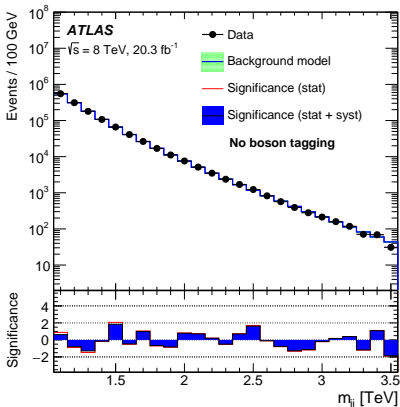
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 - **Tagger** $\epsilon \approx 2\%$



- 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

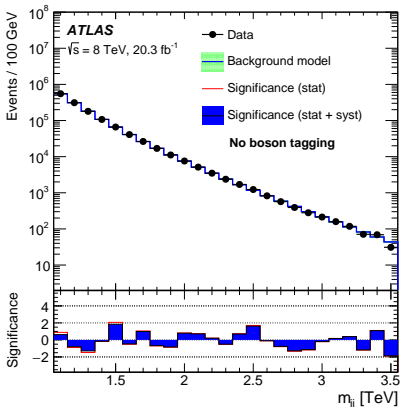


- Assume a **steeply** and **smoothly falling** distribution models the background
- Any resonance should be **narrow**, thus only affect a few bins
- Use a **parametric function** to model the background from the data

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

- 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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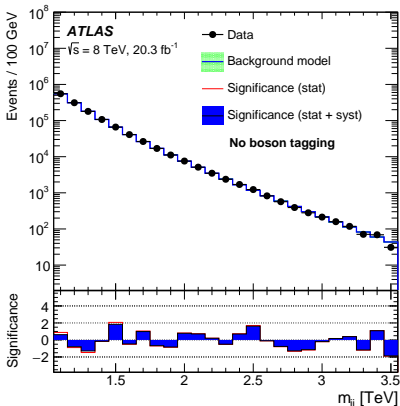


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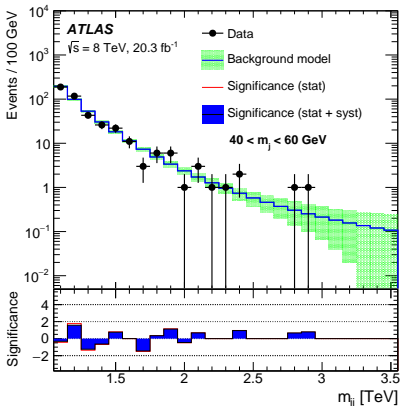
- Error taken from errors on **functional parameters**
- Fit tested on,

- Raw data
- PYTHIA/HERWIG MC
- Mass **sideband** data CRs

- Alternate fit functions give **similar** results

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

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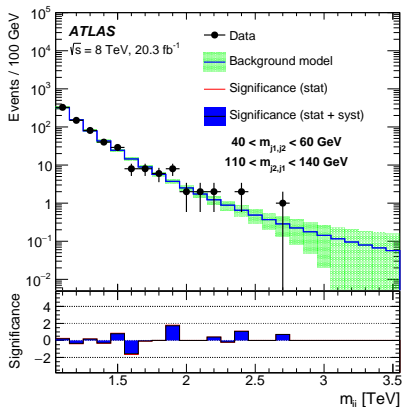
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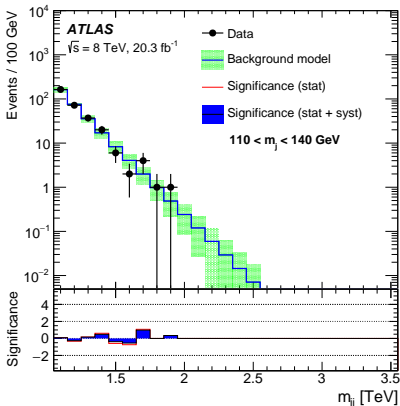
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- **Background:** Taken from the uncertainties on the **fit parameters**
- **Signal:** Various systematics affect the signal **reconstruction** and **selection efficiency**

● Shape systematics:

- The jet p_T and jet mass scale uncertainties determined by the **track/calorimeter double ratio** technique

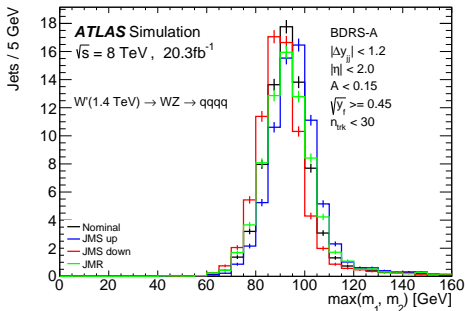
- For example for a variable x ,

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

- 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%

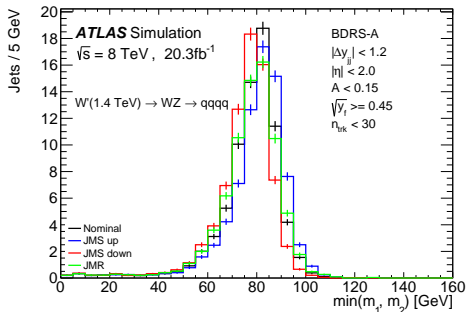


Source	Uncertainty	Constraining pdf
Jet p_T scale	2%	$G(\alpha_{PT} 1, 0.02)$
Jet p_T resolution	20%	$G(\sigma_{rE} 0, 0.05 \times \sqrt{1.2^2 - 1^2})$
Jet mass scale	3%	$G(\alpha_m 1, 0.03)$

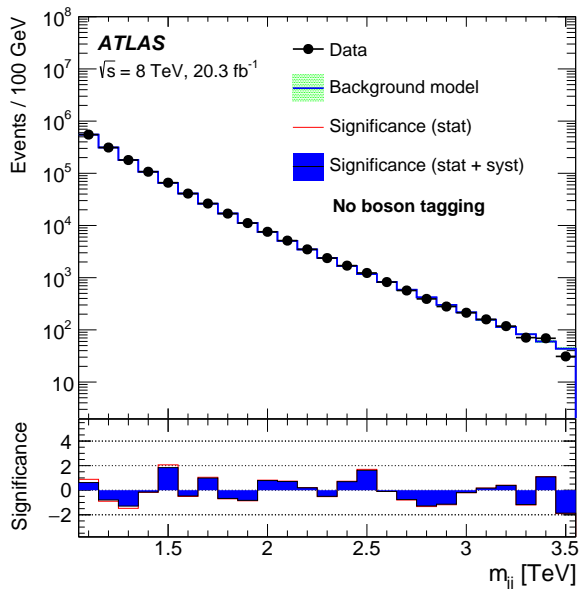
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- **Normalisation systematics:**

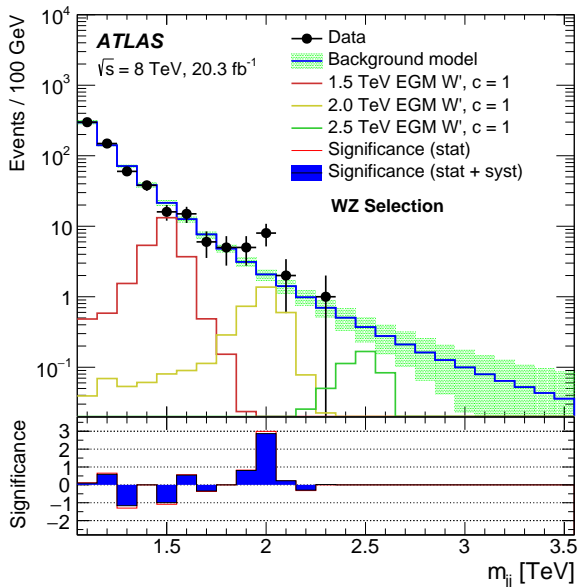
- **Large uncertainty** on the n_{trk} cut evaluated in the data driven V +jets study used to define the efficiency of the cut
- Jet mass scale affects **both** shape and normalisation strongly
- \sqrt{y} scale evaluated using the **double ratio** method
- Resolutions taken as 20% **smearings**
- **Shower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



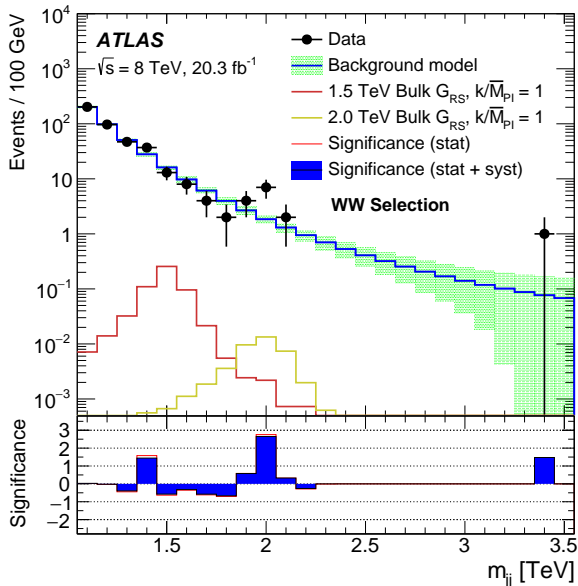
Source	Uncertainty
Efficiency of the track-multiplicity cut	20.0%
Jet mass scale	5.0%
Jet mass resolution	5.5%
Subjet momentum-balance scale	3.5%
Subjet momentum-balance resolution	2.0%
Parton shower model	5.0%
Parton distribution functions	3.5%
Luminosity	2.8%



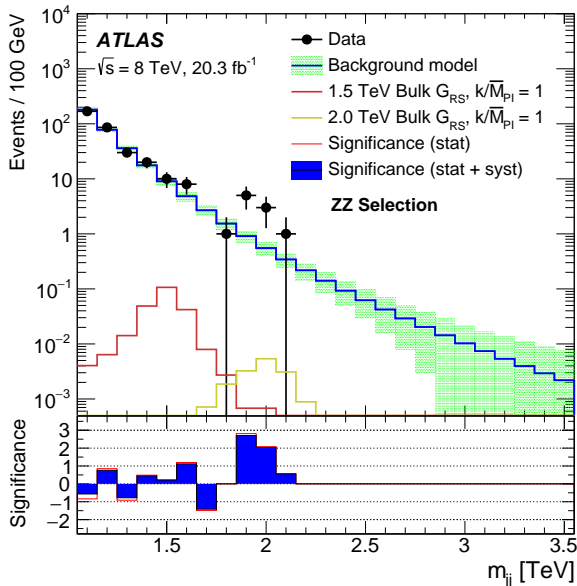
- OK, enough with the build-up....
- What does the triggered data look like after applying our selection???



- 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

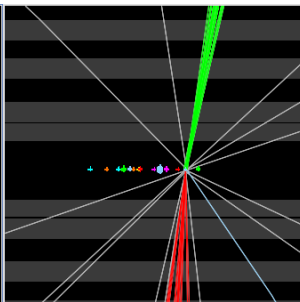
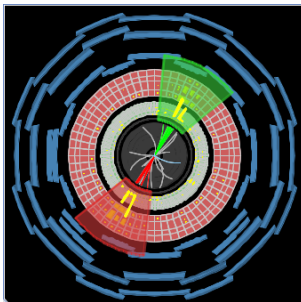


- Full **WW** selection applied to the data
 - W mass window applied to **both** jets
- **Good agreement** again seen with steeply, smoothly falling background model
- **Deviation** from the background still observed at around 2 TeV
- **Remember:** There is an **overlap** between the W/Z mass windows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



- 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
- **Benchmark** Bulk Randall-Sundrum graviton signal MC shown for **comparison** purposes

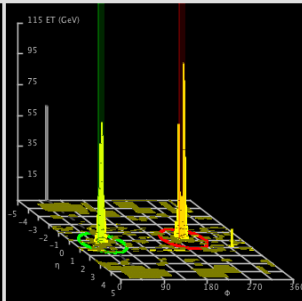
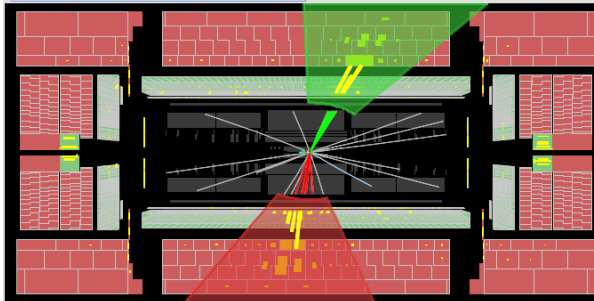
What do these events look like? Dramatic!



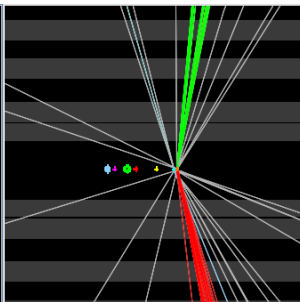
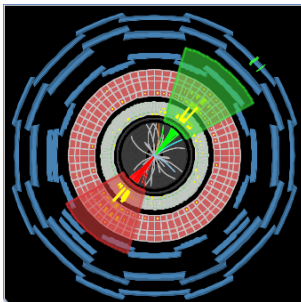
 **ATLAS**
EXPERIMENT

Run Number: 207749, Event Number: 36414089

Date: 2012-07-31 01:30:57 CEST

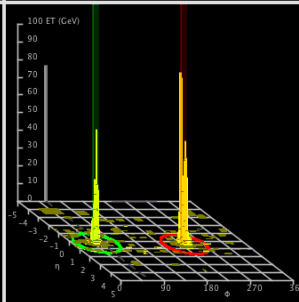
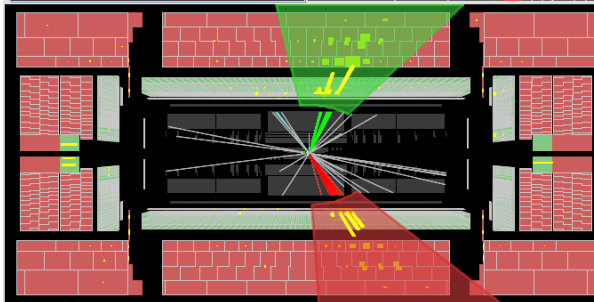


What do these events look like? Energetic!



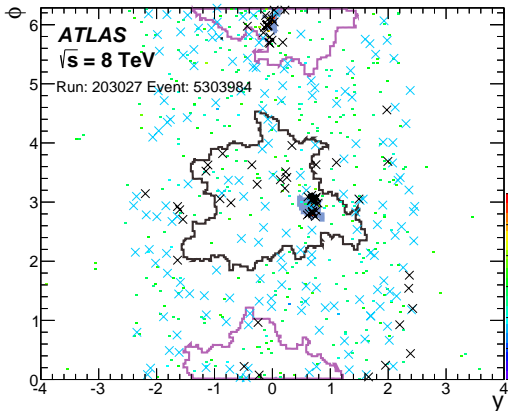
ATLAS EXPERIMENT

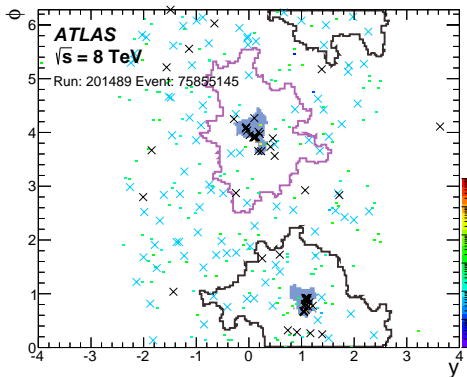
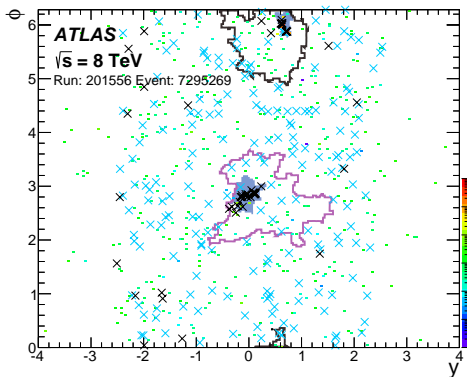
Run Number: 212815, Event Number: 157931714
Date: 2012-10-17 12:37:51 CEST



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

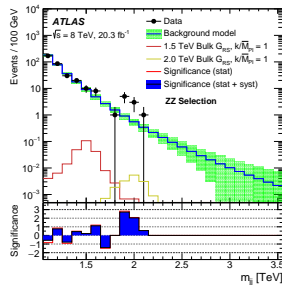
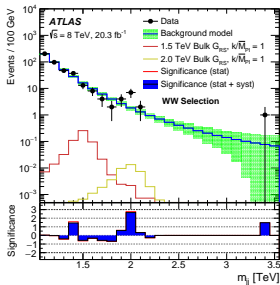
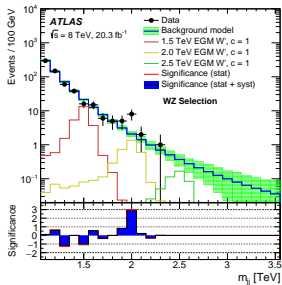


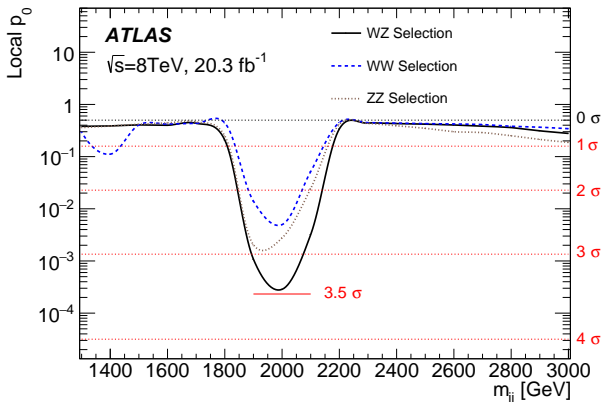


What do we see here?

- Subjects 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?

- Deviations from the expected background, especially ones at the tail of the data distribution
 - 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

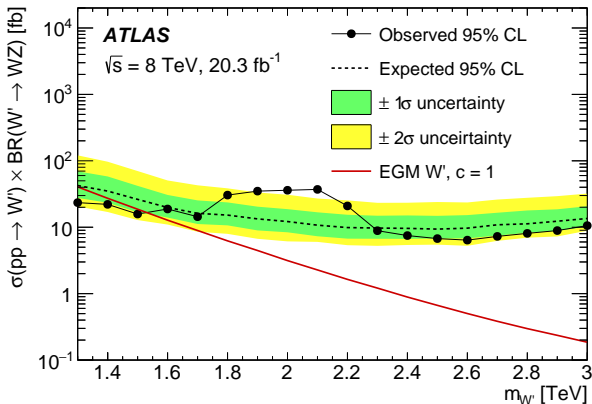




- Therefore, no **statistically significant deviation** from the background has been observed

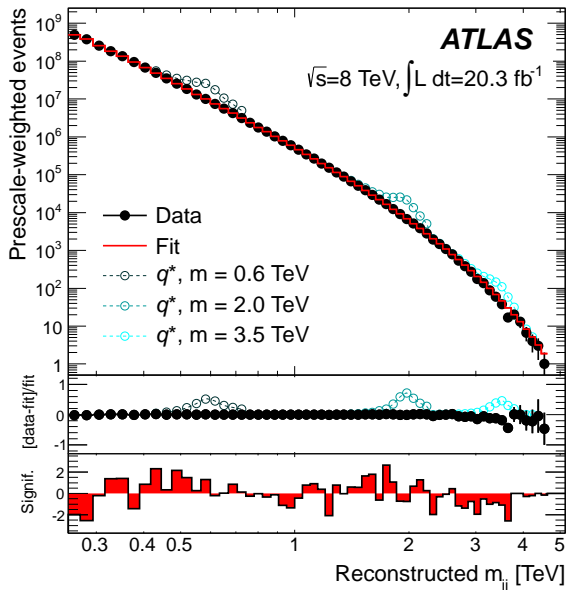
- A **discrepancy** was seen with respect to the expected background distribution
- Once suitably confident it is not an error, its significance should be **quantified**
- In the WZ channel:
- **Local** $p_0 = 3.4\sigma$
- **Global** $p_0 = 2.5\sigma$
 - Global σ takes into account the **look elsewhere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

- 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 CL_S prescription taking into account the **systematic uncertainties** and **background fit**

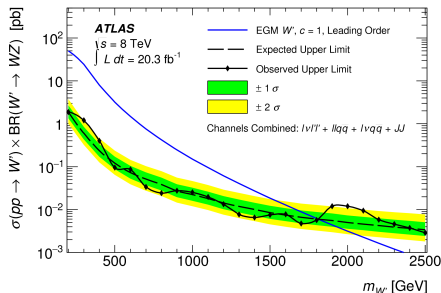
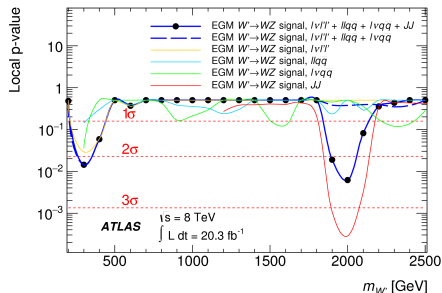


- Expected** limits broadly agree with the observed limits
- Exclusion** of EGM W' from 1.3 – 1.5 TeV
- Broad deviation** from the background observable at around 2 TeV
- Benchmark** extended gauge model $W' \sigma \times \mathcal{B}$ shown for **comparison** purposes

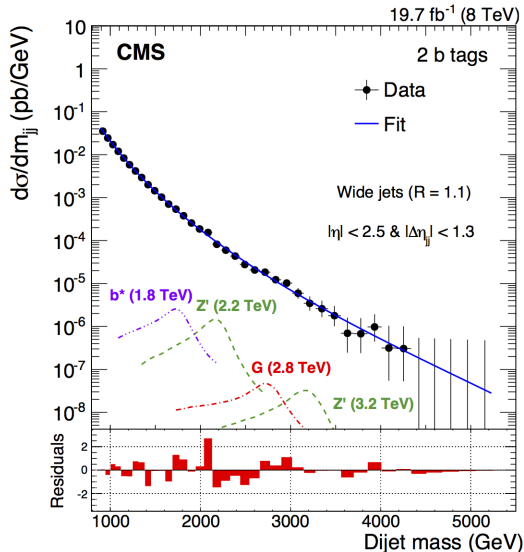
- WW/ZZ limits similar and in backup



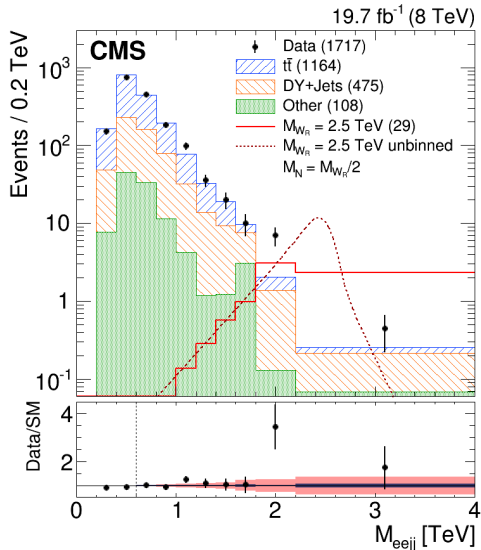
- ATLAS resolved dijet search [[arXiv:1407.1376](https://arxiv.org/abs/1407.1376)], nothing seen ☒
- ATLAS resolved Run-2 dijet search [ATLAS-CONF-2015-042](https://arxiv.org/abs/1503.04677), nothing seen ☒
- ATLAS semi-leptonic search $W(l\nu)Z(jj)$ [[arXiv:http://1503.04677](https://arxiv.org/abs/http://1503.04677)],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



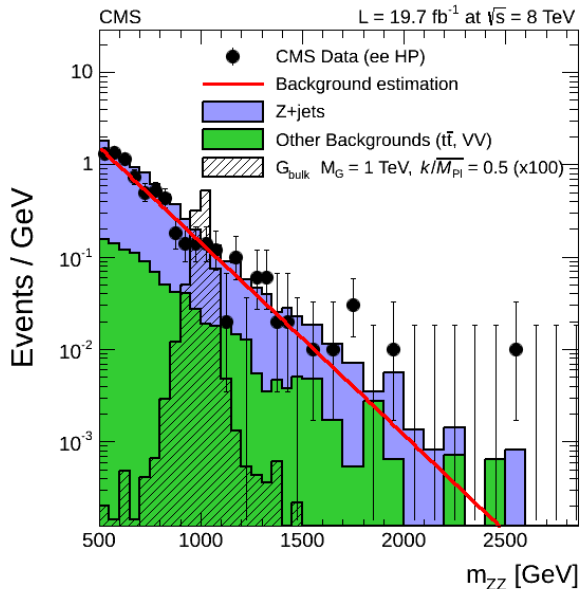
- ATLAS diboson combination [[arXiv:1512.05099](https://arxiv.org/abs/1512.05099)] (in journal yesterday!)
- In the full combination discrepancy is reduced to a 2.5σ local excess
- Limits increased to 1.81 TeV in the W' search channels
- Fully hadronic channel in (significant) tension with the leptonic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



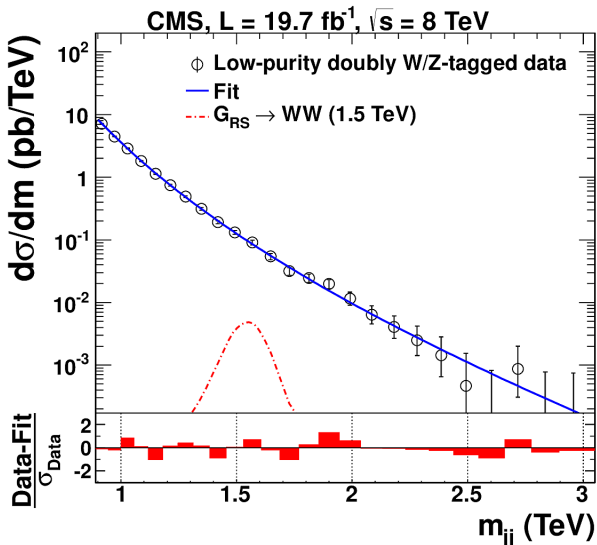
- CMS dijet search [[arXiv:1501.04198](https://arxiv.org/abs/1501.04198)], blip in 2-btag at 2 TeV? Trick of the eye? ❌
- CMS W_R search [[arXiv:1407.3683](https://arxiv.org/abs/1407.3683)], excess at 2 TeV in $eejj$ channel only ❌✅
- CMS $WW/WZ/ZZ$ semi-leptonic search [[arXiv:1405.3447](https://arxiv.org/abs/1405.3447)], in tails/nothing seen ❌
- CMS $WW/WZ/ZZ$ fully hadronic search [[arXiv:1405.3447](https://arxiv.org/abs/1405.3447)], uses n-subjettiness, broad blip at ≈ 1.8 TeV ❌✅



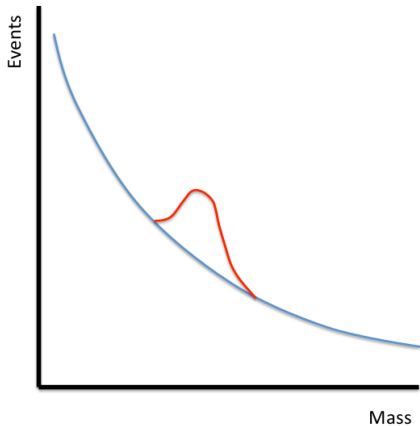
- CMS dijet search [[arXiv:1501.04198](https://arxiv.org/abs/1501.04198)], blip in 2-btag at 2 TeV? Trick of the eye? ☒
- CMS W_R search [[arXiv:1407.3683](https://arxiv.org/abs/1407.3683)], excess at 2 TeV in $eejj$ channel only ☒☑
- CMS $WW/WZ/ZZ$ semi-leptonic search [[arXiv:1405.3447](https://arxiv.org/abs/1405.3447)],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



- 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 $\approx 1.8\text{TeV}$ ☒☑



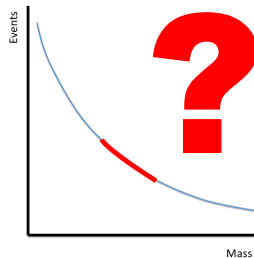
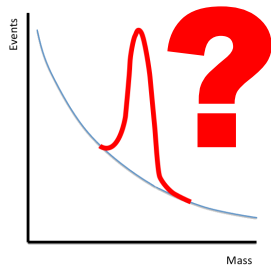
- CMS dijet search [\[arXiv:1501.04198\]](#), blip in 2-btag at 2 TeV? Trick of the eye?
- CMS W_R search [\[arXiv:1407.3683\]](#), excess at 2 TeV in $eejj$ channel only
- CMS $WW/WZ/ZZ$ semi-leptonic search [\[arXiv:1405.3447\]](#), in tails/nothing seen
- CMS $WW/WZ/ZZ$ fully hadronic search [\[arXiv:1405.3447\]](#), uses n-subjettiness, broad blip at $\approx 1.8\text{TeV}$



Get this?

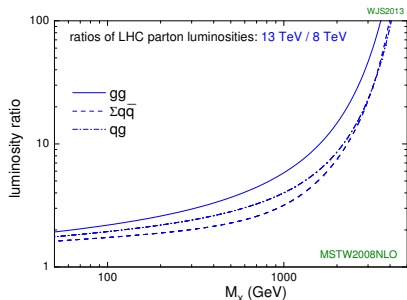
Run-2

Or this?

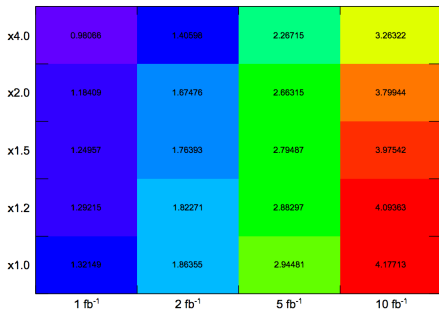


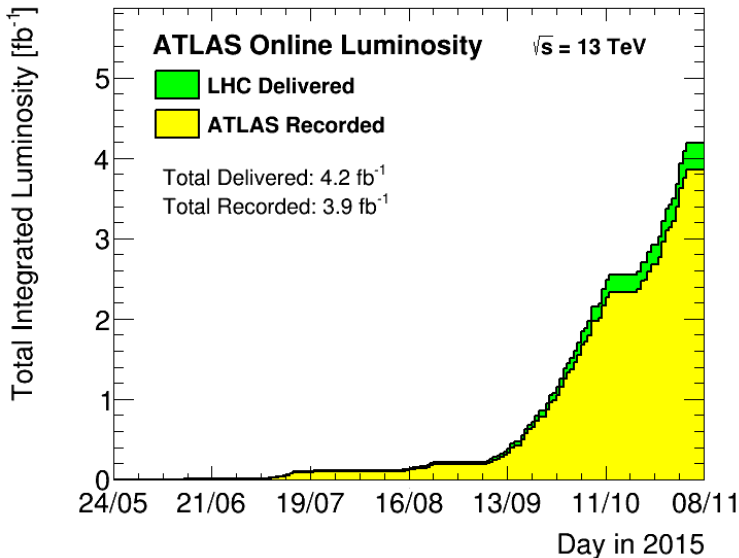
How much data is needed?

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

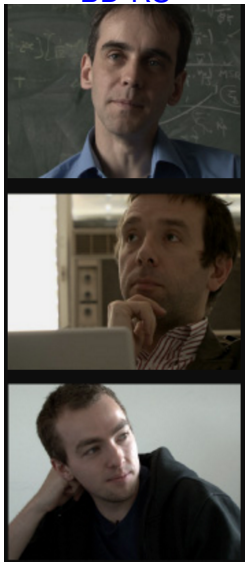


Systematics





BD-RS

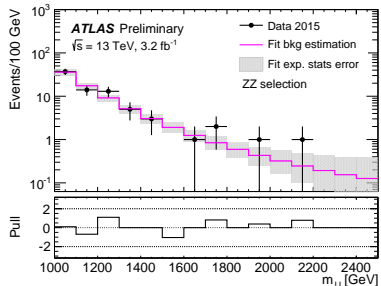
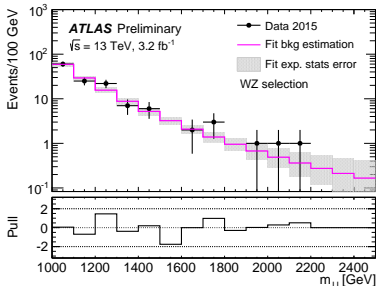
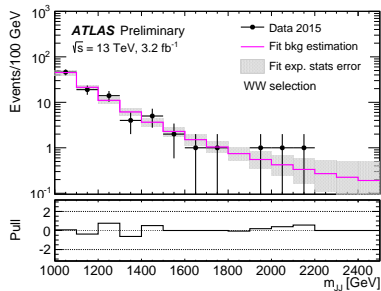


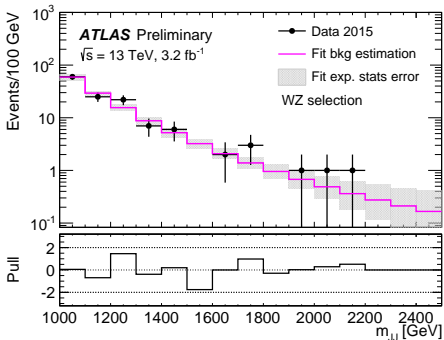
R2-D2



Replaced by.....

- 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)

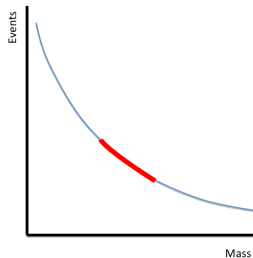
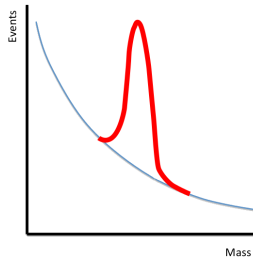




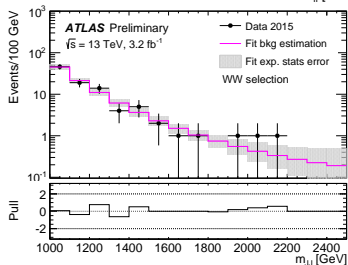
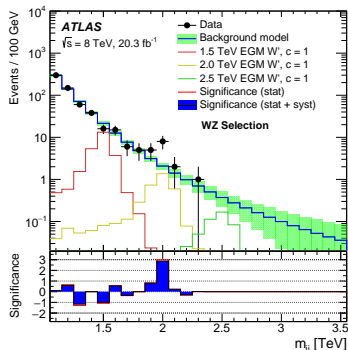
Maybe?

2016

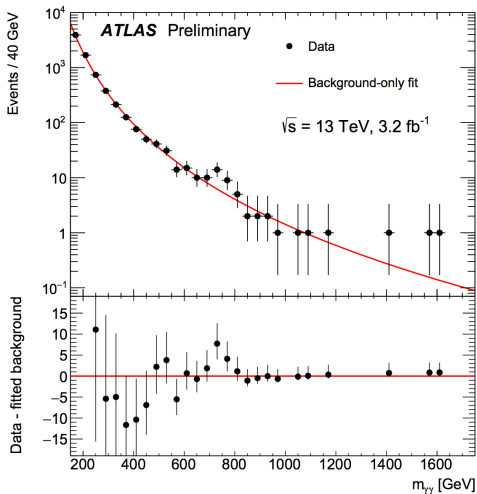
Probably not?



- Presented searches for a **high mass diboson resonance**, [[arXiv:1506.00962](https://arxiv.org/abs/1506.00962)], [[CDS:2114845](https://cds.cern.ch/record/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**



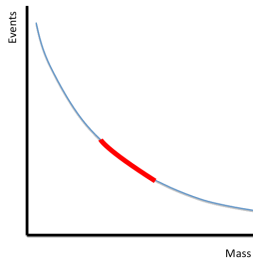
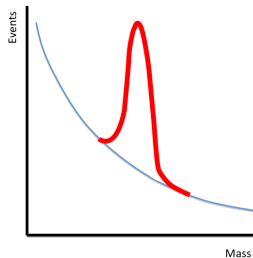
A new hope.... $X \rightarrow \gamma\gamma$ – [CDS:2114853]



Maybe?

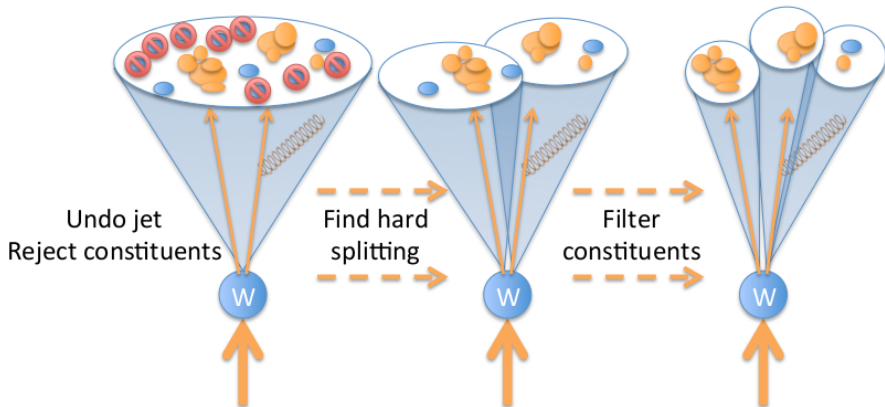
2016

Maybe not?

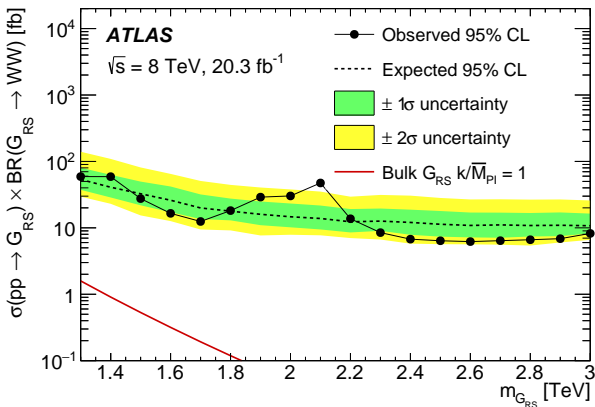


188 citations++ \gg our 150.... It's the ciiiiircle of life....

Backup

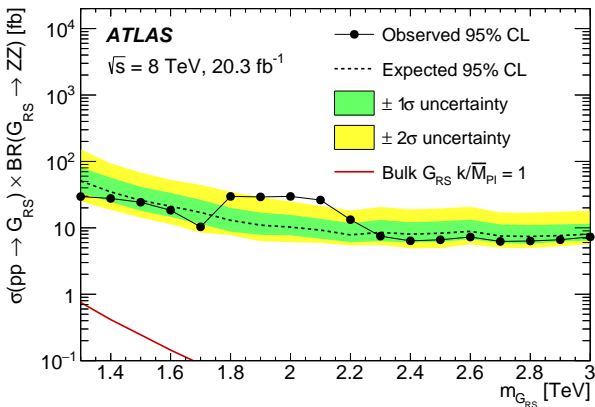


- As no significant deviation was observed, we continue to set limits on the observed distributions
- 95% confidence limits set on $\sigma \times \mathcal{B}$ using the CL_S prescription taking into account the systematic uncertainties and background fit



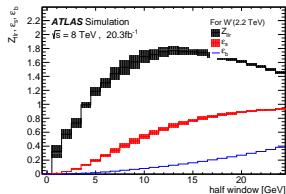
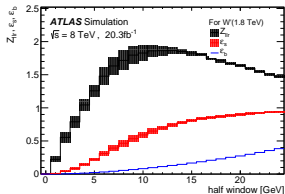
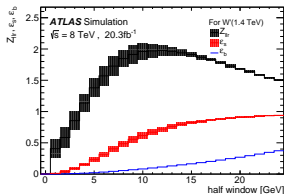
- Expected** limits broadly agree with the observed limits
- Exclusion** of graviton production at no masses
- Deviation** from the background observable at around 2.1 TeV
- Benchmark** Bulk Randall-Sundrum graviton $\sigma \times \mathcal{B}$ shown for **comparison** purposes

- 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 CL_S prescription taking into account the systematic uncertainties and background fit

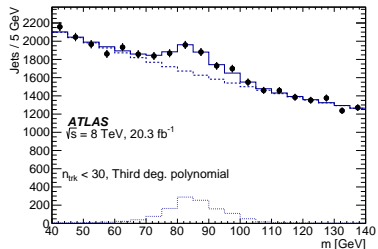
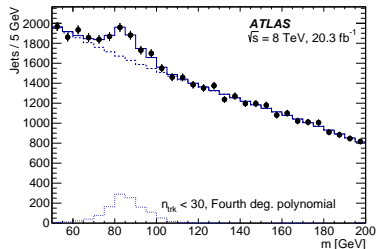


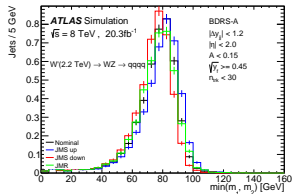
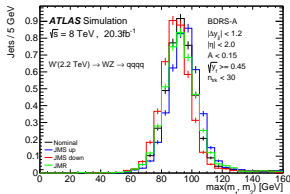
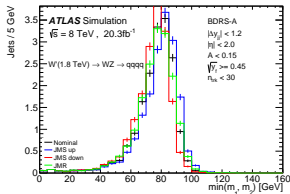
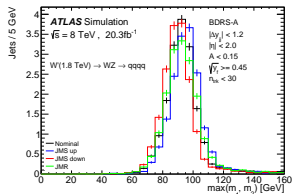
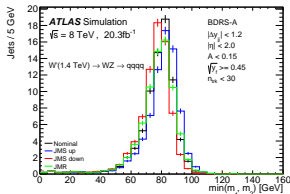
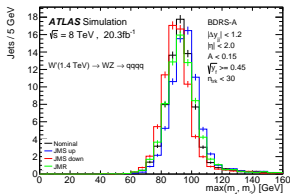
- Expected** limits broadly agree with the observed limits
- Exclusion** of graviton production at no masses
- Broad deviation** from the background observable at around 2 TeV
- Benchmark** Bulk Randall-Sundrum graviton $\sigma \times \mathcal{B}$ shown for **comparison** purposes

- 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



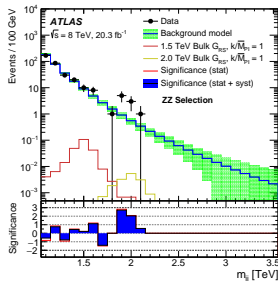
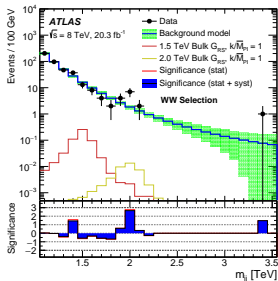
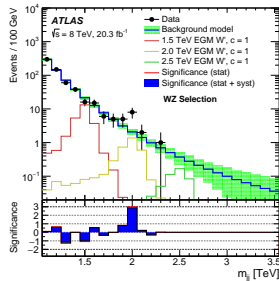
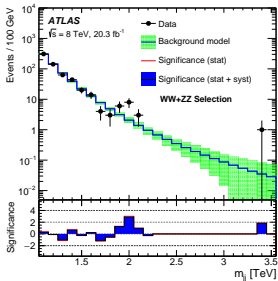
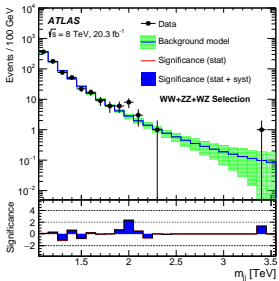
- n_{trk} is poorly modelled in MC
- Cannot trust it to optimise cut or measure its efficiency
- Select V +jets enriched data sample
 - 1 Optimise the cut by fitting QCD background vs selected signal peak
 - 2 Measure the efficiency of selected cut in data sample
- Two models used to fit background in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





Selection overlaps

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



- 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.

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

- 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 σ	-1 σ	obs	exp	+1 σ	-1 σ	obs	exp	+1 σ	-1 σ
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	4.75	2	3.98	4.54	3.43	1	1.54	1.98	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	0.18
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 on the EGM W' models in the WZ selection

m [GeV]	$W' \rightarrow WZ$		95% CL Limits [fb]					
	$\sigma_{BR_{WZ}}$ [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 on the bulk G_{RS} models in the WW selection

m [GeV]	$G_{RS} \rightarrow WW$		95% CL Limits [fb]					
	σBR_{WW} [fb]	Γ [GeV]	obs	exp	-2σ	$-\sigma$	$+\sigma$	$+2\sigma$
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 on the bulk G_{RS} models in the ZZ selection

m [GeV]	$G_{RS} \rightarrow ZZ$		95% CL Limits [fb]					
	$\sigma_{BR_{ZZ}}$ [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