Vector Boson Scattering at ATLAS

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On behalf of the ATLAS Collaboration

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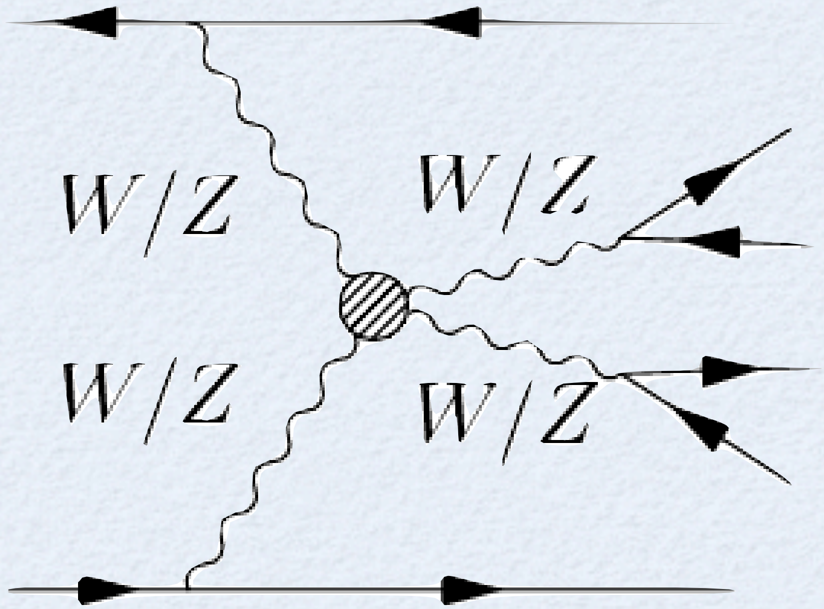
Why Build the LHC?

- Vector bosons we observe: Ws, Z and photon
  - EW sym. broken: heavy W/Z, but massless photon
- How do we explain this?
  - Higgs mechanism in the SM
    - (Partially) *Economical* but *no fundamental reason* why physics responsible for EWSB is weakly interacting.
  - Many alternatives: technicolor, 4th generation fermion condensates, string interactions, interactions in extra dimensions, bulk-brane interplay…
- If there is a light Higgs, is it fundamental/composite?

Life Without Higgs

- What happens to SM (and its extensions like SUSY) if no (light) Higgs exists?
  - $V_L V_L$ (V=W/Z) scattering x-section blows up.



- Why? When Vs are on-shell, quasi-elastic scattering amplitude will diverge at the lowest order.
  ==> There must be something to unitarize the scattering amplitude.
- Same happens also when the Higgs couplings are not right.

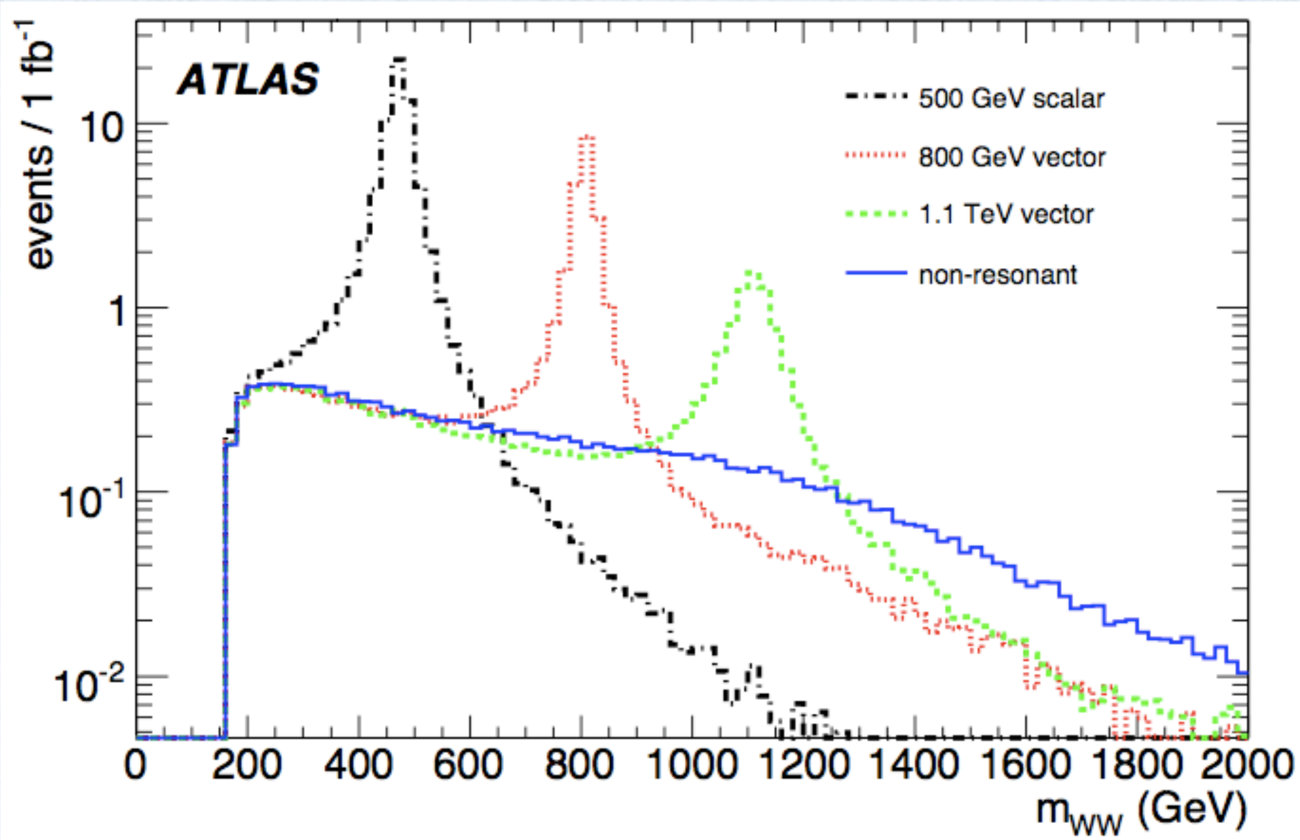
Experimental Goal

- In short: Measure differential scattering cross-section as a function of VV center-of-mass energy.
  - Identify WW, WZ or ZZ at high momenta.
  - Try to make sure they interacted with each other. (Don't want two Ws from two tops, for instance.)
  - Measure invariant mass spectrum.
    - If you see a resonance or a total cross-section higher than SM prediction => New Physics!
    - If not, stringent constraints on SM extensions.
- Do all these as model-independently as possible!

EW Chiral Lagrangian

- Start with SM Lagrangian without the Higgs.
- Introduce 3 Goldstone-boson fields to give mass to VBs.
- Starting from lowest-dimension and expanding, write all possible operators for these fields. (Keeping in mind the EW precision observables).
- A nice *low-energy* effective theory that can yield model-independent predictions.
    - Caveat: Needs to be unitarized for TeV scale.
    - After unitarization, can generate MC signal events.

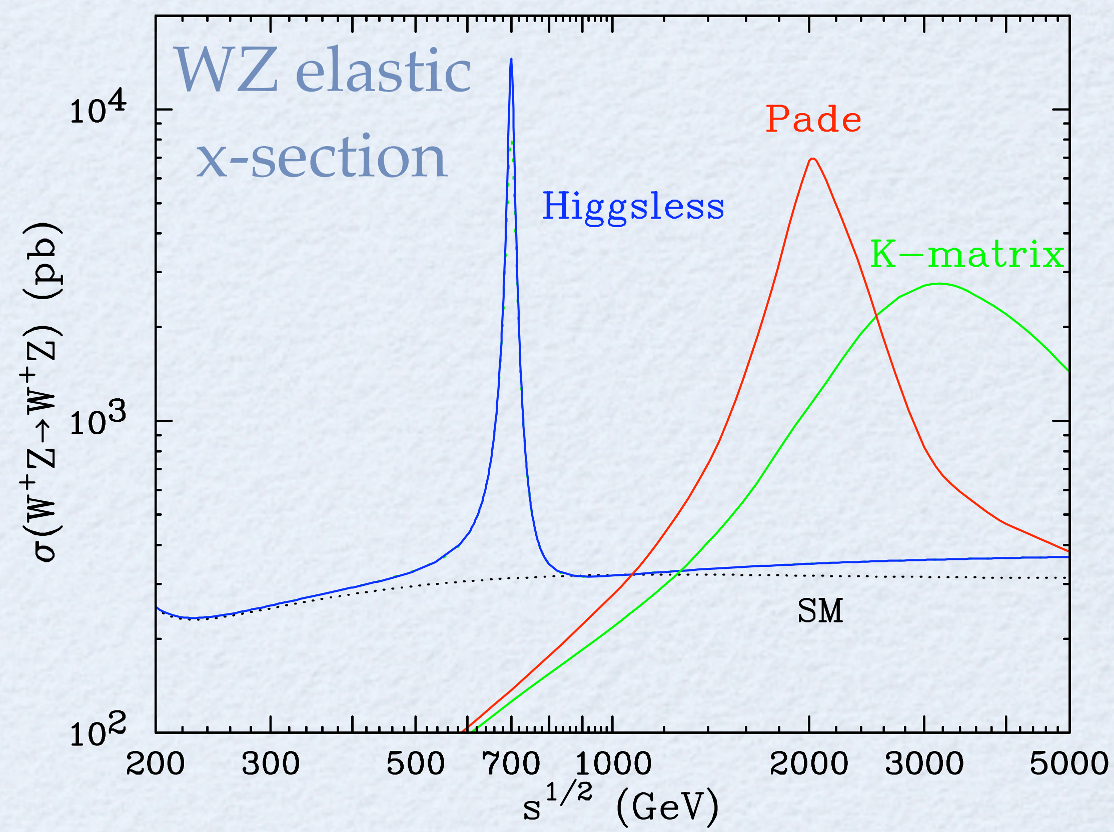
Resonances



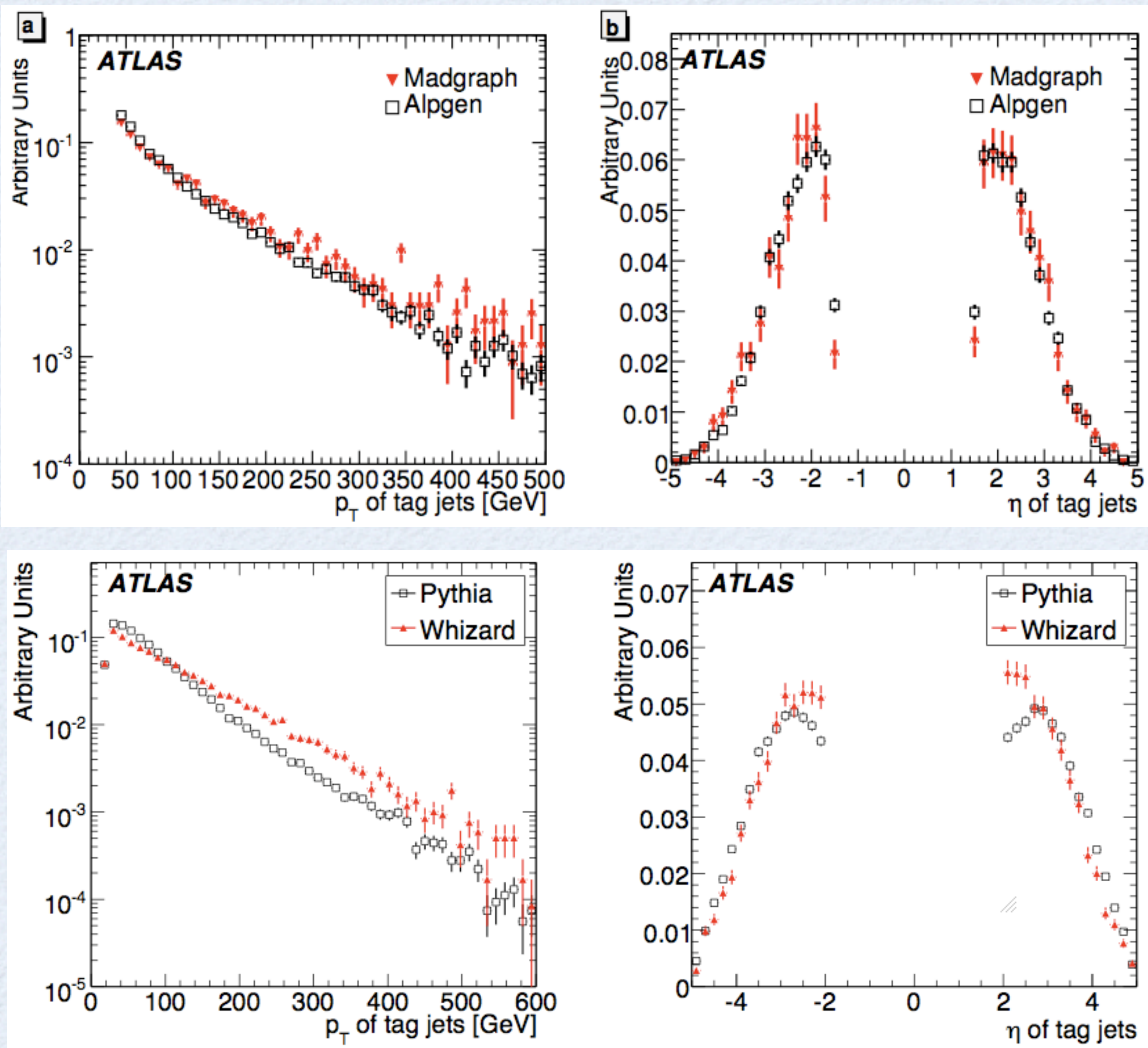
- Measure spectrum
  - Look for resonances
- For signal MC: introduce resonances with Padé unitarization scheme.

- Padé unitarization gives excellent description for π-scattering in QCD.
- (α_4,α_5) determine mass, width, spin & presence of resonances.

Birkedal, Matchev, Perelstein, hep-ph/0412278



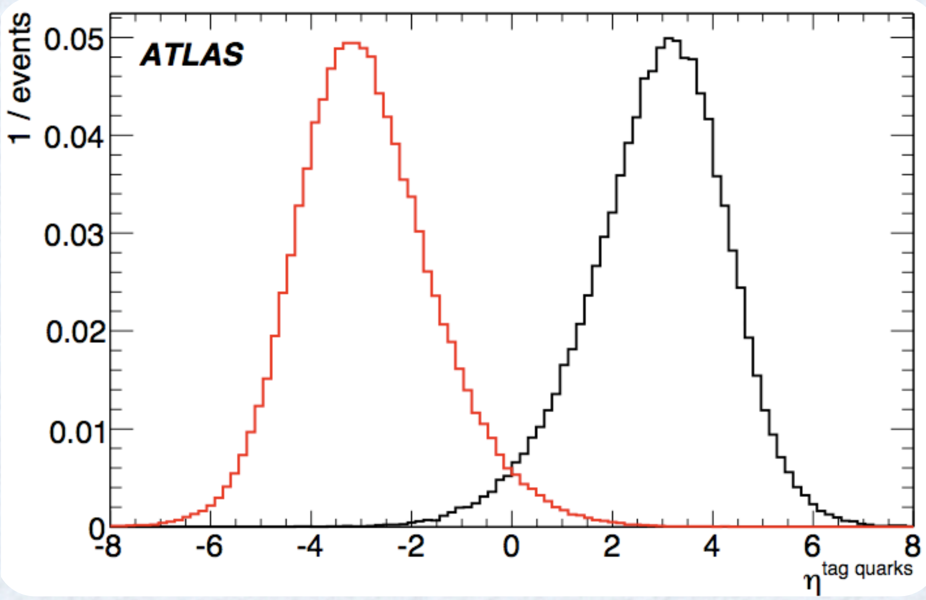
Monte Carlo

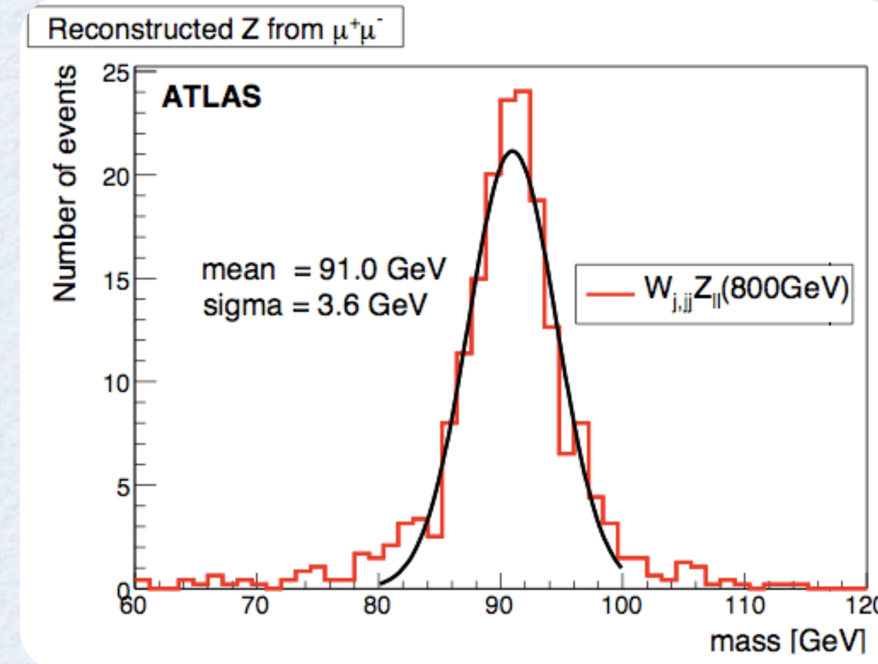


$t\bar{t}$: *MC@NLO, Herwig, Jimmy*

W/Z+3/4 jets: *Madgraph* (crosschecked against *Alpgen*)

Signal: Modified *Pythia* (crosschecked against *Whizard*)

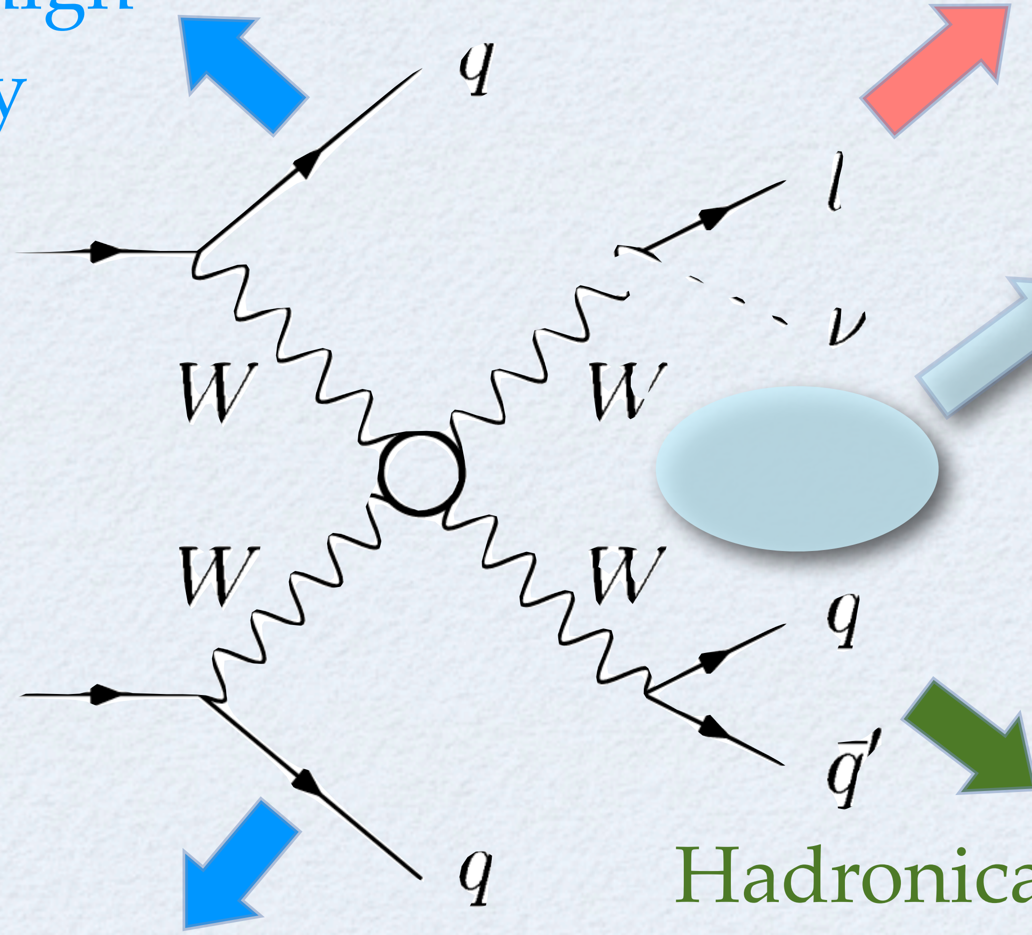




Leptonically decaying VB at high momentum

Tag jet at high rapidity

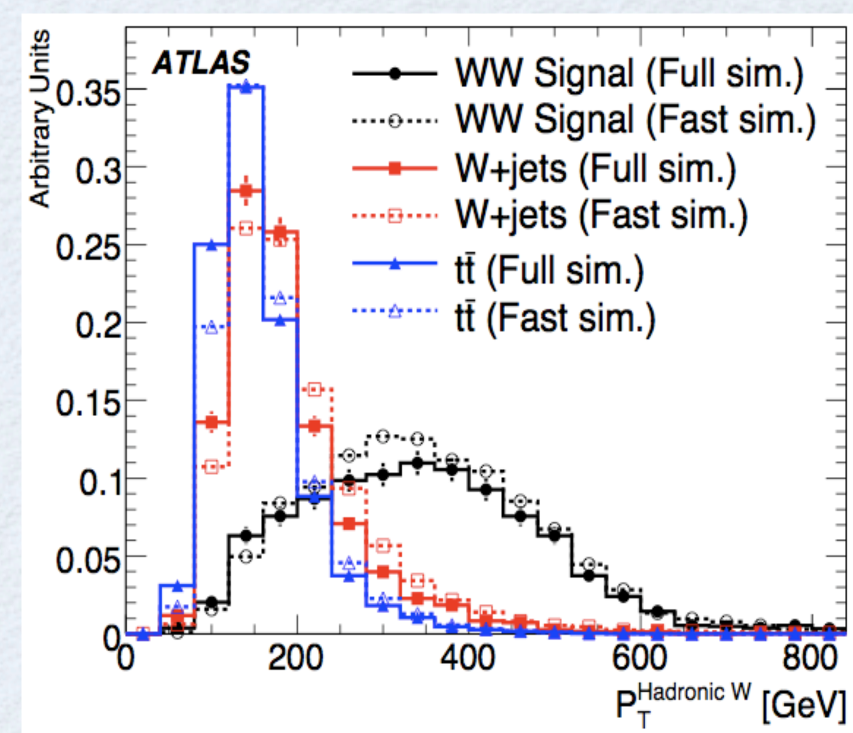
Signal at a Glance



no color exchange so suppression of QCD activity (no central jets)

Tag jet at high rapidity and on opposite side

Hadronically decaying VB at high momentum

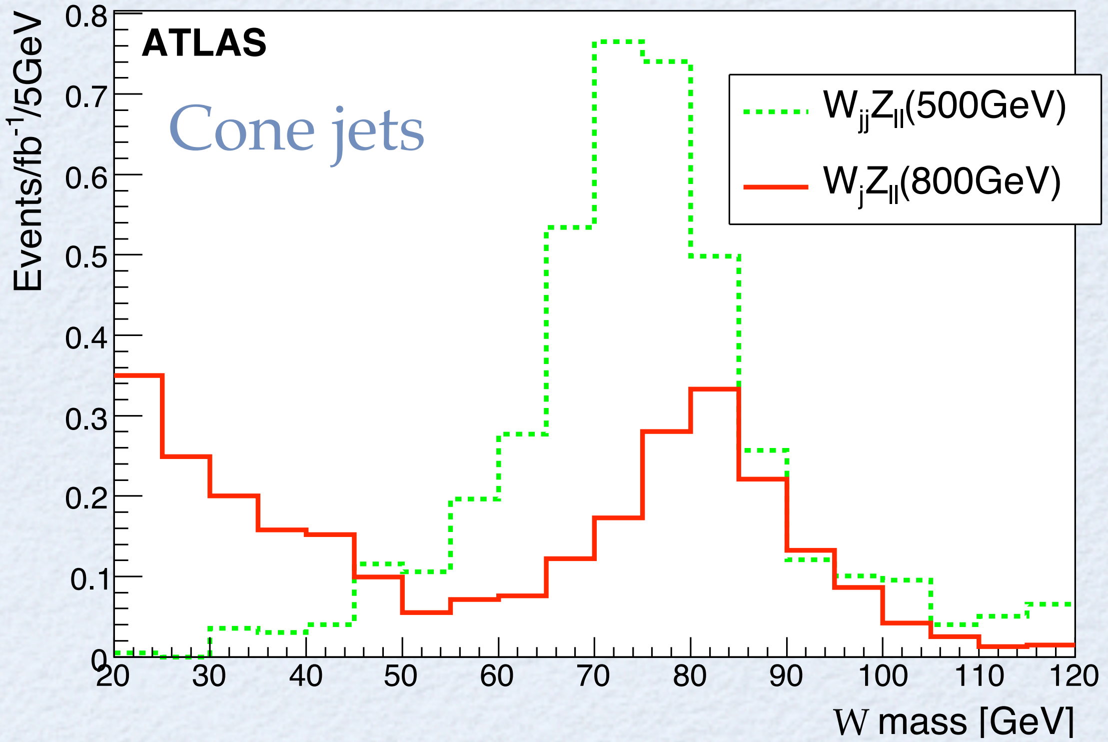


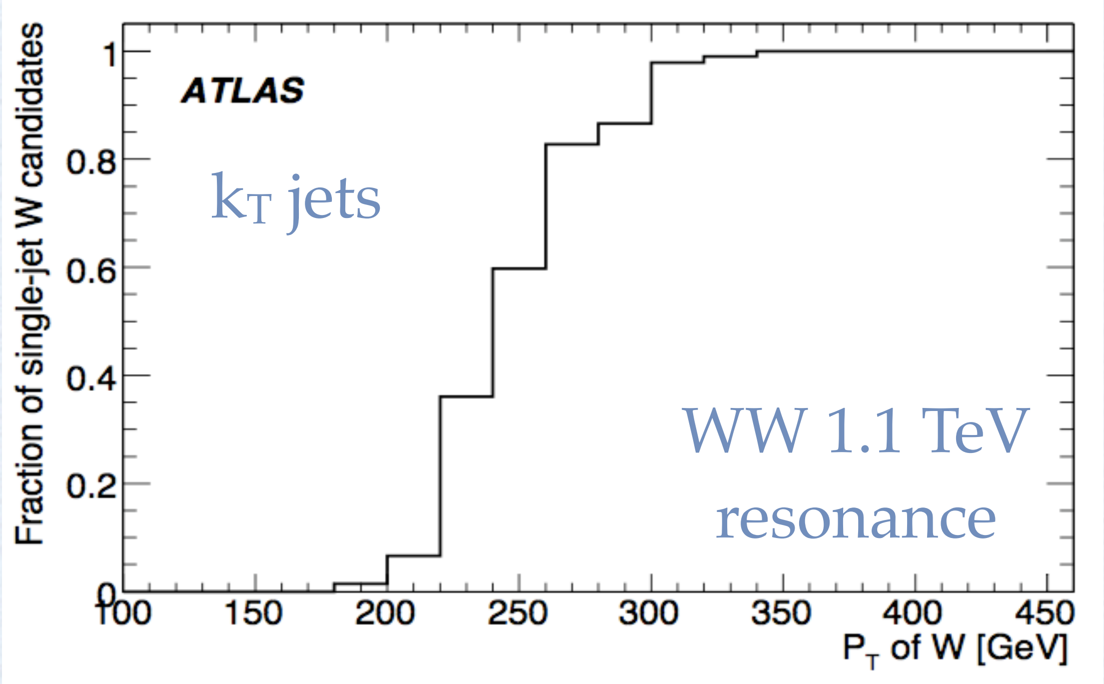
Hadronic VBs: 1 or 2 jets

- At high enough P_T, hadronic VB starts to end up in a single jet.
- In each event: Take highest P_T jet. Mass close to W/Z ?

  Yes: This jet is the VB candidate. Apply cut on jet substructure.

  No: Loop over all pairs of jets. Find the pair whose combination gives the highest P_T. The combination is the VB candidate. Apply mass and relative-momentum cuts.

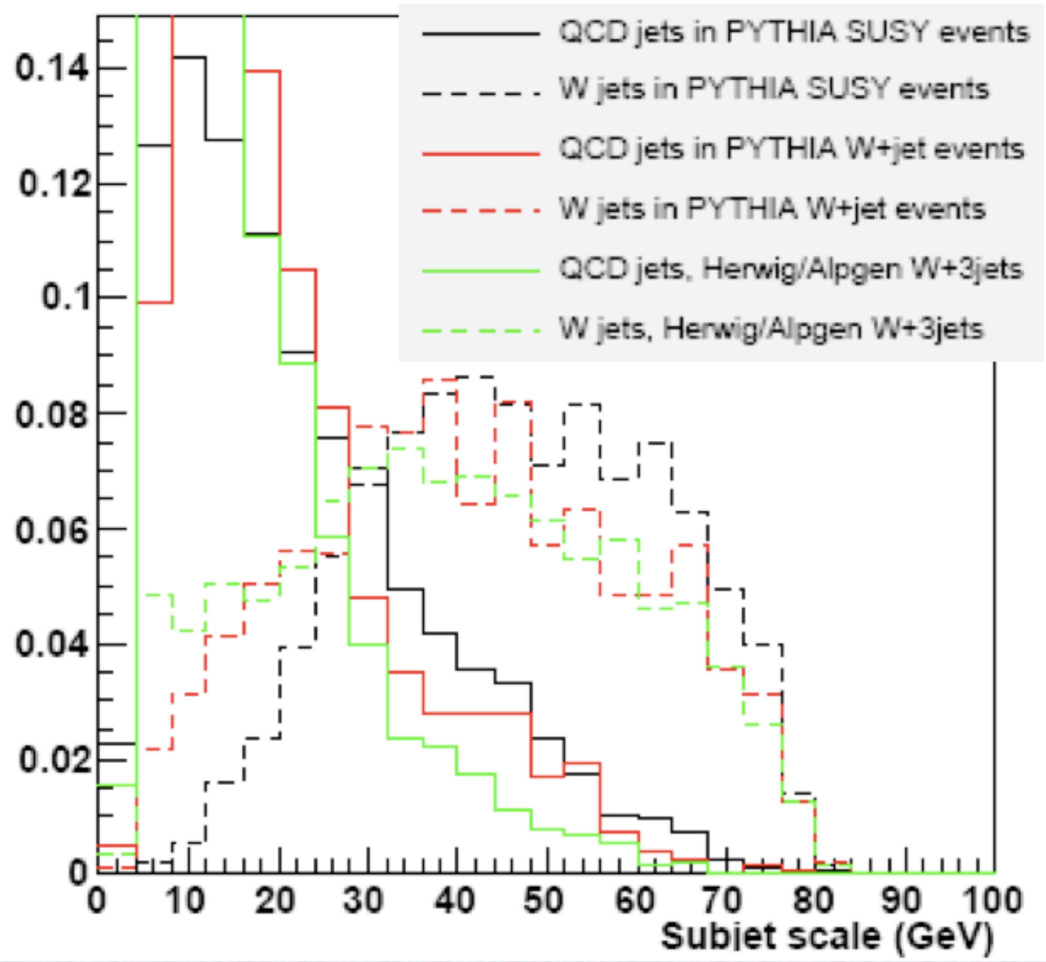


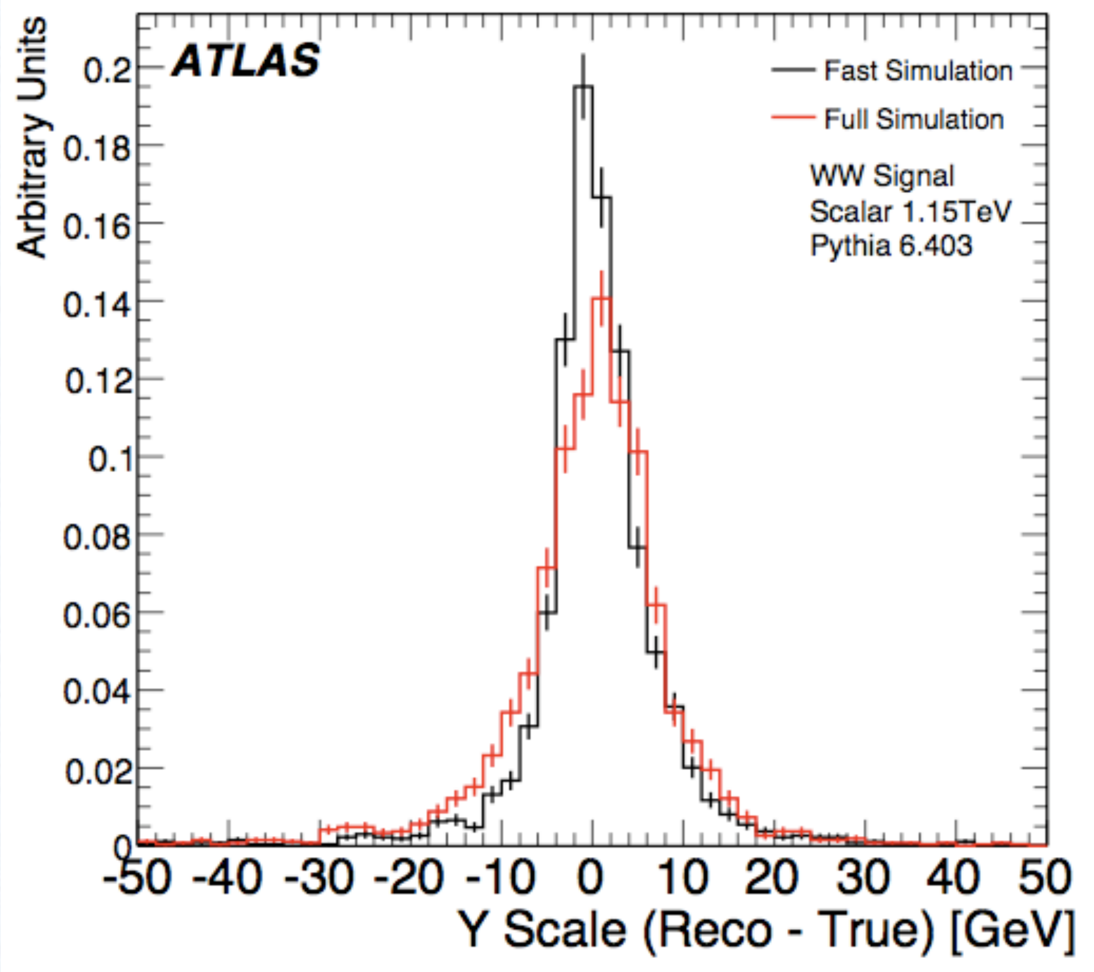


Jet Structure

- k_T merging intrinsically ordered in scale.
  - Undo last merging: Get the Y-scale at which the jet would split into two subjets.
  - Y-scale ~ $O(m_{VB}/2)$ ~ k_T of one subjet wrt. other

Butterworth, Ellis, Raklev
hep-ph/0702150





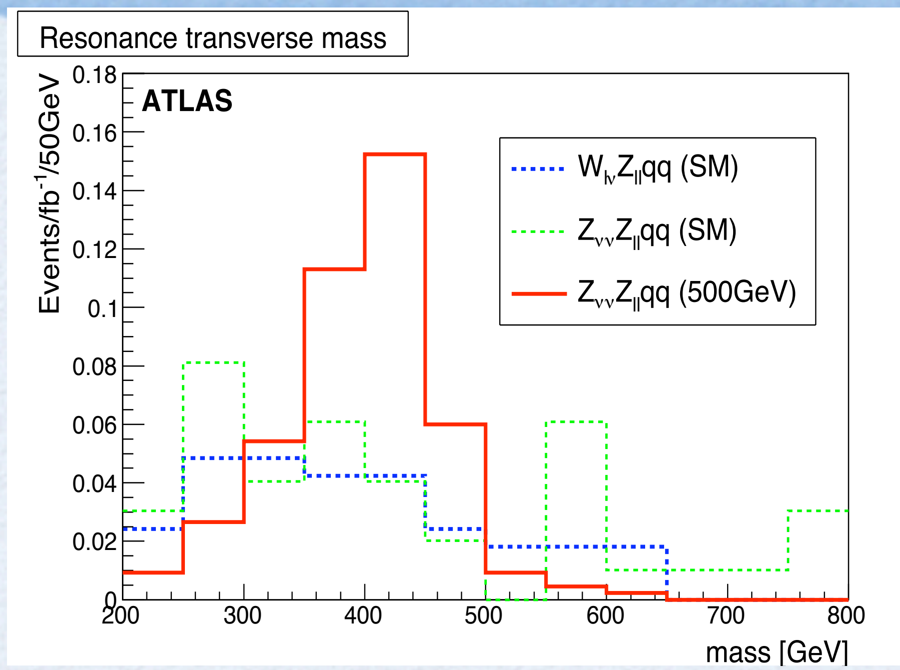
Putting it Together

Cut	Non-resonant Signal		tt Background		W+jets Backgrounds	
	Efficiency (%)	σ (fb)	Efficiency (%)	σ (fb)	Efficiency (%)	σ (fb)
Starting sample	–	10	–	450000	–	21365
$\equiv 1$ Hadronic W	38.0 ± 0.7 (41)	3.8 (4.1)	18.9 ± 0.1 (19)	85000 (84000)	8.3 ± 0.1 (9)	1760 (1820)
$\equiv 1$ Leptonic W	48.2 ± 1.1 (55)	1.8 (2.3)	22.1 ± 0.2 (29)	19000 (25000)	23.3 ± 0.7 (31)	410 (570)
p_T (Had. W) > 200 GeV	82.1 ± 1.3 (86)	1.5 (1.9)	16.8 ± 0.4 (20)	3200 (5000)	34.4 ± 1.7 (43)	140 (240)
$\|\eta\|$ (Had. W) < 2	94.4 ± 0.8 (94)	1.4 (1.8)	90.3 ± 0.7 (90)	2900 (4500)	80.1 ± 2.4 (77)	110 (190)
p_T (Lep. W) > 200 GeV	90.4 ± 1.1 (87)	1.3 (1.6)	34.5 ± 1.3 (29)	990 (1300)	48.5 ± 3.3 (40)	55 (75)
$\|\eta\|$ (Lep. W) < 2	96.0 ± 0.8 (96)	1.2 (1.5)	94.6 ± 1.0 (90)	930 (1200)	80.4 ± 3.9 (79)	44 (59)
$\equiv 2$ tag jets	45.1 ± 2.0 (54)	0.6 (0.8)	8.1 ± 1.3 (10)	76 (120)	13.9 ± 3.5 (22)	6 (13)
$\equiv 0$ top candidates	56.5 ± 3.0 (47)	0.3 (0.4)	7.9 ± 4.4 (2)	5 (2)	60.5 ± 13.1 (23)	4 (3)
Central jet veto	91.1 ± 2.3 (94)	0.3 (0.4)	< 50 (< 25)	< 5 (< 1)	84.9 ± 13.7 (91)	3 (3)
Trigger efficiency	98 ± 1	0.3 (0.4)	~ 100	< 5 (< 1)	82 ± 16	3 (3)

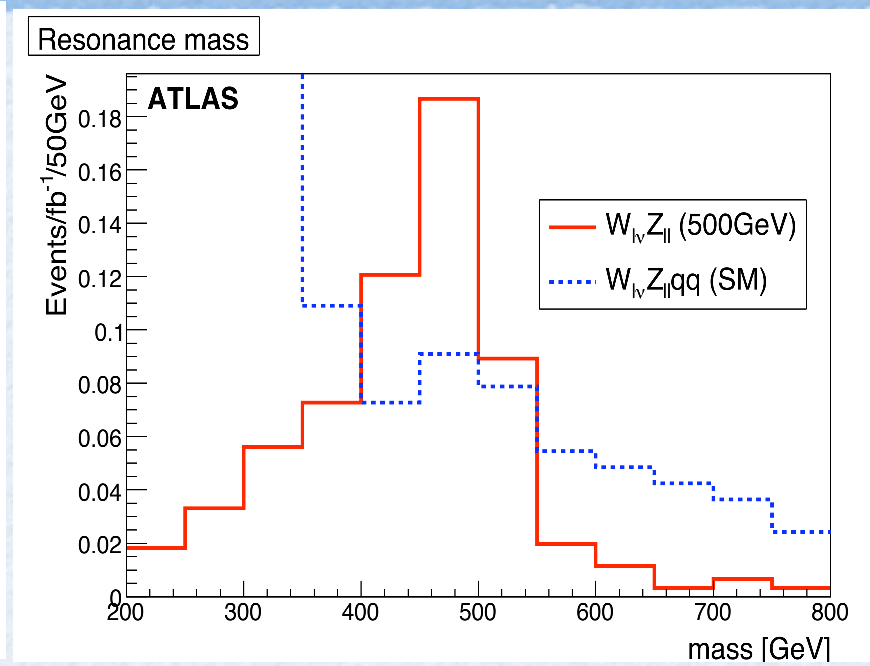
- Two VB candidates: $P_T > 200$ GeV and $|\eta| < 2$.
- Two tag jets: $|\eta| > 2$, $P_T > 20$ GeV, $E > 300$ GeV, $\Delta\eta > 4.4$
- No W + other jet close to top mass.
- No central jets with $P_T > 30$ GeV.
- Triggering no problem, thanks to many high P_T objects.

- Few% signal efficiency
- *tt* negligible
- *V*+jets reduced by $> 10^4$

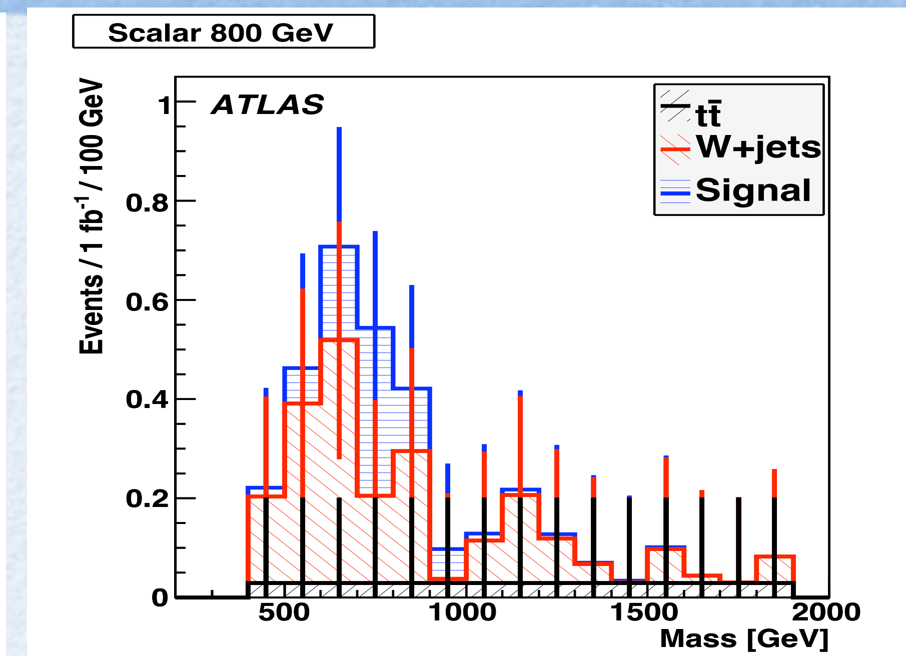
Some Results



ZZ (llνν)



WZ (lνll)



WW (lνqq)

Process	Cross-section (fb)		Luminosity (fb^{-1})		Significance
	signal	background	for 3σ	for 5σ	for 100 fb^{-1}
$WW/WZ \rightarrow \ell\nu\ jj$, 500 GeV	0.31 ± 0.05	0.79 ± 0.26	85	235	3.3 ± 0.7
$WW/WZ \rightarrow \ell\nu\ jj$, 800 GeV	0.65 ± 0.04	0.87 ± 0.28	20	60	6.3 ± 0.9
$WW/WZ \rightarrow \ell\nu\ jj$, 1.1 TeV	0.24 ± 0.03	0.46 ± 0.25	80	230	3.3 ± 0.8
$W_{jj}Z_{\ell\ell}$, 500 GeV	0.28 ± 0.04	0.20 ± 0.18	30	90	5.3 ± 1.9
$W_{\ell\nu}Z_{\ell\ell}$, 500 GeV	0.40 ± 0.03	0.25 ± 0.03	20	55	6.6 ± 0.5
$W_{jj}Z_{\ell\ell}$, 800 GeV	0.24 ± 0.02	0.30 ± 0.22	60	160	3.9 ± 1.2
$W_{j}Z_{\ell\ell}$, 800 GeV	0.20 ± 0.02	0.09 ± 0.06	30	90	5.3 ± 1.3
$W_{j}Z_{\ell\ell}$, 1.1 TeV	0.11 ± 0.01	0.10 ± 0.06	90	250	3.1 ± 0.8
$W_{\ell\nu}Z_{\ell\ell}$, 1.1 TeV	0.070 ± 0.004	0.020 ± 0.009	70	200	3.6 ± 0.5
$Z_{\nu\nu}Z_{\ell\ell}$, 500 GeV	0.32 ± 0.02	0.15 ± 0.03	20	60	6.6 ± 0.6

Conclusions

- VBS = A flagship channel to keep on looking year after year.
  - Even if we see nothing, that means a lot in model building.
  - Will complement a systematic program to look also for model-dependent signatures of strong EW breaking.
  - One of the strong motivations for SLHC.
- Possible discovery of resonances with few tens of fb^{-1}.
  - Worse than earlier optimistic estimates - the first full simulation study with more reliable background estimates.
- Techniques developed applicable to real data.
  - Good agreement between fast and full simulation.
  - Excellent way to reconstruct high-P_T vector bosons.
  - Jet structure analyses useful in many other topics: heavy quarks, single jet tops, HV, SUSY particles, etc.