Vector Boson Scattering at ATLAS

V. Erkcan Özcan

University College London

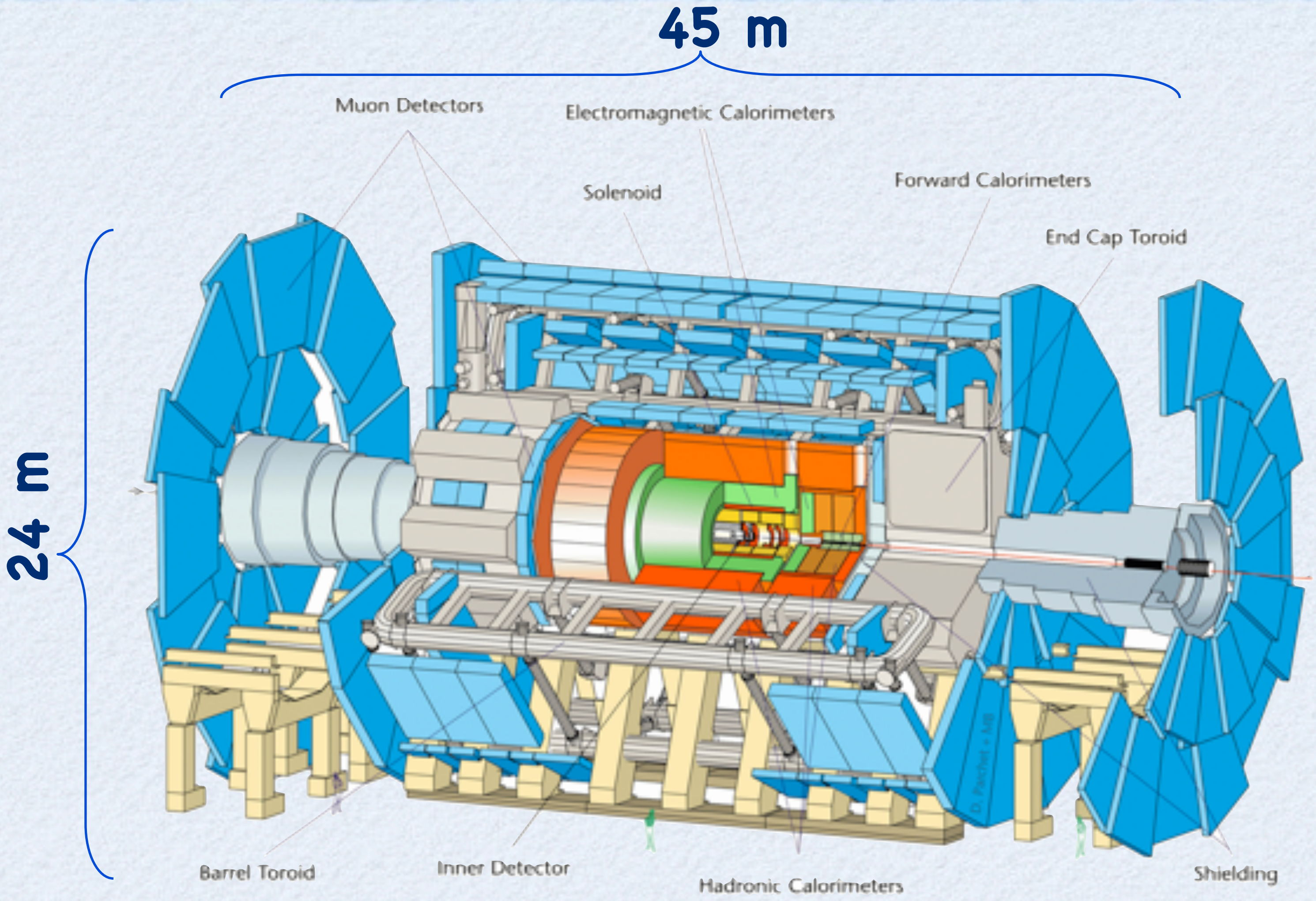
On behalf of the ATLAS Collaboration

LHC2FC WS @ CERN, February 12, 2009

SOURCES

- Details on various aspects of what is in this presentation can be obtained from:
  - Expected Performance of the ATLAS Experiment Detector, Trigger, Physics, CERN-OPEN-2008-020 [arXiv:0901.0512].
  - The ATLAS Experiment at the CERN Large Hadron Collider, J. Instrum. 3 (2008) S08003.

ATLAS DETECTOR



7000 tones

- Tracking and muon coverage: $|\eta|<2.5$
- Calorimeters with presamplers: $|\eta|<1.8$
- Forward calorimeters : $3.2<|\eta|<5.9$

- e/γ energy resolution

  $\sigma/E \approx 10\text{-}15\%/\surd E \oplus {\sim}1\%$
- Central jet energy resolution

  $\sigma/E \approx 60\%/\surd E \oplus 3\%$
- Missing $E_{x,y}$ resolution

  $\sigma \approx 0.55\text{GeV} \times \surd(\Sigma E_T)$
- Track inverse-P_T resolution

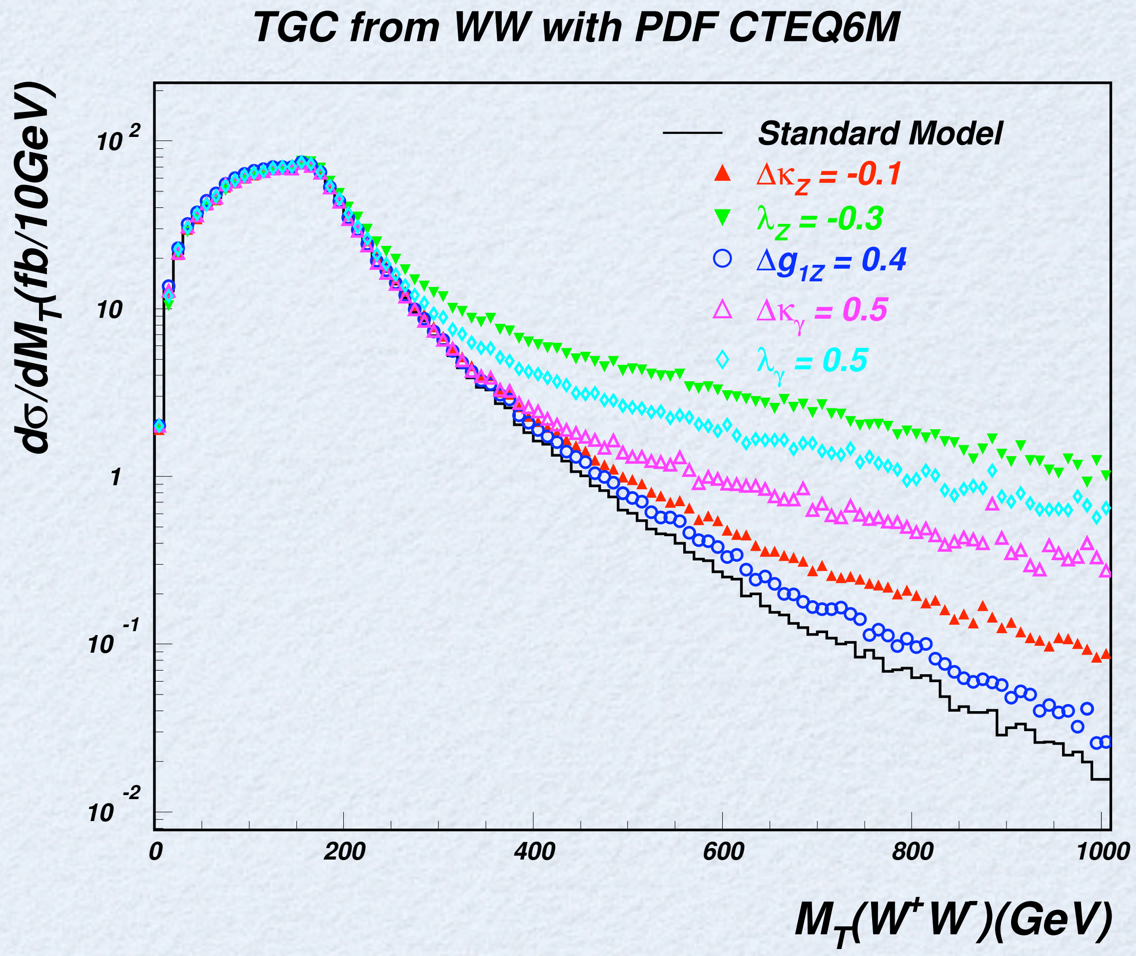
  $\sigma_{\{1/PT\}} \approx 35\text{TeV}^{-1} \times (1 \oplus 50/P_T)$
- Muon system standalone momentum resolution

  $\sigma/P_T < 10\%$ up to 1 TeV

Backup slides: η dependence

MEASURING TGCs

- Cross-sections @ LHC ~ 10 × σ @ Tevatron
- All electron and muon decay channels (except νννν) studied for WW, WZ, ZZ, Wγ, Zγ.
- WW, WZ, ZZ with MC@NLO; Wγ,Zγ with Pythia.
  - BHO and BosoMC to extract event weights for a grid of anomalous TGCs.
- Analysis using boosted decision trees.
- Maximum log likelihood to extract limits.

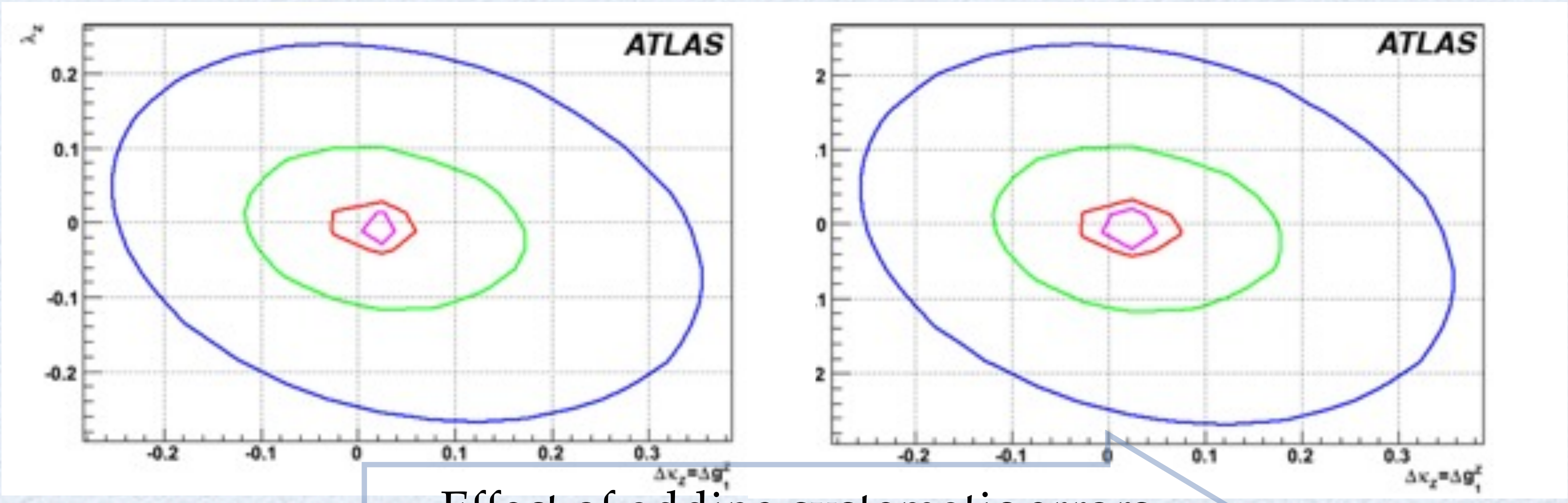


SENSITIVITY TO TGCs

Lumi. fb^{-1}	λ_z	$\Delta\kappa_Z$	Δg_1^Z	$\Delta\kappa_\gamma$	λ_γ
	WZ	WW	WZ	WW	$W\gamma$
1	[-0.028,0.024]	[-0.117,0.187]	[-0.021,0.054]	[-0.24,0.25]	[-0.09,0.04]
10	[-0.015,0.013]	[-0.035,0.072]	[-0.011,0.034]	[-0.088,0.089]	[-0.05,0.02]
30	[-0.012,0.008]	[-0.026,0.0048]	[-0.005,0.023]	[-0.056,0.054]	[-0.02,0.01]
D0/CDF best	[-0.13,0.14]	[-0.82,1.27]		[-0.88,0.96]	[-0.2,0.2]

Luminosity fb^{-1}	f_4^Z	f_5^Z	f_4^γ	f_5^γ
1	[-0.018,0.018]	[-0.018,0.019]	[-0.022,0.022]	[-0.022,0.022]
10	[-0.009,0.009]	[-0.009,0.009]	[-0.01,0.01]	[-0.011,0.01]
30	[-0.006,0.006]	[-0.006,0.007]	[-0.008,0.008]	[-0.008,0.008]
LEP	[-0.3,0.3]	[-0.34,0.38]	[-0.17,0.19]	[-0.32,0.36]

- 95% CL limits on charged and neutral anomalous TGCs.



Effect of adding systematic errors

EXPERIMENTER'S GOAL

- In short: Measure differential scattering cross-section as a function of VV center-of-mass energy.
  - Identify VV at high momenta, within certain well-defined η range.
  - Try to make sure they interacted with each other (ie. reject BGs)
  - Measure invariant mass spectrum
    - Hope to see a resonance or a total cross-section significantly different than SM prediction
    - If not, publish spectrum with efficiency corrections, ask theorists to extract constraints
- Do all these as model-independently as possible.

EW CHIRAL LAGRANGIAN

$$\mathcal{L}_1 = \alpha_1 g g' \,\mathrm{tr}\left[\Sigma \mathbf{B}_{\mu\nu} \Sigma^\dagger \mathbf{W}^{\mu\nu}\right]$$

$$\mathcal{L}_2 = i\alpha_2 g' \,\mathrm{tr}\left[\Sigma \mathbf{B}_{\mu\nu} \Sigma^\dagger [V^\mu, V^\nu]\right]$$

$$\mathcal{L}_3 = i\alpha_3 g \,\mathrm{tr}\left[\mathbf{W}_{\mu\nu} [V^\mu, V^\nu]\right]$$

$$\boxed{\begin{aligned}\mathcal{L}_4 &= \alpha_4 (\mathrm{tr}\,[V_\mu V_\nu])^2 \\ \mathcal{L}_5 &= \alpha_5 (\mathrm{tr}\,[V_\mu V^\mu])^2\end{aligned}}$$

$$\mathcal{L}_6 = \alpha_6 \,\mathrm{tr}\,[V_\mu V_\nu]\,\mathrm{tr}\,[T V^\mu]\,\mathrm{tr}\,[T V^\nu]$$

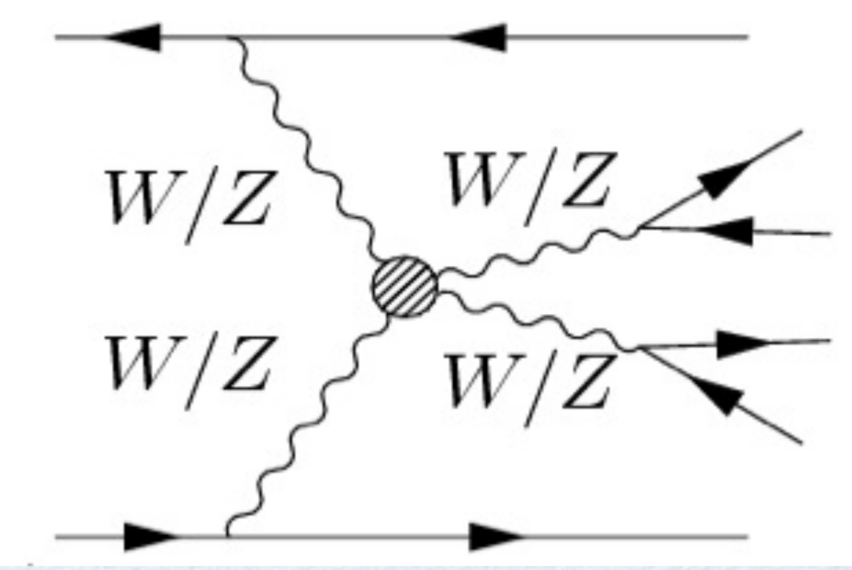
$$\mathcal{L}_7 = \alpha_7 \,\mathrm{tr}\,[V_\mu V^\mu]\,\mathrm{tr}\,[T V_\nu]\,\mathrm{tr}\,[T V^\nu]$$

$$\mathcal{L}_8 = \tfrac{1}{4}\alpha_8 g^2 (\mathrm{tr}\,[T \mathbf{W}_{\mu\nu}])^2$$

$$\mathcal{L}_9 = \tfrac{i}{2}\alpha_9 g \,\mathrm{tr}\,[T \mathbf{W}_{\mu\nu}]\,\mathrm{tr}\,[T [V^\mu, V^\nu]]$$

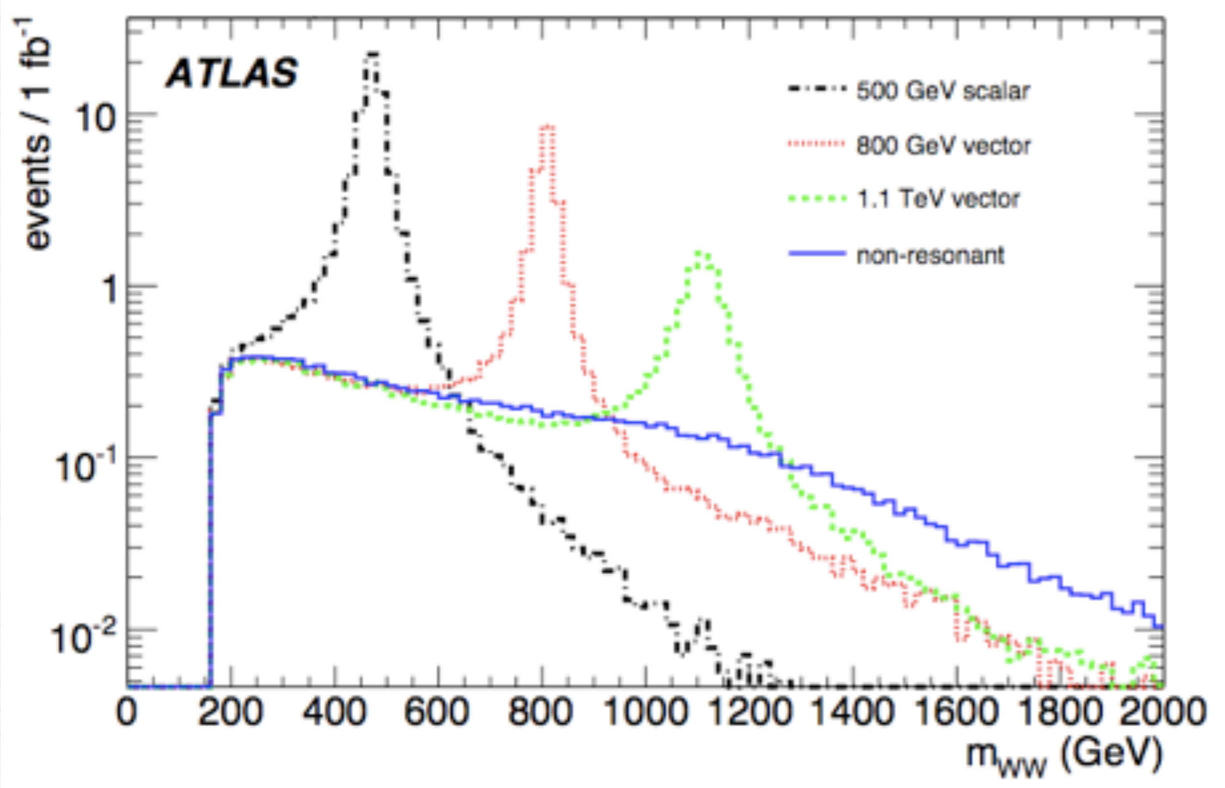
$$\mathcal{L}_{10} = \tfrac{1}{2}\alpha_{10} (\mathrm{tr}\,[T V_\mu]\,\mathrm{tr}\,[T V_\nu])^2$$

$$\mathcal{L}_{11} = \alpha_{11} g \epsilon^{\mu\nu\rho\lambda} \,\mathrm{tr}\,[T V_\mu]\,\mathrm{tr}\,[V_\nu \mathbf{W}_{\rho\lambda}]$$



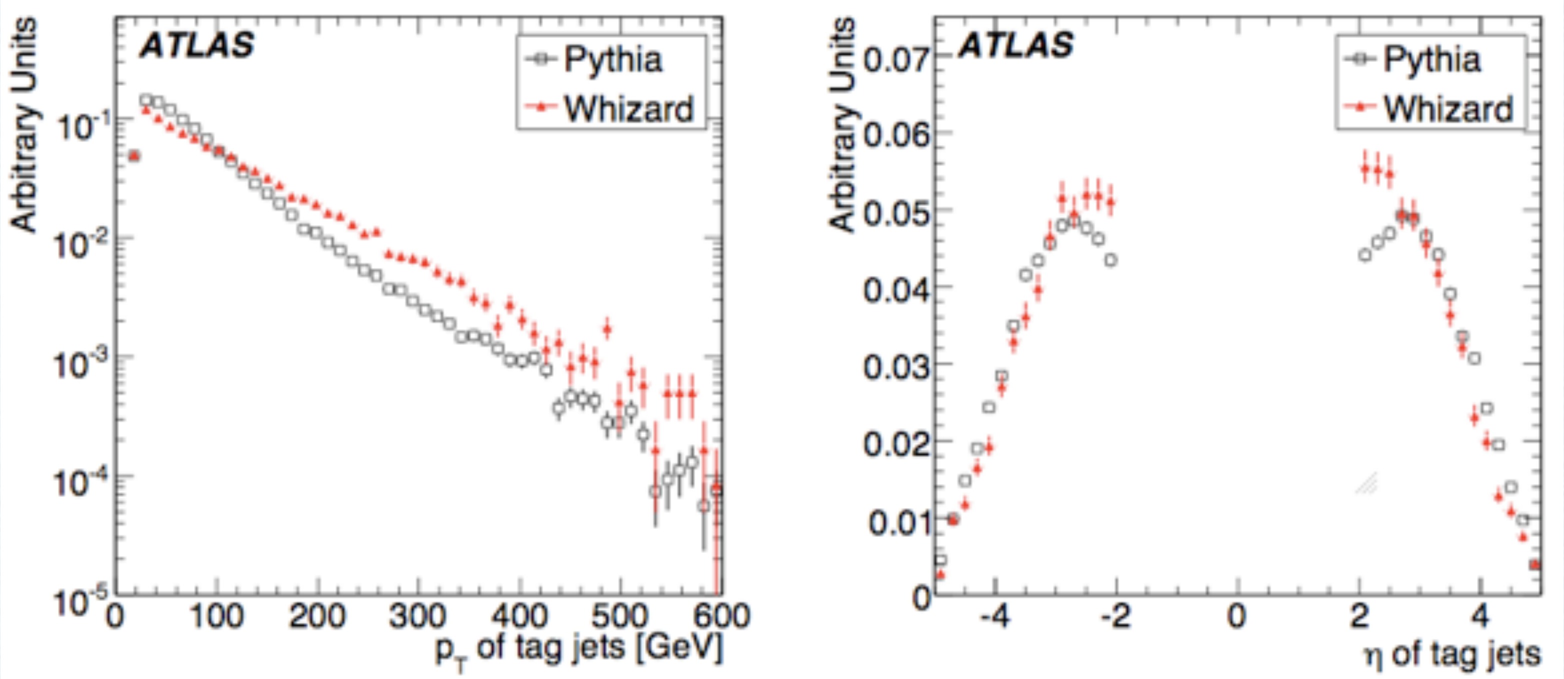
- See Tao's talk from tuesday's discussion session.
- (α_4,α_5) are the main parameters to modify for the VV scattering.
- Needs unitarization.

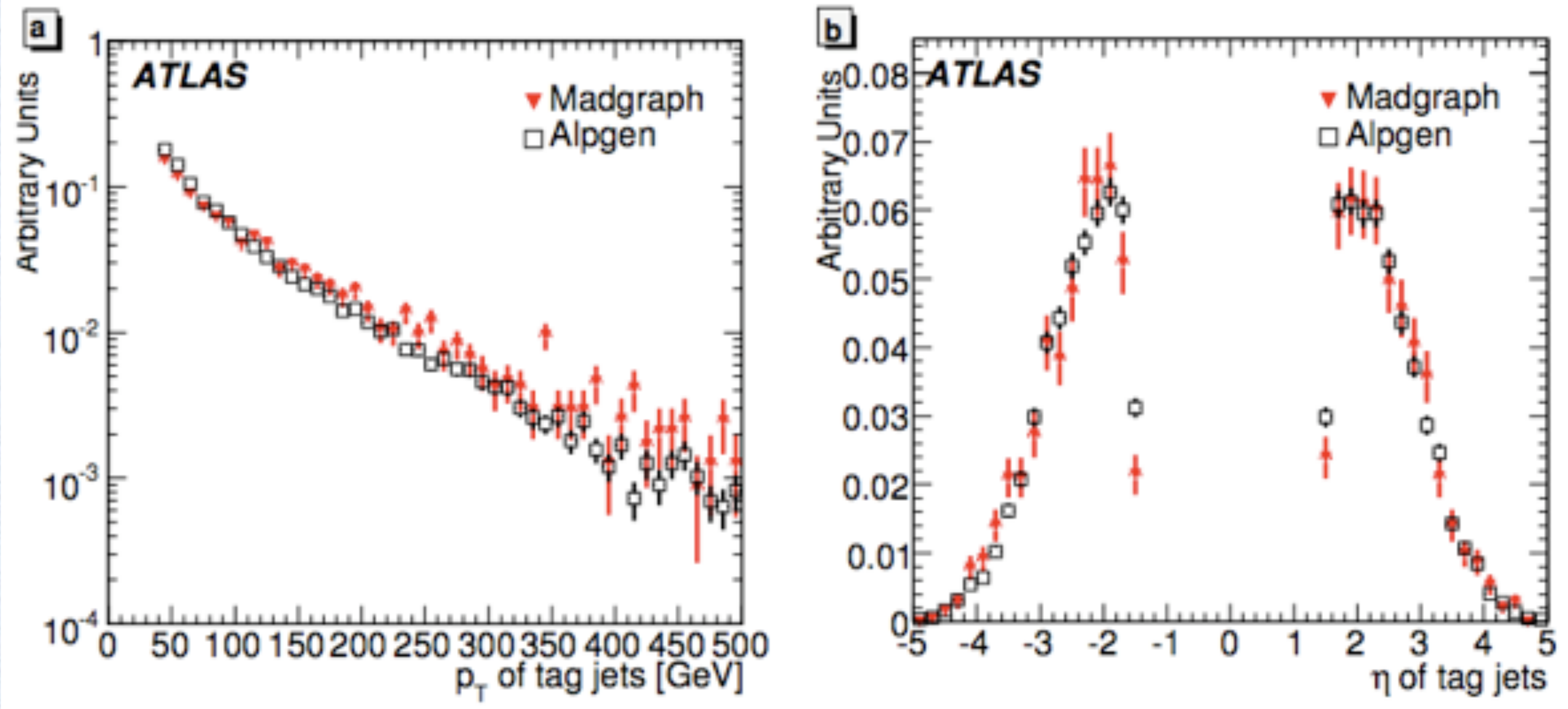
RESONANCES



- Padé unitarization gives good description for π-scattering in QCD.
- Following, Dobado et al (PRD62, 055011) we connect (α_4,α_5) to mass, width, spin & presence of resonances.
- Modify the longitudinal VV scattering processes in Pythia (73-77) by editing routine PYSGHG.
- Vector WZ and scalar ZZ resonances, both vector and scalar WW resonances possible. Also a non-resonant sample is generated with (α_4,α_5)=(0,0).

Monte Carlo Checks





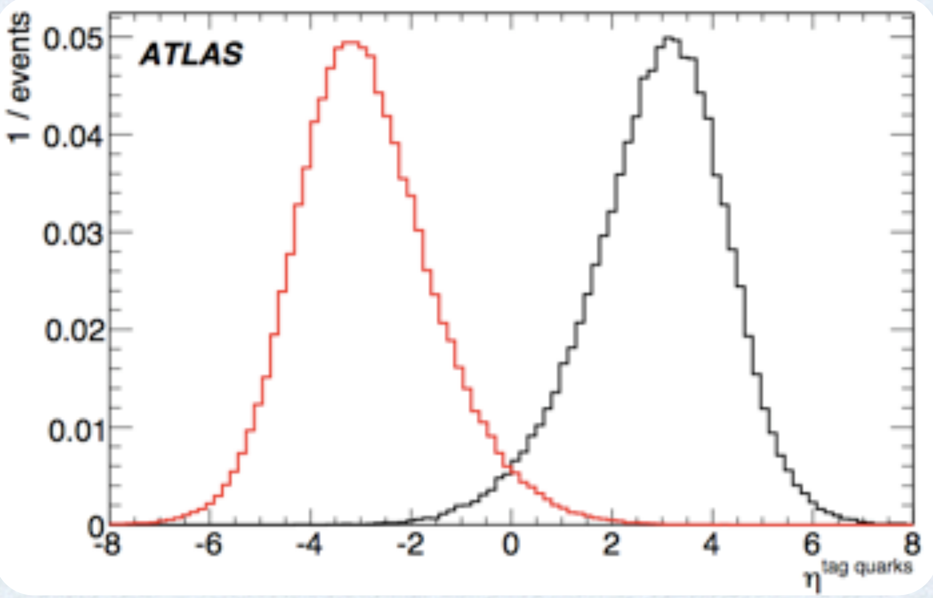
Signal: Crosscheck modified *Pythia* against *Whizard*

(no effective W approximation, K-matrix unitarization)

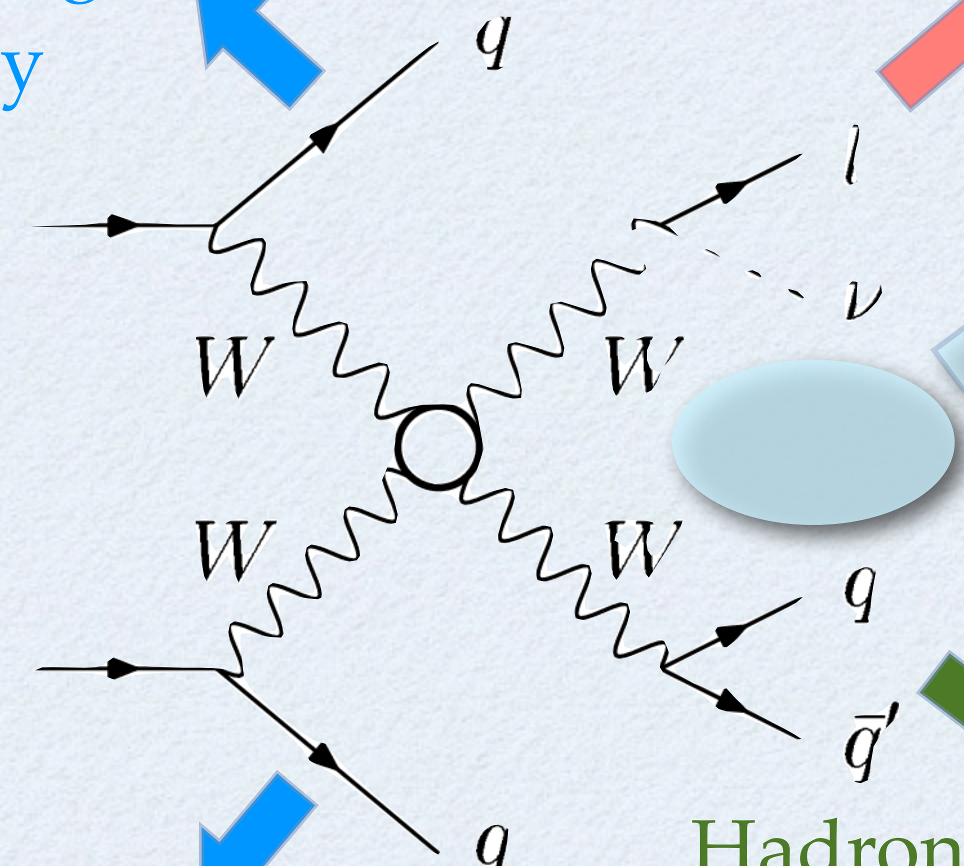
t$\bar{t}$: *MC@NLO, Herwig, Jimmy*

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

SIGNAL AT A GLANCE

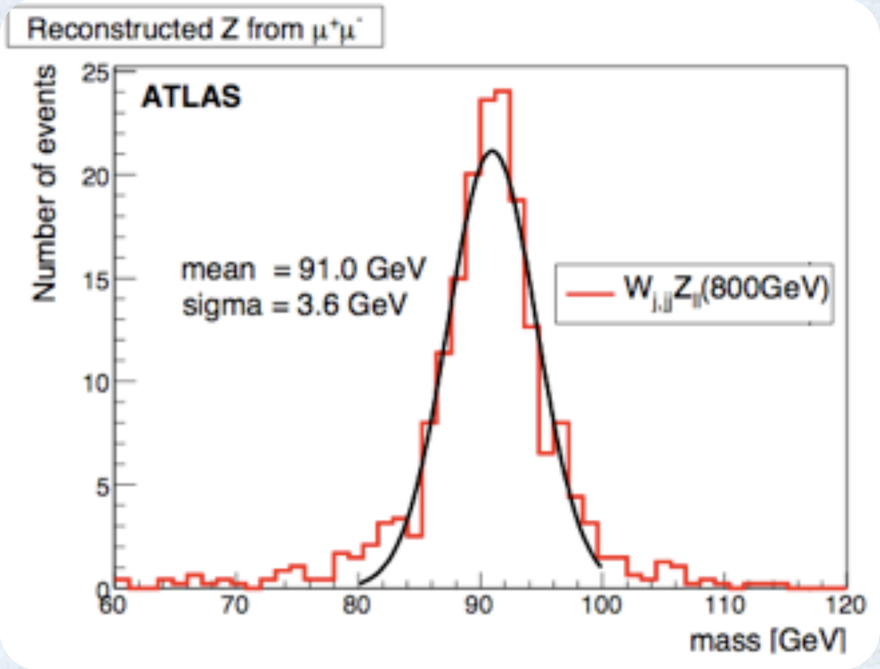


Tag jet at high rapidity



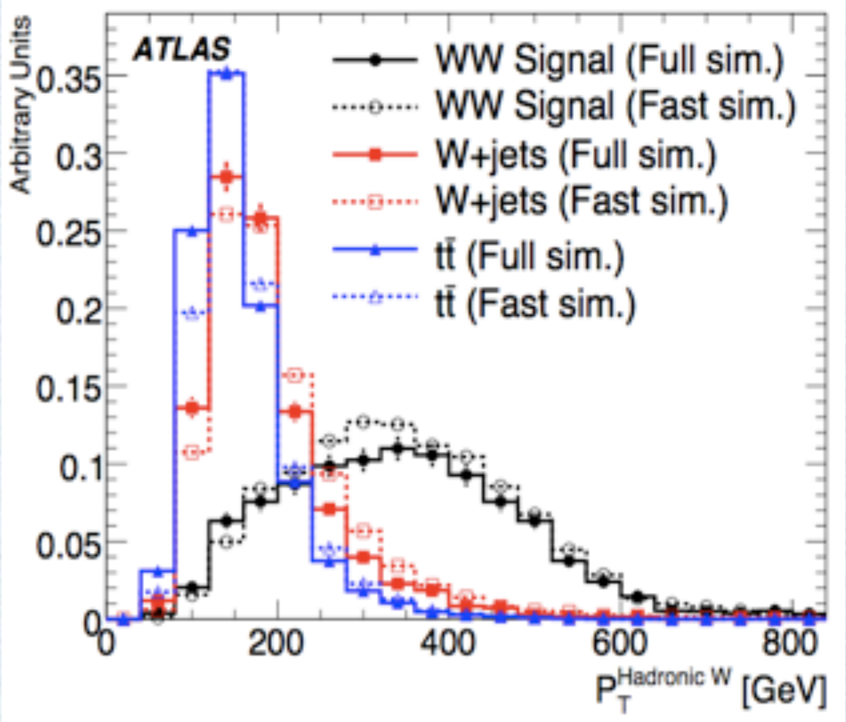
Tag jet at high rapidity and on opposite side

Leptonically decaying VB at high momentum



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

Hadronically decaying VB at high momentum



SINGLE JET METHOD

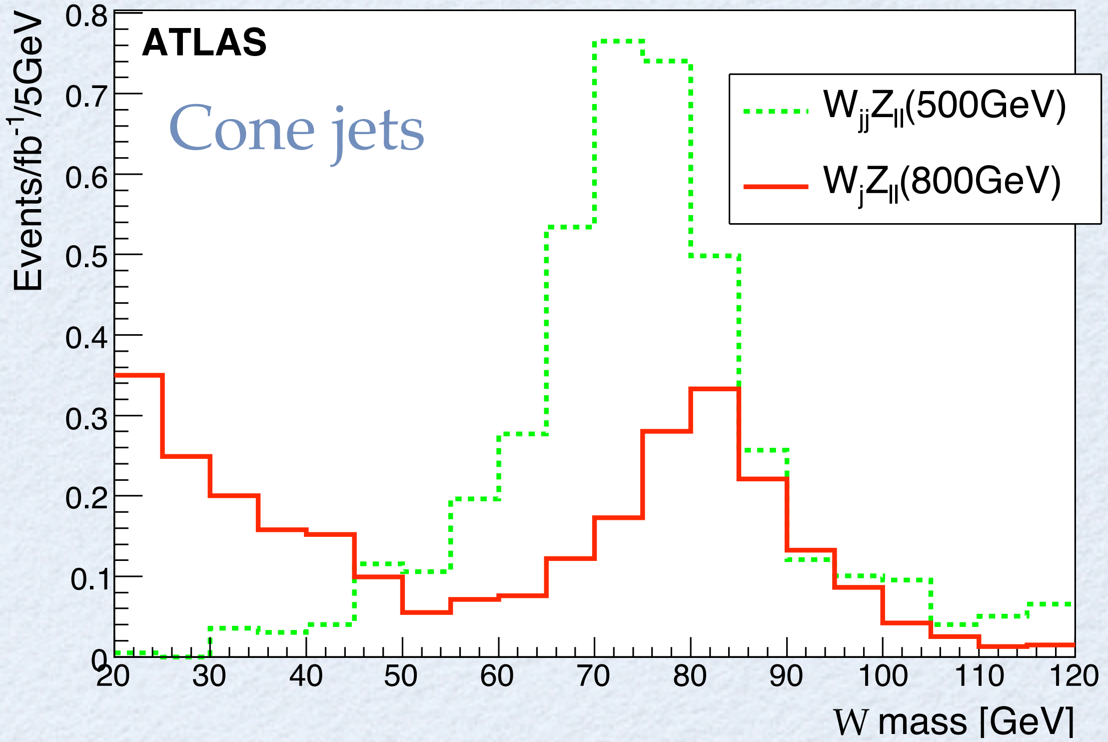
- All WW, WZ, ZZ final states, except qqqq, llll and νννν, and no tau channels.
- Particularly interesting are semi-leptonic channels.
    - Technique proposed by Butterworth et al. in 2002 (PRD 65, 096014) to reconstruct hadronically decaying vector bosons as single jets.
    - Test on full-simulation data and improvements.

HADRONIC VBs: 1 OR 2 JETS

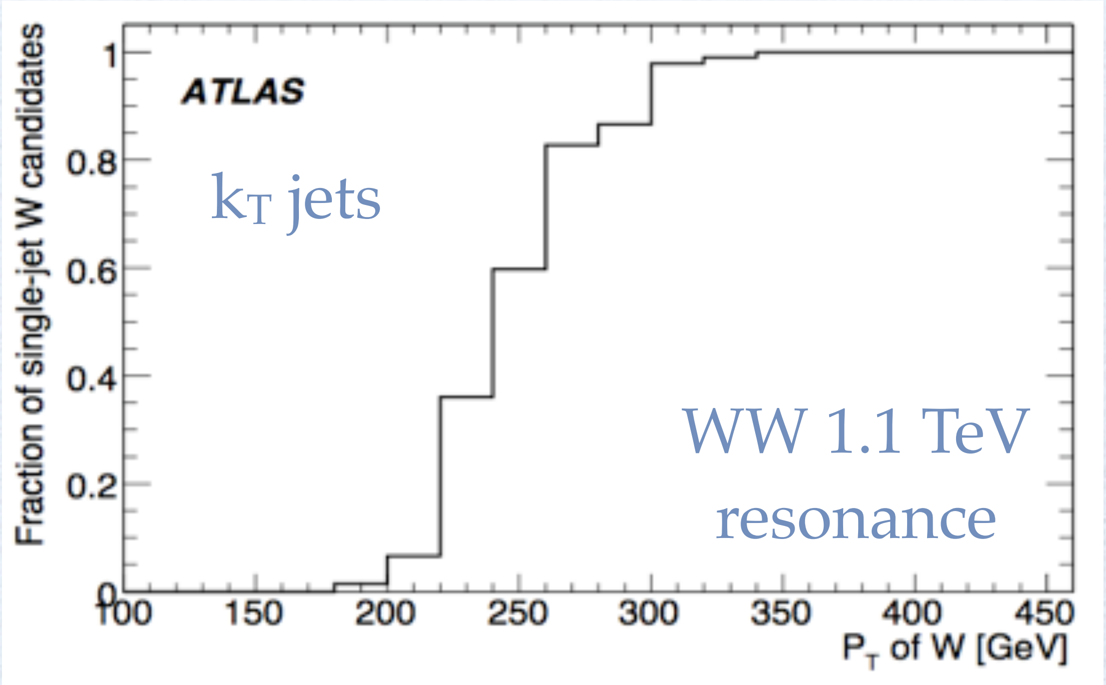
- At high enough P_T, hadronic VB starts to end up in a single jet.
- In each event: Take highest P_T jet. Mass close to W/Z ?

  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.



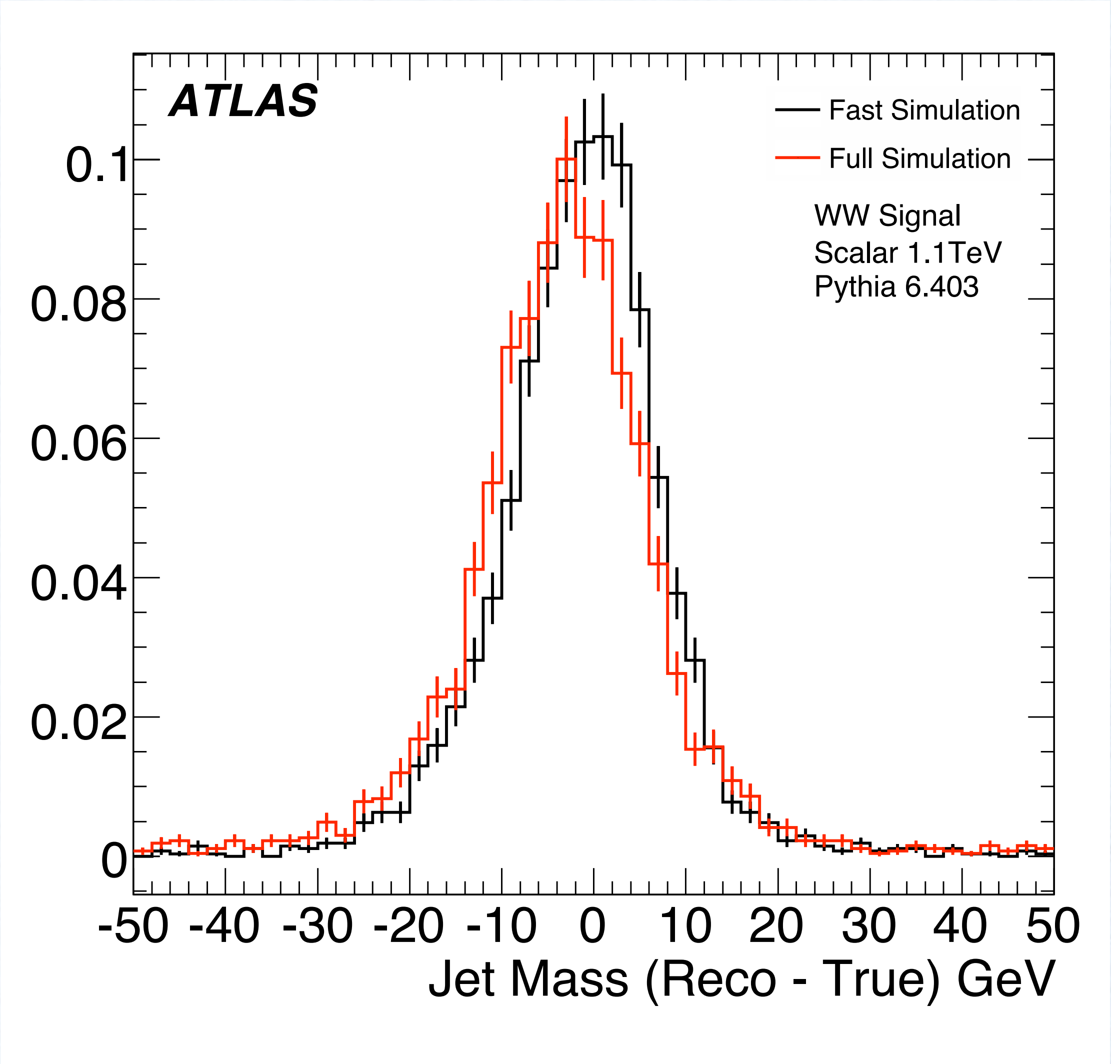
Cone jets

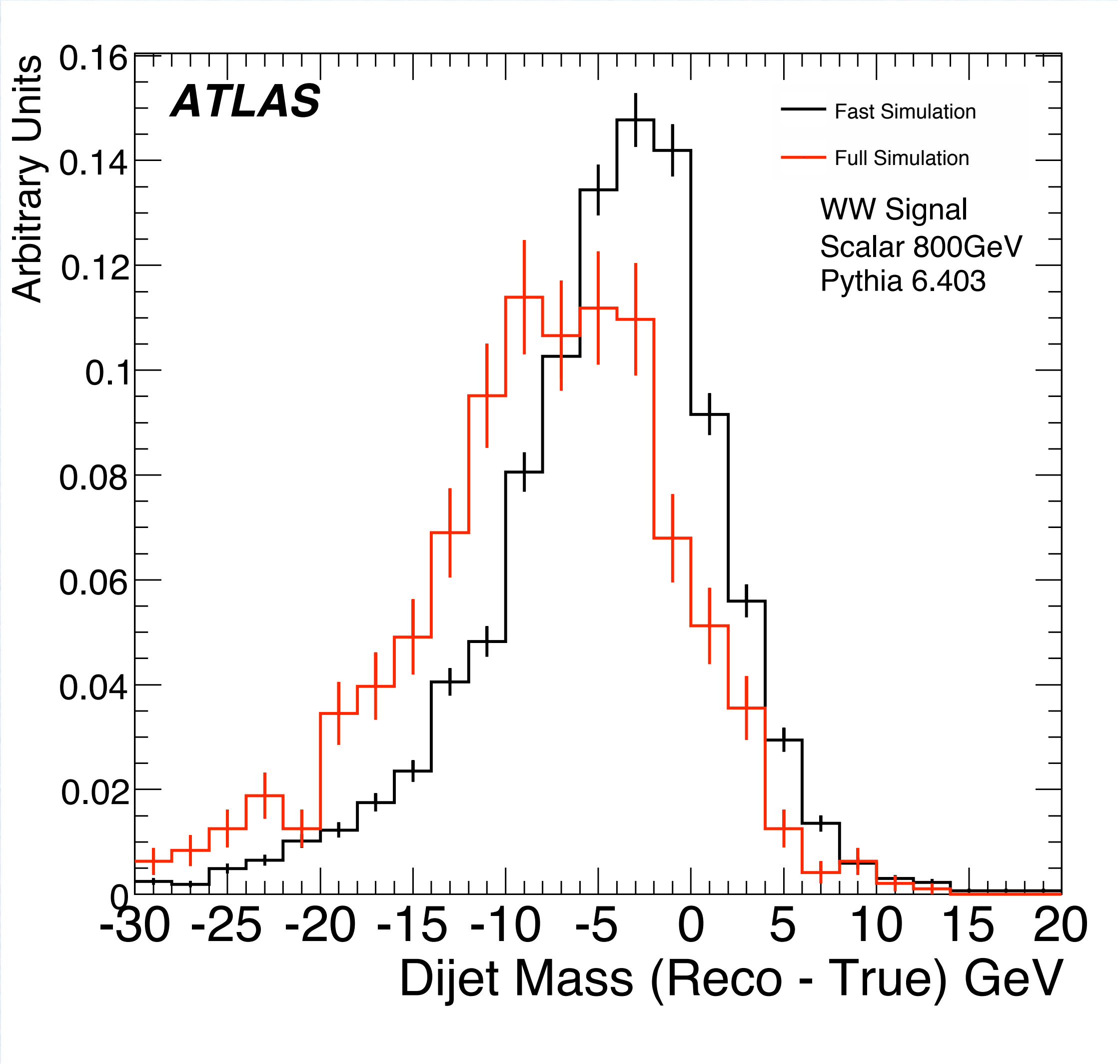


k_T jets

WW 1.1 TeV resonance

W MASS RESOLUTIONS

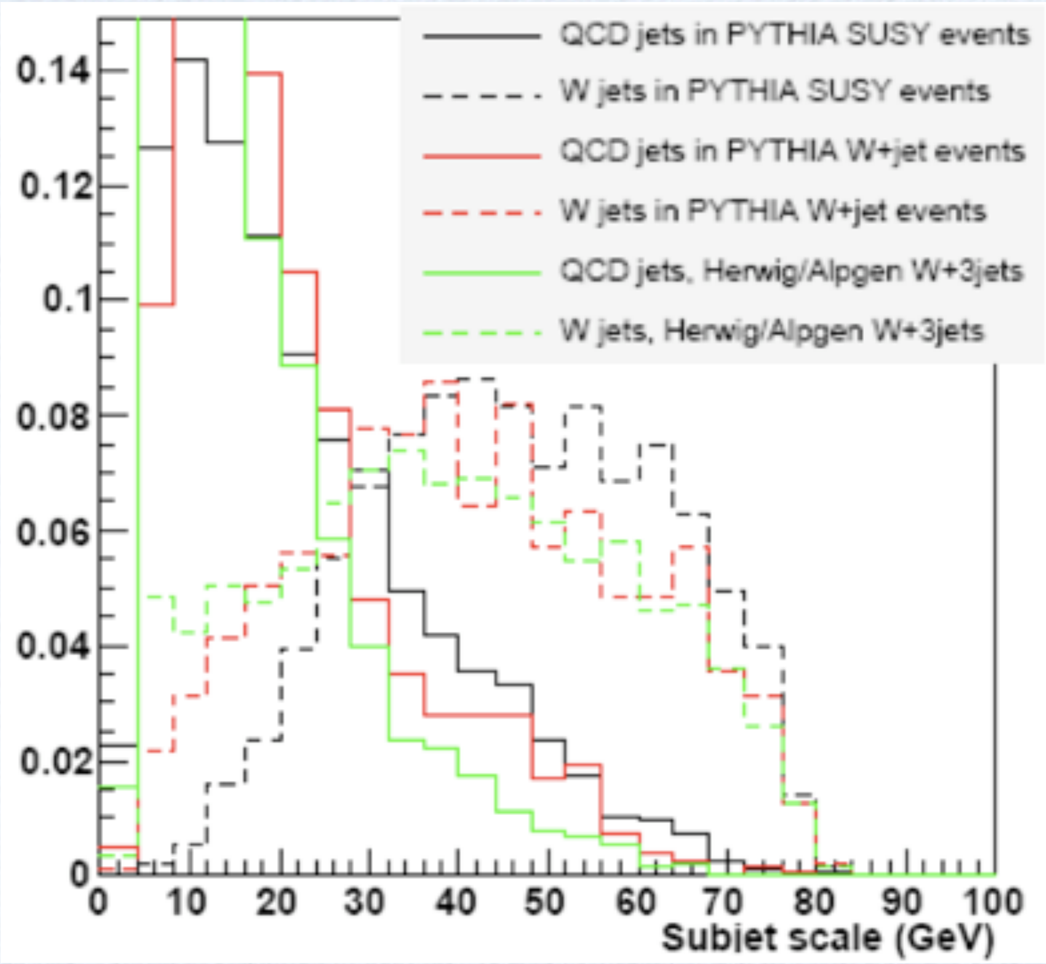




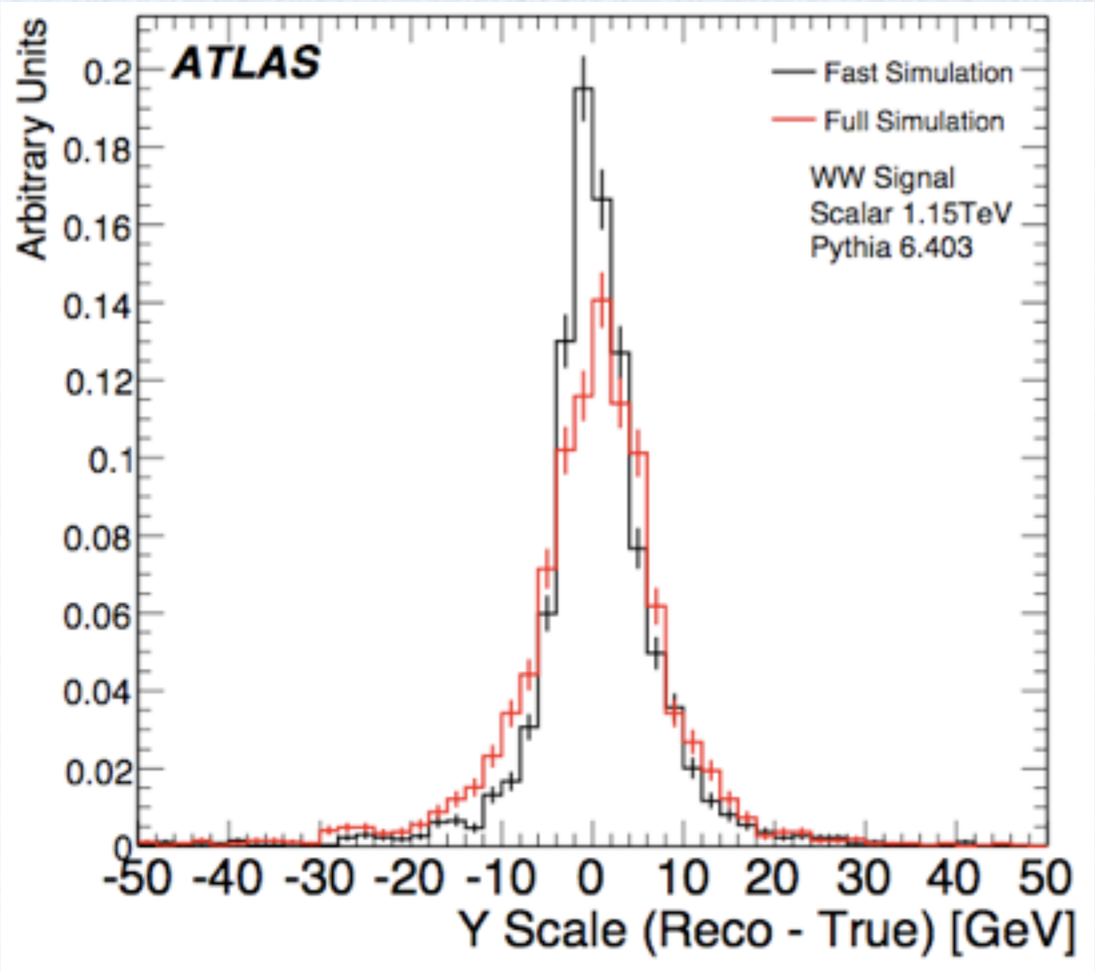
- Generator level reconstruction vs. reconstruction after detector simulation
- Good agreement, slight shift in mean due to incorrect e-calibration.
  - Fast simulation also in good agreement with full.

JET STRUCTURE

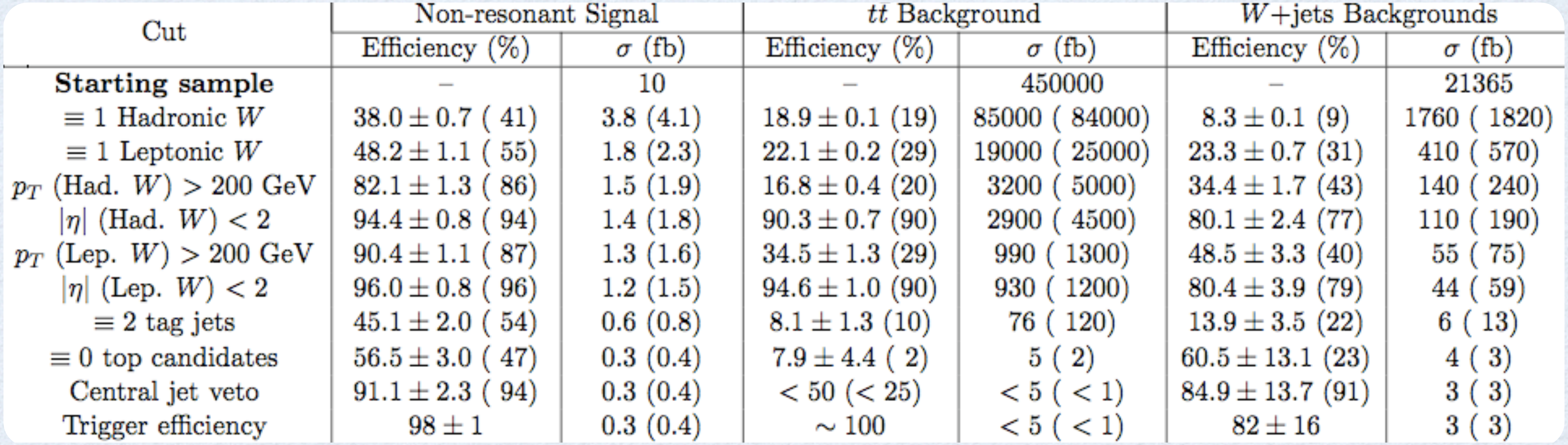
- k_T merging intrinsically ordered in scale.
  - Undo last merging: Get the Y-scale at which the jet would split into two subjets.
  - Y-scale ~ $O(m_{VB}/2)$ ~ k_T of one subjet wrt. other



Butterworth, Ellis, Raklev
hep-ph/0702150



Putting it Together

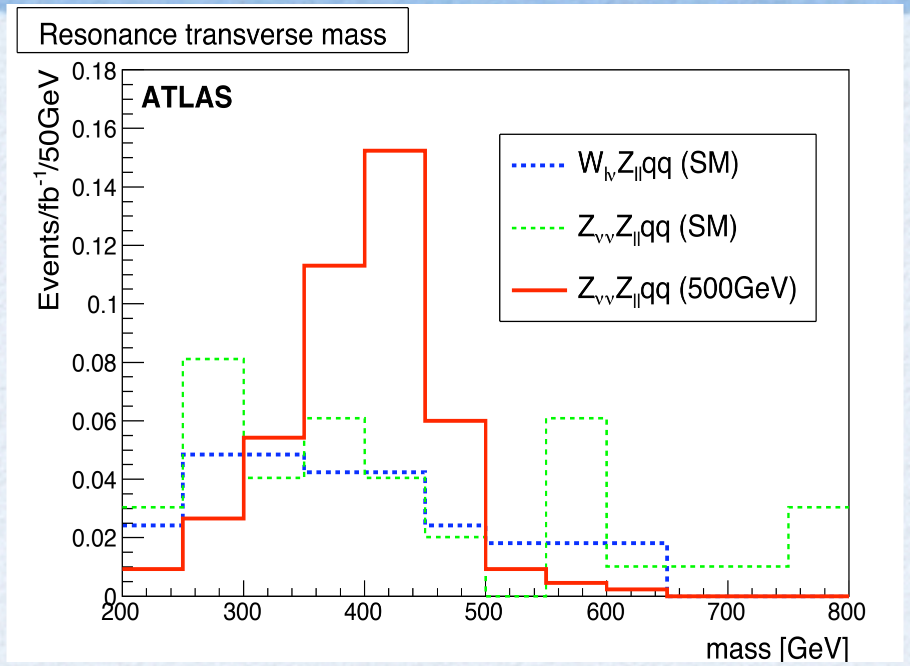


Cut	Non-resonant Signal		tt Background		W+jets Backgrounds	
	Efficiency (%)	σ (fb)	Efficiency (%)	σ (fb)	Efficiency (%)	σ (fb)
Starting sample	–	10	–	450000	–	21365
$\equiv 1$ Hadronic W	38.0 ± 0.7 (41)	3.8 (4.1)	18.9 ± 0.1 (19)	85000 (84000)	8.3 ± 0.1 (9)	1760 (1820)
$\equiv 1$ Leptonic W	48.2 ± 1.1 (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)
$\lvert\eta\rvert$ (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)
$\lvert\eta\rvert$ (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)

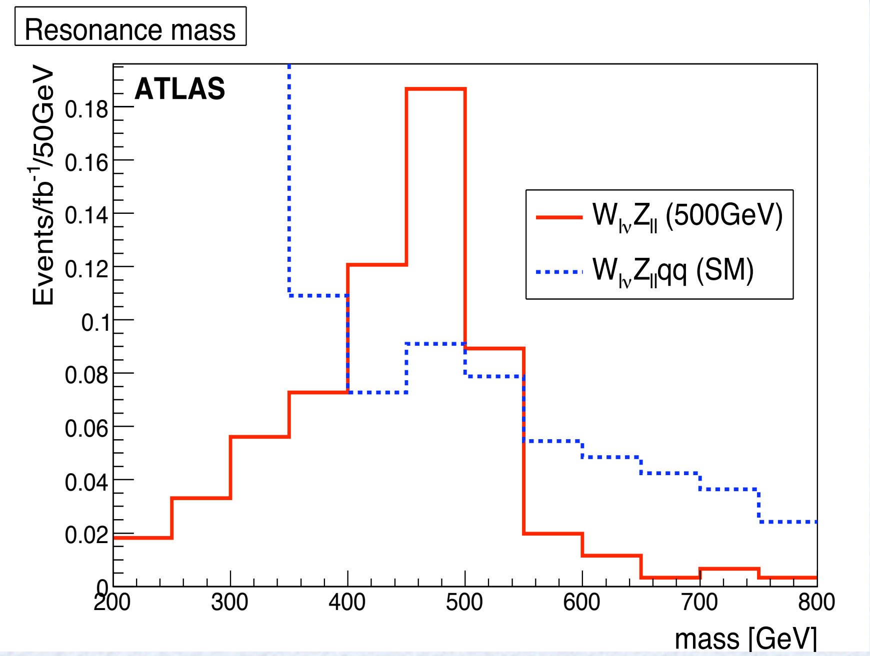
- Two VB candidates: $P_T > 200$ GeV and $|\eta| < 2$.
- Two tag jets: $|\eta| > 2$, $P_T > 20$ GeV, $E > 300$ GeV, $\Delta\eta > 4.4$
- No W + other jet close to top mass.
- No central jets with $P_T > 30$ GeV.
- Triggering no problem, thanks to many high P_T objects.

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

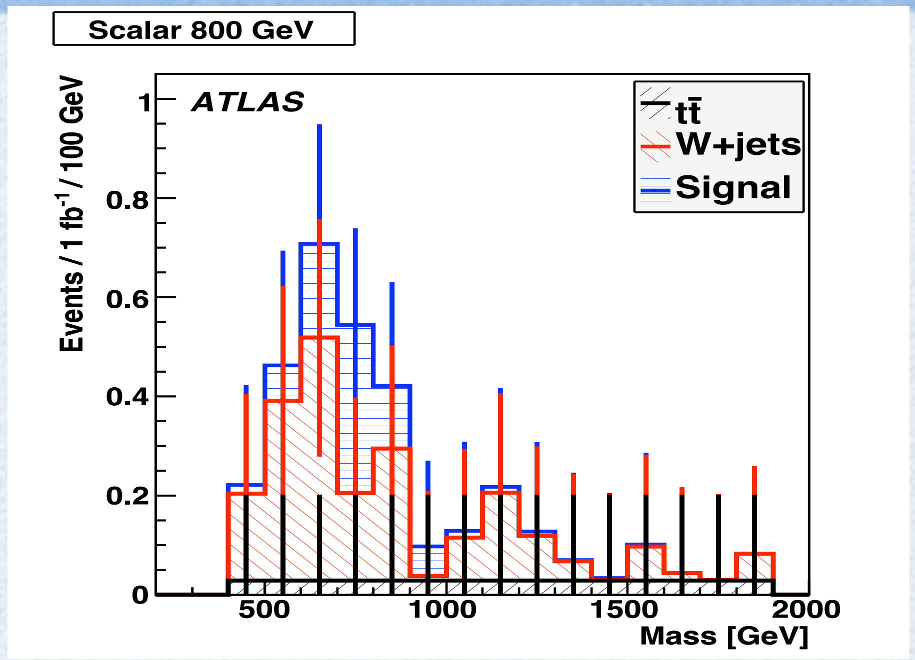
RESULTS



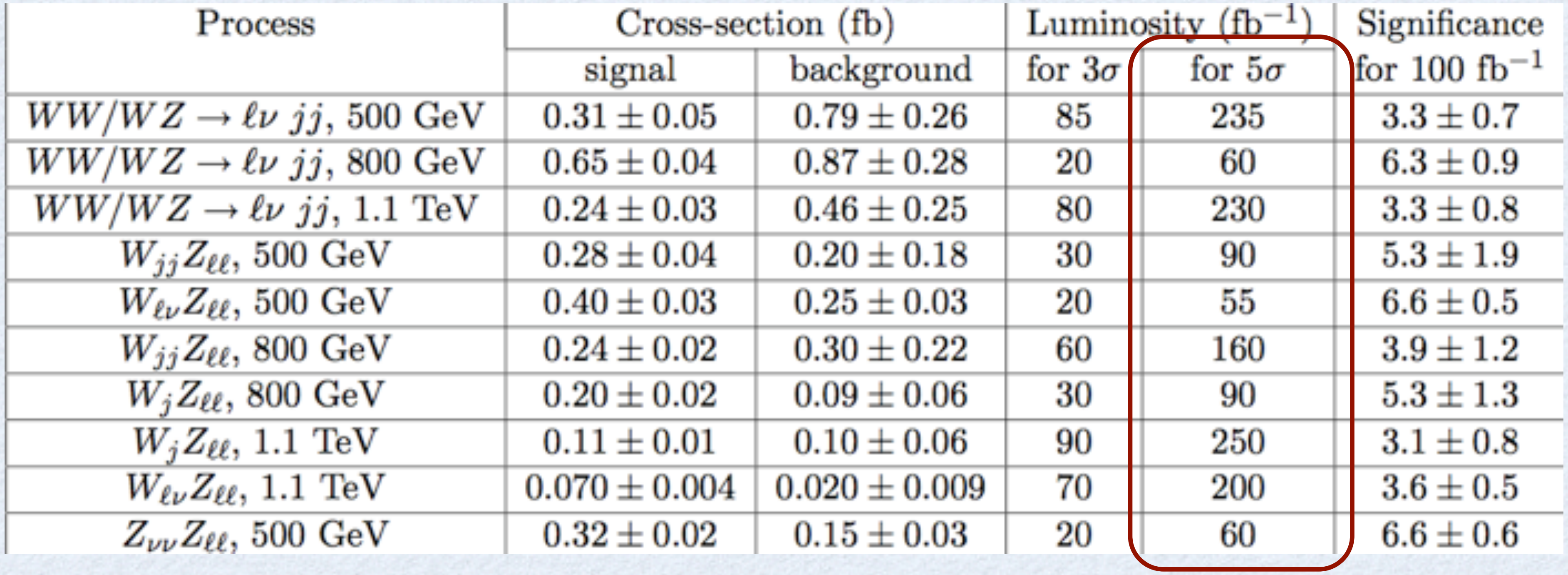
ZZ (llνν)



WZ (lνll)



WW (lνqq)



Process	Cross-section (fb)		Luminosity (fb^{-1})		Significance
	signal	background	for 3σ	for 5σ	for 100 fb^{-1}
$WW/WZ \to \ell\nu\ jj$, 500 GeV	0.31 ± 0.05	0.79 ± 0.26	85	235	3.3 ± 0.7
$WW/WZ \to \ell\nu\ jj$, 800 GeV	0.65 ± 0.04	0.87 ± 0.28	20	60	6.3 ± 0.9
$WW/WZ \to \ell\nu\ jj$, 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

50-100 fb^{-1} to see first possible resonances

NEXT FEW YEARS

- TGC period: With even as low as few hundred pb^{-1}, competitive limits will be possible. Will keep on getting better up to tens of fb^{-1}, when systematic uncertainties become important.
- Model-dependent search period: With $O(10\ fb^{-1})$, various discoveries could be possible for some resonances in models like technicolor.
  - Some recent fast simulation studies in arXiv:0802.3715.
- Generic searches for VV resonances with few tens of fb^{-1}.
  - Worse than earlier optimistic estimates - the first full simulation study with more reliable background estimates.
- Spectrum era: Hundreds of fb^{-1} to extract a spectrum up to ~2TeV.
  - Measuring angular distributions, spin measurements, etc.
- Techniques developed <u>applicable to real data</u>.
  - Good agreement between fast and full simulation. Jet structure analyses useful in many other topics: heavy quarks, single jet tops, HV, SUSY particles, etc.

BACKUPS

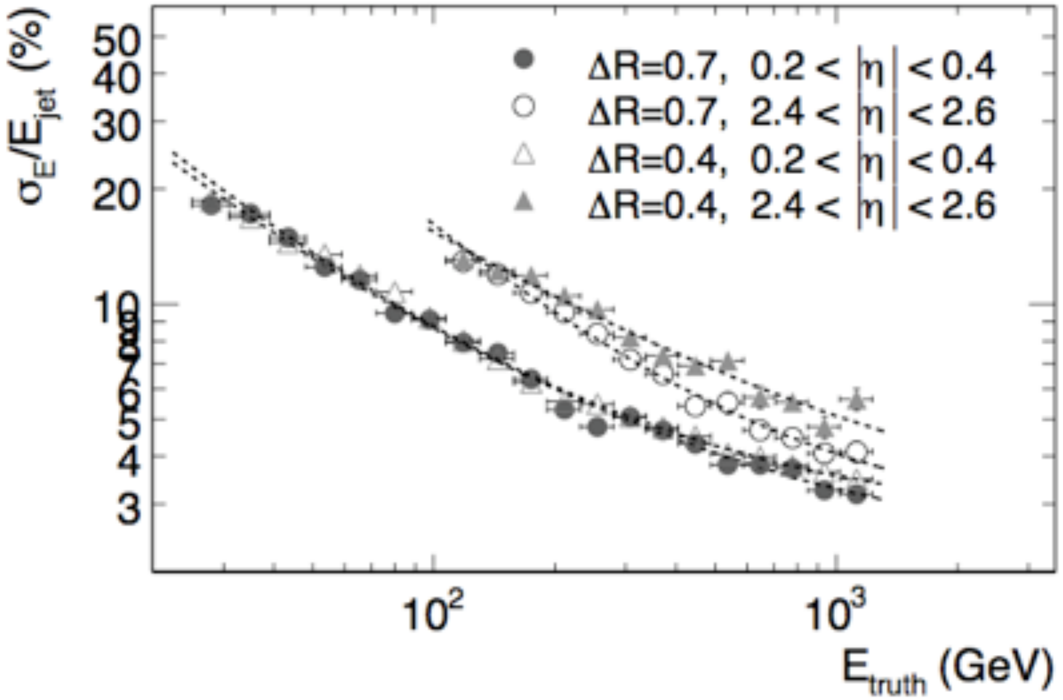
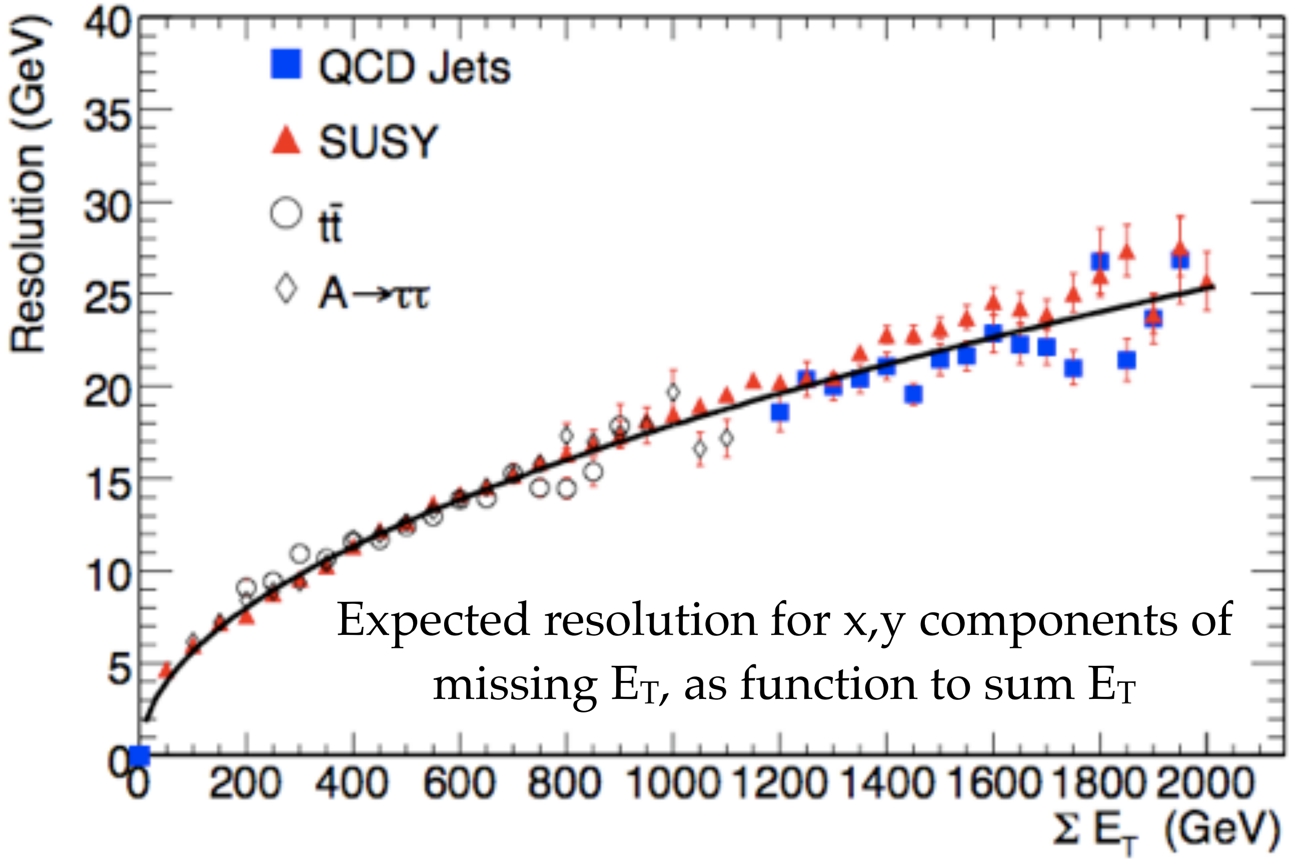


Figure 10.71: Fractional energy resolution for calibrated cone-tower jets reconstructed with $\Delta R = 0.7$ and Δ

of $|\eta|$ and as a



Expected resolution for x,y components of missing E_T, as function to sum E_T

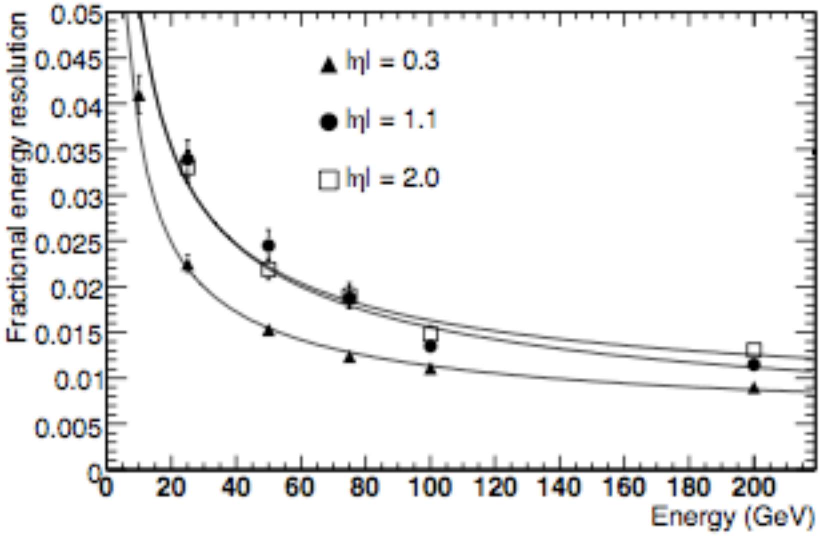


Figure 10.50: Expected relative energy resolution as a function of energy for electrons at $|\eta| = 0.3$, 1.1, and 2.0. The curves represent fits to the points at the same $|\eta|$ by a function containing a stochastic term, a constant term and a noise term.

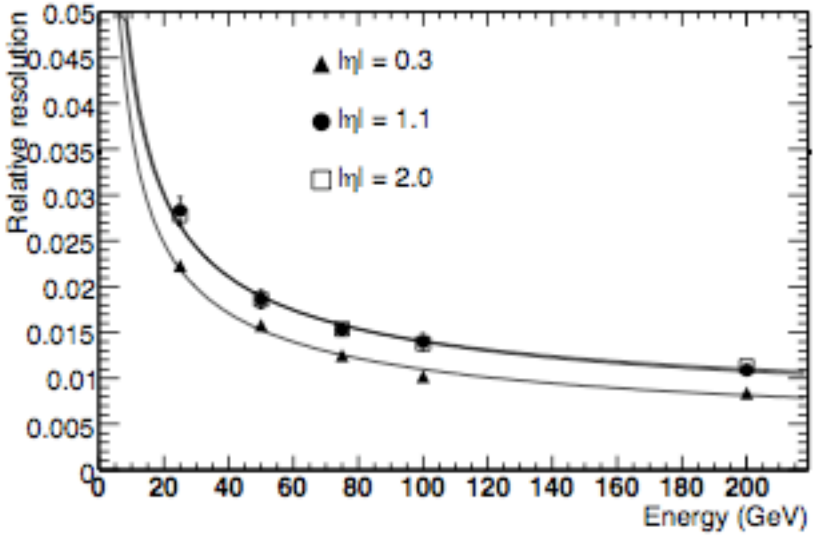


Figure 10.51: Expected relative energy resolution as a function of energy for photons at $|\eta| = 0.3$, 1.1, and 2.0. The curves represent fits to the points at the same η by a function containing a stochastic term, a constant term and a noise term.

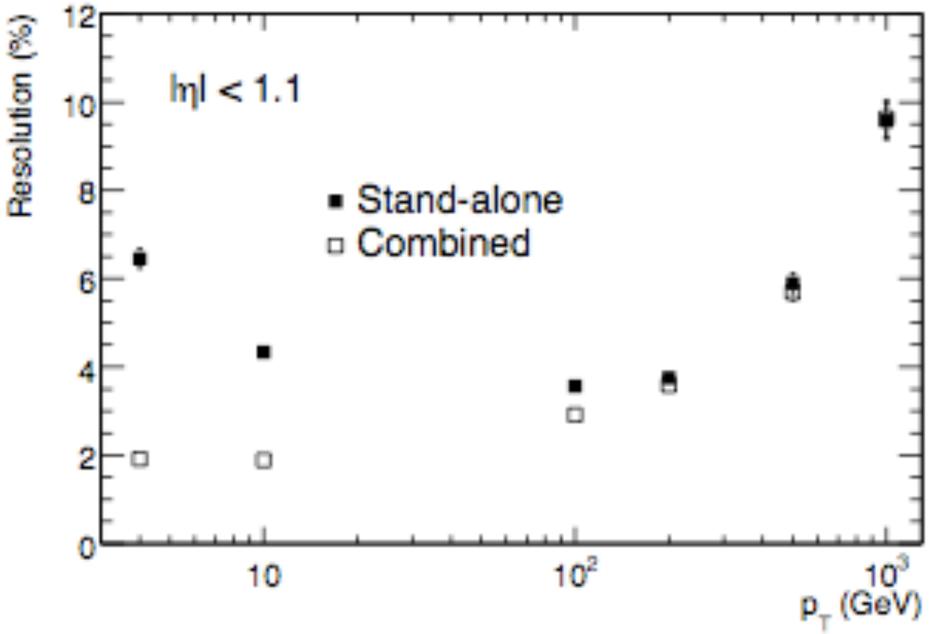


Figure 10.35: Expected stand-alone and combined fractional momentum resolution as a function of p_T for single muons with $|\eta| < 1.1$.

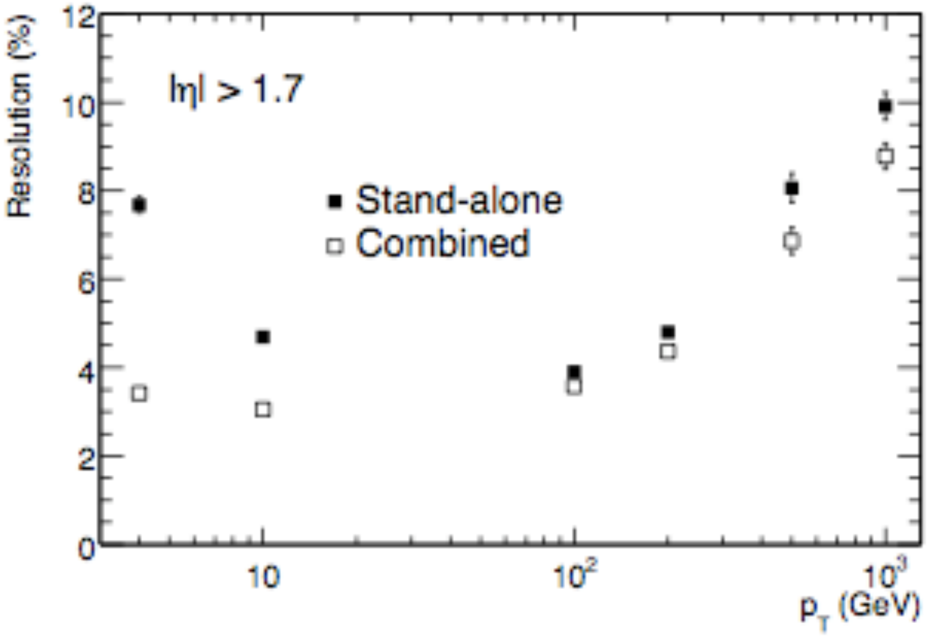
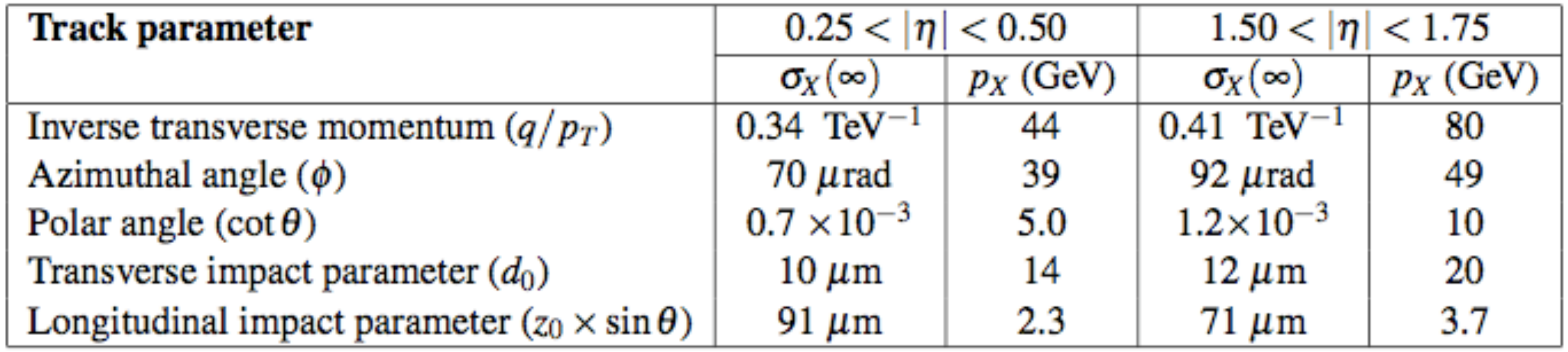


Figure 10.36: Expected stand-alone and combined fractional momentum resolution as a function of p_T for single muons with $|\eta| > 1.7$.



Track parameter	$0.25 < \|\eta\| < 0.50$		$1.50 < \|\eta\| < 1.75$	
	$\sigma_X(\infty)$	p_X (GeV)	$\sigma_X(\infty)$	p_X (GeV)
Inverse transverse momentum (q/p_T)	0.34 TeV^{-1}	44	0.41 TeV^{-1}	80
Azimuthal angle (ϕ)	70 μrad	39	92 μrad	49
Polar angle ($\cot\theta$)	0.7×10^{-3}	5.0	1.2×10^{-3}	10
Transverse impact parameter (d_0)	10 μm	14	12 μm	20
Longitudinal impact parameter ($z_0 \times \sin\theta$)	91 μm	2.3	71 μm	3.7

Table 3: Expected track-parameter resolutions (RMS) at infinite transverse momentum, $\sigma_X(\infty)$, and transverse momentum, p_X, at which the multiple-scattering contribution equals that from the detector resolution (see Eq. (1)). The momentum and angular resolutions are shown for muons, whereas the impact-parameter resolutions are shown for pions (see text). The values are shown for two η-regions, one in the barrel inner detector where the amount of material is close to its minimum and one in the end-cap where the amount of material is close to its maximum. Isolated, single particles are used with perfect alignment and calibration in order to indicate the optimal performance.

$$\sigma_X(p_T) = \sigma_X(\infty)(1 \oplus p_X/p_T)$$

READY FOR FIRST BEAM

- MDT: >99% of chambers stable
- RPC: All 16 sectors commissioned (2 have missing HV supplies, 1 has noise on clock propagation)
- TGC: All wheels ready
- CSC: Chambers work, but read-out being worked on.
- LAr Cal: 0.02% isolated (dead) channels, 0.8% dead read-out, 1 of 8 Had EC PS needs replacement
- Tilecal: 2 of 256 sectors off (PS problem), only 0.2% isolated (dead) channels.
- Pixels: >95% of modules stable
- SCT: 97.6% of EC & 99.8% of barrel operational
- TRT: 98% of channels operational

TGCs Eff. Lagrangian

Effective Lagrangian for charged TGCs

$$L/g_{WWV} = ig_1^V (W^*_{\mu\nu} W^{\mu} V^{\nu} - W^*_{\mu} V_{\nu} W^{\mu\nu}) + i\kappa_V W^*_{\mu} W_{\nu} V^{\mu\nu} + i\frac{\lambda_V}{M_W^2} W^*_{\rho\mu} W_{\nu}^{\ \mu} V^{\rho\nu}$$

Effective Lagrangian for neutral TGCs

$$L_{ZZV} = -\frac{e}{M_Z^2} [f_4^V (\partial_\mu V^{\mu\beta}) Z_\alpha (\partial^\alpha Z_\beta) - f_5^V (\partial^\sigma V_{\sigma\mu}) \tilde{Z}^{\mu\beta} (\partial^\alpha Z_\beta)$$

$$\tilde{Z}^{\mu\beta} = \tfrac{1}{2} \varepsilon_{\mu\nu\rho\sigma} Z^{\rho\sigma}$$

Bauer, Rainwater, PRD 62,113011

- At tree level, no s-channel in SM
- $f_4^V = 0$ (CP invariance), $f_5^V = 0$ (P conservation)