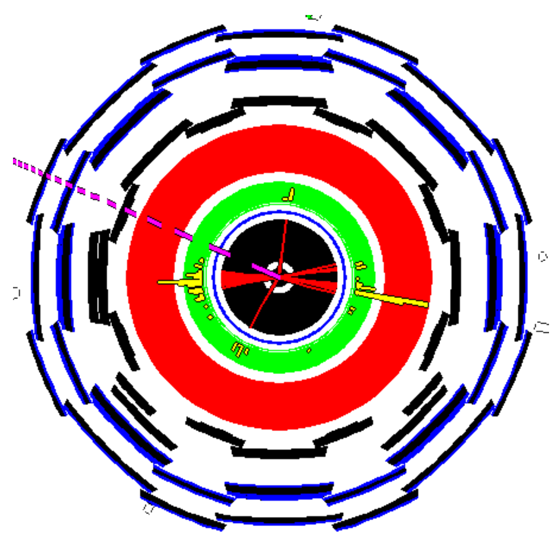
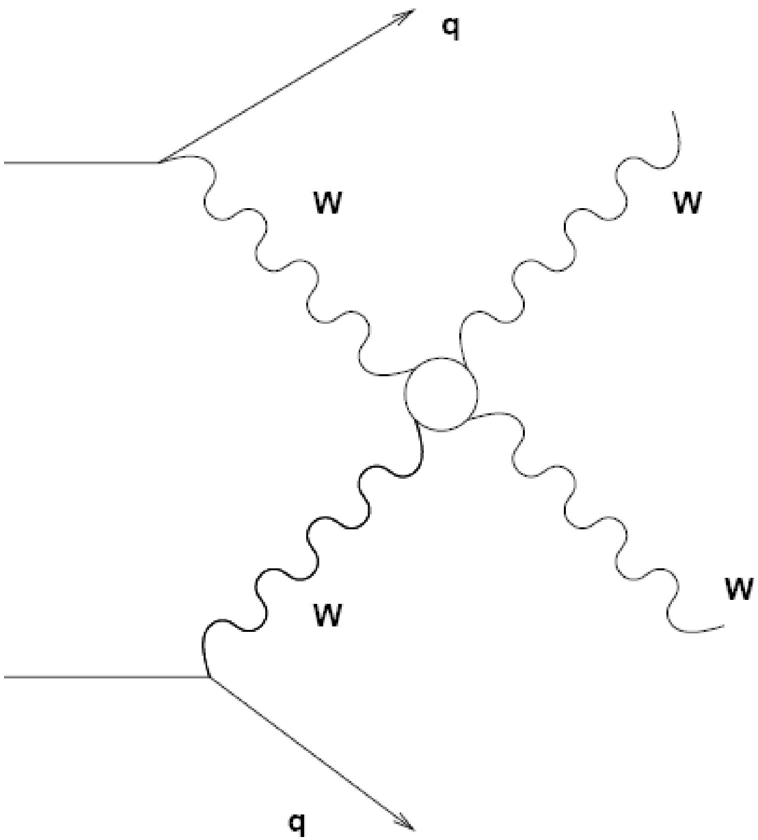
Vector Boson Scattering
at High Mass, with ATLAS

Adam Davison on behalf of the ATLAS Collaboration



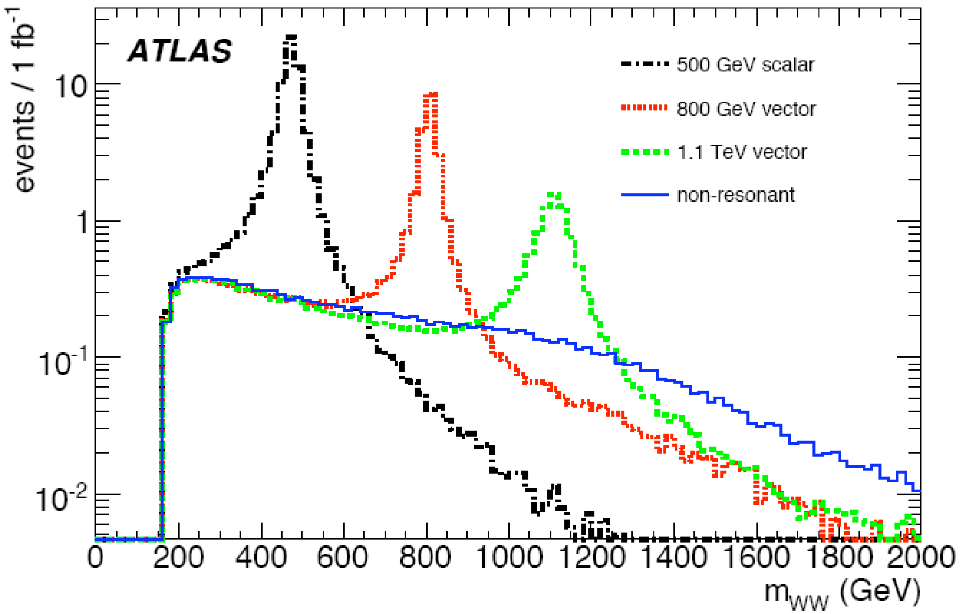
Vector Boson Scattering

- In the Standard Model (without Higgs) the cross-section for vector boson scattering violates unitarity at the TeV scale
- New physics guaranteed to manifest itself at the LHC for this reason
- Could be the Higgs but could be something else entirely...



Vector Boson Scattering at ATLAS

- Has recently been studied with detector simulation as part of the ATLAS preparation for first data
- Perform an essentially model independent search
- Introduce generic resonances and study observability with ATLAS



Vector Boson Scattering at ATLAS

- Various different channels which can be studied
  - WW, WZ, ZZ
  - Hadronic and leptonic decays
- Have been studying semi or fully leptonic case
- Generally W vs Z $\rightarrow$ qq will be indistinguishable
- Broadly speaking within ATLAS analyses are:
  - VW $\rightarrow$ qlν
  - VZ $\rightarrow$ qqll
  - ZW $\rightarrow$ lllν
- Generally to be observable above V+jets and $t\bar{t}$ backgrounds we must look at high p_T (> 200 GeV)

Experimental Signature

- Leptonic Vector Boson
  - Lepton pair which reconstructs within Z mass window
  - Or for leptonic W channels, 1 lepton + missing ET
- Hadronic Vector Boson
  - Often highly boosted so 1 or 2 jets (more on this later)
- Tag Jets
  - Vector boson scattering at high mass is associated with tag jets from the incoming quarks
  - Presence of one “tag jet” in both forward and backwards directions is a strongly discriminating variable

Monte Carlo

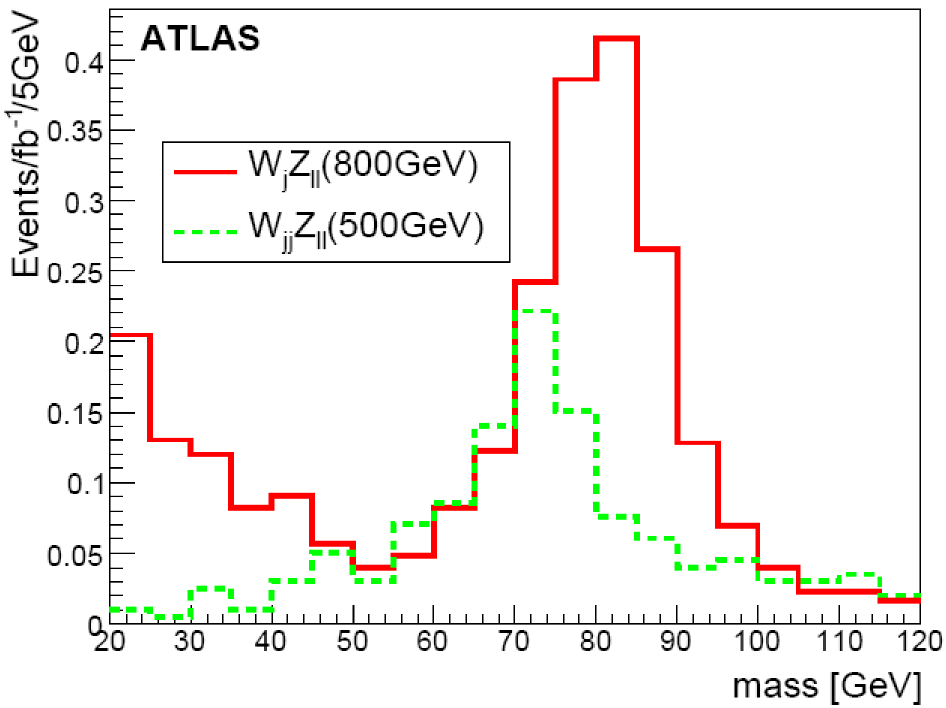
- Was assumed that $t\bar{t}$ would be the big problem
- Previous ATLAS studies used Pythia for V+jets
- Showed that actually V+jets as important
- Here we use MadGraph to generate V+jets
- Signal is done with Pythia
  - EWChL model
  - Padé unitarisation which produces resonances
- Also experimented with:
  - Alpgen for V+jets - reasonable agreement w/ MadGraph
  - Whizard for signal

Hadronic Vector Boson Identification

- The most unique part of this analysis in many ways is the attempt to identify hadronically decaying vector bosons against large QCD backgrounds
- Since vector bosons from a TeV scale resonance tend to be very boosted, usually reconstruct hadronic decays as a single jet
- Must be able to distinguish these jets from those from pure QCD jets
- Make p_T cut but still need more rejection...
- ... so need to look at substructure of the jets

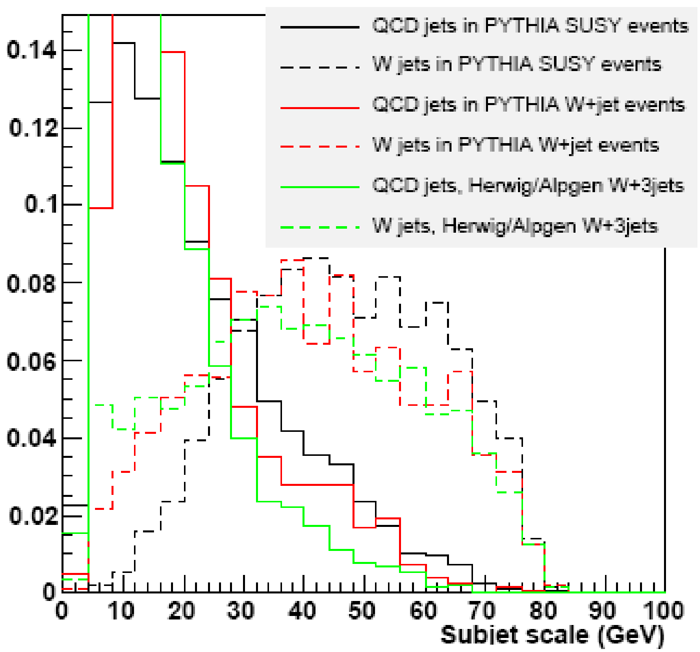
Jet Mass

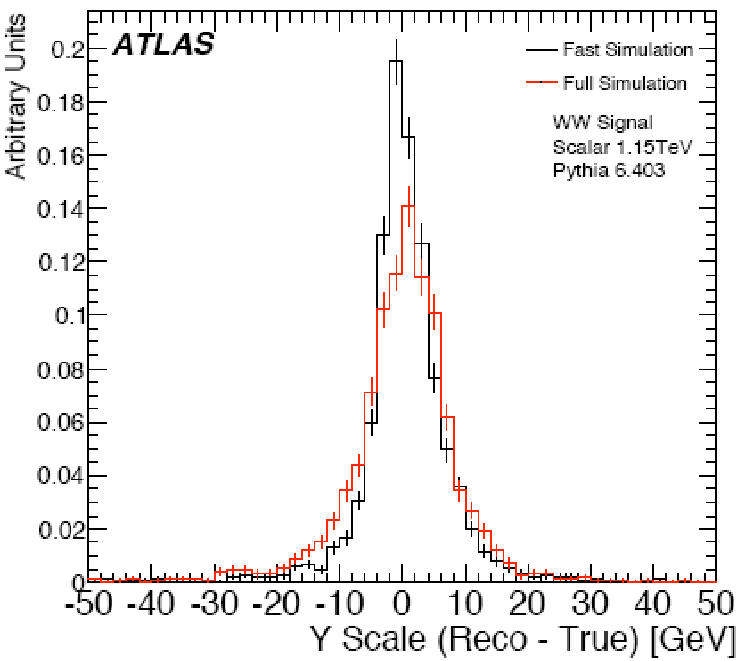
- Jet masses are obtained by jet finding with a recombination scheme of 4-vector addition
- If the jets is composed of all decay products of heavy bosons have mass of $O(M_{boson})$
- Quark/gluon jets tend to have lower mass



With k_T Algorithm

- When using k_T it is possible to do further analysis of the structure of a jet
- k_T jets are produced by ordered pairwise merging
- Can undo this merging and measure the (y-)scale





Butterworth, Ellis, Raklev hep-ph/0702150

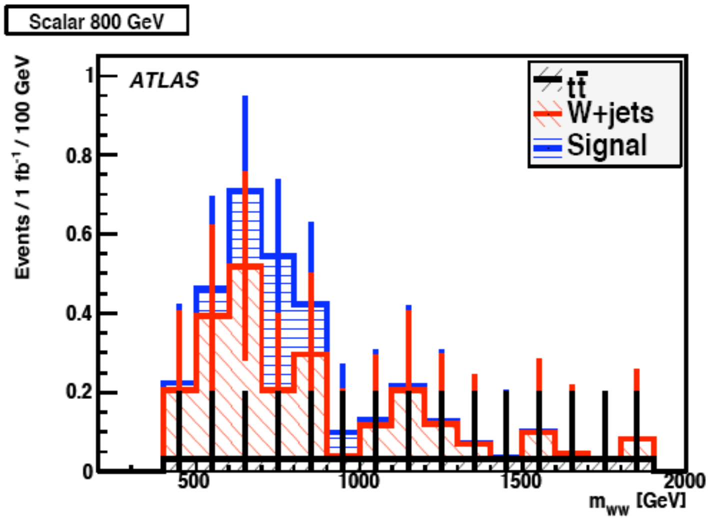
Event Selection

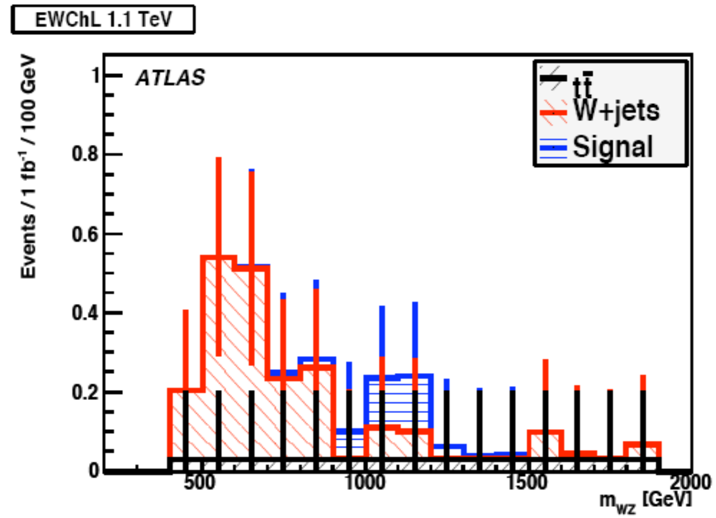
- A hadronic and leptonic vector boson candidate reconstructed with p_T > 200GeV and $|\eta| < 2$
- "tag jets" in the forward and backward hemispheres with $|\eta| > 2$, p_T > 20GeV, E > 300GeV, $\Delta\eta > 4.4$
- No W candidate + light jet makes a top
- No additional central jet activity

Cut	$m = 500$ GeV Scalar Resonance		$m = 800$ GeV Scalar Resonance	
	Efficiency (%)	σ (fb)	Efficiency (%)	σ (fb)
Starting sample	–	66	–	28
$\equiv 1$ Hadronic W	32.1 ± 0.5 (34)	21 (23)	40.0 ± 0.5 (45)	11 (13)
$\equiv 1$ Leptonic W	45.4 ± 0.9 (54)	9.6 (12)	48.5 ± 0.8 (57)	5.4 (7.1)
p_T (Had. W) > 200 GeV	57.6 ± 1.3 (69)	5.5 (8.5)	88.2 ± 0.7 (90)	4.8 (6.4)
$\|\eta\|$ (Had. W) < 2	91.9 ± 0.9 (93)	5.1 (7.9)	95.3 ± 0.5 (95)	4.6 (6.1)
p_T (Lep. W) > 200 GeV	43.8 ± 1.8 (42)	2.2 (3.3)	91.3 ± 0.7 (89)	4.2 (5.4)
$\|\eta\|$ (Lep. W) < 2	95.5 ± 1.1 (94)	2.1 (3.1)	95.3 ± 0.6 (95)	4.0 (5.1)
$\equiv 2$ tag jets	32.0 ± 2.6 (37)	0.7 (1.1)	42.4 ± 1.3 (49)	1.7 (2.5)
$\equiv 0$ top candidates	50.0 ± 5.0 (40)	0.3 (0.5)	52.0 ± 2.1 (41)	0.9 (1.0)
Central jet veto	100.0 ± 0.0 (98)	0.3 (0.4)	96.7 ± 1.0 (97)	0.8 (1.0)
Trigger efficiency	96 ± 3	0.3 (0.4)	98 ± 1	0.8 (1.0)

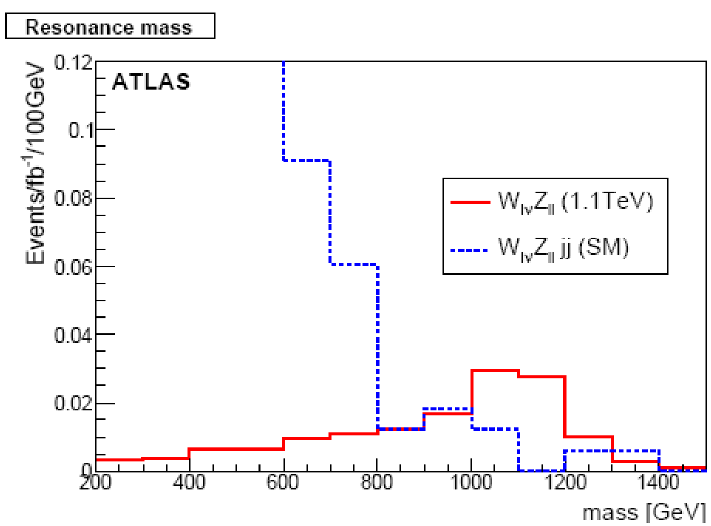
Sample of Results

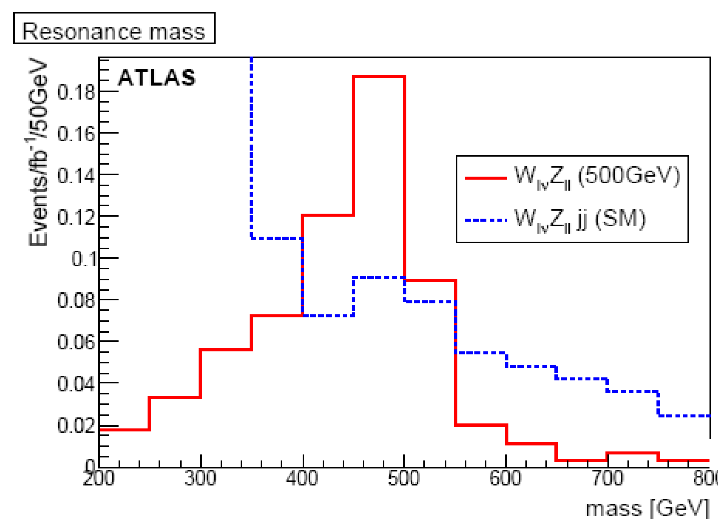
$WW \to qql\nu$





$ZW \to lll\nu$





Sensitivity

- Clearly not a low luminosity measurement
- However some channels can be combined

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	236	3.3 ± 0.7
$WW/WZ \to \ell\nu\ jj$, $m = 800$ GeV	0.65 ± 0.04	0.87 ± 0.28	22	62	6.3 ± 0.9
$WW/WZ \to \ell\nu\ jj$, $m = 1.1$ TeV	0.24 ± 0.03	0.46 ± 0.25	83	232	3.3 ± 0.8
$W_{\ell\nu}Z_{\ell\ell}$, $m = 500$ GeV	0.40 ± 0.03	0.25 ± 0.03	20	55	6.6 ± 0.5
$W_{jj}Z_{\ell\ell}$, $m = 800$ GeV	0.20 ± 0.02	0.09 ± 0.06	30	90	5.3 ± 1.3
$W_{jj}Z_{\ell\ell}$, $m = 1.1$ TeV	11.5 ± 3.7	10 ± 6	90	250	3.1 ± 1.2
$W_{\ell\nu}Z_{\ell\ell}$, $m = 1.1$ 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

Outcome of the Study

- ATLAS is capable of observing vector boson scattering processes at the LHC
- With first ~10fb^{-1} of well understood data we should be able to start ruling out more extreme models
- Potential for discovery of resonances with around 3 years of LHC running at design luminosity (~30fb^{-1})

Plans For First Data

- Understanding of jets will be critical for this analysis
- Subjet analysis techniques are relatively new
- Many people will be calibrating the ATLAS jet energy scale and so on with early data
- Fewer will be looking at the structure of jets
- Also can start looking for first vector boson scattering events even with early data
- There are lots of more extreme models with higher cross-sections than those studied in this work

Future Improvements

- More advanced subjet techniques could be tried to achieve an improvement over this study
- Recent publication:

  J. M. Butterworth, **A. R. Davison**, **M. Rubin** and **G. P. Salam**

  Jet substructure as a new search channel for the Higgs at the LHC

  arXiv:0802.2470v1 [hep-ph]
- Find that using Cambridge-Aachen jets and a different decomposition procedure allows for extraction of heavy particle decay (Higgs here)
- Possibly similar techniques could be successfully applied to vector boson scattering

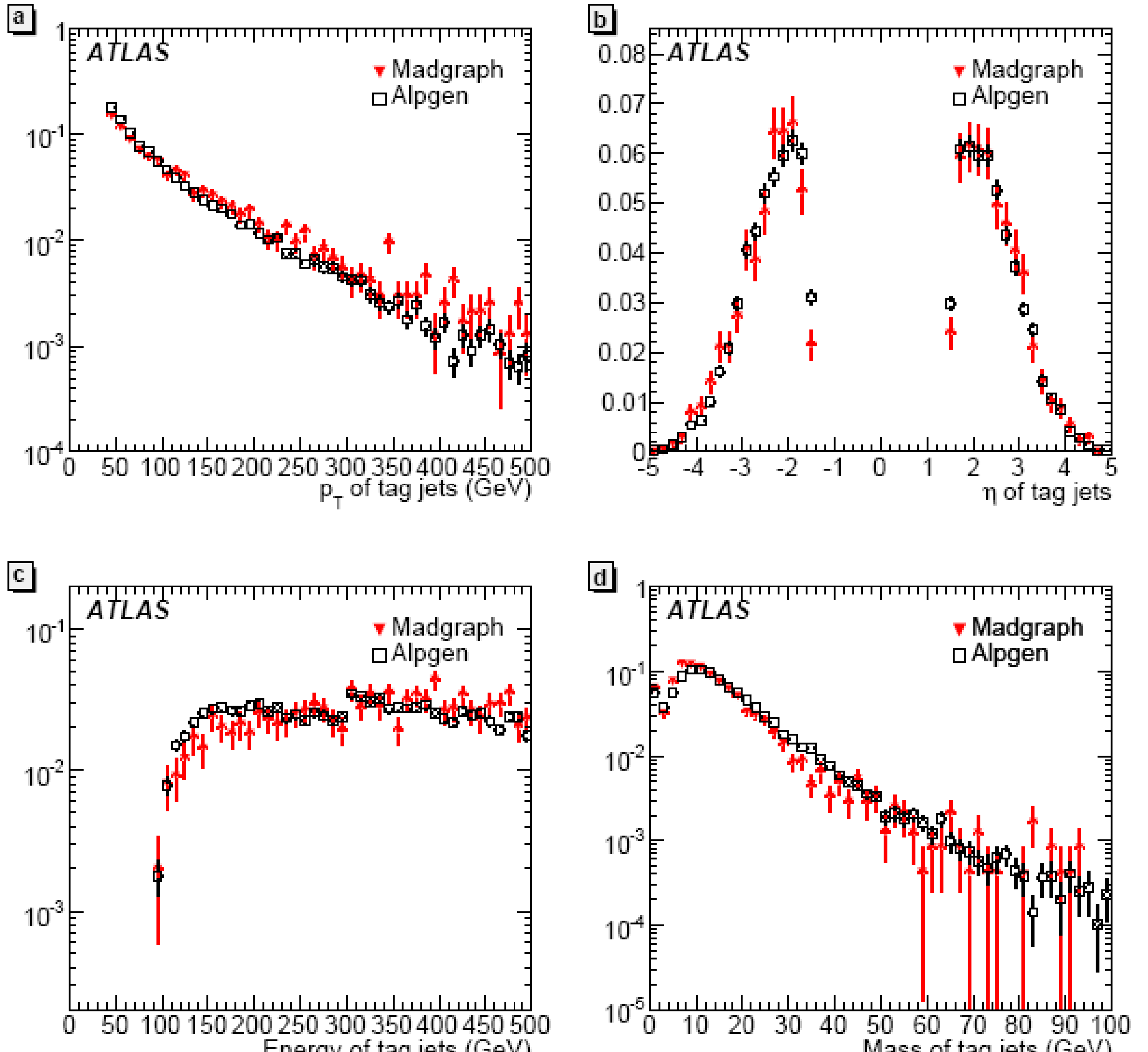
Conclusion

- Vector boson scattering is a key process at ATLAS
- Opportunity to study wide variety of scenarios
- This is the first fully detector simulated study using modern Monte Carlo techniques
- Find that measurements with ATLAS are viable
- Also a motivation for an LHC upgrade
- Like everyone else: looking forward to first data

BACKUP

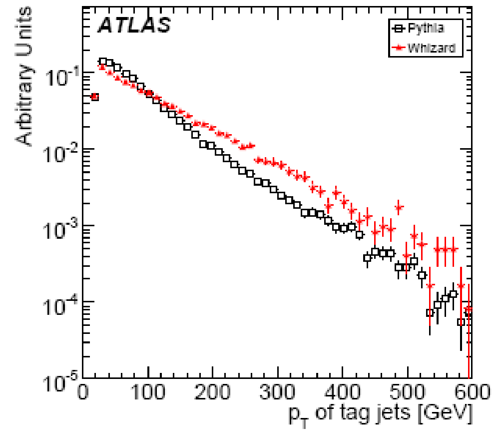
MadGraph vs Alpgen

- Comparison of various variables for the W+4 jets background
- MadGraph not using PS/ME matching here
- Normalised

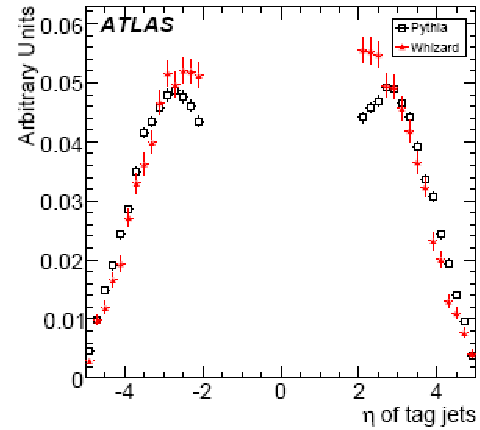


Whizard

- No effective W approximation
- Full 2->4 ME
- Differences not substantial
- Possibly more sensitivity to signal in η distribution



(a)



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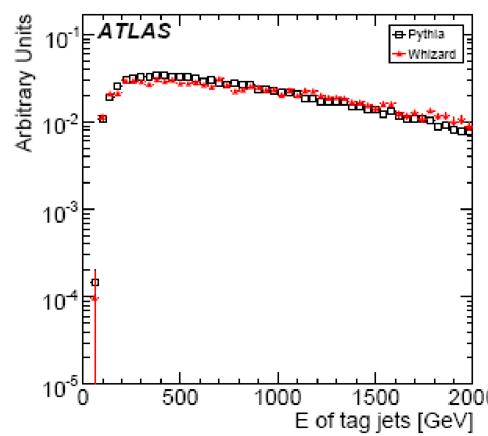
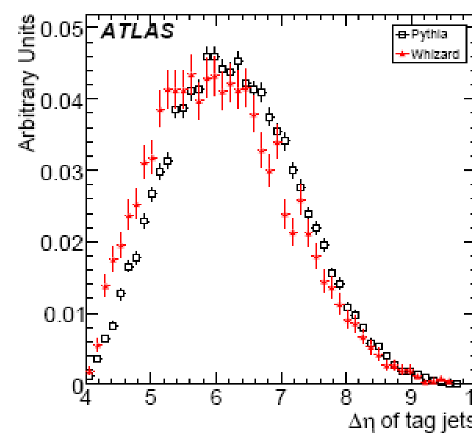
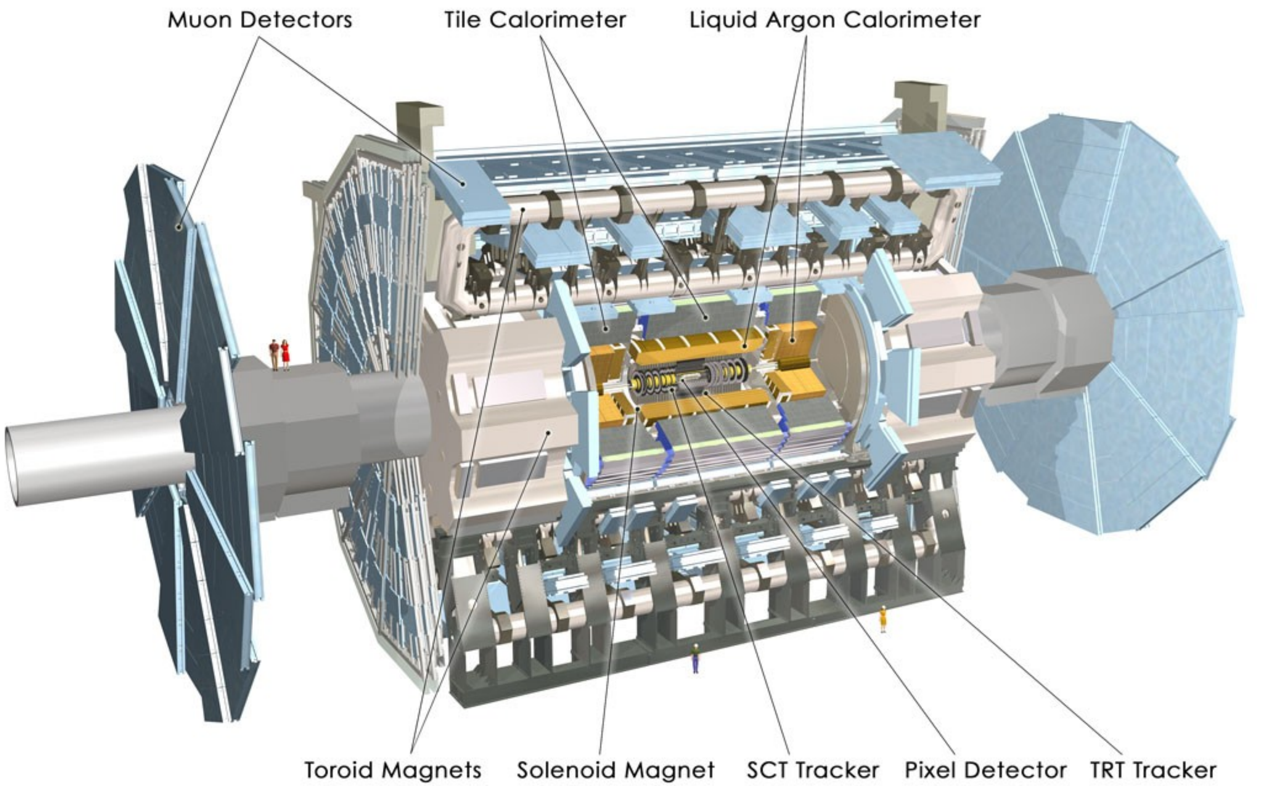


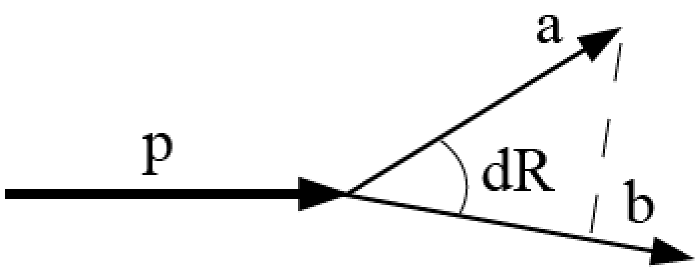


ATLAS

- Detector for studying 14TeV pp collisions at LHC
- "General purpose detector"
- Good resolution for hadronic systems



Y Scale



$$y_{cut} = \frac{\min\left(p_{Ta}^2, p_{Tb}^2\right) dR_{ab}^2}{p_{Tcut}^2}$$

Kt "y-values" (left) represent the scale at which a parent jet subdivides into two smaller child jets a and b