Vector Boson Scattering at High Mass

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for the ATLAS collaboration

Motivation

In the Standard Model, Vector Boson Scattering (VBS) violates unitarity for high mass Higgs, or in the absence of the Higgs.

If there is no light Higgs, some new physics must be invoked.

The Electroweak Chiral Langrangian describes low energy effects of strongly interacting symmetry breaking models.

This is an effective theory - for which perturbative calculations valid up to a ~3 TeV. At LHC energies, requires unitarization. One possible unitarisation scheme (Inverse Amplitude Method) gives rise to resonances in the VBS cross sections.

The mass and width of these resonances are controlled by 2 parameters ('a_4, a_5') of the EWChL.

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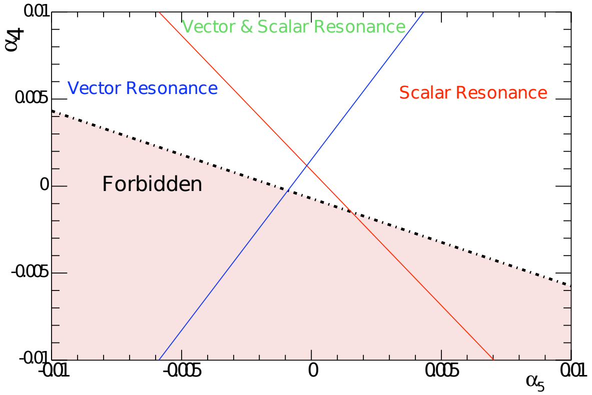
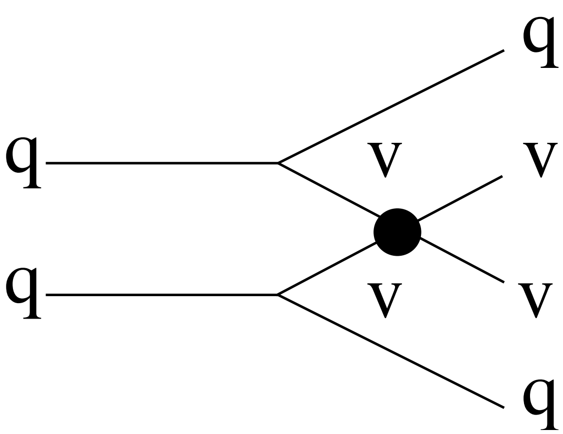
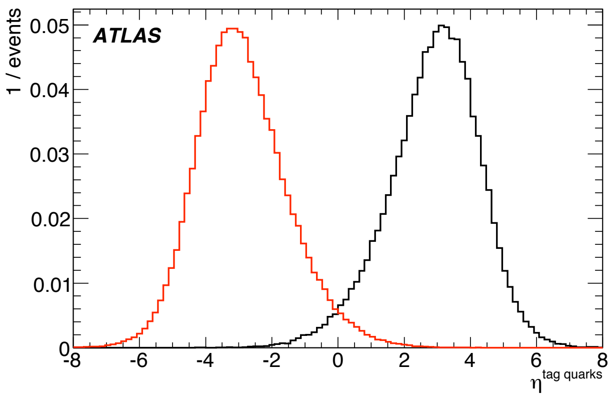


Signal Events

The signal is characterised by:

the presence of tag jets at high $|\eta|$.
the absence of hadronic activity between the tag jets.
the presence of two vector bosons.





Signal Event Generation

We have investigated the following channels:

$qqWW \rightarrow qq\ \ell\nu qq$
$qqWZ \rightarrow qq\ \ell\nu qq$
$qqWZ \rightarrow qq\ qq\ell\ell$
$qqWZ \rightarrow qq\ \ell\nu\ell\ell$
$qqZZ \rightarrow qq\ \nu\nu\ell\ell$

ℓ = e, μ

mass points
500, ~800, ~1100 GeV
continuum

Generated using a version of Pythia 6.403 modified to use amplitudes of Dobado et al: Chiral Langrangian, Inverse Amplitude unitarization.

one point at m = 500 Gev Generated with unmodified Pythia(MSTP(46)=5): no Higgs, QCD-like model, Padé unitarization.

CTEQ6L pdfs
renormalization and factorisation scales $Q^2 = M_W^2$

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K⊥/cone analysis
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Requires reconstruction of:

electrons
muons
W and Z leptonic decays
W and Z hadronic decays

For high mass resonances the bosons are highly boosted, and we need to reconstruct the bosons from monojets

Background Samples

Z+3 jets	(2 tag jets and Z →monojet)
W+3 jets	(2 tag jets and W →monojet)
Z+4 jets	(2 tag jets and Z → dijet)
W+4 jets	(2 tag jets and W → dijet)
$t\bar{t}$	contains (virtual) WW decay products

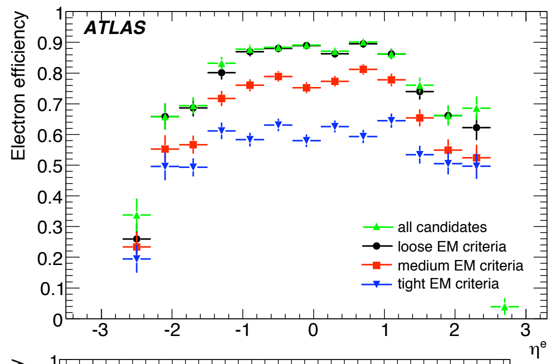
VB + jet generated with MADGRAPH, with Pythia for parton shower, hadronisation and underlying event. Renormalization and refactorization scale $Q^2 = M_Z^2$. CTEQ6L1 pdfs.

ttbar generated with MC@NLO with Herwig for parton shower and hadronisation, JIMMY for the underlying event.

Analysis Procedure

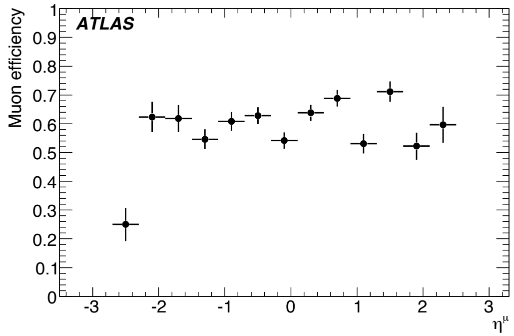
Identify leptonic VB decay
Identify hadronic VB decay
apply tag jet requirements
apply central jet veto
apply top jet veto
kinematic cuts on VBs

Leptonic decay $W \rightarrow \ell\nu$

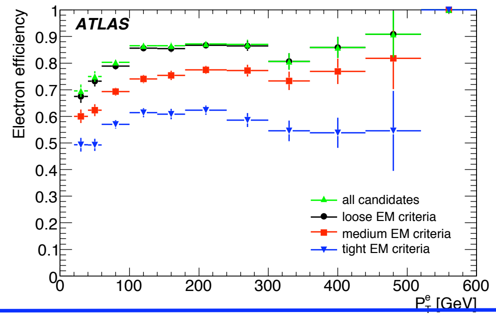


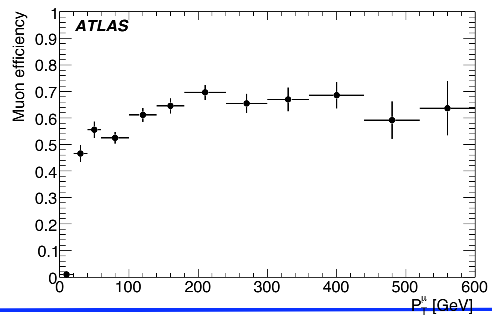
For the highest p_T lepton in event

with $p_T^{\nu} = p_T^{missing}$, $m_W = 80.42$ GeV



W "reconstructed" if there is a real solution to resulting quadratic in p_z^{ν}.





Leptonic decay $Z \rightarrow \ell^+\ell^-$

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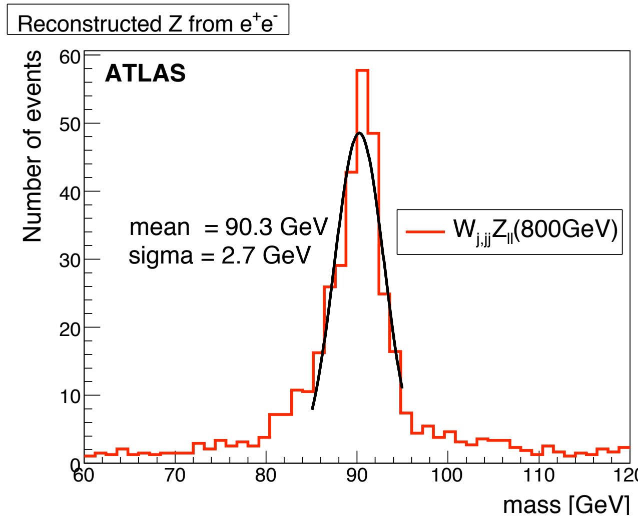
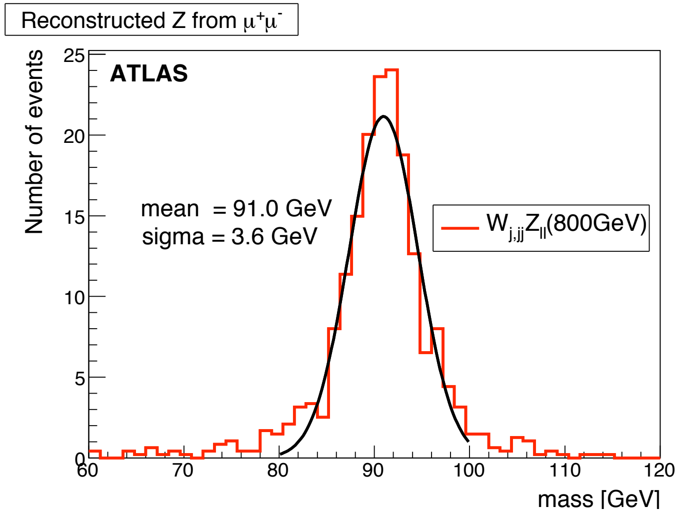


85<m<97 GeV

highest p_T leptons in the event
$p_T^{\ell 1}$>50 GeV, $p_T^{\ell 2}$>35 GeV



83<m<99 GeV

Hadronic Vector Boson decays

Low momentum decays: V $\rightarrow$ dijet
As momentum increases: V $\rightarrow$ monojet

Two reconstruction approaches were taken:

The $K_{\perp}$ reconstruction algorithm, and used internal structure of the highest p_T jet to determine whether a single jet or a dijet analysis was to be performed.

In the cone analysis, the mass region to be examined determined whether a single jet for dijet analysis was to be performed. For high masses, jets were reconstructed with a large cone. For low mass resonances two jets reconstructed with a smaller cone were used.

Both algorithms reconstruct jets which have calorimeter clusters as constituents. Jets overlapping with electrons removed from analysis.

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$K_\perp$ algorithm (longitudinally invariant formulation)

- clustering by walking backwards through QCD shower tree
- softest splits combined first, hardest last.
- combination parameter (y) constructed to follow QCD process
- heavy objects have large value for scale of final merge

$K_\perp$ analysis

if m_{low} < mass(highest p_T jet) < m_{high}

Single Jet Analysis

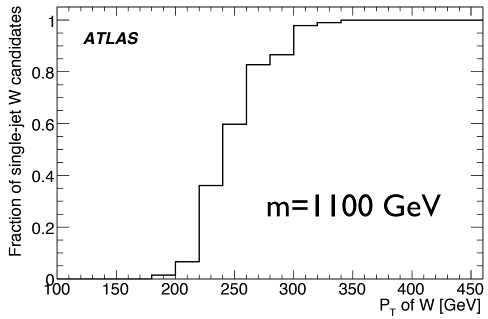
$Y = E_T \times \sqrt{y} \simeq O(m_V/2)$ for final merge for VB, much lower for light jets.

select as VB if $Y_{low} < Y_{last\ merge} < Y_{high}$

if m_{low} < mass(highest p_T jet pair) < m_{high}

Di-jet Analysis

select as VB if $y_{low} < y_{jj} < y_{high}$



$K_\perp$ Single Jet Analysis Details (1.1 TeV Sample)

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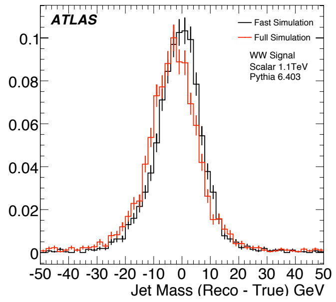
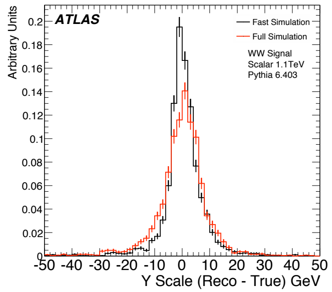
mass resolution ~ 9%
W mass window 68.4 - 97.2 GeV
Z mass window 68.7 - 106.3 GeV

Y resolution ~ 9-12%
Y window 30 - 100 GeV





Reconstructed-Generated highest p_T jet

Cut/Sample	1.1 TeV Resonance	W+4 jets	$t\bar{t}$
Jet Mass	68%	14%	28%
Y scale	77%	29%	63%

for jets with p_T > 300 GeV

K⊥ Di-jet Analysis Details (800 GeV Sample)

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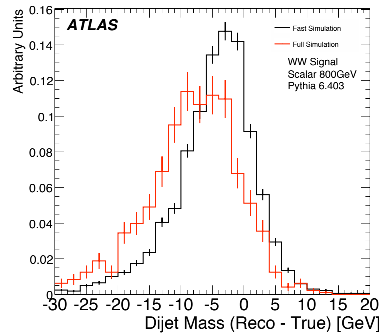
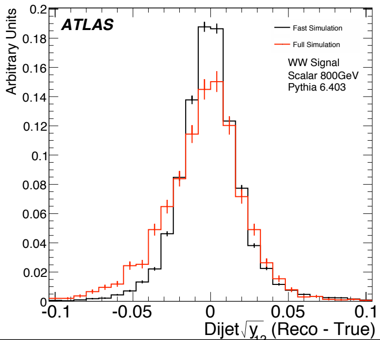
mass resolution ~ 5-6%
W mass window 62 - 94 GeV
Z mass window 66.6 -106.2 GeV



y resolution ~ 4-5%
y window 0.1 - 0.45



Cut/Sample	800 GeV Resonance	W+4 jets	ttbar
Jet Mass	17%	6%	14%
Y scale	79%	48%	84%

Cone algorithm

- For a seed constituent ($p_T > 1$ GeV) combine all constituents with $R = \sqrt{(\Delta\eta^2 + \Delta\varphi^2)} < R_0$
- recalculate jet direction and repeat until direction is stable.

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Cone analysis

resonance mass

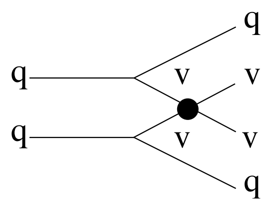
$\geq$ 800 GeV → **Single Jet Analysis**

$R_0 = 0.8$ (large jet)
$m_{low} < m_{jet} < m_{high}$

$\leq$ 800 GeV → **Di-jet Analysis**

2 jets with $R_0 = 0.4$
$m_{low} < m_{jj} < m_{high}$

Veto Cuts



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Color-free VBs exchanged and the forward jet are not color connected → little QCD activity in central region.

Central jet veto: require no jet with $p_T > p_T^{min}$ between tag jet in η.
p_T^{min} is analysis channel dependent

$t\bar{t}$ and tW events are backgrounds to VBS events containing W bosons

top quark veto: remove events for which a W candidate combines with a jet to give mass within some exclusion window, (typically 130-240 GeV) if that jet is far from any W candidate (typically $\Delta R = 0.8$) and does not overlap with an electron.

Further Analysis Details

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Channel	Forward Jets	Central Veto	VBs
$qqWW \to qq\ell\nu jj$ $K_\perp$	P_T>10 GeV E>300 GeV $\lvert\Delta\eta\rvert$>5	Yes	P_T>200 GeV $\lvert\eta\rvert$<2
$qqWZ \to qq\ell\nu jj$ $K_\perp$	P_T>10 GeV E>300 GeV $\lvert\Delta\eta\rvert$>5	Yes	P_T>200 GeV $\lvert\eta\rvert$<2
$qqWZ \to qqjj\ell\ell$ $K_\perp$ and cone	p_T>20 GeV E>300 GeV $\lvert\Delta\eta\rvert$>4.5 m_{jj}>700GeV	No (no top background)	P_T>250 GeV $\lvert\eta\rvert$<2 $\Delta\varphi(W,Z)$<2.0
$qqWZ \to qq\ell\nu\ell\ell$ cone	p_T>20 GeV E>300 GeV $\lvert\Delta\eta\rvert$>4.5 m_{jj}>700GeV	No	None
$qqZZ \to qq\nu\nu\ell\ell$ cone missing E_T>150 GeV	p_T>20 GeV E>300 GeV $\lvert\Delta\eta\rvert$>4.5 m_{jj}>700GeV	No	None

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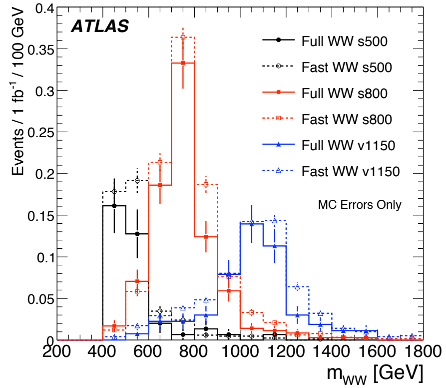
$WW \to \ell\nu jj$
$WZ \to \ell\nu jj$

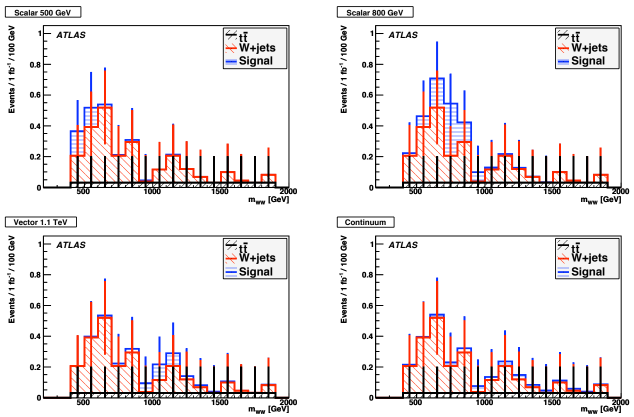
using $K_{\perp}$ analysis

Require

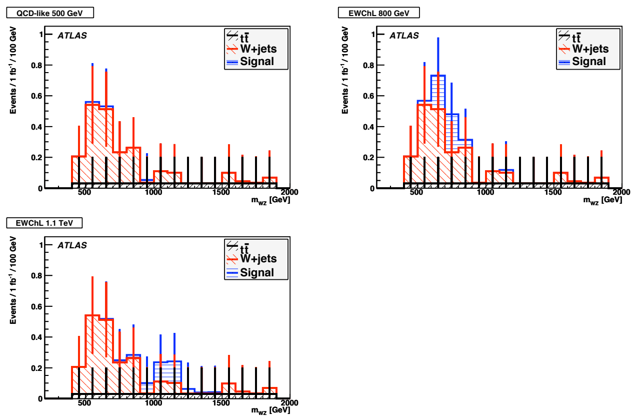
- Leptonic W identification
- Hadronic W identification using $K_{\perp}$ analysis
- pT > 200 GeV, $|\eta|<2$ both W
- tag jets with pT > 10 GeV, Ecut = 300 GeV, $\Delta|\eta| = 5$
- top veto applied
- central jet veto applied



$qqWW \to qq\ \ell\nu qq$ signal



$qqWW \to qq\ \ell\nu qq$ signal and background



$qqWZ \to qq\ \ell\nu qq$ signal and background

WZ $\rightarrow jj\ell\ell$

Analysis 1

- Leptonic Z decay
- Cone jet with 70<m<100 GeV
  - with lower |η| than fwd jets
- $\Delta\varphi$(W,Z) > 2 rad.
- Forward jet requirement
  - 2 jets pT>20 GeV
  - E > 300 GeV
  - $|\eta| > 1.5$
  - $\Delta\eta > 4.5$

Analysis 2

- Leptonic Z decay as analysis 1
- remaining cuts as $K_{\perp}$ analysis
- for qqWZ→$\ell\nu$jj

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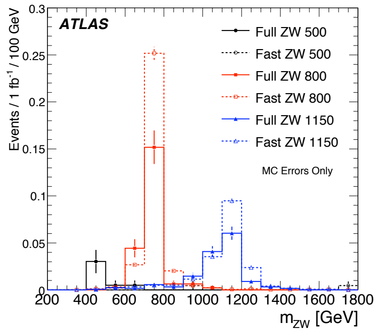
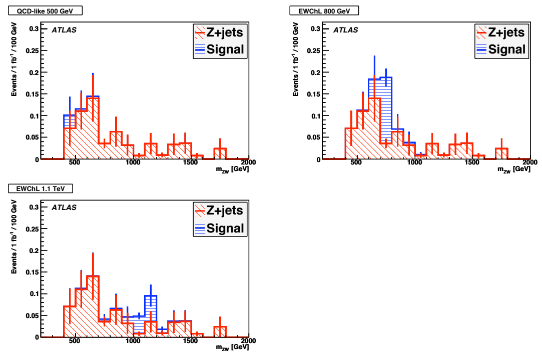
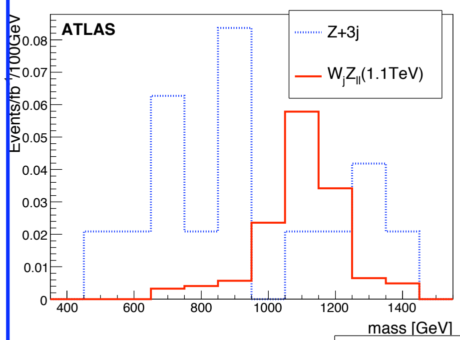
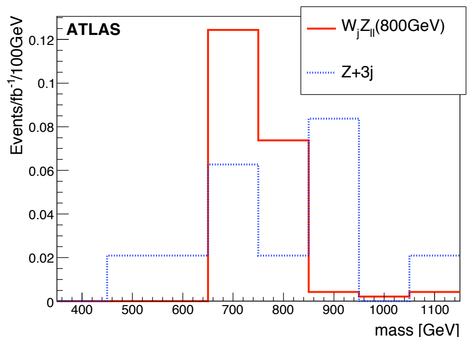


qqWZ→ qq qq$\ell\ell$ (K$_\perp$) signal

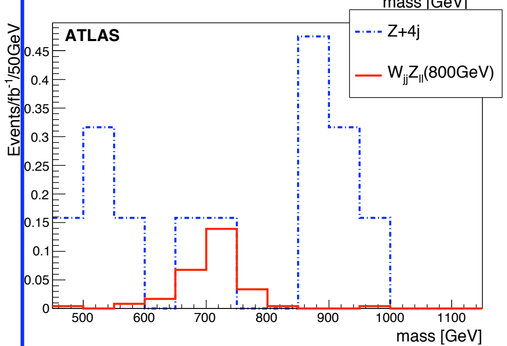


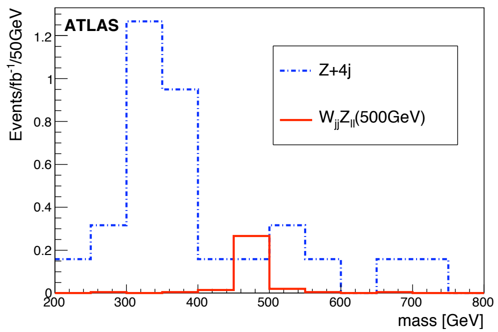
qqWZ→ qq qq$\ell\ell$ (K$_\perp$) signal and bkgd





single jet





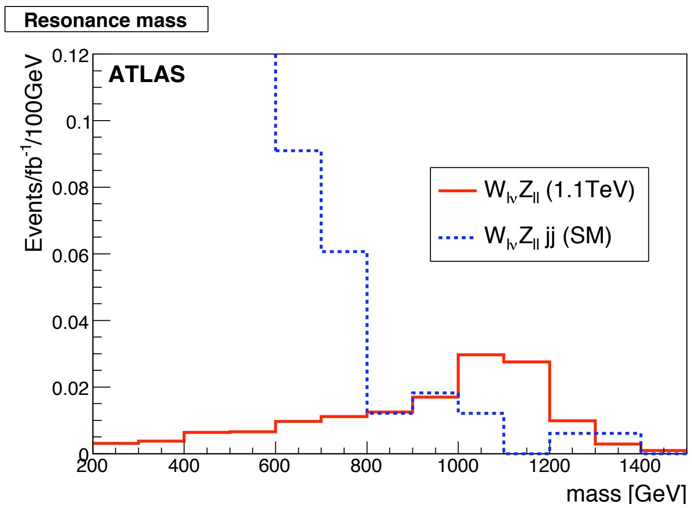
dijet

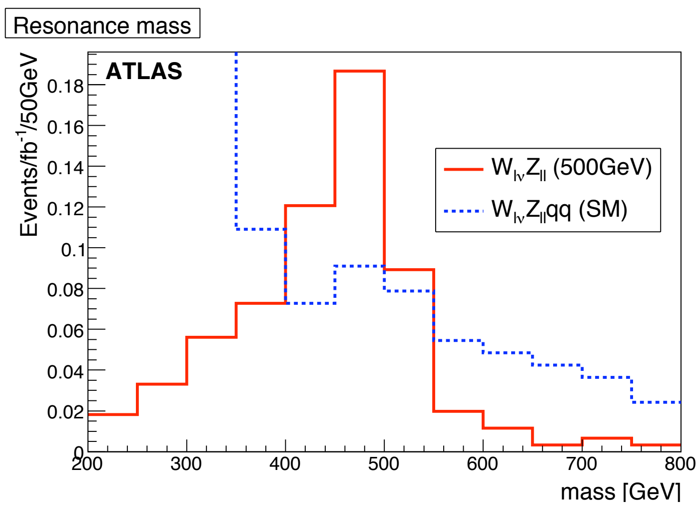
qqWZ→ qq qq$\ell\ell$ (cone) signal and bkgd

Two purely leptonic channels

$qqWZ \rightarrow qq\ \ell\nu\ell\ell$

Main background : SM WZ + jets
tag jets important for background suppression





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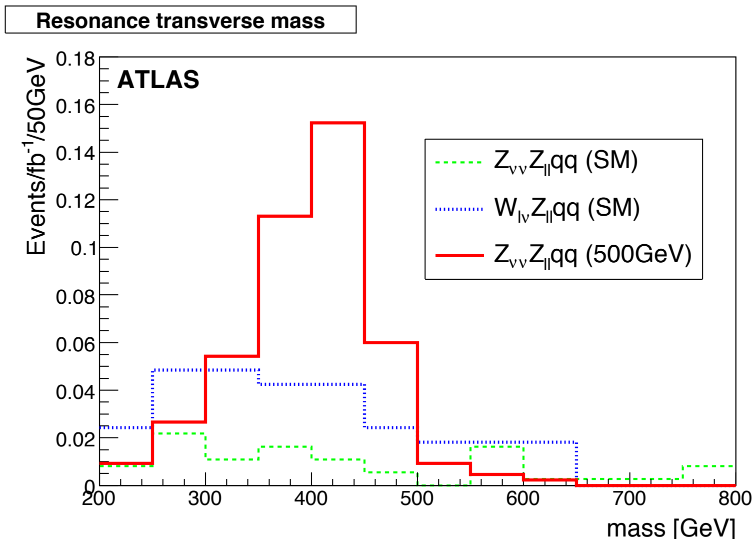
qqZZ → qq $\nu\nu\ell\ell$

Require a leptonic Z, large missing E_T and tag jets.

qqZZ→qq $\nu\nu\ell\ell$

Backgrounds:

- ZZjj
- WZjj →qq $\ell\nu\ell\ell$
- Z+jets with high missing E_T due to tail of E_T distribution



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Process	Cross section (fb)		Luminosity (fb^{-1})		Significance
	signal	background	for 3σ	for 5σ	for 100 fb^{-1}
$WW/WZ \to \ell\nu\, jj$, $m = 500$ GeV	0.31 ± 0.05	0.79 ± 0.26	85	235	3.3 ± 0.7
$WW/WZ \to \ell\nu\, jj$, $m = 800$ GeV	0.65 ± 0.04	0.87 ± 0.28	20	60	6.3 ± 0.9
$WW/WZ \to \ell\nu\, jj$, $m = 1.1$ TeV	0.24 ± 0.03	0.46 ± 0.25	85	230	3.3 ± 0.8
$W_{jj}Z_{\ell\ell}$, $m = 500$ GeV	0.28 ± 0.04	0.20 ± 0.18	30	90	5.3 ± 1.9
$W_{\ell\nu}Z_{\ell\ell}$, $m = 500$ GeV	0.40 ± 0.03	0.25 ± 0.03	20	55	6.6 ± 0.5
$W_{jj}Z_{\ell\ell}$, $m = 800$ GeV	0.24 ± 0.02	0.30 ± 0.22	60	160	3.9 ± 1.2
$W_{j}Z_{\ell\ell}$, $m = 800$ GeV	0.20 ± 0.02	0.09 ± 0.06	30	90	5.3 ± 1.3
$W_{j}Z_{\ell\ell}$, $m = 1.1$ TeV	0.11 ± 0.01	0.10 ± 0.06	90	250	3.1 ± 0.8
$W_{\ell\nu}Z_{\ell\ell}$, $m = 1.1$ TeV	0.070 ± 0.004	0.020 ± 0.009	70	200	3.6 ± 0.5
$Z_{\nu\nu}Z_{\ell\ell}$, $m = 500$ GeV	0.32 ± 0.02	0.15 ± 0.03	20	60	6.6 ± 0.6

20-85 fb^{-1}	3σ
55-235 fb^{-1}	5σ

1

Systematic Effects (1)

Background cross sections

Uncertainty due to renormalisation and factorisation scales by a factor of 2

Signal cross sections

From comparison with the WHIZARD MC, the tag jets given by Pythia are too soft - signal efficiencies are under estimated.

Event sample sizes

The limited number of surviving events (sometimes 0) limits the statistical precision of the results.

Systematic Effects (2)

Pile-up and underlying event.

These have an impact on the forward jet cuts, and the central jet and top vetoes, and the jet mass resolution.

Pile-up.

One channel (WZ →jj$\ell\ell$) was analysed with data that simulated pile up for $\mathscr{L} = 10^{33}$. An error of ~ 5% due to the degradation of the jet energy resolution.

Underlying Event

The Monte Carlo programs are tuned to the underlying event data from the Tevatron. Needs to be updated for the LHC.

Other effects

Uncertainties in the $\mathscr{L}$, efficiencies, resolutions, and the jet energy scale are expected to be a few %.

Summary

We have provided a sketch of how we intend to study Vector Boson scattering in ATLAS,

The Chiral Lagrangian with Padé normalisation to provided cross sections for VBS scattering in the scenario that no light Higgs Boson is found.
We have taken representative points in the (a4, a5) plane that correspond to resonances at 500, 800 and 1100 GeV as well as a continuum.

The extraction of the signal, particularly at high mass, has been achieved in part by the new technique of exploiting subjet structure to identify highly boosted vector bosons which decay to monijets.

It was essential to use other techniques - requirements of tag jets and central jet suppression.

We will perform evaluate backgrounds and efficiencies from the data itself rather than from simulation

We estimate it will require some 10s of fb^{-1} to observe such resonances.

Backup

Kt Jet Finder Algorithm

(longitudinally invariant formulation)

1. For each pair of particles i, j work out the kt distance
$d_{ij} = \min(k^2_{ti}, k^2_{tj}) R^2_{ij}$

with $R^2_{ij} = (\eta_i - \eta_j)^2 + (\phi_i - \phi_j)^2$,

where k_{ti} , η_i and ϕ_i are the transverse momentum, rapidity and azimuth of particle i; for each parton i also work out the beam distance $d_{iB} = k^2_{ti}$.

2. Find the minimum d_{min} of all the d_{ij} , d_{iB} . If d_{min} is a d_{ij} merge particles i and j into a single particle, summing their four-momenta (alternative recombination schemes are possible); if it is a d_{iB} then declare particle i to be a final jet and remove it from the list.

3. Repeat from step 1 until no particles are left.

(from M Cacciari, hep-ph/0607071)

Generation points in the (a4,a5) plane

10^3.a4	10^3. a5	mass(Gev)
9	-9	800
8.75	-1.25	1150
10	9	499
3	3	821
0	2	1134
9	-7	808
4	-4	1115
0	0	continuum
9	9	500

Data Sets

Sample name	Generator	$\sigma \times Br$, fb
$qqWZ \to qqjj\ell\ell$, $m = 500$ GeV	PYTHIA-73	25.2
$qqWZ \to qq\ell\nu jj$, $m = 500$ GeV	PYTHIA-73	83.9
$qqWZ \to qq\ell\nu\ell\ell$, $m = 500$ GeV	PYTHIA-73	8.0
$qqWZ \to qqjj\ell\ell$, $m = 800$ GeV	PYTHIA-ChL	10.5
$qqWZ \to qq\ell\nu jj$, $m = 800$ GeV	PYTHIA-ChL	35.2
$qqWZ \to qq\ell\nu\ell\ell$, $m = 800$ GeV	PYTHIA-ChL	3.4
$qqWZ \to qqjj\ell\ell$, $m = 1.1$ TeV	PYTHIA-ChL	3.7
$qqWZ \to qq\ell\nu jj$, $m = 1.1$ TeV	PYTHIA-ChL	12.3
$qqWZ \to qq\ell\nu\ell\ell$, $m = 1.1$ TeV	PYTHIA-ChL	1.18
$qqWW \to qq\ell\nu jj$, $m = 499$ GeV (s)	PYTHIA-ChL	66.5
$qqWW \to qq\ell\nu jj$, $m = 821$ GeV (s)	PYTHIA-ChL	27.5
$qqWW \to qq\ell\nu jj$, $m = 1134$ GeV (s)	PYTHIA-ChL	17.0
$qqWW \to qq\ell\nu jj$, $m = 808$ GeV (v)	PYTHIA-ChL	29.8
$qqWW \to qq\ell\nu jj$, $m = 1115$ GeV (v)	PYTHIA-ChL	17.9
$qqWW \to qq\ell\nu jj$, non-resonant	PYTHIA-ChL	10.0
$qqZZ \to qq\nu\nu\ell\ell$, $m = 500$ GeV	PYTHIA-ChL	4.0
$jjWZ \to jj\ell\nu\ell\ell$, bckg	MADGRAPH	96
$jjZZ \to jj\nu\nu\ell\ell$, bckg	MADGRAPH	123
		σ (no Br), pb
$W^+ + 4$ jets, QCD diagrams	MADGRAPH	163.3 ± 0.1
$W^+ + 4$ jets, EW diagrams	MADGRAPH	1.76 ± 0.03
$Z + 4$ jets, QCD	MADGRAPH	85.7 ± 0.7
$Z + 4$ jets, EW	MADGRAPH	1.04 ± 0.02
$W^+ +$ 3jets, QCD	MADGRAPH	6.08 ± 0.02
$W^+ + 3$ jets, EW	MADGRAPH	0.219 ± 0.001
$Z + 3$ jets, QCD	MADGRAPH	3.72 ± 0.02
$Z + 3$ jets, EW	MADGRAPH	0.106 ± 0.006
$t\bar{t}$	MC@NLO	833 ± 100