Direct and Indirect Searchs for New Physics with Diboson Final States

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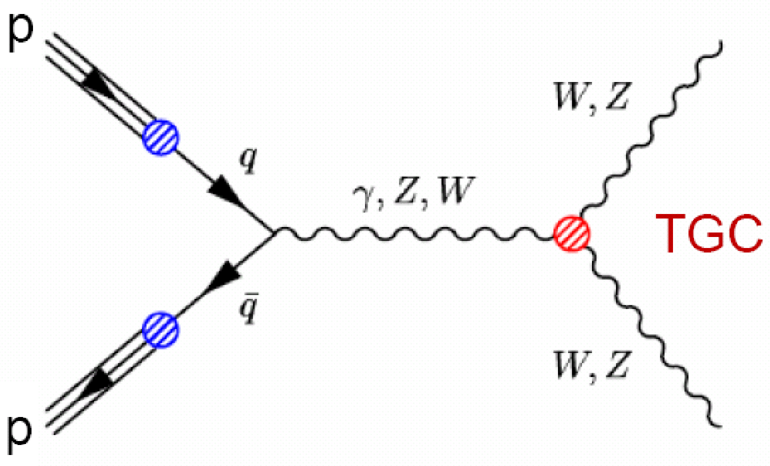
Physics motivations

- One of the fundamental questions LHC could address:
  - Why do we have massive bosons?
  - What is the source of the EW symmetry breaking?
- There must be some new physics leading to EWSB. So, we can search for
  - direct evidence – new particles such as the Higgs, technicolor , etc, have experimental signatures with diboson final states, or
  - indirect evidence – observe deviations of vector boson self-interactions from the SM.
- At the TeV energy scale there must be one or the other

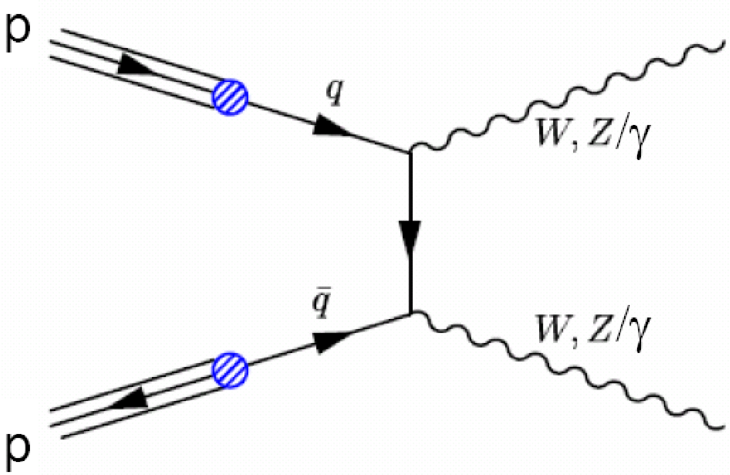
Experimental advantages

- W’s & Z’s provide experimentally clean signals
  - Identification of W and Z is well established
    - Observation of a Z peak will be one of the early tests of a properly working detector.
  - Mass provides a valuable constraint and
  - They are a good source of high pT leptons
    - Efficient observation with low background
    - Trigger at low momentum threshold.

Standard model diboson production in hadron colliders



s-channel



t-channel

S-channel depends on trilinear gauge coupling (TGC)

Charged couplings (WWZ/) are allowed in the SM

Neutral couplings (VVV where V=Z or) are disallowed

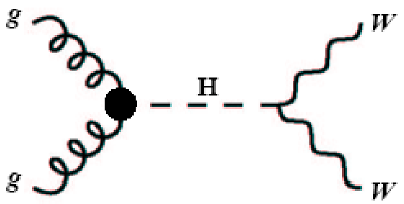
Production cross-sections

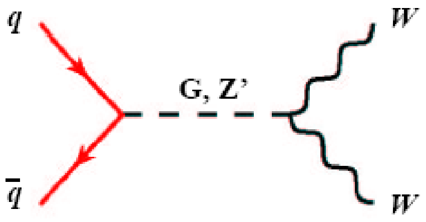
Diboson mode	Conditions	Tevatron $\sqrt{s} = 1.96$ TeV $\sigma(pb)$ NLO	LHC $\sqrt{s} = 14\ TeV$ $\sigma(pb)$ NLO	LHC $\sqrt{s} = 14\ TeV$ $\sigma(pb)$ LO
W^+W^-	W's on mass shell	12.4 ± 0.3	111.6 ± 5.6	70.71 ± 7.1
$W^\pm Z^0$	Z and W on mass shell, no $Z/\gamma*$	3.7 ± 0.3	47.8 ± 3.3	27.12 ± 2.7
$Z^0 Z^0$	Z's on mass shell, no $Z/\gamma*$	1.43 ± 0.1	14.8 ± 1.3	$11.13 \pm 1.1^*$
$W^\pm \gamma$	$E_T^\gamma > 20$ GeV	19.3 ± 1.4	119.1 ± 6.0	60.6 ± 6.1
$Z^0 \gamma$	$E_T^\gamma > 20$ GeV, $\Delta R(\ell, \gamma) > 0.7$	4.74 ± 0.22	69.0 ± 3.5	56.0 ± 5.6

Production rate at LHC will be at least 100x higher at Tevatron. 10x higher cross-section and 10-100x higher luminosity ($10^{33} - 10^{34}$).

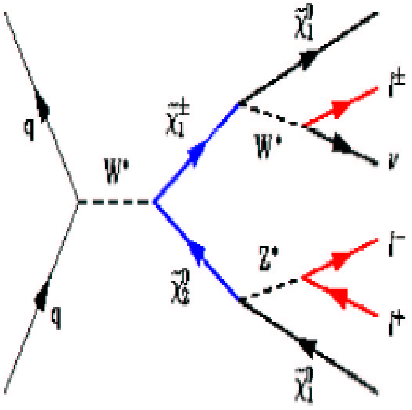
Probes much higher energy region, so sensitive to new physics.

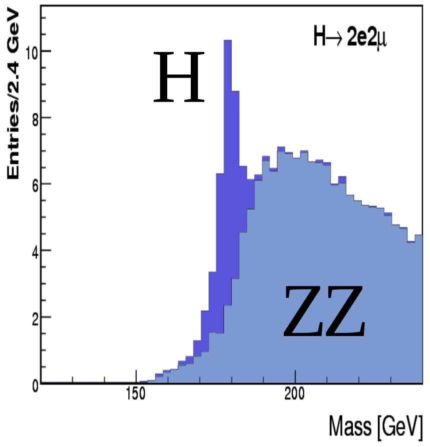
Examples of new physics with dibosons



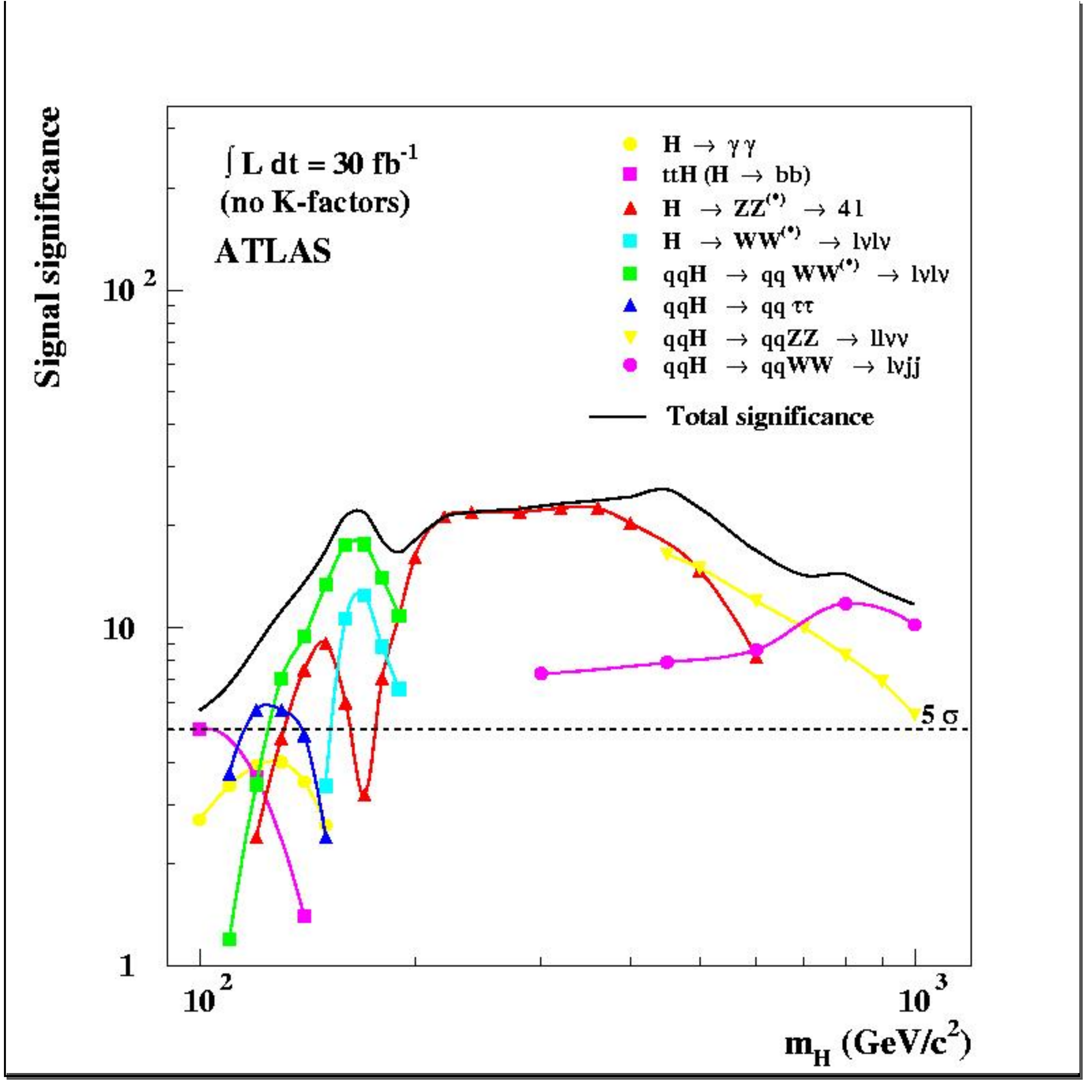


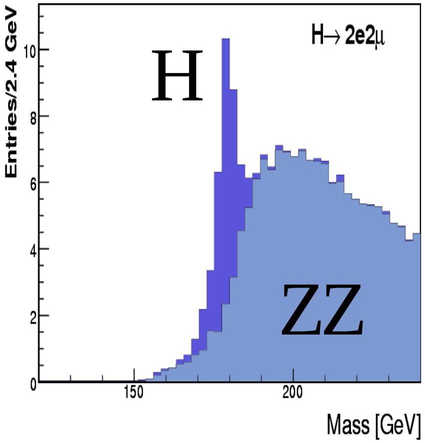
- WW
  - Higgs, Z', G, anomalous TGCs
- WZ
  - SUSY, technicolor, W', anomalous TGCs
- W
  - anomalous TGCs
- Z
  - anomalous TGCs
- ZZ
  - Higgs, heavy lepton pair, anomalous TGCs

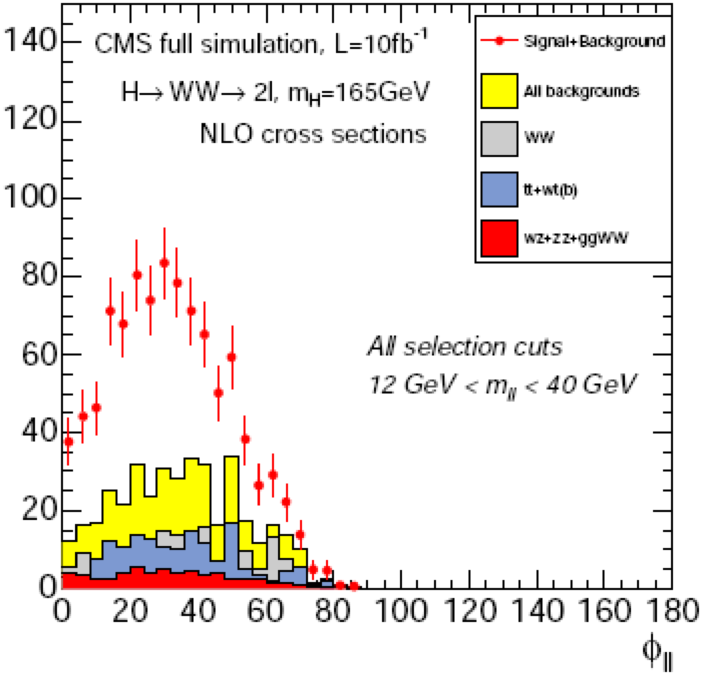




Dibosons are discovery channels

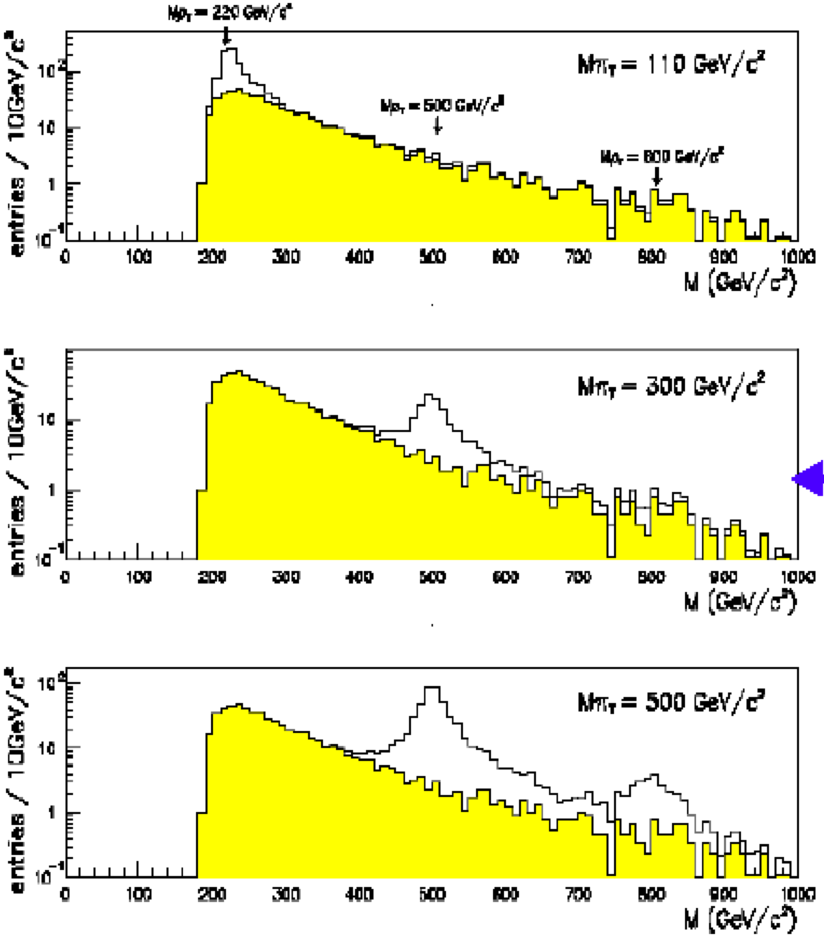






Technicolor model – composite higgs

Reconstructed invariant mass for $\rho_T \rightarrow WZ \rightarrow l\nu ll$ channel. Solid line is signal. Filled area is background.



Lower limits required for 5σ significance with 30 fb^{-1} :
in some cases,
signals are below observability,
but combination of signals
could provide strong evidence.

$\rho_T \rightarrow WZ \rightarrow l\nu ll$ for 30 fb^{-1}

(a) $\sigma \times BR_{model}$ = 0.16 fb

$\sigma \times BR_{5\sigma\ discovery}$ = 0.025 fb

$\rho_T \rightarrow W\pi \rightarrow l\nu bb$ for 30 fb^{-1}

(c) $\sigma \times BR_{model}$ = 0.064 fb

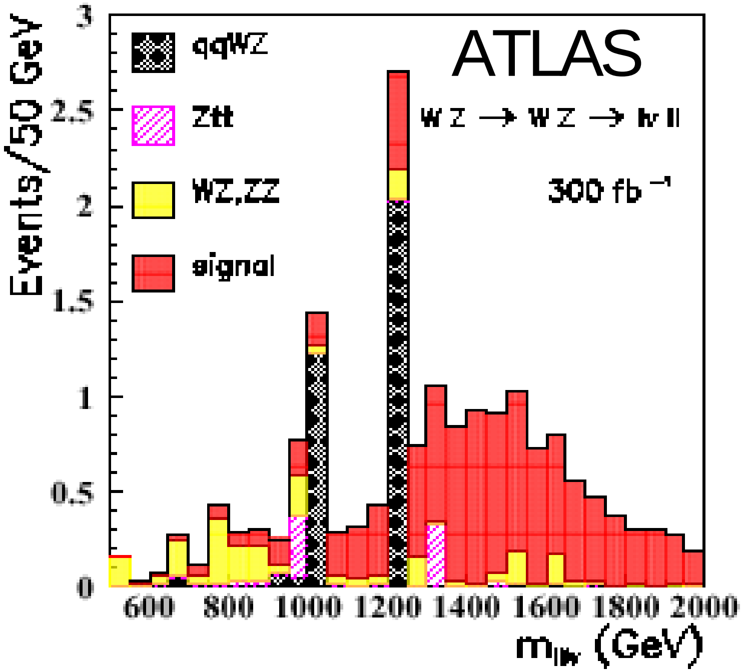
$\sigma \times BR_{5\sigma\ discovery}$ = 0.15 fb

Strongly-coupled vector boson system

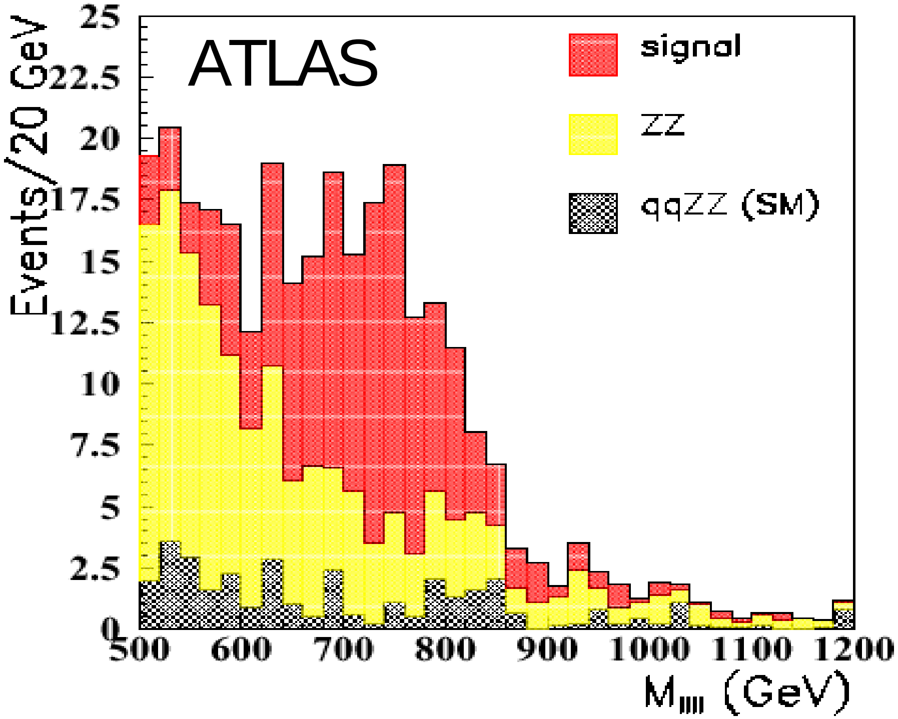
No light Higgs boson? Study Longitudinal gauge boson scattering in high energy regime (the L-component which provides mass to these bosons).

$W_L\,Z_L$ $W_L\,Z_L$ l ll

S / B = 6.6/2.2

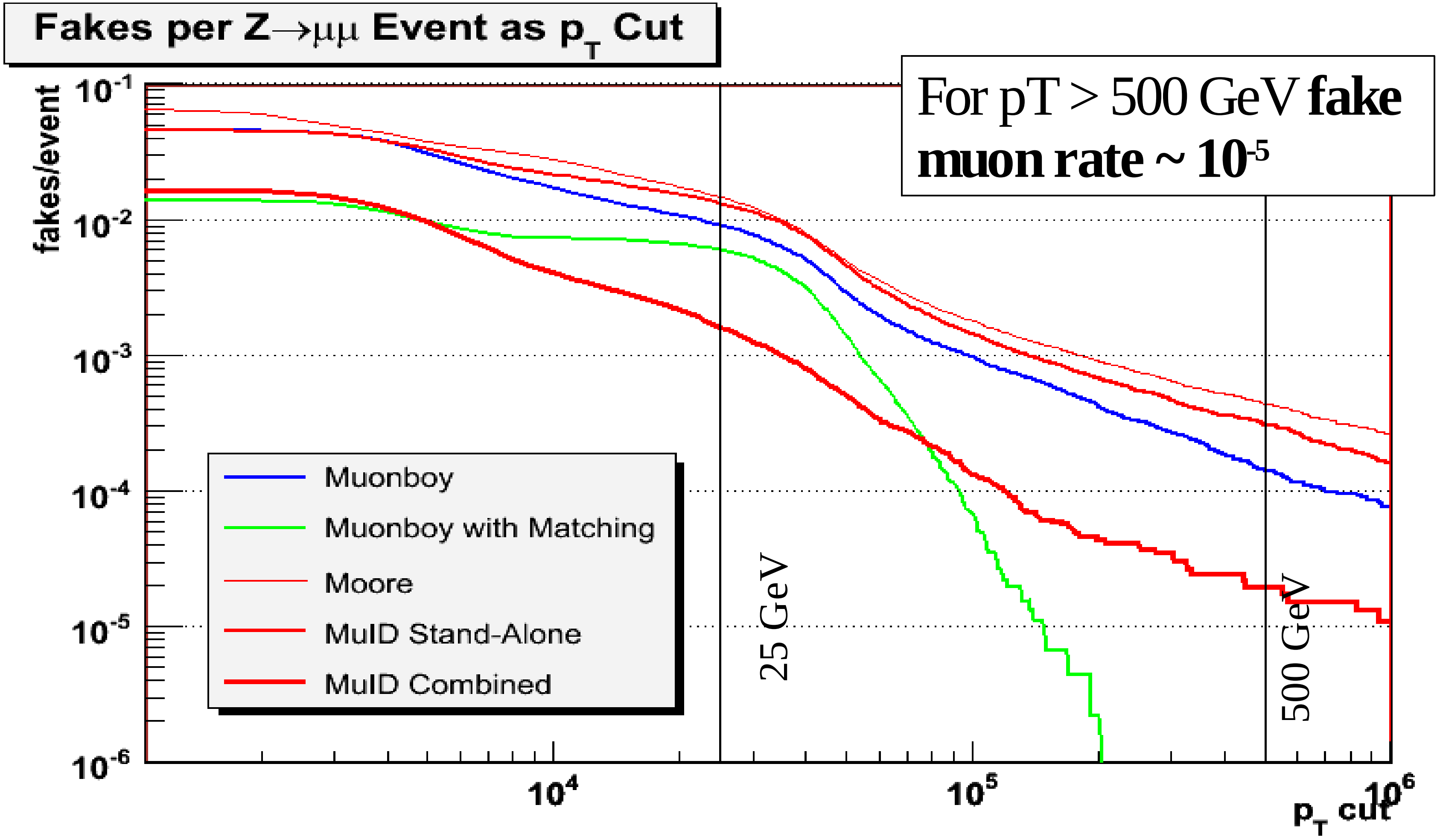


$W_L\,W_L$ $Z_L\,Z_L$ 4 leptons
$Z_L\,Z_L$ $Z_L\,Z_L$ 4 leptons



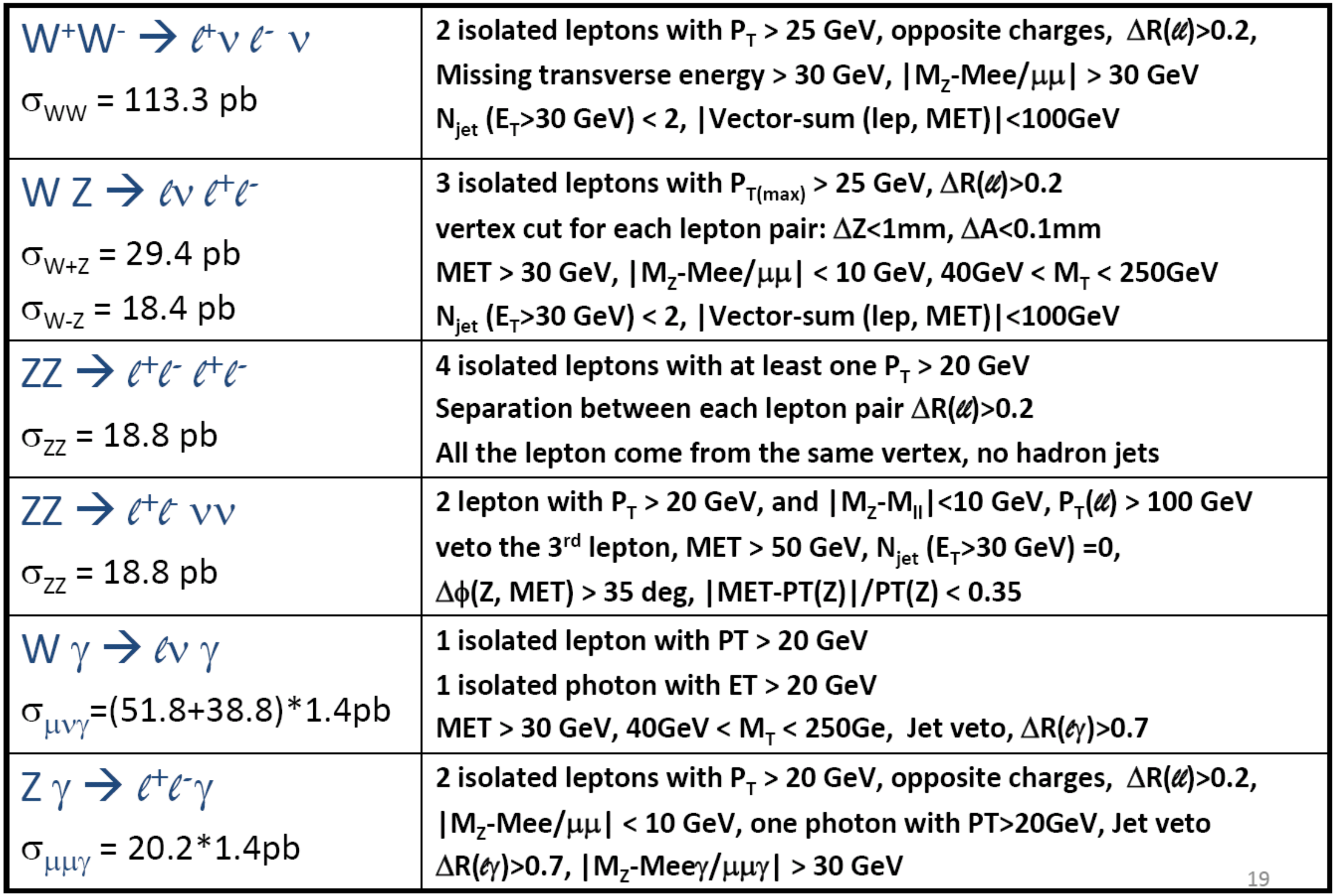
High p_T fake leptons

Understanding the fake high pT leptons is the key for new physics discovery in the TeV energy scale.



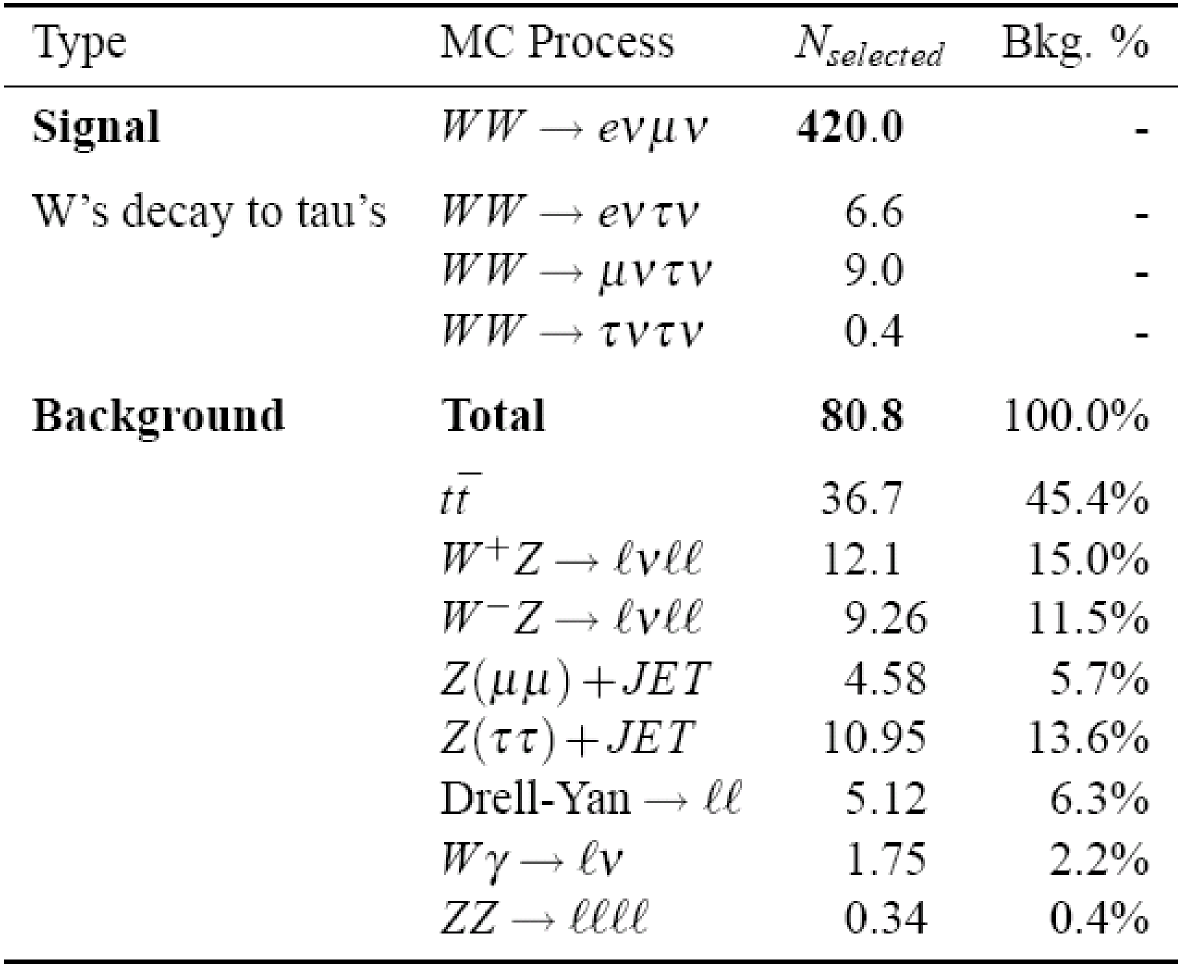
For pT > 500 GeV **fake muon rate ~ 10^{-5}**

ATLAS diboson analysis



$W^+W^- \rightarrow \ell^+\nu\ \ell^-\ \nu$ σ_{WW} = 113.3 pb	2 isolated leptons with $P_T > 25$ GeV, opposite charges, $\Delta R(\ell\ell)>0.2$, Missing transverse energy > 30 GeV, $\lvert M_Z\text{-}Mee/\mu\mu \rvert > 30$ 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: $\Delta Z<1$mm, $\Delta A<0.1$mm MET > 30 GeV, $\lvert M_Z\text{-}Mee/\mu\mu \rvert < 10$ GeV, 40GeV < M_T < 250GeV N_{jet} (E_T>30 GeV) < 2, |Vector-sum (lep, MET)|<100GeV
$ZZ \rightarrow \ell^+\ell^-\ \ell^+\ell^-$ 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 $\lvert M_Z\text{-}M_{ll} \rvert<10$ 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 < 250Ge, 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, $\Delta R(\ell\ell)>0.2$, $\lvert M_Z\text{-}Mee/\mu\mu \rvert < 10$ GeV, one photon with PT>20GeV, Jet veto $\Delta R(\ell\gamma)>0.7$, $\lvert M_Z\text{-}Mee\gamma/\mu\mu\gamma \rvert > 30$ GeV

Signal and background contamination for WW eμνν

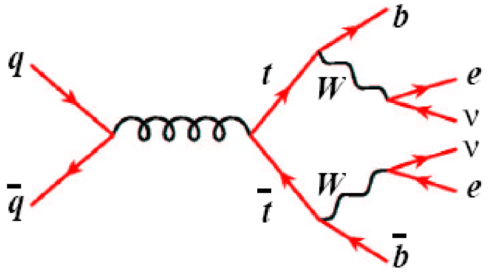


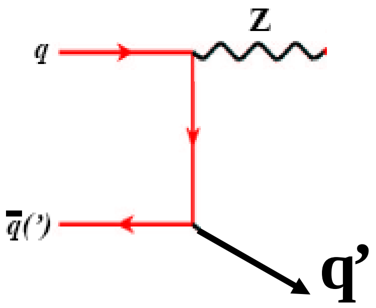
Type	MC Process	$N_{selected}$	Bkg. %
Signal	$WW \to e\nu\mu\nu$	**420.0**	-
W's decay to tau's	$WW \to e\nu\tau\nu$	6.6	-
	$WW \to \mu\nu\tau\nu$	9.0	-
	$WW \to \tau\nu\tau\nu$	0.4	-
Background	**Total**	**80.8**	100.0%
	$t\bar{t}$	36.7	45.4%
	$W^+Z \to \ell\nu\ell\ell$	12.1	15.0%
	$W^-Z \to \ell\nu\ell\ell$	9.26	11.5%
	$Z(\mu\mu)+JET$	4.58	5.7%
	$Z(\tau\tau)+JET$	10.95	13.6%
	Drell-Yan $\to \ell\ell$	5.12	6.3%
	$W\gamma \to \ell\nu$	1.75	2.2%
	$ZZ \to \ell\ell\ell\ell$	0.34	0.4%

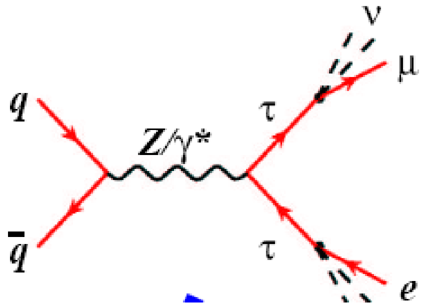
Backgrounds to WZ

Major backgrounds,

- pp tt (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/ ee, mm (12.4%)
  - Fake missing E_T and third lepton
- pp ZZ 4 leptons (47.8%)
  - Lose a lepton







Diboson sensitivity with 1 fb^{-1} int. lum.

Diboson mode	Signal	Background	S/√B	Analysis
W^+W^- $e^+\nu e^-\nu$	78.0±1.6	35.4±3.6	13	BDT (=20.5%)
W^+W^- $\mu^+\nu\mu^-\nu$	90.3±1.6	20.2±2.8	20	BDT (**=15.5%)**
W^+W^- $e^+\nu\mu^-\nu$	419.9±3.5	80.8±6.0	47	BDT (=39.6%)
W^+W^- $l^+\nu l^-\nu$	104.4±2.4	19.3±2.4	24	Straight cuts
W Z $l\nu\ l^+l^-$	152.6±1.7	16.1±2.5	38	BDT (=65.1%)
	53.4±1.6	6.7±1.2	20	Straight cuts
ZZ 4l	16.5±0.14	1.90±0.2	7.6	Straight cuts
ZZ $l^+l^-\ \nu\nu$	10.2±0.2	5.2±2.6	4.5	Straight cuts
W γ $e\nu\ \gamma$	2462±61	1134±34	73	BDT (**=67%)**
W γ $\mu\nu\ \gamma$	3855±77	1783±42	91	BDT (**=67%)**
Z γ $e^+e^-\ \gamma$	374±17	144±13	31	BDT (**=67%)**
Z γ $\mu^+\mu^-\ \gamma$	827±25	359±19	44	BDT (**=67%)**

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}.

Search for new physics through anomalous TGCs

Model independent effective Lagrangian with anomalous couplings

$$L_{WWV}/g_{WWV} = ig_1^V(W^\dagger \; W V \; - W^\dagger \; V W \;)$$
$$+ i \; _V W^\dagger W V \; + i(\; _V/M_W^2) \, W^\dagger \; W \; V$$

where V = Z, .

In the standard model $g_1^V = \; _V = 1$ and $\; _V = 0$.

The goal is to measure these values, usually expressed as the five anomalous parameters g_1^Z, $\; _Z$, $\; _Z$, , and

In many cases the terms have an ŝ dependence which means the higher center-of-mass energies at the LHC greatly enhance our sensitivity to anomalous couplings

Complementary studies through different diboson channels

Production	$_Z$, term	g_1^Z term	$_Z$, term
WW	grow as ŝ	grow as $ŝ^{½}$	grow as ŝ
WZ	grow as $ŝ^{½}$	grow as ŝ	grow as ŝ
Wγ	grow as $ŝ^{½}$	---	grow as ŝ

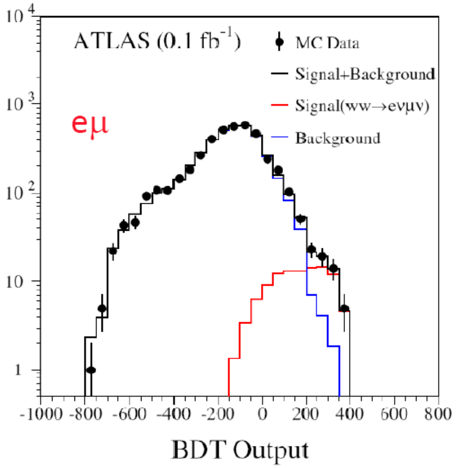
Probing anomalous TGCs in ATLAS

To probe the anomalous couplings we need a model of the kinematic distributions for various couplings. To do this we use

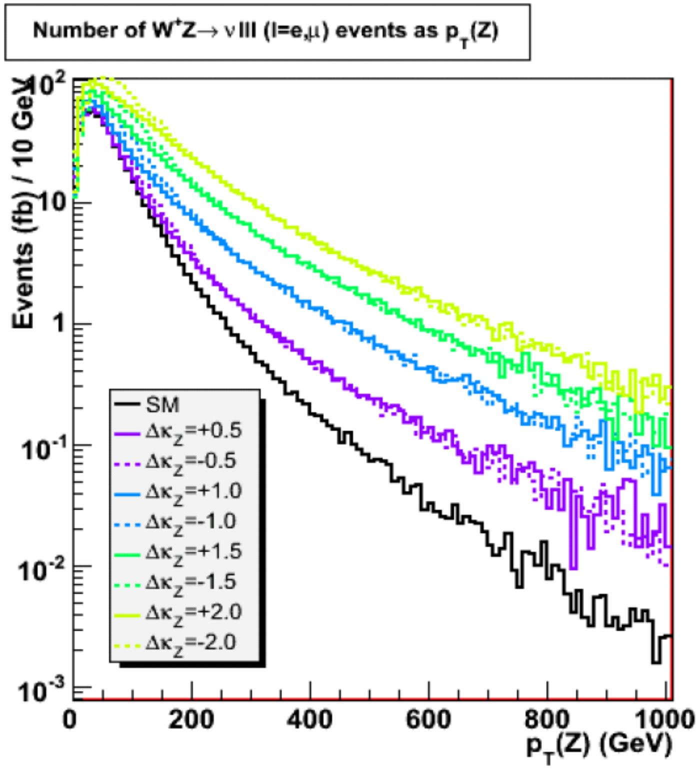
- NLO generators
    - MC@NLO produces events that are fully simulated in ATLAS
    - BHO MC is used to generate events with anomalous couplings
- Reweighting
    - Using kinematic distributions from BHO we reweight the fully simulated MC@NLO events to produce expected distributions for a range of anomalous couplings.

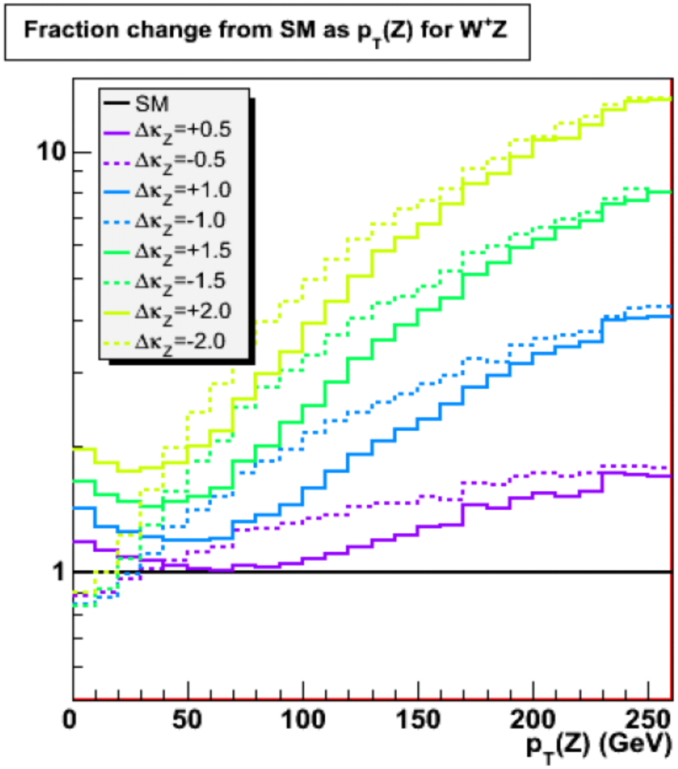
Boosted decision tree selection

A multivariate event selection method that is very effective, stable, and relatively transparent.



Anomalous spectra and reweighting ratio



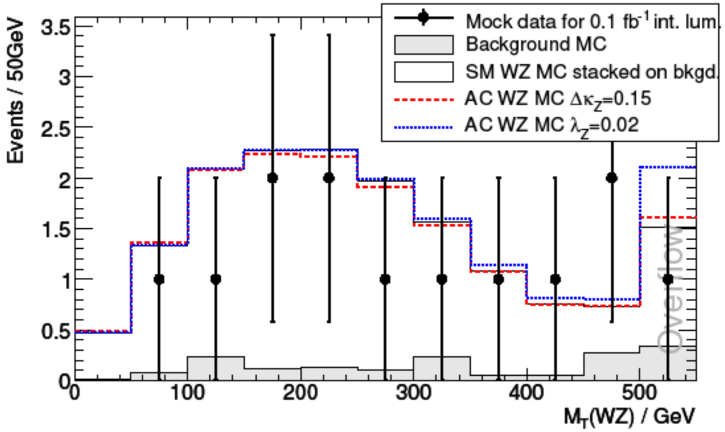


Deviations of the P_T(Z) spectrum for W$^+$Z events with anomalous $_Z$ using the BHO Monte Carlo.

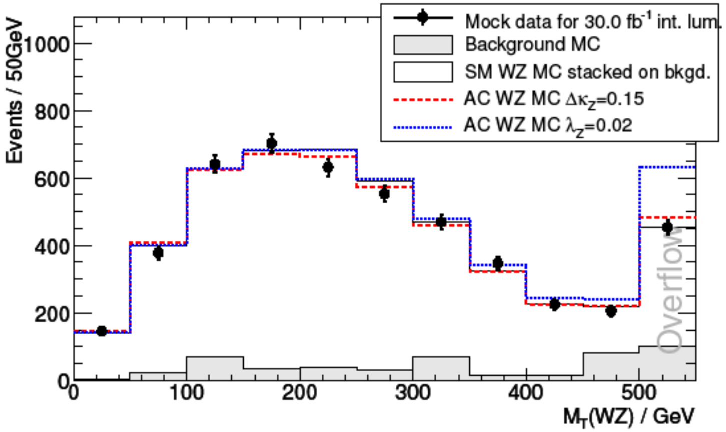
At right are the values used to weight fully simulated events.

M_T(WZ) spectrum sensitive to WWZ couplings

0.1 fb^{-1}



30 fb^{-1}

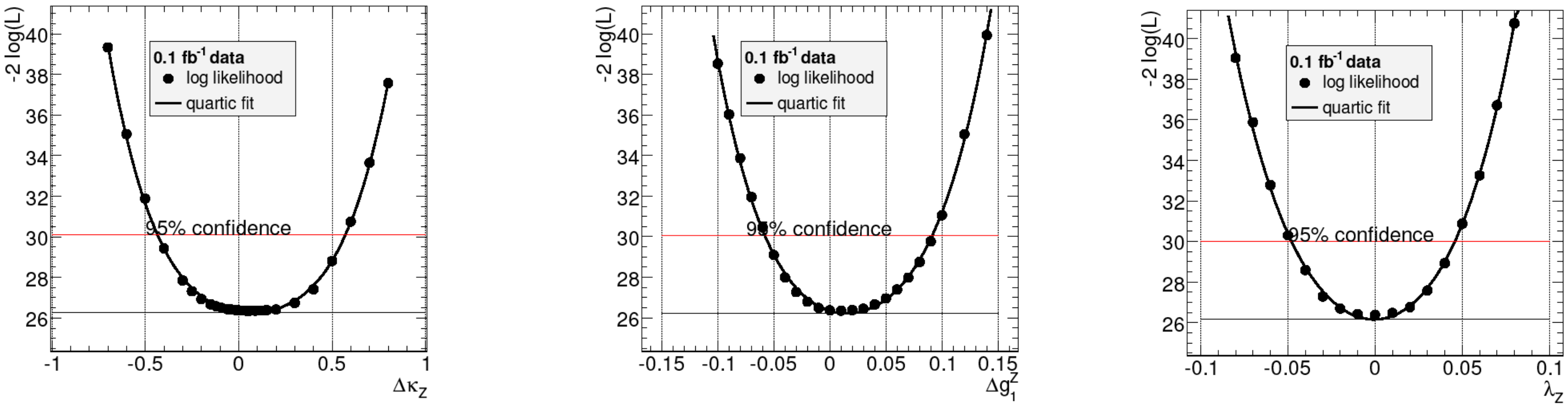


Binned likelihood comparing mock SM observations to a SM profile and two reweighted anomalous profiles

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 $M_T(WZ)$ with $0.1 fb^{-1}$ integrated luminosity



One parameter limits (assuming other couplings are SM)

$-0.4 < \quad {}_Z < 0.6$

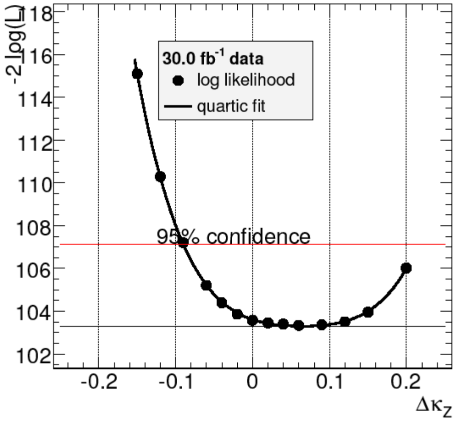
$-0.06 < \quad g_1^Z < 0.1$

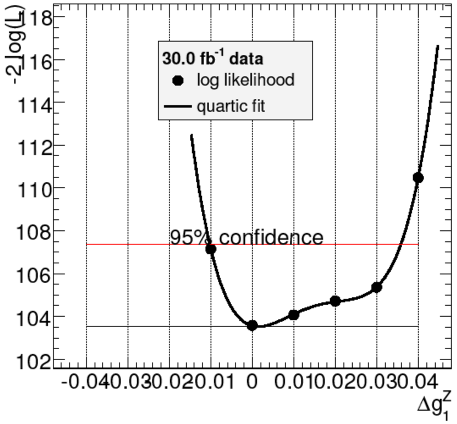
$-0.06 < \quad {}_Z < 0.05$

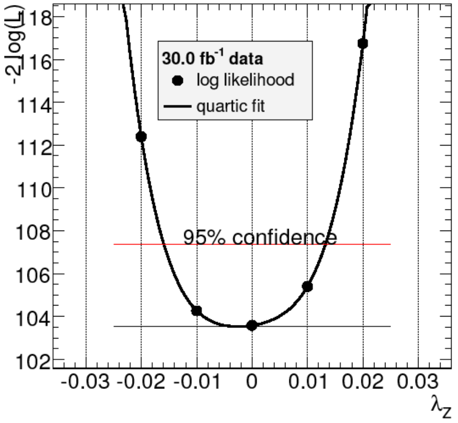
Tevatron results

$-0.12 < \Delta\kappa_z < 0.29$	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}
$-0.13 < \lambda_z < 0.14$		

TGC sensitivity using M_T(WZ) with 30fb^{-1} integrated luminosity





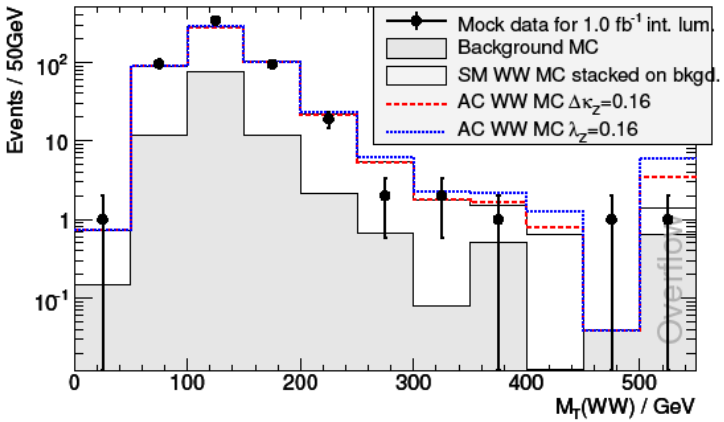


One parameter limits (assuming other couplings are SM)

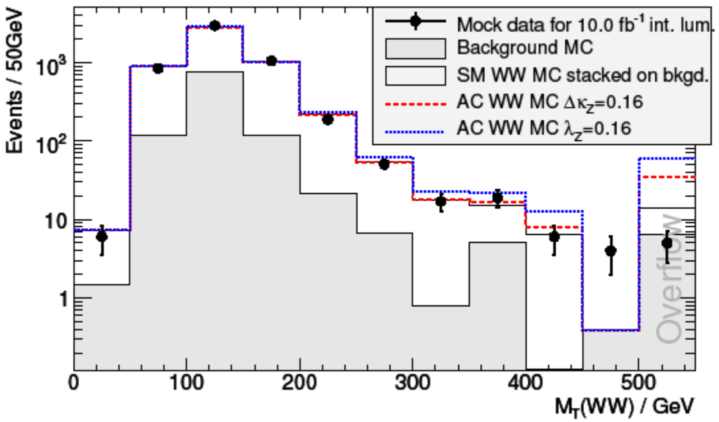
Λ=2 TeV	Λ=3 TeV
$-0.08 < \quad_Z < 0.17$	$-0.07 < \quad_Z < 0.13$
$-0.01 < \quad g_1^Z < 0.008$	$-0.003 < \quad g_1^Z < 0.018$
$-0.005 < \quad_Z < 0.023$	$-0.008 < \quad_Z < 0.005$

M_T(WW) sensitive to WWZ & WW couplings

1 fb^{-1}



10 fb^{-1}

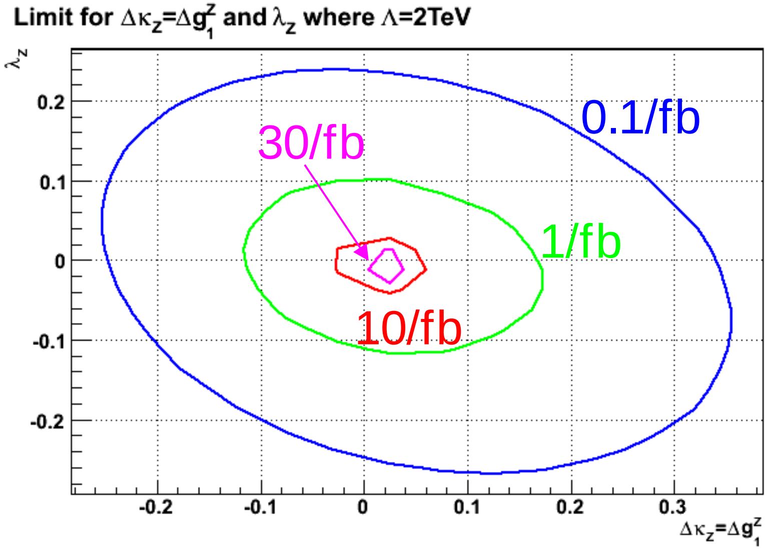


Binned likelihood comparing mock SM observations to a SM profile and two reweighted anomalous profiles

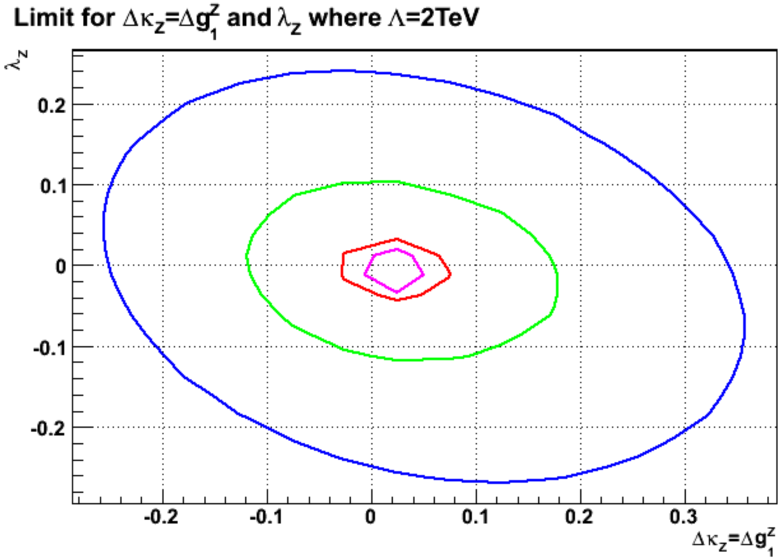
Using 10 bins from 0-500GeV and one overflow bin.

In addition, the three decay channels, ee, e , and , are binned separately for a total of 33 bins.

Systematic Error Effect on TGCs
2D Limits,   =2TeV, using P_T(Z)



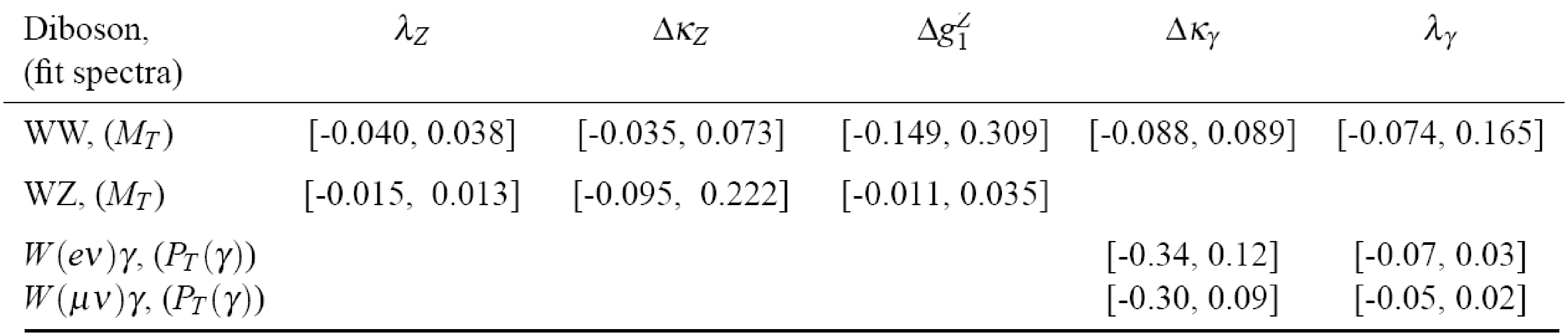
No systematic errors



9.2% signal, 18.3% background

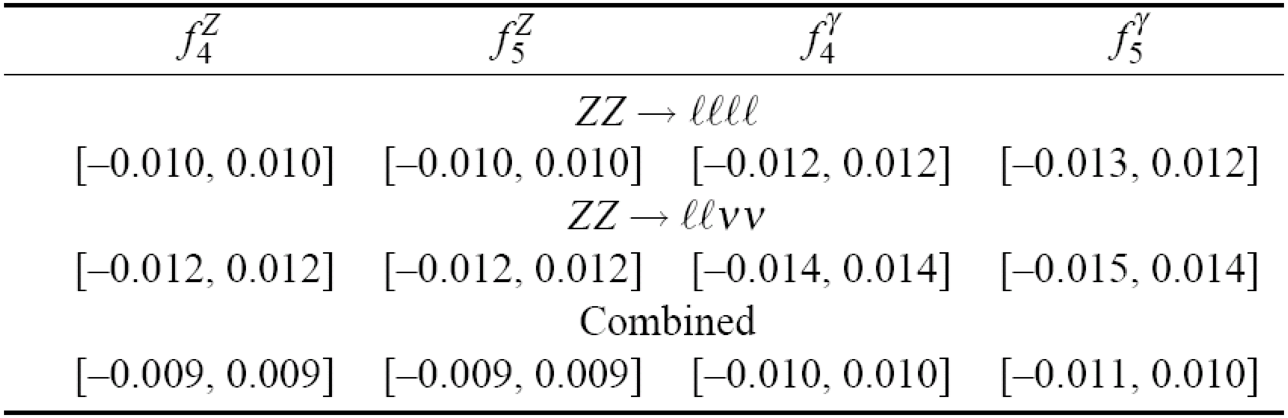
Altas TGC sensitivity for the first 10 fb^{-1}

95% CL intervals for anomalous charged TGCs



Diboson, (fit spectra)	λ_Z	$\Delta\kappa_Z$	Δg_1^Z	$\Delta\kappa_\gamma$	λ_γ
WW, (M_T)	[-0.040, 0.038]	[-0.035, 0.073]	[-0.149, 0.309]	[-0.088, 0.089]	[-0.074, 0.165]
WZ, (M_T)	[-0.015, 0.013]	[-0.095, 0.222]	[-0.011, 0.035]		
$W(e\nu)\gamma$, $(P_T(\gamma))$				[-0.34, 0.12]	[-0.07, 0.03]
$W(\mu\nu)\gamma$, $(P_T(\gamma))$				[-0.30, 0.09]	[-0.05, 0.02]

95% CL intervals for anomalous neutral TGCs



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]

Conclusion

Dibosons are key to understanding the EW symmetry breaking mechanism.

Direct and indirect searches for new physics can be performed with diboson final states.

ATLAS detector can establish the SM diboson signal with the first 100 pb^{-1}, which serves as a stepping stone to discovering new physics.

With 30 fb^{-1} the anomalous couplings will be probed with at least an order of magnitude better sensitivity over Tevatron and LEP.

Additional slides

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

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

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

Boosted decision trees (BDT)

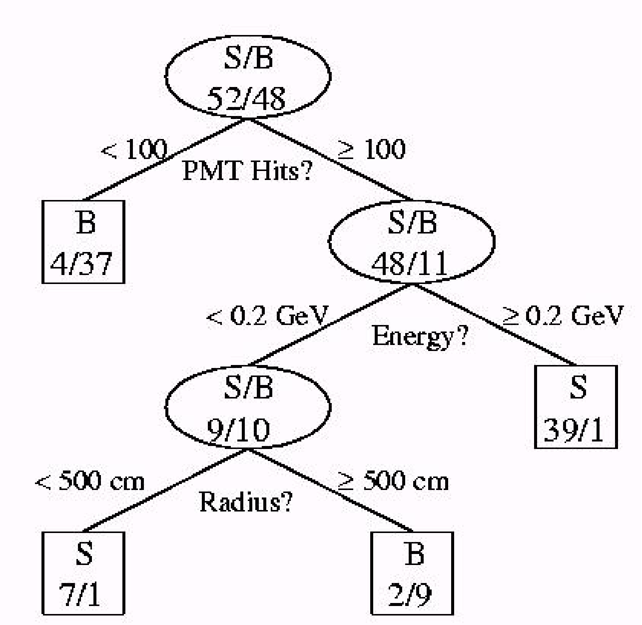
Split sample in half, one for training, one for test.

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.



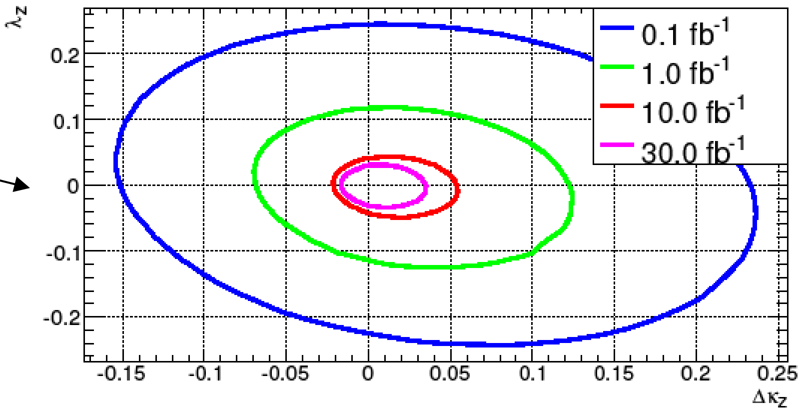
One decision tree

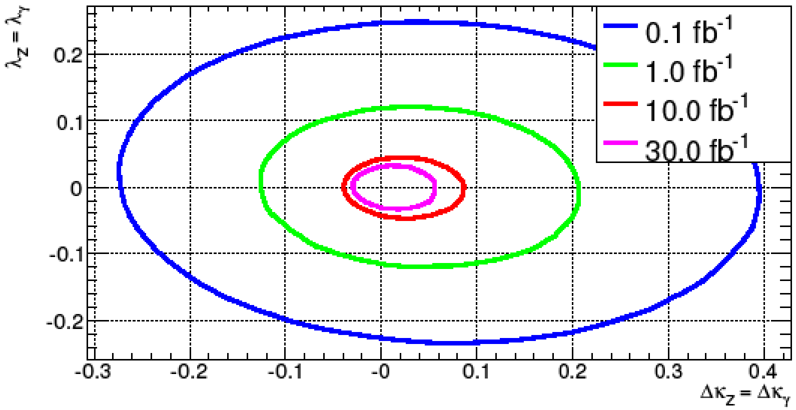
2D anomalous TGC sensitivity using M_T(WW)

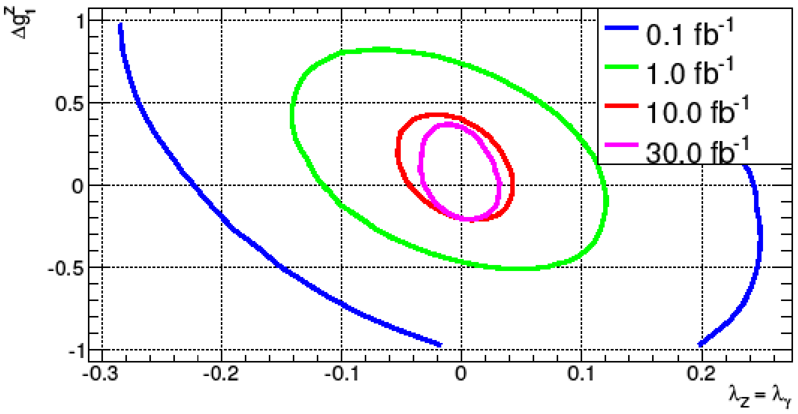
95% confidence contours for 0.1, 1, 10, and 30 fb^{-1} integrated luminosity

Right: HISZ assumption (2 parameters)

Bottom: “Standard” assumption,
Z param. =   param. (3 parameters)







Details can be found in the ATLAS Diboson CSC note

ATLAS CSC NOTE

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Diboson Physics Studies With the ATLAS Detector

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Abstract

We present studies of the Standard Model (SM) diboson (W^+W^-, $W^\pm Z^0$, Z^0Z^0, $W^\pm\gamma$, and $Z^0\gamma$) productions in pp collisions at $\sqrt{s} = 14$ TeV, through their leptonic decay channels with electron, muon and photon final states. Our studies use the ATLAS CSC (Computer-System-Commissioning) datasets, which include the trigger information and the detector calibration and alignment corrections. We aim to establish the SM diboson detection sensitivities with the ATLAS experiment in early LHC physics runs (for 0.1 to 1 fb^{-1} integrated luminosities). We have included large fully simulated background events in our studies to understand the sources of background for diboson detection. We estimate the cross section measurements uncertainties (both statistic and systematic) as a function of integrated luminosity (from 0.1 to 30 fb^{-1}) and to establish the ATLAS experiment sensitivities to anomalous triple gauge boson couplings. This note shows that the SM W^+W^-, $W^\pm Z^0$, $W^\pm\gamma$, $Z^0\gamma$ signals can be established with the signal statistical sensitivity better than 5σ for the first 0.1 fb^{-1} integrated luminosity, and the Z^0Z^0 signals can be established with 1.0 fb^{-1} integrated luminosity with ATLAS detector. The anomalous triple gauge boson coupling sensitivities can be significantly improved even with 0.1 fb^{-1} data over the results from Tevatron based on 1 fb^{-1} data.