Associated production of weak bosons at LHC with the ATLAS detector

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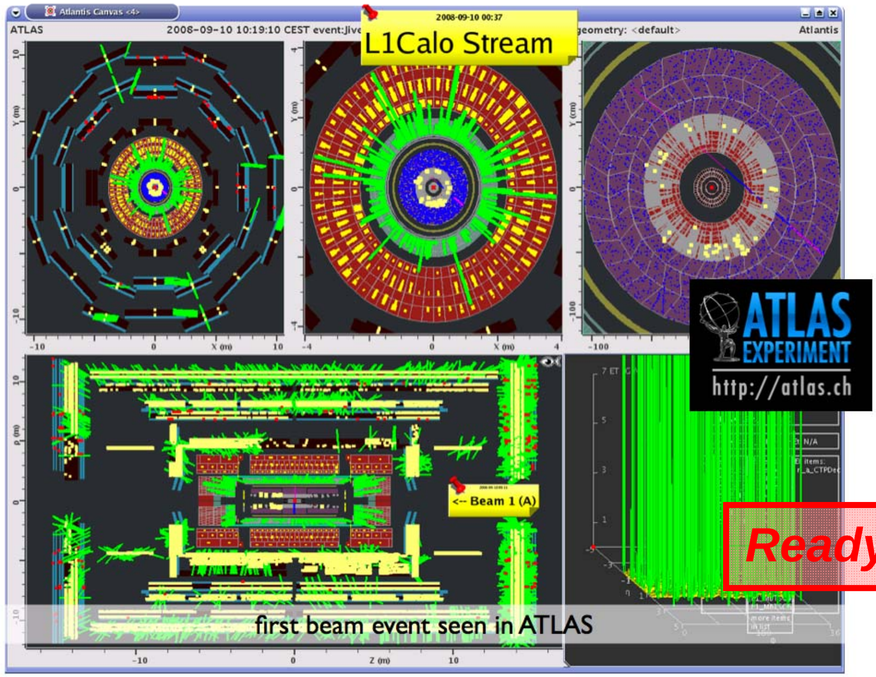
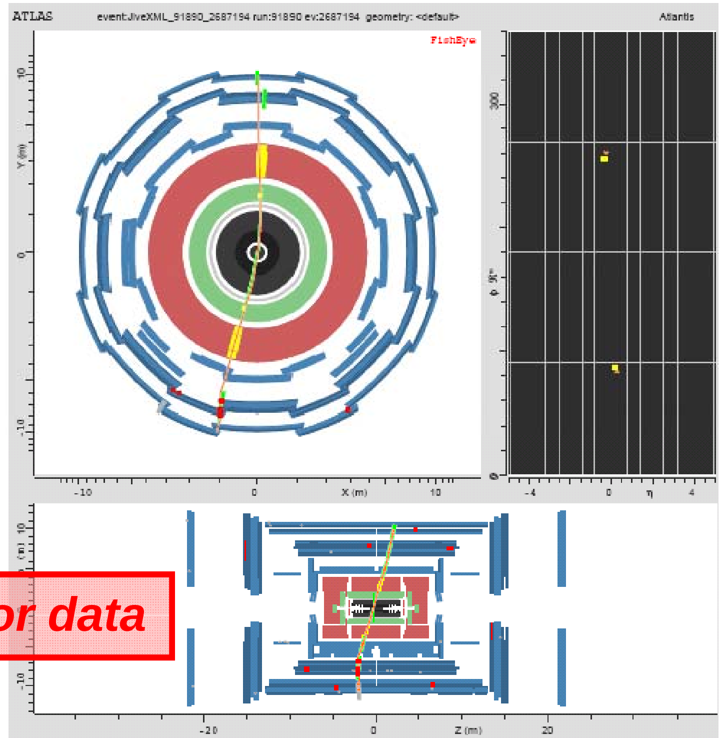
BMBF-Forschungsschwerpunkt
ATLAS Experiment
Physics on the TeV-scale at the Large Hadron Collider
FSP 101
ATLAS

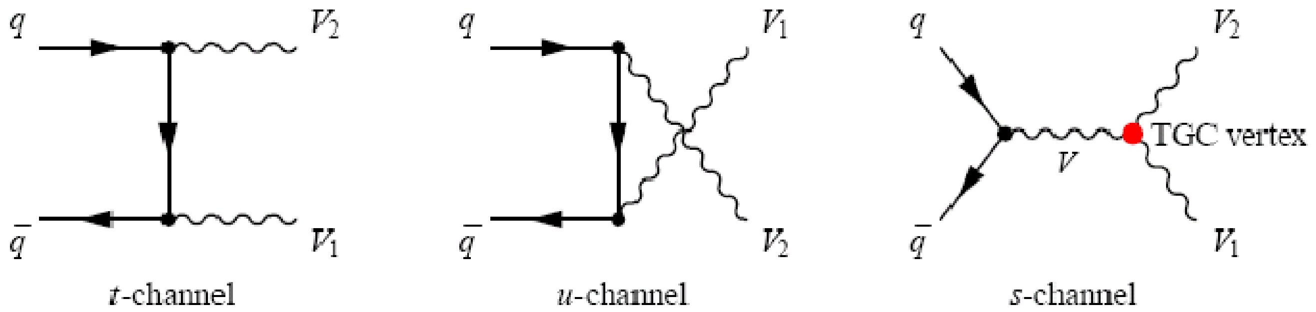
Outline

- Diboson production at LHC
- Event selection
- Triple gauge boson couplings
- ATLAS sensitivity to Diboson production and Triple Gauge Coupling (TGC)





Diboson production at the LHC



- LO Feynman diagram: V_1, V_2, V = Z, W , γ ➔ WW, ZW, ZZ, Wγ, Wγ
- Only s-channel has three boson vertex
- Diboson final states have predictable σ-production and manifest the gauge boson coupling

SM:

- Pure neutral vertexes ZZZ, ZZγ are forbidden

(Z/γ carry no charge and weak isospin that needed for gauge bosons couple)

- Only charged couplings WWγ, WWZ are allowed

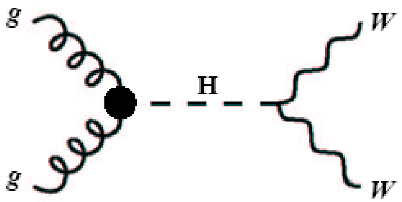
Motivation

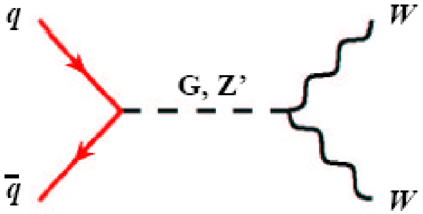
- Measure **diboson production σ** and **TGCs**
- Explore none-Abelian SU(2) x U(1) gauge structure of SM
- Probe **new physics** if production cross section, or TGCs deviate from SM prediction (deviations of $10^{-3} – 10^{-4}$)
- Understand the **backgrounds** of many important physics analyses

  Search for Higgs, SUSY, graviton and study of ttbar

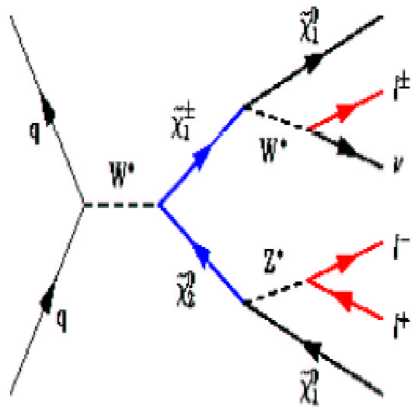
New physics

e.g. WW

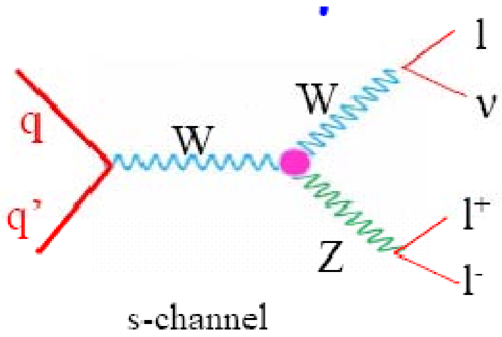


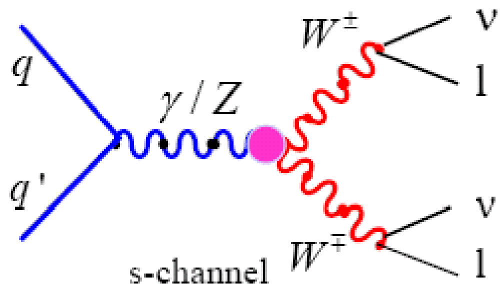


e.g. WZ



Examples: WZ, WW





- s-channel dominates: σ(SM) = 47.8 pb
- Sensitive to WWZ
- Clean signal eee, eeμ, μμe, μμμ
- 3 isolated high p_T-leptons with large missing E_T
- invariant mass from e^+e^- or $\mu^+\mu^-$ pairs within Z mass window

- σ(SM) = 111.6 pb
- Sensitive to WWZ and WWγ
- Clean signal ee, μμ,eμ
- 2 isolated high p_T-leptons with opposite charge and large missing E_T
- Z mass veto

SM Cross sections of dibosons

Diboson mode	Conditions	$p\bar{p}$ $\sqrt{s} = 1.96$ TeV $\sigma[pb]$	pp $\sqrt{s} = 14$ TeV $\sigma[pb]$
W^+W^- [14]	W-boson width included	12.4	111.6
$W^\pm Z^0$ [14]	Z and W on mass shell	3.7	47.8
$Z^0 Z^0$ [14]	Z's on mass shell	1.43	14.8
$W^\pm \gamma$ [15]	$E_T^\gamma > 7$ GeV, $\Delta R(\ell, \gamma) > 0.7$	19.3	451
$Z^0 \gamma$ [16]	$E_T^\gamma > 7$ GeV, $\Delta R(\ell, \gamma) > 0.7$	4.74	219

Measurements of the Tevatron experiments are consistent with the SM (NLO)

Production rate at LHC will be at least 100x higher at Tevatron.
10x higher cross section and at least 10x higher luminosity.
Theoretical uncertainties around 5%

➔ Probes much higher energy region 7x
➔ Increased sensitivity to anomalous TGCs

Event Selection

Two approaches: *cut-based* on kinematic quantities & multivariate Boosted-Decision-Trees (BDT)

- improvement of detection sensitivity
- Pattern recognition on a set of distributions
- Classification with weighting and score sum

- W's and Z's leptonic decay final states provide experimentally *clean signals* (only e and μ considered)
- Identification of W and Z bosons are *well established*
  - Observation of a Z peak will be one of the early tests of a properly working detector
- Z and W (transverse) masses provide *valuable constraints*
- They are good sources of high P_T leptons
  - Efficient observation with *low background*
  - Trigger at low momentum threshold

Physics Objects

electrons, photons, muons, missing E_T & had. jets

Electons: 1 electron: E_T> 25 GeV
2 electrons: E_T>10 GeV
$|\eta|$<2.5, isolated & track/cluster correlation
ID: **75%** barrel, **60%** endcaps

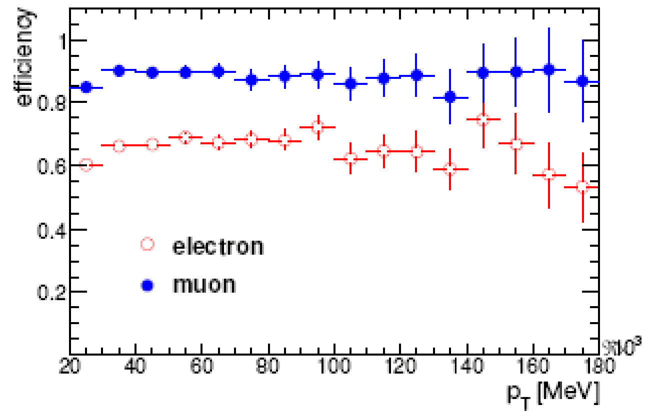
Muons: P_T > 5 GeV, $|\eta|$<2.5,
tracking algorithm (muon spectrometer & ID & CALO)
ID: **95%**

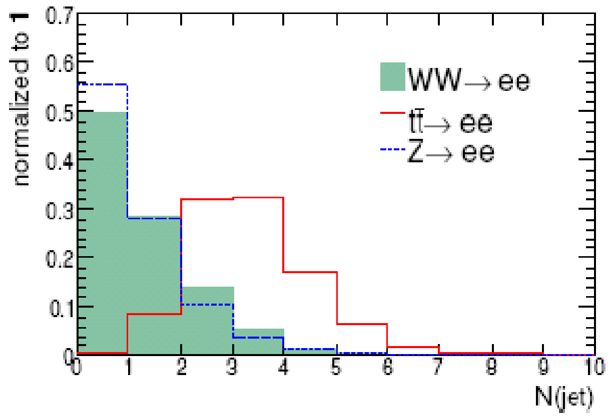
Jets: fixed-cone jet algorithm (0.7), min. **Jet E_T ~20 GeV**

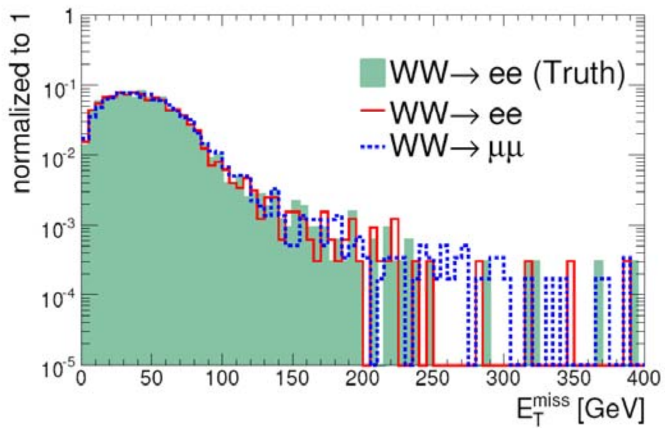
Missing transverse energy: CALO + muon
WW: MET resolution ~6.5 GeV

Trigger efficiency: p_T > 20 GeV, $|\eta|$<2.5
high trigger efficiency

	1e25i		1mu20		1e25i or 1mu20	
W^+W^-	L1	L1 & HLT	L1	L1 & HLT	L1	L1 & HLT
ee	100.0	98.2	0.0	0.0	100.0	98.2
$\mu\mu$	13.5	0.0	98.4	95.9	98.5	95.9
$e\mu$	99.7	87.9	85.3	79.3	100.0	97.4







Event selection summary

$W^+W^- \rightarrow \ell^+\nu\ \ell^-\ \nu$ σ_{WW} = 111.6 pb	2 isolated leptons with P_T > 25 GeV, opposite charges, $\Delta R(\ell\ell)$>0.2, Missing transverse energy > 30 GeV, $\|M_Z$-Mee/$\mu\mu\|$ > 30 GeV N_{jet} (E_T>30 GeV) < 2, |Vector-sum (lep, MET)|<100GeV
$W\ Z \rightarrow \ell\nu\ \ell^+\ell^-$ σ_{W+Z} = 29.4 pb σ_{W-Z} = 18.4 pb	3 isolated leptons with $P_{T(max)}$ > 25 GeV, $\Delta R(\ell\ell)$>0.2 vertex cut for each lepton pair: ΔZ<1mm, ΔA<0.1mm MET > 30 GeV, $\|M_Z$-Mee/$\mu\mu\|$ < 10 GeV, 40GeV < M_T < 250GeV N_{jet} (E_T>30 GeV) < 2, |Vector-sum (lep, MET)|< 120GeV
$ZZ \rightarrow \ell^+\ell^-\ \ell^+\ell^-$ σ_{ZZ} = 18.8 pb	4 isolated leptons with at least one P_T > 20 GeV Separation between each lepton pair $\Delta R(\ell\ell)$>0.2 All the lepton come from the same vertex, no hadron jets
$ZZ \rightarrow \ell^+\ell^-\ \nu\nu$ σ_{ZZ} = 18.8 pb	2 lepton with P_T > 20 GeV, and $\|M_Z-M_{ll}\|$<10 GeV, $P_T(\ell\ell)$ > 100 GeV veto the 3rd lepton, MET > 50 GeV, N_{jet} (E_T>30 GeV) =0, $\Delta\phi$(Z, MET) > 35 deg, |MET-PT(Z)|/PT(Z) < 0.35
$W\ \gamma \rightarrow \ell\nu\ \gamma$ $\sigma_{\mu\nu\gamma}$=(51.8+38.8)*1.4pb	1 isolated lepton with PT > 20 GeV 1 isolated photon with ET > 20 GeV MET > 30 GeV, 40GeV < M_T < 120GeV Jet veto, $\Delta R(\ell\gamma)$>0.7
$Z\ \gamma \rightarrow \ell^+\ell^-\gamma$ $\sigma_{\mu\mu\gamma}$ = 20.2*1.4pb	2 isolated leptons with P_T > 20 GeV, opposite charges, $\Delta R(\ell\ell)$>0.2, $\|M_Z$-Mee/$\mu\mu\|$ < 10 GeV, one photon with PT>20GeV, Jet veto $\Delta R(\ell\gamma)$>0.7, $\|M_Z$-Meeγ/$\mu\mu\gamma\|$ > 30 GeV

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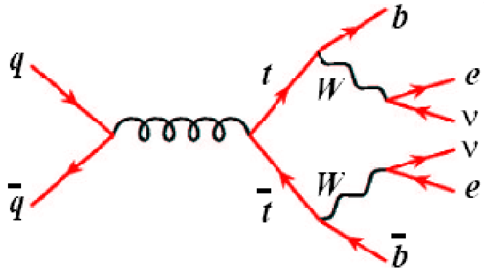
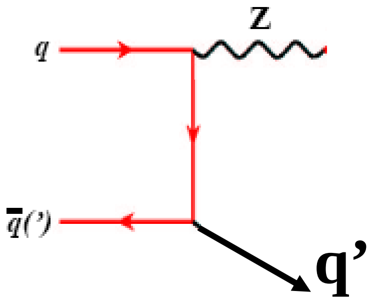
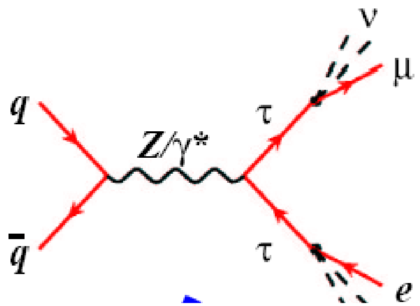
Example: $W^{\pm}Z$

- 3 isolated high p_T charged leptons
- Large missing E_T > 25 GeV
- Small hadronic jet activity:
  1 Jet with E_T>30 GeV
  hadronic ΣE_T < 200 GeV
- Z-mass window
- Major backgrounds
  - pp → $t\bar{t}$ (17.4% of background)
    - Pair of leptons fall in Z mass window
    - Jet produces lepton signal
  - pp → Z+jets (15.5%)
    - Fake missing E_T
    - Jet produces third lepton signal
  - pp → Z/γ → ee, μμ (12.5%)
    - Fake missing E_T and third lepton
  - pp → ZZ→ 4 leptons (47.8%)
    - Loose one lepton







Example: $W^{\pm}Z$

- **Trigger efficiency:** (98.9 ± 0.1)%
  combination of single lepton and dilepton triggers
- **Signal efficiency:** 8.7 % W^-Z / 7.1 % for W^+Z

Cut-based:

1 fb⁻¹

	WZ	ZZ	$t\bar{t}$	$Z+$jet	$Z+\gamma$	DY	Total bkg	N_{WZ}/N_B
N events	**53.43**	2.68	0.023	1.89	0.18	2.52	**7.30**	7.32
% of background	-	36.71	0.32	25.92	2.47	34.58	-	-

- ***0.1 fb⁻¹:*** 5 signal events & 1 background event ➔ 4 σ detection significance

BDT: 1000 trees with 20 tree-split nodes

	WZ	ZZ	$t\bar{t}$	$Z+$jet	$Z+\gamma$	Other	Total bkg	N_{WZ}/N_B
N events	**152.6 (65%)**	7.7	2.8	2.5	2.0	1.1	**16.1**	9.5
% of background		47.8	17.4	15.5	12.5	7.0	-	-

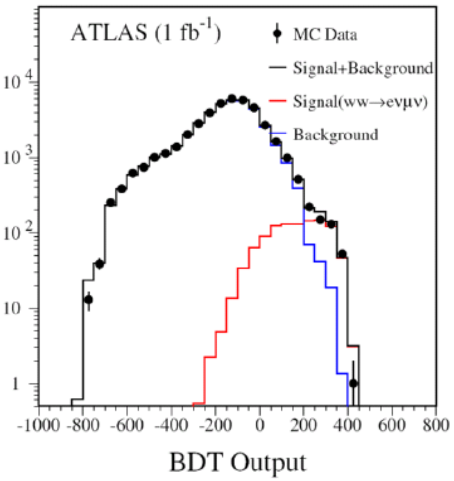
- ***0.1 fb⁻¹:*** 15 signal events & 2 background event ➔ 7 σ detection significance

ATLAS diboson sensitivity with 1fb^{-1}

Diboson mode	Signal #evt.	Background #evt.	S/√B	Analysis
$W^+W^- \to e^+\nu e^-\nu$	78.0±1.6	35.4±3.6	13	BDT (ε=5.7%)
$W^+W^- \to \mu^+\nu\mu^-\nu$	90.3±1.6	20.2±2.8	20	BDT (ε=6.6%)
$W^+W^- \to e^+\nu\mu^-\nu$	419.9±3.5	80.8±6.0	47	BDT (ε =15.2%)
$W^+W^- \to \ell^+\nu\ell^-\nu$	103.1±2.6	16.6±2.0	25	Cut based (ε =2.0%)
$W Z \to \ell\nu\, \ell^+\ell^-$	152.6±1.7	16.1±2.5	38	BDT (ε=17.9%)
	53.4±1.6	7.3±1.1	19	Cut based (ε ~8%)
$ZZ \to 4\ell$	16.5±0.1	1.90±0.2	7.2	Cut based (ε =7.7%)
$ZZ \to \ell^+\ell^-\nu\nu$	10.2±0.2	5.2±2.0	3.7	Cut based (ε =2.6%)
$W\gamma \to e\nu\gamma$	1901±77	1474±147	50	BDT (ε=6.7%)
$W\gamma \to \mu\nu\gamma$	2976±121	2318±232	62	BDT (ε=10.5%)
$Z\gamma \to e^+e^-\gamma$	337.4±12	187.2±19	25	BDT (ε=5.5%)
$Z\gamma \to \mu^+\mu^-\gamma$	774.8±25	466.7±47	36	BDT (ε=12%)

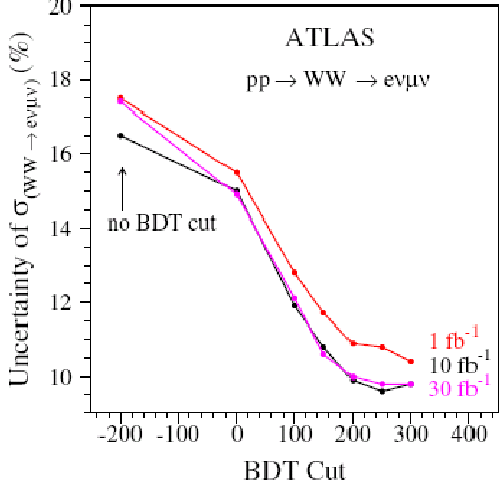
Measurement errors

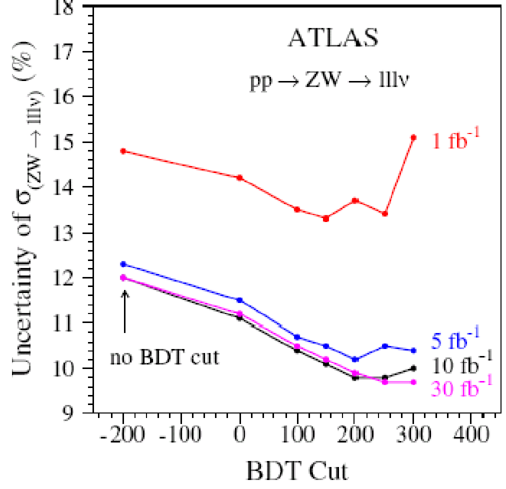
Log-Likelihood build with BDT output



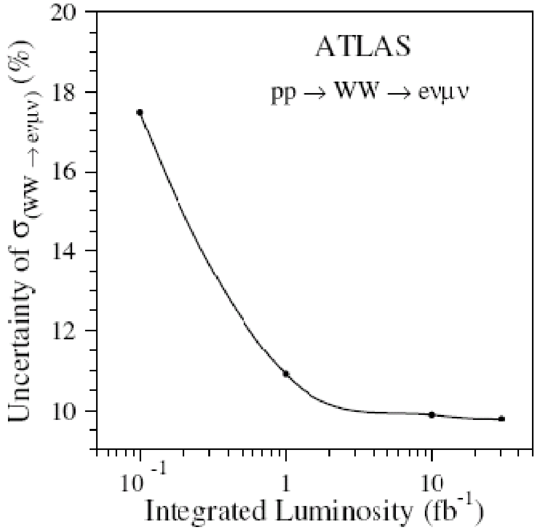
MC data:
simulated events with appropriate statistics according to the luminosity + SM

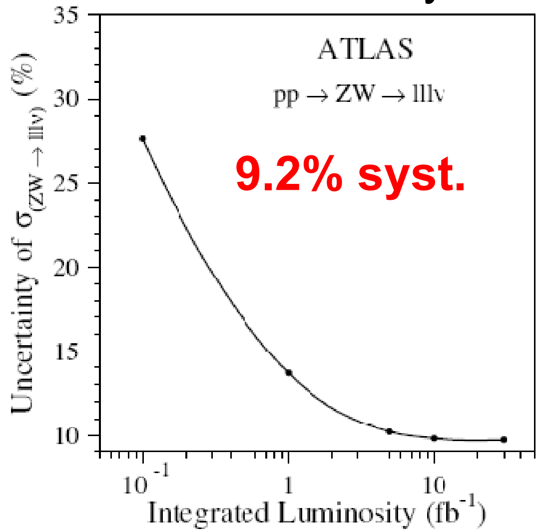
Cross section measurement error vs. selection cut





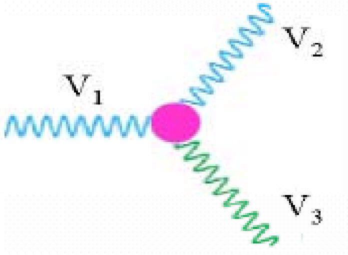
Cross section measurement error vs. luminosity





Triple Gauge Boson Coupling

TGC are characterised by an effective Lagrangian



$$L/g_{WWV} = i g_1^V \left(W^*_{\mu\nu} W^\mu V^\nu - W_{\mu\nu} W^{*\mu} V^\nu \right) + i\kappa^V W^*_\mu W_\nu V^{\mu\nu} + \frac{\lambda^V}{M_W^2} W^*_{\rho\mu} W^\mu_\nu V^{\nu\rho}$$

SM: $g_1^V = \kappa^V = 1$ and $\lambda^V = 0$

Experiment: Search for deviations from the SM

➔ Anomalous coupling parameters for charged TGC (neutral TGC have 4 different parameters) are:

$$\Delta g_1^Z \equiv g_1^Z - 1, \quad \Delta\kappa_\gamma \equiv \kappa_\gamma - 1, \quad \Delta\kappa_Z \equiv \kappa_Z - 1, \quad \lambda_\gamma, \text{ and } \lambda_Z$$

terms have normally an $\hat{s}$ dependence which means the higher center-of-mass energies at the LHC greatly enhance our sensitivity to anomalous couplings

➔ Amplitude for gauge boson pair production grows with energy (cutoff Λ needed)

$$\Delta\kappa(\hat{s}) = \frac{\Delta\kappa}{(1 + \hat{s}/\Lambda^2)^2}$$

$\sqrt{\hat{s}}$ Invariant mass of boson pair

$\Delta\kappa$ Coupling at the low energy limit

Event Generators

NLO MC Generators:

- **MC@NLO** with Jimmy/HERWIG:
  W^+W^-, $W^\pm Z$, ZZ

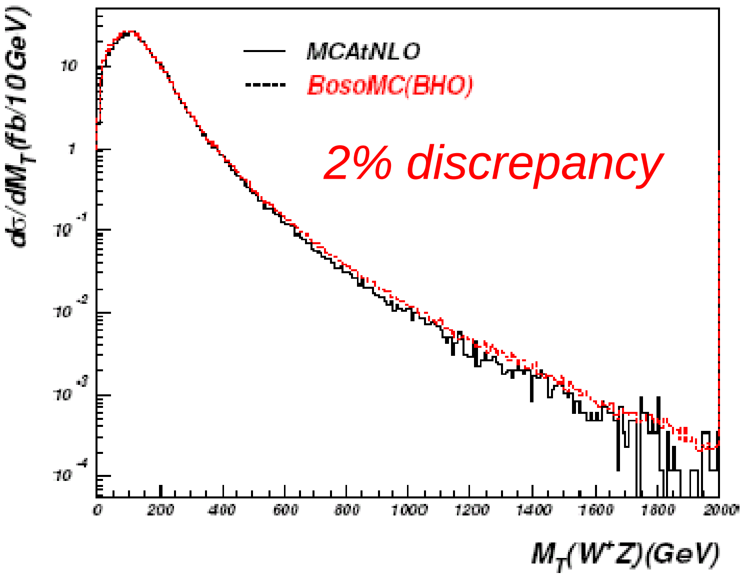
  Pythia: $W^\pm\gamma$, ZZ, $Z\gamma$
  no anomalous coupling

- **BHO**: W^+W^-, ZZ, $Z\gamma$
  BosoMC: $W^\pm Z$, $W^\pm\gamma$
  with anomalous coupling

Signal

Background

- Background:
  top pairs and QCD jets with W and Z bosons
  MC@NLO $t\bar{t} \to \ell + X$ 700k events
  PYTHIA/ALPGEN incl. W+X and Z+X (X=jets, γ) 30M events

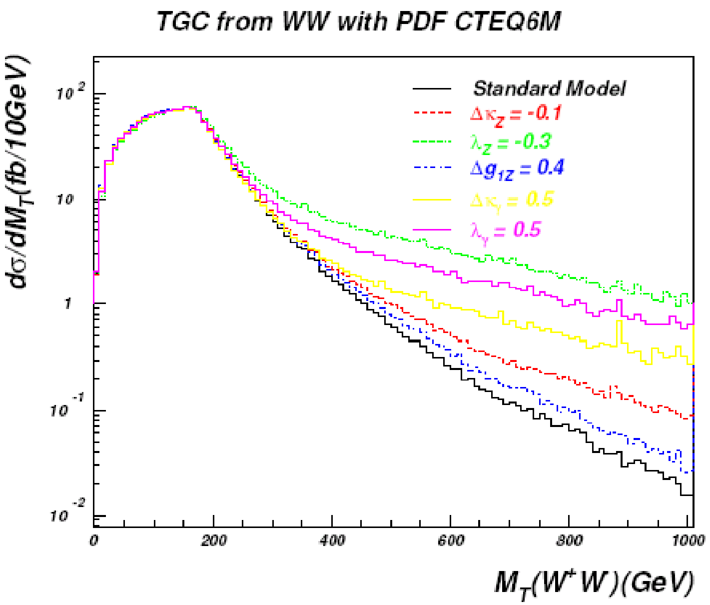


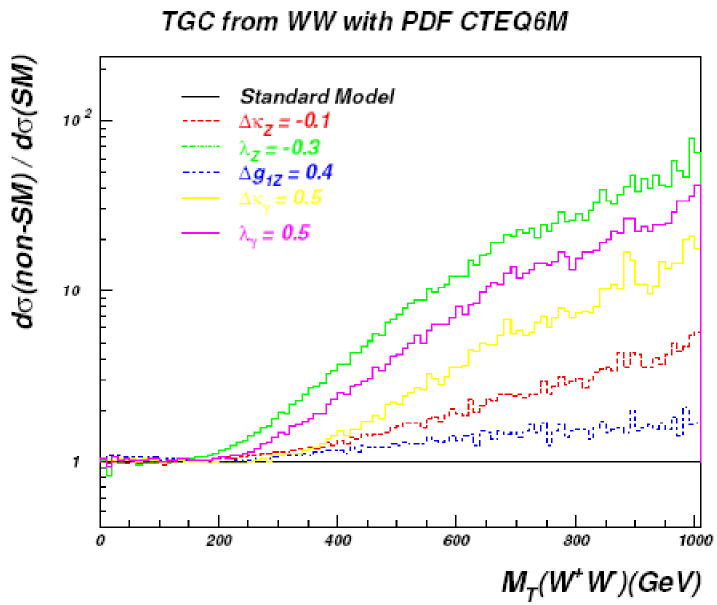
- **Reweighting**
  Using kinematic distributions from BHO the fully simulated MC@NLO events are reweighted to produce expected distributions for a range of anomalous couplings

Fully simulated:
detector response, electronic digitisation, final event reconstruction

Anomalous spectra and reweighting ratio

The $M_T(WW)$ spectrum for W+W- events with anomalous coupling parameters using the BHO Monte Carlo

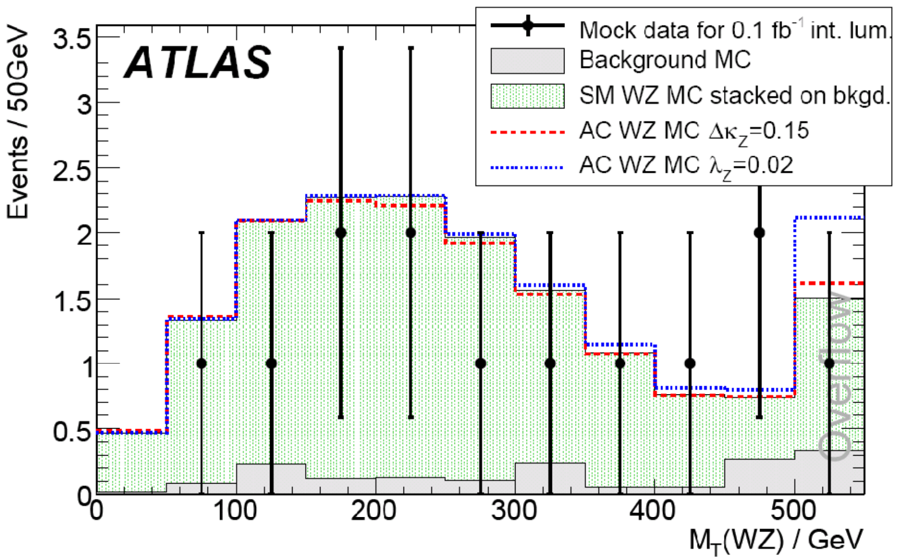




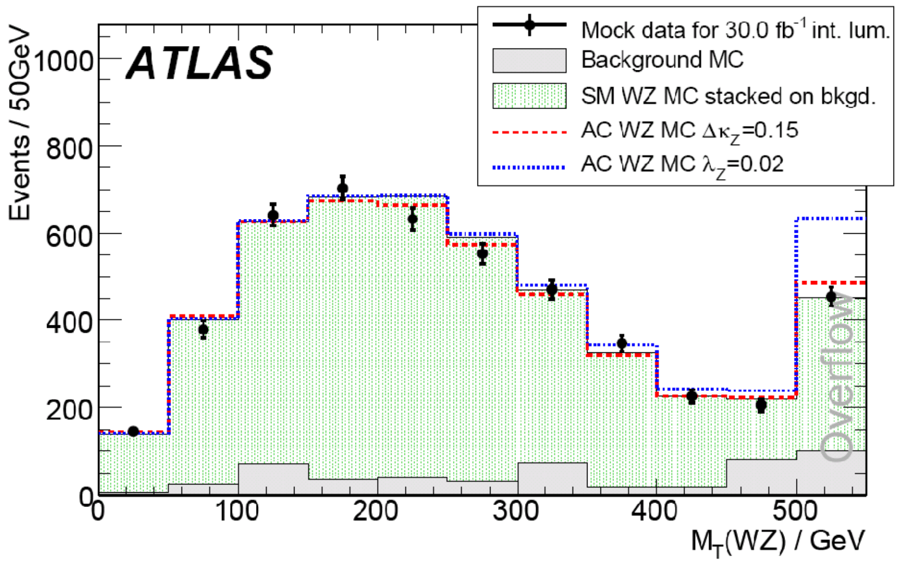
the 'weights = $d\sigma$(non-SM)/$d\sigma$(SM)' are used to reweight fully simulated events

M_T(WZ) spectrum sensitive to WWZ couplings

0.1 fb^{-1}



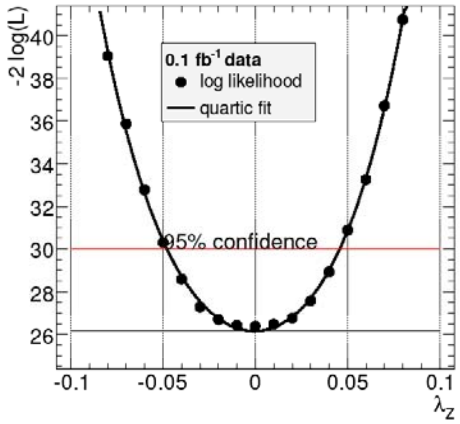
30 fb^{-1}



- **Binned likelihood** comparing mock SM observations to a SM profile and two reweighted anomalous profiles
- **M_T(WZ)** was found to be the most sensitive kinematics quanitity (P_T(Z), M(ll), and others are also useful, but not as sensitive)
- Using 10 bins from 0-500GeV and one overflow bin

TGC sensitivity using $M_T(WZ)$

0.1 fb^{-1}



One parameter limits (assuming other couplings are SM)

$-0.4 < \Delta\kappa_Z < 0.6$

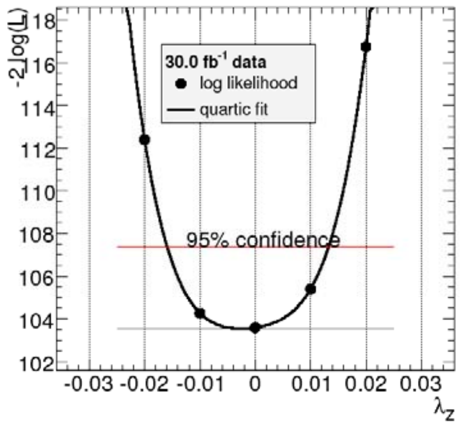
$-0.06 < \Delta g_1^Z < 0.1$

$-0.06 < \lambda_z < 0.05$

Tevatron results

$-0.12 < \Delta\kappa_z < 0.29$	2 TeV	D0 with 1.0 fb^{-1}
$-0.17 < \lambda_z < 0.21$		
$-0.82 < \Delta\kappa_z < 1.27$	2 TeV	CDF with 1.9 fb^{-1}
$-0.13 < \lambda_z < 0.14$		

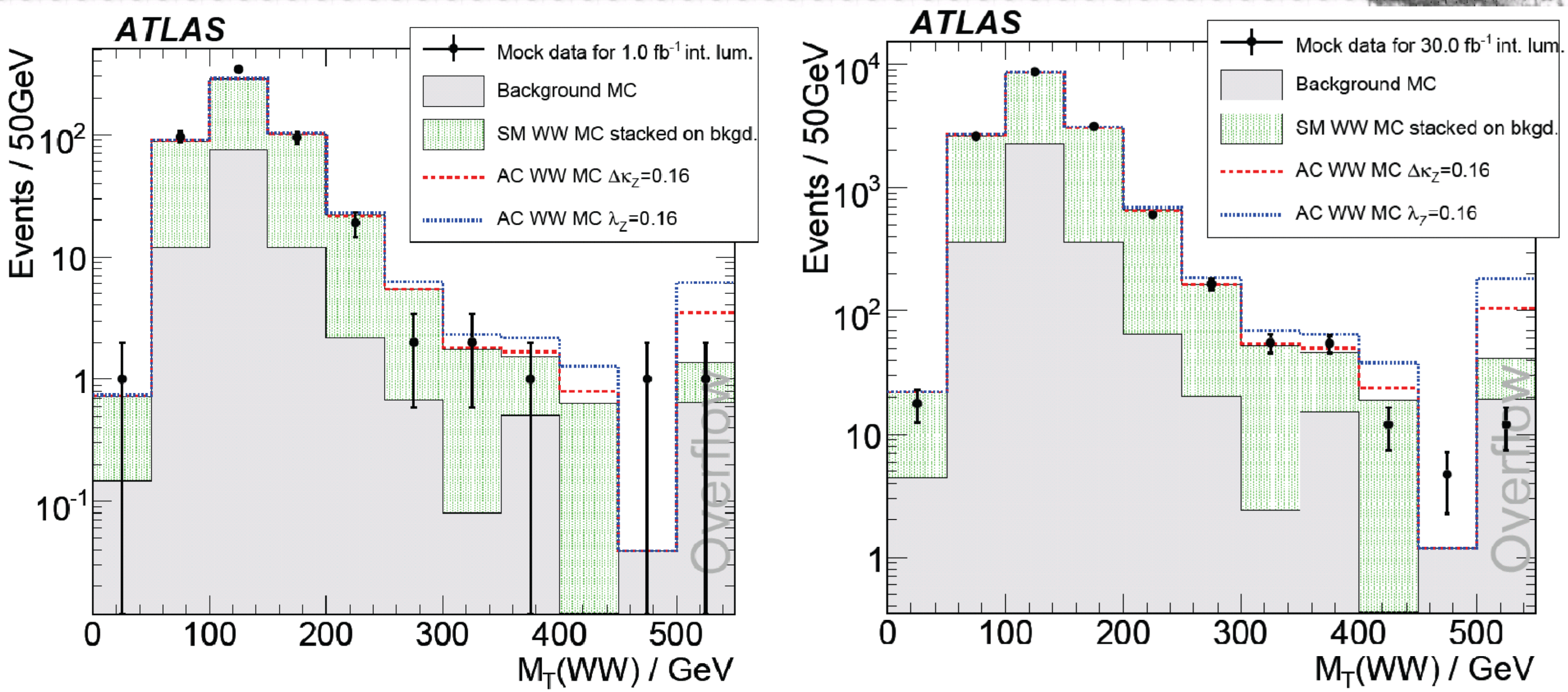
30 fb^{-1}



One parameter limits

Λ=2 TeV	Λ=3 TeV
$-0.08 < \Delta\kappa_Z < 0.17$	$-0.07 < \Delta\kappa_Z < 0.13$
$-0.01 < \Delta g_1^Z < 0.008$	$-0.003 < \Delta g_1^Z < 0.018$
$-0.005 < \lambda_z < 0.023$	$-0.008 < \lambda_z < 0.005$

$M_T(WW)$ sensitive to WWZ & WWγ couplings



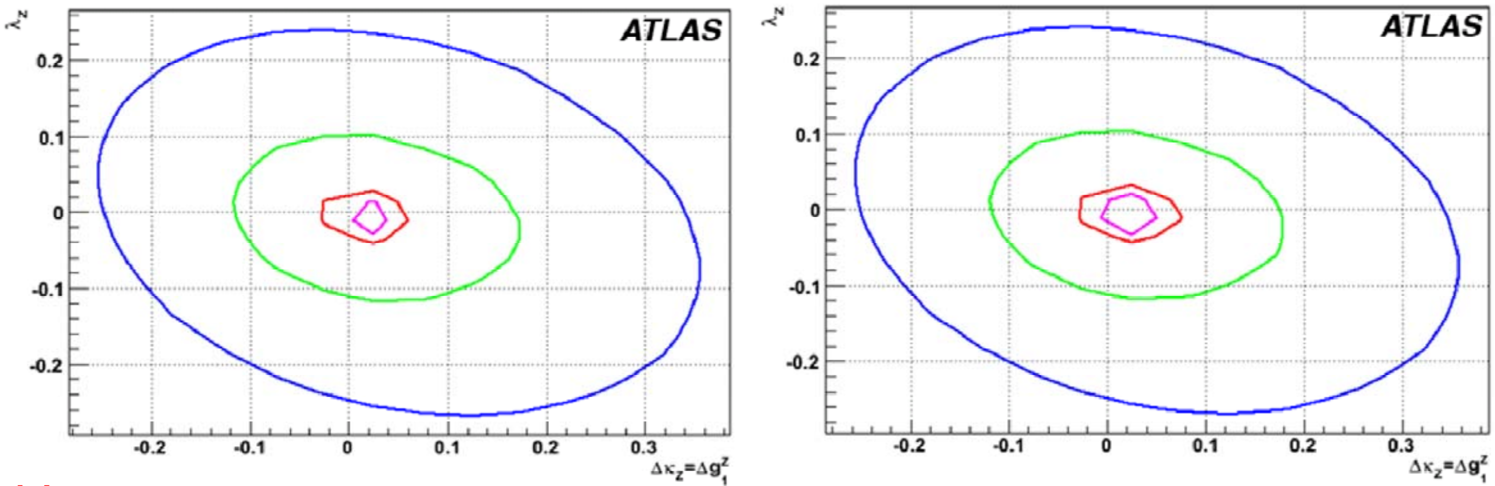
- Binned likelihood comparing mock SM observations to a SM profile & two reweighted anomalous profiles
- Using 10 bins from 0-500GeV and one overflow bin
- In addition, the three decay channels, ee, eμ, and μμ, are binned separately for a total of 33 bins

ATLAS TGC sensitivity

One-dimensional anomalous coupling parameter 95% CL sensitivities using the M_T ($W^{\pm}Z$)

Int. Lumi (fb^{-1})	Cutoff Λ (TeV)	$\Delta\kappa_Z$	λ_Z	Δg_1^Z
0.1	2.0	[-0.440, 0.609]	[-0.062, 0.056]	[-0.063, 0.119]
1.0	2.0	[-0.203, 0.339]	[-0.028, 0.024]	[-0.021, 0.054]
10.0	2.0	[-0.095, 0.222]	[-0.015, 0.013]	[-0.011, 0.034]
30.0	2.0	[-0.080, 0.169]	[-0.012, 0.008]	[-0.005, 0.023]
0.1	3.0	[-0.399, 0.547]	[-0.050, 0.046]	[-0.054, 0.094]
1.0	3.0	[-0.178, 0.281]	[-0.020, 0.018]	[-0.017, 0.038]
10.0	3.0	[-0.135, 0.201]	[-0.015, 0.013]	[-0.013, 0.018]
30.0	3.0	[-0.069, 0.131]	[-0.008, 0.005]	[-0.003, 0.016]

Systematic Error Effect on TGCs 2D Limits



Λ = 2 TeV

No systematic errors

9.2% signal, 18.3% background

ATLAS TGC sensitivity

95% C.L. interval of the anomalous coupling sensitivities with 10.0 fb^{-1} and cutoff Λ = 2 TeV.

Diboson, (fit spectra)	λ_Z	$\Delta\kappa_Z$	Δg_1^Z	$\Delta\kappa_\gamma$	λ_γ
WZ, (M_T)	[-0.015, 0.013]	[-0.095, 0.222]	[-0.011, 0.035]		
$W\gamma$, (p_T^γ)				[-0.26, 0.07]	[-0.05, 0.02]
WW, (M_T)	[-0.040, 0.038]	[-0.035, 0.073]	[-0.149, 0.309]	[-0.088, 0.089]	[-0.074, 0.165]
WZ, (D0) (1.0fb^{-1})	[-0.17, 0.21]	[-0.12, 0.29] ($\Delta g_1^Z = \Delta\kappa_Z$)			
$W^\pm\gamma$ (D0), (0.16fb^{-1})				[-0.88,0.96]	[-0.2,0.2]
WW, (LEP) ($\lambda_\gamma = \lambda_Z$,$\Delta\kappa_Z = \Delta g_1^Z - \Delta\kappa_\gamma \tan^2\theta_W$)			[-0.051,0.034]	[-0.105,0.069]	[-0.059,0.026]

	f_4^Z	f_5^Z	f_4^γ	f_5^γ
$ZZ \to \ell\ell\ell\ell$	[–0.010, 0.010]	[–0.010, 0.010]	[–0.012, 0.012]	[–0.013, 0.012]
$ZZ \to \ell\ell\nu\nu$	[–0.012, 0.012]	[–0.012, 0.012]	[–0.014, 0.014]	[–0.015, 0.014]
Combined	[–0.009, 0.009]	[–0.009, 0.009]	[–0.010, 0.010]	[–0.011, 0.010]
LEP Limit	[–0.30, 0.30]	[–0.34, 0.38]	[–0.17, 0.19]	[–0.32, 0.36]

Summary

- The Diboson studies use ~30 M ATLAS fully simulated datasets

- WW, WZ, Wγ and Zγ signal can be established with statistical sensitivity better than 5σ for the first 0.1 fb^{-1} integrated luminosity, and ZZ signal can be established with 1.0 fb^{-1} data

- The anomalous triple gauge boson coupling sensitivities from LHC/ATLAS can be significant improved over the results from Tevatron and LEP using the first 1.0 fb^{-1} data

- SM Diboson productions are important control samples for Higgs, SUSY, Technicolor, new particle searches with diboson final states

- LHC: hopefully soon collision data available

- Details: ATLAS Collaboration,
  Expected Performance of the ATLAS Experiment, Detector, Trigger and Physics,
  CERN-OPEN-2008-020, Geneva, 2008, to appear

BACKUP

TGC limits from LEP

- Charged TGC limits from WW

$$-0.051 < \Delta g_1^Z < +0.034$$

$$-0.105 < \Delta\kappa_\gamma < +0.069$$

$$-0.059 < \lambda_\gamma < +0.026.$$

The TGC parameters are related by $\lambda_\gamma = \lambda_Z$ and $\Delta\kappa_Z = \Delta g_1^Z - \Delta\kappa_\gamma \tan^2\theta_W$.

- Neutral TGC limits from ZZ

  $-0.30 < f_4^Z < 0.30$ $-0.34 < f_5^Z < 0.38$

  $-0.17 < f_4^\gamma < 0.19$ $-0.32 < f_5^\gamma < 0.36$

Tevatron Results

- CDF and D0: 2 fb^{-1} of integrated luminosity
- Cross section measurements consitent with SM predictions

Coupling	Source	L (fb^{-1})	λ_Z	$\Delta\kappa_Z$	$\Delta\kappa_\gamma$	λ_γ
$WW\gamma$ from $W^{\pm}\gamma$	D0 [18]	0.16			[-0.88, 0.96]	[-0.2, 0.2]
WWZ from $W^{\pm}Z$	D0 [15]	1.0	[-0.17, 0.21]	[-0.12, 0.29]		
WWZ from $W^{\pm}Z$	CDF	1.9	[-0.13, 0.14]	[-0.82, 1.27]		
$WWZ = WW\gamma$ from W^+W^-	D0 [47]	0.25	[-0.31, 0.33]	[-0.36, 0.33]		
from W^+W^-, $W^{\pm}Z$	CDF [48]	0.35	[-0.18, 0.17]	[-0.46, 0.39]		

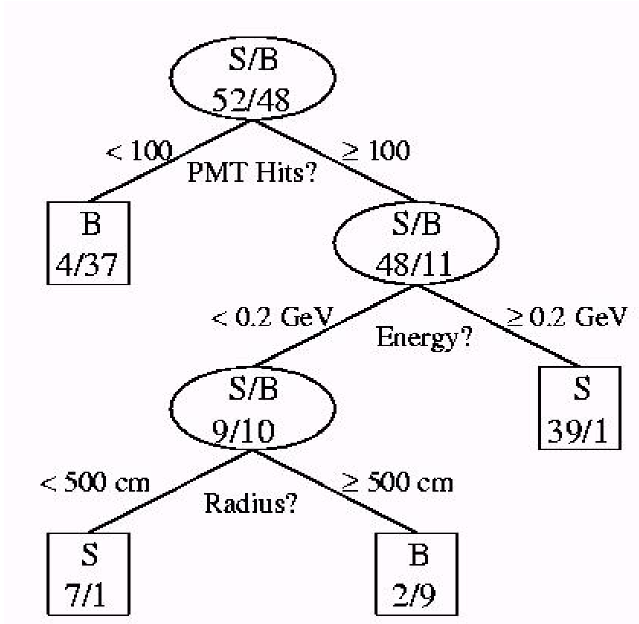
Anomalous gauge coupling limits (95% C.L.) for WWγ and WWZ from the Tevatron experiments

Predictions for TGC for L=30 fb-1 (incl. syst.)

$-0.0035 < \lambda_\gamma < +0.0035$
$-0.0073 < \lambda_Z < +0.0073$
$-0.075 < \Delta\kappa_\gamma < +0.076$
$-0.11 < \Delta\kappa_Z < +0.12$
$-0..86 < \Delta g^1_Z < +0.011$

Boosted Decision Tree

- Split sample in half, one for training, one for test.
- Select a set of variables (p_T, isolation, inv. mass, …) to cut on.
- Build a decision tree by choosing the best variable to cut on, put events in signal and background leaves, and continue splitting each leaf until all leaves have too few events or are pure signal/background.
- Boosting: give misclassified events higher weight and produce a new tree.
- Total 200 or more trees. Each tree classifies events as signal (+1) or background (-1). The result is a score for each event which is the sum of the ±1 from all the trees.



One decision tree

Systematic Uncertainties

- Signal systematics ~9%
  - Luminosity measurement 6.5%
  - PDF assumption 3%
  - NLO scaling 5%
  - Particle ID 3%
- Background systematics ~18%
- (in addition to the above)
  - MC sample statistics 15% (may drop to 10%)
  - Calibration on lepton, jet energy 5%
- The systematic errors start to dominate the cross-section measurement uncertainties after 5-10 fb-1.

2D anomalous TGC sensitivity using $M_T(WW)$

95% confidence contours for 0.1, 1, 10, and 30 fb^{-1} integrated luminosity

Right: HISZ assumption (2 parameters)

Bottom: "Standard" assumption, Z param. = γ param. (3 parameters)