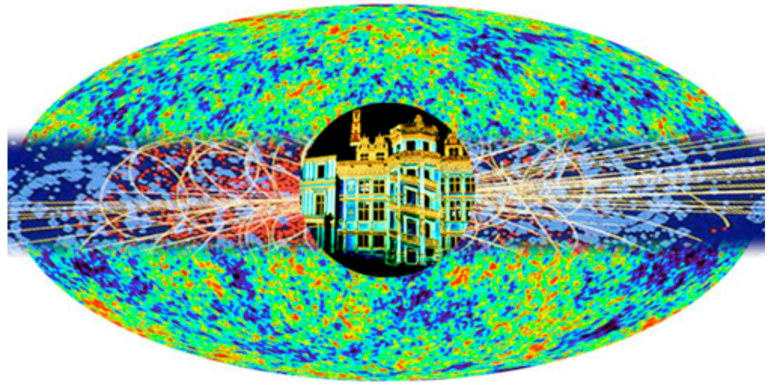
Gauge Couplings at the LHC



22nd Rencontres de Blois

Château Royal de Blois, July15th-20th, 2010

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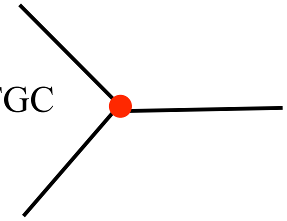
Academia Sinica

On behalf of the ATLAS and CMS Collaborations

Gauge Couplings

- In Standard Model (SM) non-abelian nature of $SU(2)_L \times U(1)_Y$ allow gauge bosons to interact with one another



  - Coupling between 3 gauge bosons $\Rightarrow$ Triple Gauge-Boson Coupling (TGC)

- SM only allows charged coupling (WWZ,WWγ), does not allow pure neutral coupling (ZZZ, ZZγ, Z$\gamma\gamma$, $\gamma\gamma\gamma$) since Z/γ has no charge nor weak isospin

- Physics beyond SM can introduce anomalous TGC which may allow neutral couplings, or increased the charged TGC coupling strength

- Effective Lagrangians which characterized the charged and neutral TGC, introduced a few anomalous coupling parameters (assuming C,P symmetry conservation and QED gauge invariance)

Charged TGC:

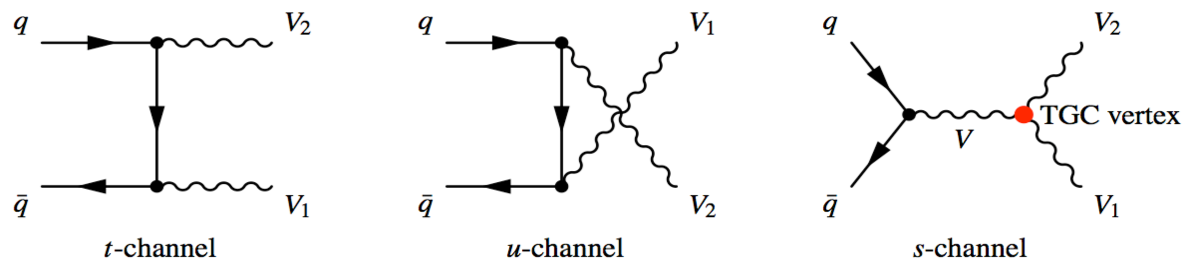
- λ_γ , λ_Z
- $\Delta\kappa_\gamma = \kappa_\gamma - 1$, $\Delta\kappa_Z = \kappa_Z - 1$, $\Delta g^Z_1 = g^Z_1 - 1$
- SM at tree level: $\lambda_\gamma = \lambda_Z = \Delta\kappa_\gamma = \Delta\kappa_Z = \Delta g^Z_1 = 0$

Neutral TGC:

- f^Z_4 , f^Z_5 , f^γ_4 , f^γ_5
- SM at tree level: $f^Z_4 = f^Z_5 = f^\gamma_4 = f^\gamma_5 = 0$

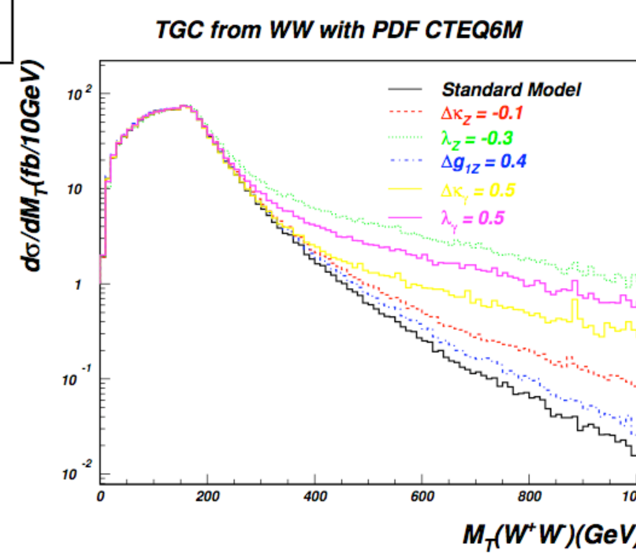
Diboson at LHC

- At the LHC one can study TGC through the measurement of diboson production



Final State	WZ	Wγ	WW	ZZ	Zγ
SM	W± W± TGC Z	W± W± TGC γ	W+ Z/γ TGC W-		
an.TGC	W± W± TGC Z	W± W± TGC γ	W+ Z/γ TGC W-	Z γ/Z TGC Z	γ γ/Z TGC Z

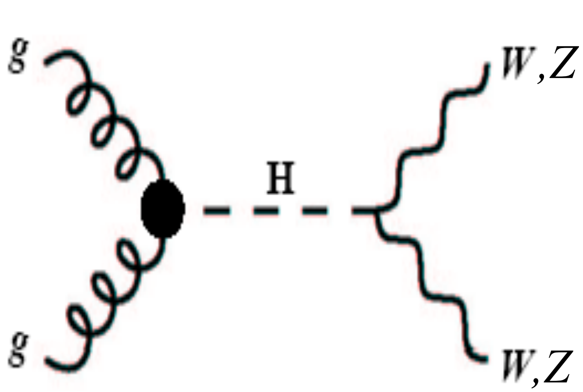
- Each diboson production can probe one or more TGC:
  - WZ : WWZ vertex
  - WW : WWZ,WWγ vertex
- Measures the anomalous coupling parameters



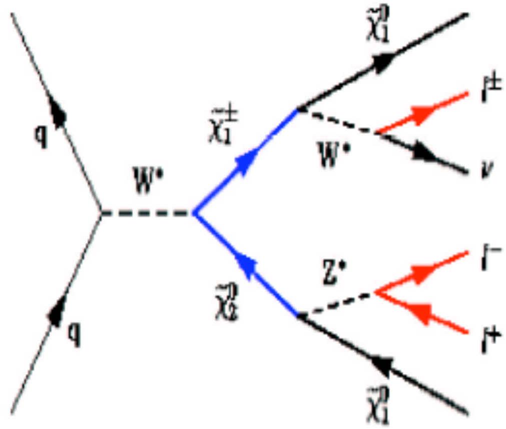
- The presence of anomalous TGC will enhance diboson production rate, particularly at high transverse momentum of bosons

Diboson and Searches

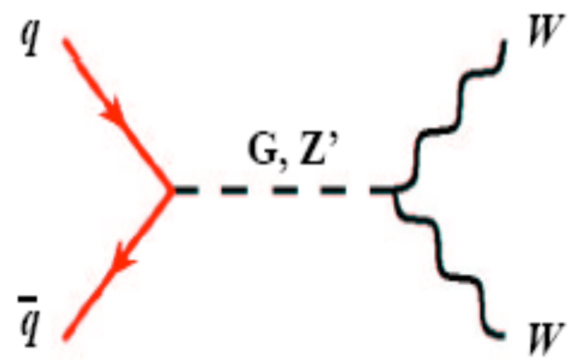
•Diboson productions are also background to other searches :



Higgs



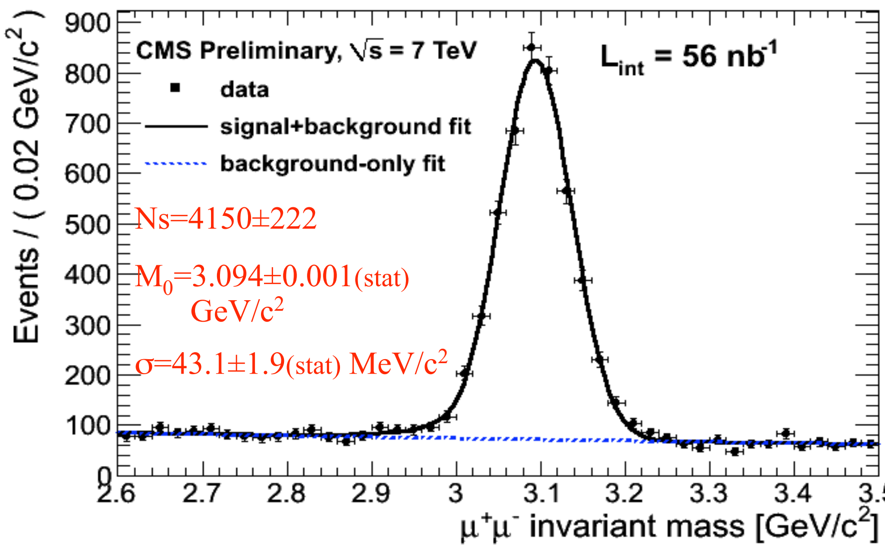
SUSY

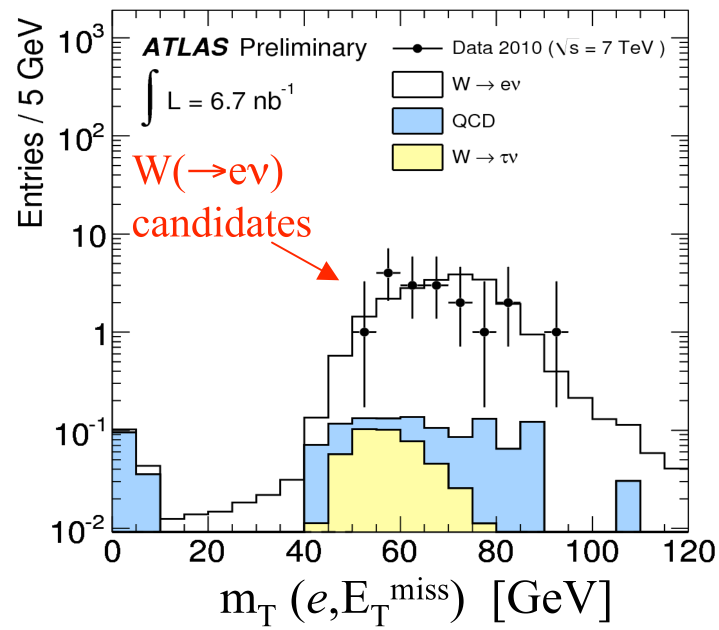


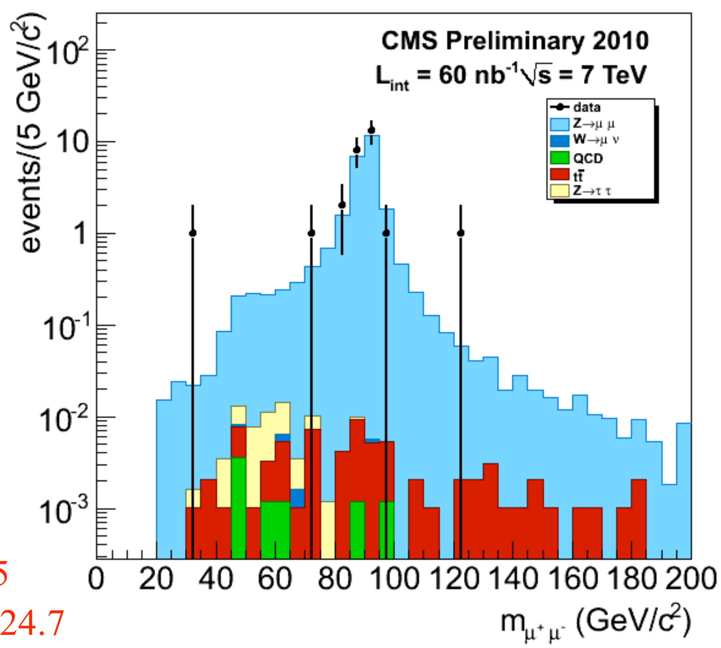
New Gauge Boson

⇒ Important to understand this production process !

Performances of ATLAS & CMS on Early LHC Data



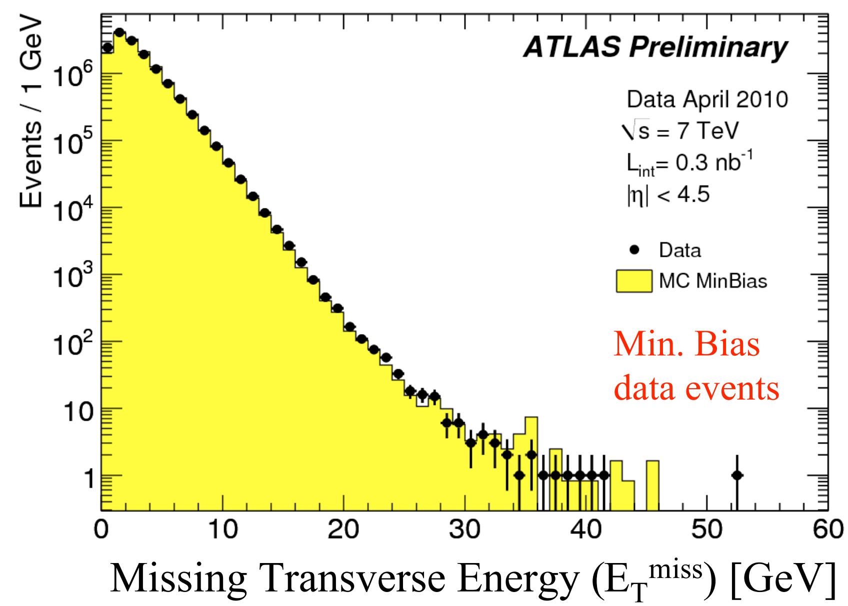




Ncand=25

Nexpect=24.7

Nbkg(expect)=0.08



Diboson Studies at the LHC

- Performed simulation studies on the sensitivity to the SM diboson production
  - Most studies were at $\sqrt{s}$=14 TeV
  - Look at leptonic decay modes of W/Z

Diboson mode	Conditions	$\sqrt{s}$=1.96 TeV $\sigma(p\bar{p})$ [pb]	$\sqrt{s}$=14 TeV $\sigma(pp)$ [pb]	$\sqrt{s}$=7 TeV $\sigma(pp)$ [pb]
W^+W^-	W-boson width included	12.4	111.6	44.8
$W^{\pm}Z$	Z and W on mass shell	3.7	47.8	23.3
ZZ	Z's on mass shell	1.43	14.8	6.0
$W^{\pm}\gamma$	E_T^{γ}>7 GeV, $\Delta R(l,\gamma)$>0.7	19.3	451	
$Z\gamma$	E_T^{γ}>7 GeV, $\Delta R(l,\gamma)$>0.7	4.74	219	

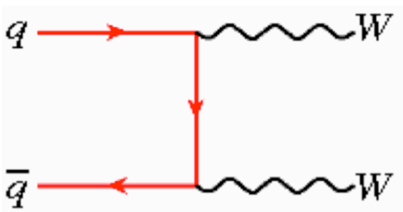
σ: for all W/Z decay modes

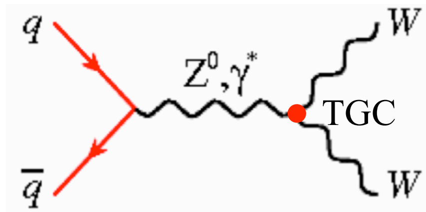
- Expect LHC sensitivity to anomalous TGC to be much better than Tevatron and LEP
  - Higher diboson production rate (>5~10X in cross section, >10X in instantaneous luminosity)
  - Higher energy reach

References :

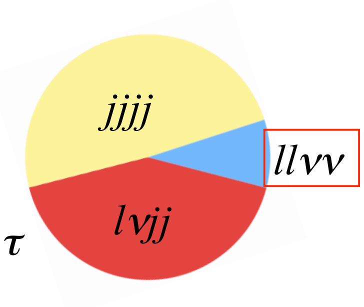
- CERN-OPEN-2008-020
- CMS PAS EWK-09-002
- CMS PAS EWK-08-003
- CMS NOTE 2006/108
- CMS NOTE CMS CR 2004/044

WW→$l\nu l\nu$



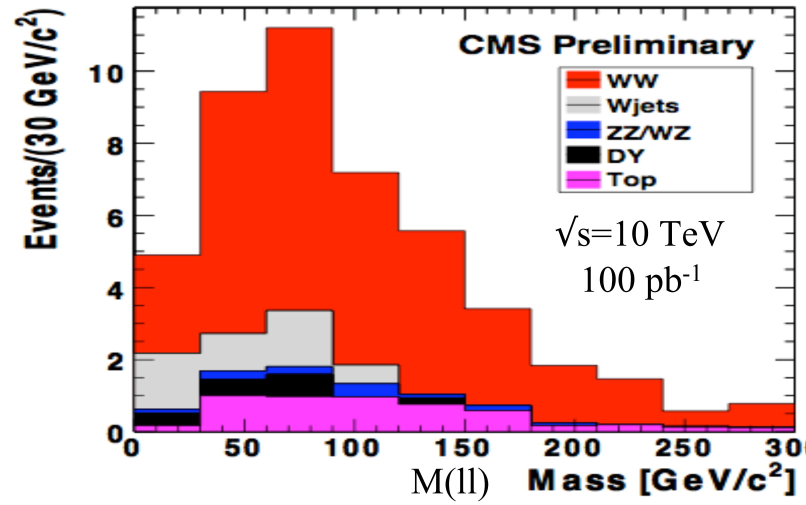


- Small BR: ~5-6% (l=e or μ)
- Clean sample

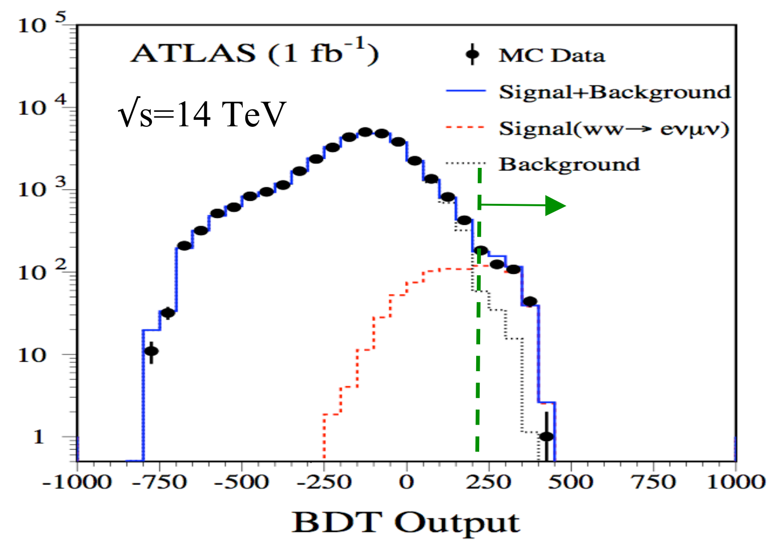


$l=e,\mu,\tau$

- Probes WWγ & WWZ TGC
- Main background from :
  - ttbar
  - W+jets
  - Drell-Yan



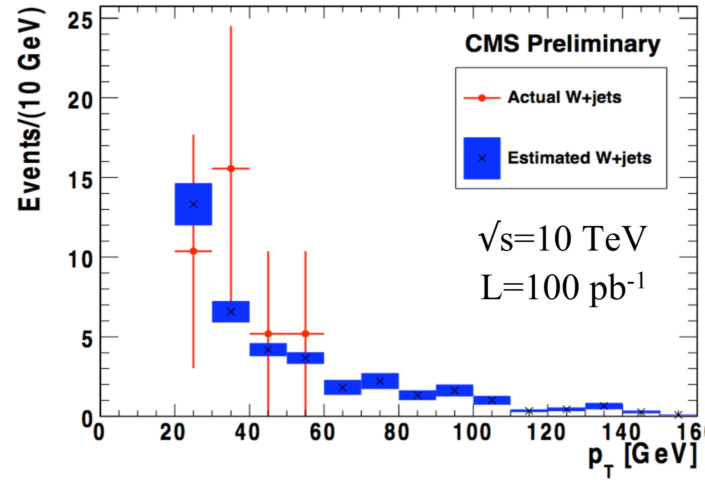
- CMS performed a cut based study
- ATLAS performed studies with:
  - cut based
  - a multivariate algorithm (Boosted Decision Tree, BDT), trained to separate signal from background. Cut on BDT output to select signal enriched region.



WW→lνlν

Background Estimation:

- Most are estimated from simulation
- CMS and ATLAS developed data-driven method to estimate some background contributions
  - E.g. measure jet faking lepton rate to predict W+jets background



Experiment	#Signal (Ns)	#Bkg (Nb)	Ns/Nb
CMS (cut based) $\sqrt{s}$=10 TeV, L=100 pb^{-1}	37.5	12.9	2.9
ATLAS (cut based) $\sqrt{s}$=14 TeV, L=1 fb^{-1}	104.4	19.3	5.4
ATLAS (BDT based) $\sqrt{s}$=14 TeV, L=1 fb^{-1}	469	92	5.1

Assume signal, background rate decrease by 2X going from 14 TeV to 7 TeV ⇒ Ns~23, Nb~4.6 @ L=0.1 fb^{-1}

- Predictions at 10,14 TeV
- Sensitivities still good at 7 TeV (signal/bkg scale down with energy), may observe clear signal with L~100 pb^{-1}

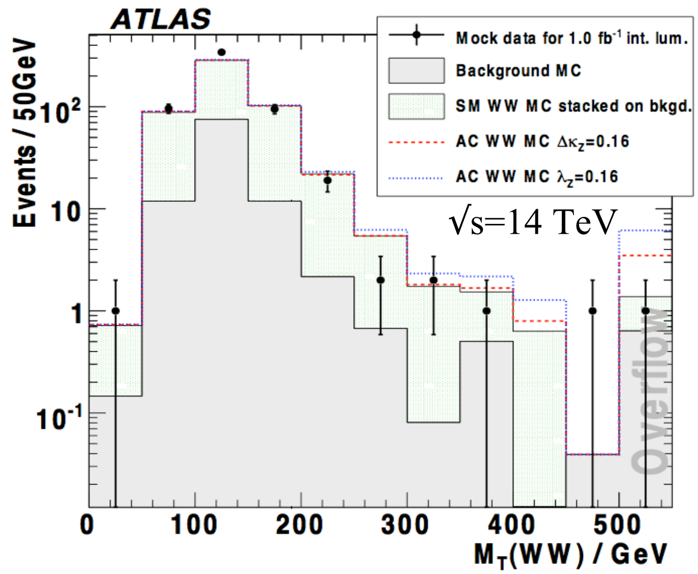
WWZ, WWγ Anomalous TGC in WW Analysis

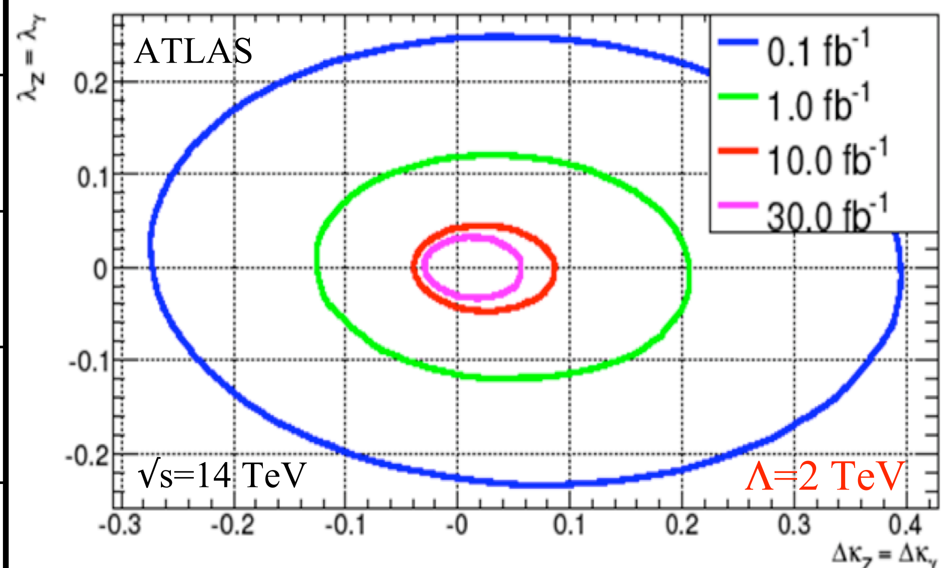
- Fit transverse mass (M_T) spectrum of WW to obtain WWZ and WWγ anomalous TGC sensitivity at 95% C.L.

- 1-D sensitivity interval :

$\int L$ (fb^{-1})	0.1	1.0	10.0	30.0
$\Delta\kappa_Z$	[-0.242 , 0.356]	[-0.117 , 0.187]	[-0.035 , 0.072]	[-0.026 , 0.048]
λ_Z	[-0.206 , 0.225]	[-0.108 , 0.111]	[-0.040 , 0.038]	[-0.028 , 0.027]
Δg^Z_1	[-0.741 , 1.177]	[-0.355 , 0.616]	[-0.149 , 0.309]	[-0.149 , 0.251]
$\Delta\kappa_\gamma$	[-0.476 , 0.512]	[-0.240 , 0.251]	[-0.088 , 0.089]	[-0.056 , 0.054]
λ_γ	[-0.564 , 0.775]	[-0.259 , 0.421]	[-0.074 , 0.165]	[-0.052 , 0.100]

Λ=2 TeV

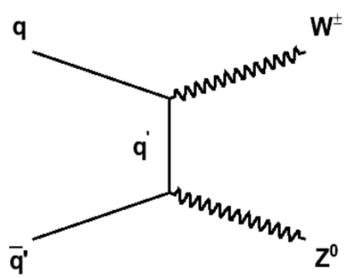


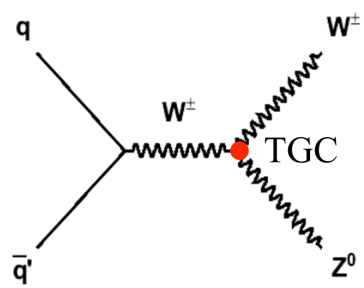


- 2-D anomalous TGC limit:

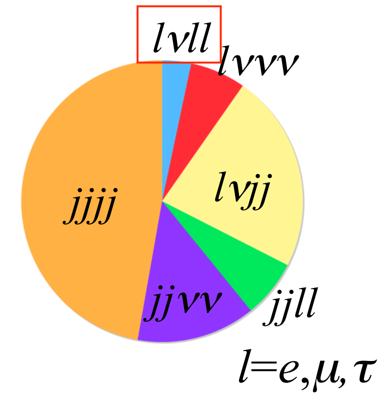
- Assume: $\lambda_Z=\lambda_\gamma$, $\Delta\kappa_Z=\Delta\kappa_\gamma$

WZ→$l\nu ll$

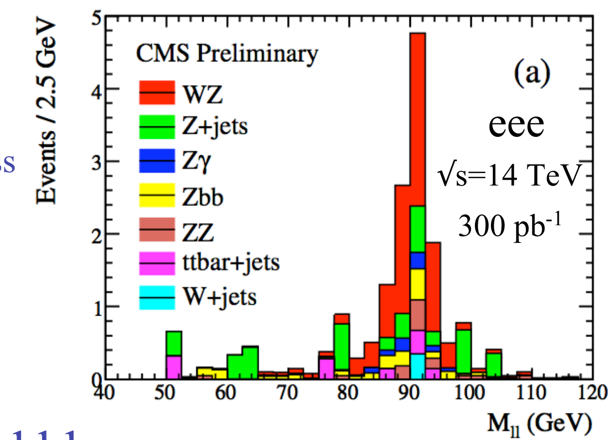


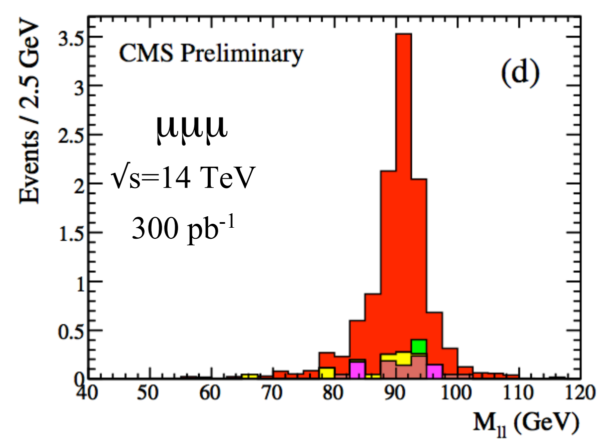


- Small BR:~2% (l=e or μ)
- Clean final state



- Probe WWZ TGC
- Select events with 3 isolated high Pt lepton and large E_T^{miss}
- Main backgrounds:
  - Z+jets, ZZ, Zγ, ttbar





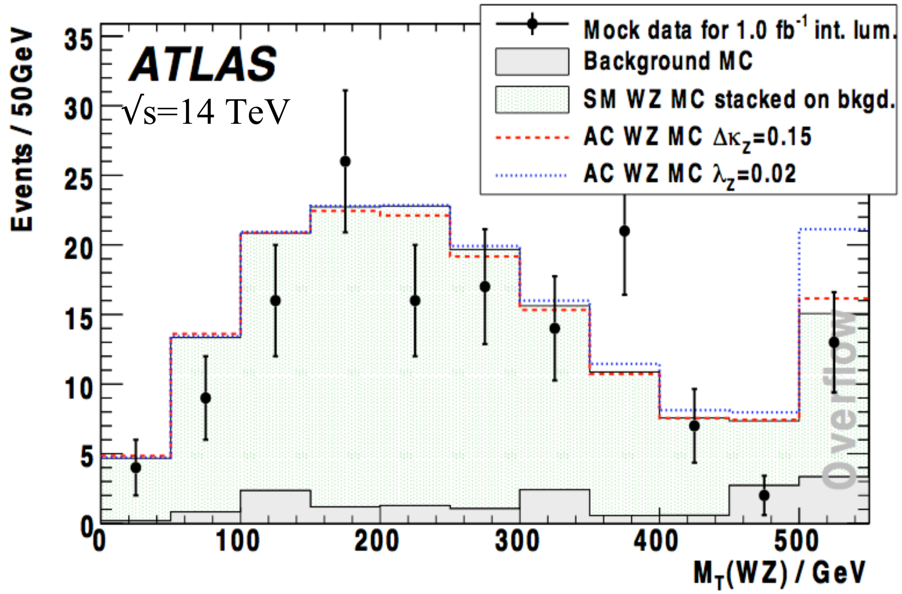
- Number of expected signal and bkg

Experiment	#Signal	#Bkg
CMS (cut based) √s=14 TeV, L=300 pb^{-1}	34.9	13.6
ATLAS (cut based) √s=14 TeV, L=1 fb^{-1}	53	7.3
ATLAS (BDT based) √s=14 TeV, L=1 fb^{-1}	128	16

- CMS: expect 5σ reach for WZ with L~ 350 pb^{-1}
- ATLAS: expect 5.9σ significant when applying BDT and with L~100 pb^{-1}

WWZ Anomalous TGC in WZ Analysis

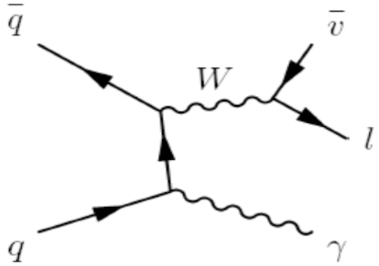
- $M_T(WZ)$ and $P_T(Z)$ spectra are fit to extract WWZ anomalous parameters at 95% C.L.

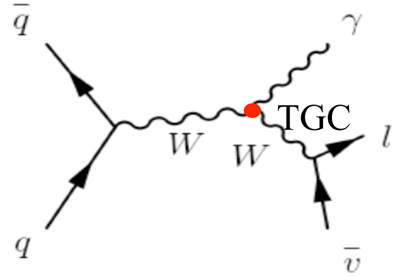


1-D sensitivity interval :

$\int L$ (fb^{-1})	0.1	1.0	10.0	30.0
$\Delta\kappa_Z$	[-0.440 , 0.609]	[-0.203 , 0.339]	[-0.095 , 0.222]	[-0.080 , 0.169]
λ_Z	[-0.062 , 0.056]	[-0.028 , 0.024]	[-0.015 , 0.013]	[-0.012 , 0.008]
Δg^Z_1	[-0.063 , 0.119]	[-0.021 , 0.054]	[-0.011 , 0.034]	[-0.005 , 0.023]

Λ=2 TeV



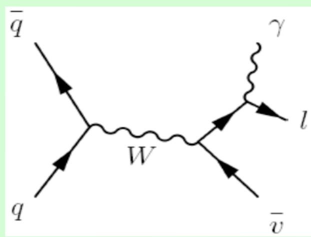


Wγ→lνγ

- Wγ measurement can probe WWγ TGC
- Events selected with 1 isolated lepton (e,μ) , 1 isolated photon, large E_T^{miss}

•Main background:

- W+jets (jet fakes as γ)
- Z+γ/jets (one lepton not Id, jet mis-Id as γ)
- W+γ (γ from FSR)



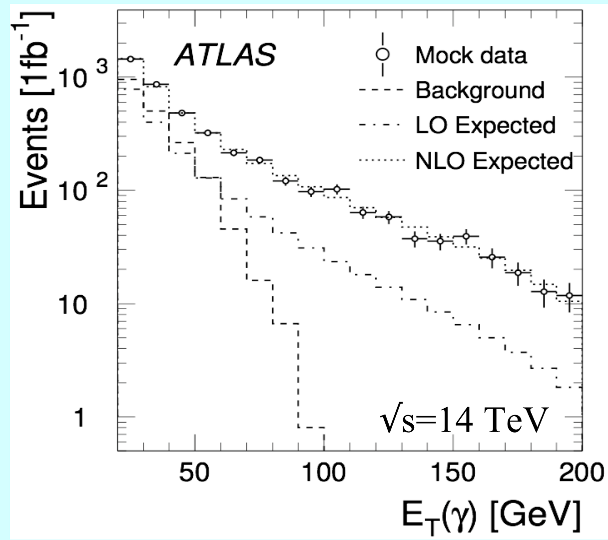
<u>ATLAS:</u>

- Train BDT to discriminate Wγ signal from background

√s=14 TeV, L=1 fb^{-1}	#signal	#bkg
$l = e$	1604	1183
$l = \mu$	2166	1342

Still can achieve S/√B>~10 at √s=7 TeV, for L=0.1 fb^{-1}, if assume signal and background scale by ~0.5 going from √s=14 TeV to 7 TeV

WWγ Anomalous TGC

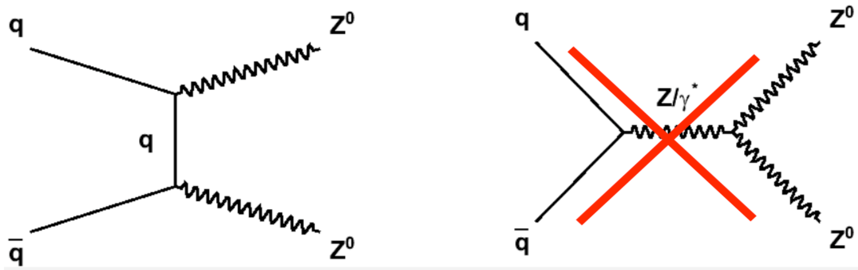


- $E_T(\gamma)$ distribution to determine WWγ anomalous parameters at 95% C.L.

(ATLAS, √s=14 TeV, Λ=2 TeV)

	$W(\ell\nu)\gamma$		
	1 fb^{-1}	10 fb^{-1}	30 fb^{-1}
λ_γ	[-0.09, 0.04]	[-0.05, 0.02]	[-0.02,0.01]
$\Delta\kappa_\gamma$	[-0.43, 0.20]	[-0.26, 0.07]	[-0.11,0.05]

ZZ→llll, ννll



- *llll* : BR ~ 0.5%
- *ννll* : BR ~ 3%
- ZZZ and ZZγ couplings forbidden in SM

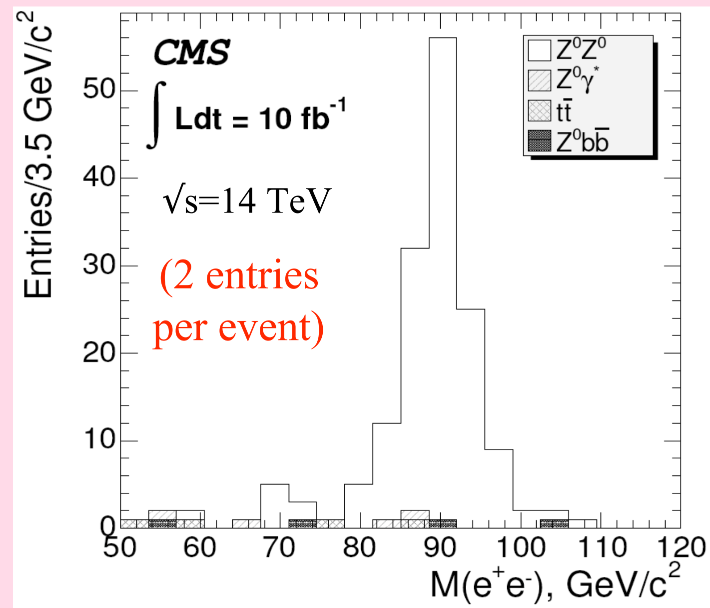
ZZ→llll :

- Require 2 pairs of opposite charged isolated leptons of same flavor
- ATLAS considers : *eeee, eeμμ, μμμμ*
- CMS considers : *eeee* in the study (will also include muon channel in measurement)

(ZZ→llll)

√s=14 TeV, L=1 fb^{-1}	#signal	#bkg
CMS	7.1	0.36
ATLAS	13.3	0.2

Clear signal with 1 fb^{-1} of data !

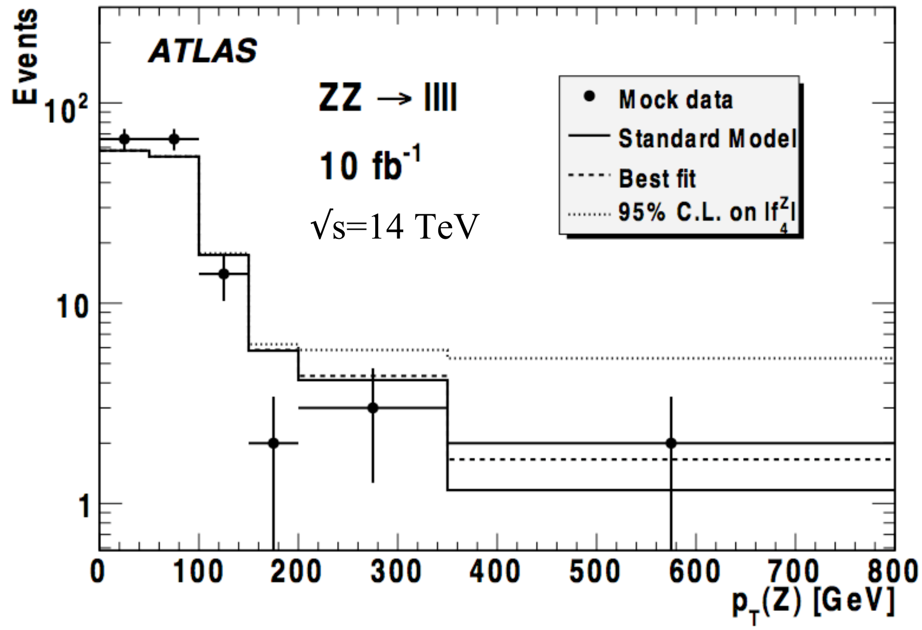


ZZ→ννll :

- ATLAS expects (@ 1 fb^{-1}) :
  - #signal = 10.2 , #bkg = 5.2

ZZZ and ZZγ Anomalous TGC in ZZ Analysis

- ZZZ and ZZγ anomalous parameters are extracted from fit to $P_T(Z)$ distribution



- Expected 95% C.L. intervals :

	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]

L=10 fb^{-1} , Λ=2 TeV

Anomalous TGC from LHC and Other Experiments

- Anomalous TGC limits at 95% C.L.
- Λ=2 TeV
- ATLAS : $\sqrt{s}$ = 14 TeV, L = 10 fb^{-1}

Diboson	Assumption	λ_Z	$\Delta\kappa_Z$	Δg^Z_1	$\Delta\kappa_\gamma$	λ_γ
WZ(ATLAS)		[-0.015,0.013]	[-0.095,0.222]	[-0.011,0.034]		
Wγ(ATLAS)					[0.26,0.07]	[-0.05,0.02]
WW(ATLAS)		[-0.040,0.038]	[-0.035,0.073]	[-0.149,0.309]	[-0.088,0.089]	[-0.074,0.165]
WZ (D0, 1 fb^{-1})	($\Delta g^Z_1 = \Delta\kappa_Z$)	[-0.017,0.21]	[-0.12,0.29]			
WW+Wγ+WZ (D0, 1 fb^{-1})	($\lambda_\gamma = \lambda_Z$, $\Delta\kappa_Z = \Delta g^Z_1 - \Delta\kappa_\gamma * \tan^2\theta_W$)			[-0.07,0.16]	[-0.29,0.38]	[-0.08,0.08]
WW (CDF, 3.6 fb^{-1})	($\lambda_\gamma = \lambda_Z$, $\Delta\kappa_Z = \Delta g^Z_1 - \Delta\kappa_\gamma * \tan^2\theta_W$)			[-0.22,0.30]	[-0.57,0.65]	[-0.14,0.15]
WW (LEP)	($\lambda_\gamma = \lambda_Z$, $\Delta\kappa_Z = \Delta g^Z_1 - \Delta\kappa_\gamma * \tan^2\theta_W$)			[-0.051,0.034]	[-0.105,0.069]	[-0.059,0.026]

- Many LHC results can be better than current best limits from Tevatron and LEP

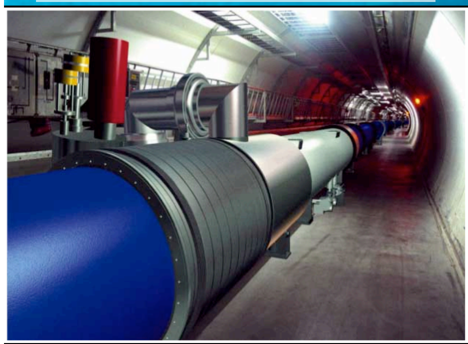
Summary

- LHC physics has started !
  - Both experiments are performing WELL !
- Perspectives for SM diboson measurements at LHC and sensitivity to anomalous TGC have been investigated
  - Although studies performed at $\sqrt{s}$=10,14 TeV, sensitivity results indicate diboson cross sections can still be measured at $\sqrt{s}$=7 TeV with low luminosity (e.g. Wγ, WW with few hundreds pb^{-1})
  - Expect limits on anomalous TGC will be much improved at LHC compared to Tevatron and LEP
- So let’s measure it *NOW* !!!

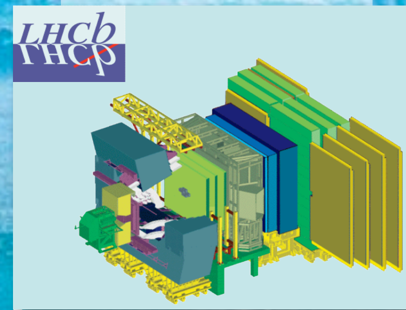
BACK UP

Large Hadron Collider (LHC)

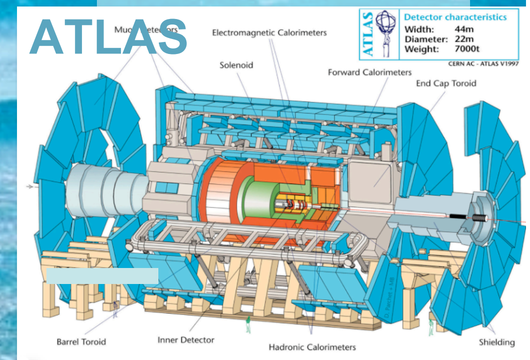
LHC : 27 km long
100m underground



pp, B-Physics,
CP Violation

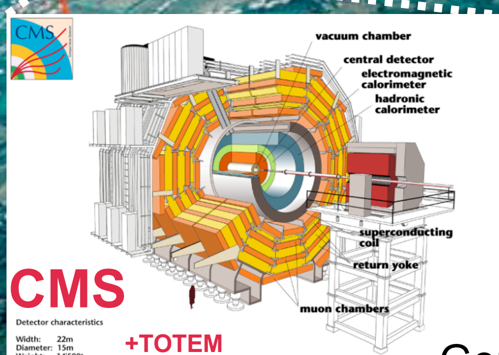


General Purpose,
pp, heavy ions



- **p-p collider**
- **Design parameters:**
  - **$\sqrt{s}$ = 14 TeV**
  - **L_{inst} = ~10^{34} cm^{-2} s^{-1}**
- **Current operation:**
  - **$\sqrt{s}$ = 10 TeV**
  - **L_{inst} = ~10^{30} cm^{-2} s^{-1}**

CERN

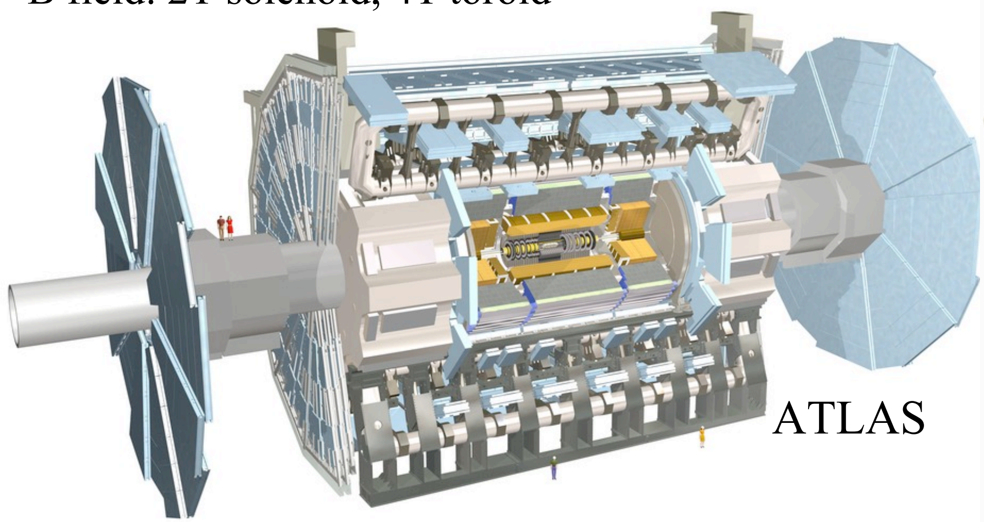


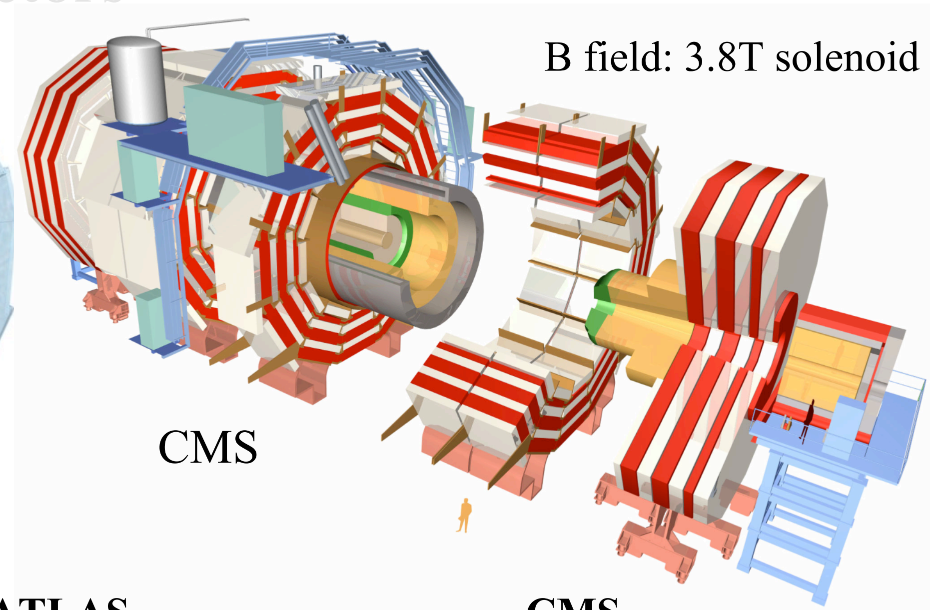
General Purpose,
pp, heavy ions

Heavy ions, pp

Detectors

B field: 2T solenoid, 4T toroid





	ATLAS	**CMS**
Inner tracker : $\|\eta\|$ coverage	2.5	2.5
$\sigma(P_T)/P_T$ at P_T=100 GeV	3.8%	1.5%
EM calorimeter: $\|\eta\|$ coverage	3.2	3.0
$\sigma(E)/E$	$10\%/\sqrt{E}+0.7\%$	$3\%/\sqrt{E}+0.5\%$
HAD calorimeter: $\|\eta\|$ coverage	4.9	5.2
$\sigma(E)/E$ (EM+HAD combined)	$50\%/\sqrt{E}+3\%$	$85\%/\sqrt{E}+7\%$
Muon system: $\|\eta\|$ coverage	2.7	2.4
$\sigma(P_T)/P_T$ at P_T=1 TeV (standalone)	12% ($\|\eta\|<1.5$)	15-40% (depend on η range)

Performances of ATLAS & CMS on Early LHC Data

ATLAS (W(eν) selection)

- ≥1 electron candidate, Et>20 GeV, |η|<2.47, (not in 1.37<|η|<1.52)
- $E_t^{miss} > 25$ GeV
- $m_T > 40$ GeV
  - $m_T = \sqrt{2 p_T^l p_T^\nu (1 - \cos(\phi^l - \phi^\nu))}$

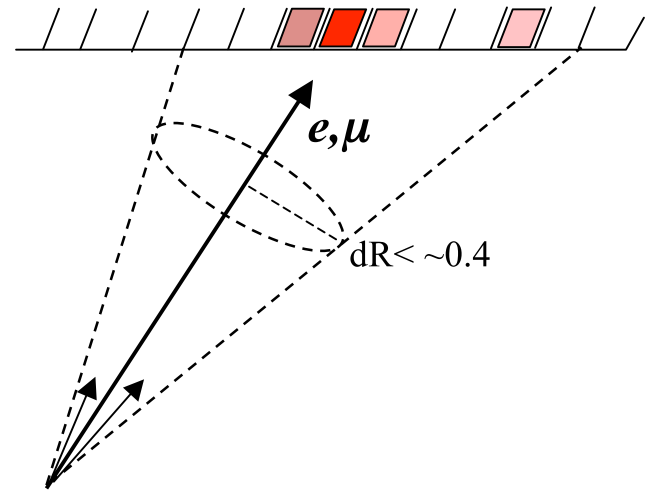
ATLAS (Missing Transverse Energy)

- Calorimeter based
- Cell energies at EM scale
- $$E_x^{miss} = -\sum_{i=1}^{N_{cell}} E_i \sin\theta_i \cos\phi_i ,$$
  $$E_y^{miss} = -\sum_{i=1}^{N_{cell}} E_i \sin\theta_i \sin\phi_i ,$$
  $$E_T^{miss} = \sqrt{(E_x^{miss})^2 + (E_y^{miss})^2} ,$$

- Remove events with bad jets
  - Jets caused by noise or by out-of-time energy deposition in calorimeter

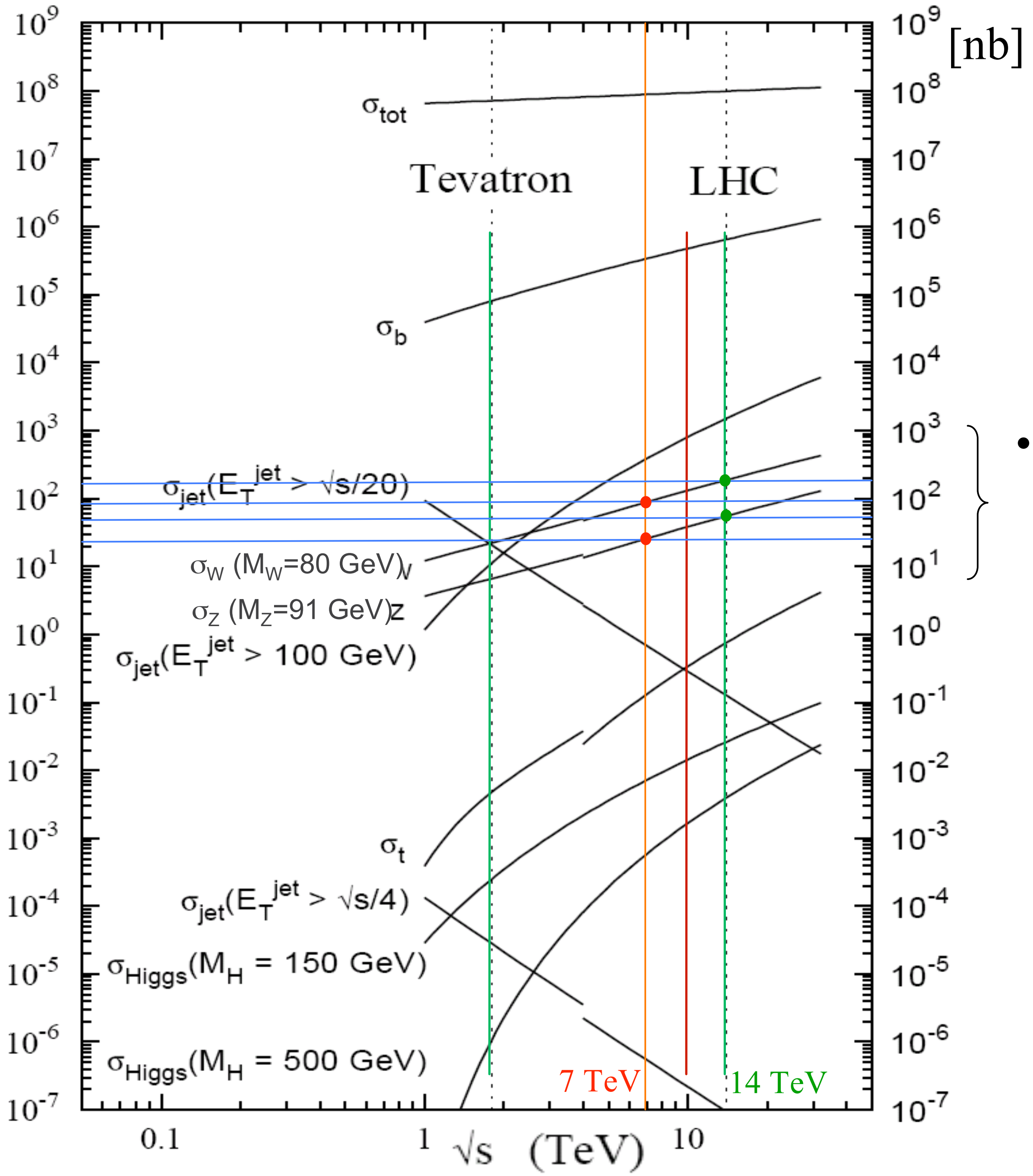
Basic Selection Criteria in Diboson Studies

- List several selection cuts common in the diboson simulation studies which focus on leptonic decays of W/Z boson



- **Lepton (*e,μ*) selection:**
  - p_T > ~20 GeV, $|\eta|<2.5$ (tracking coverage)
  - Isolated : little activity recorded in calorimeter or tracking volume surrounding lepton (reduce bkg from jet faking lepton)
- **Require large E_T^{miss} :** E_T^{miss} > ~20-50 GeV
  - Missing energy from ν in W decay
  - Cut reduce background from Drell-Yan
- **Di-lepton invariant mass :**
  - If Z boson is produced
  - Consistent with Z mass
    - ($|m_{l+l-} - m_Z| < 10$~20 GeV)
- **Jet Veto :**
  - Backgrounds with leptons and hadronic jets in final state (W+jets, Z+jets, ttbar)
  - Require no presence of jet (Et>20~30 GeV, $|\eta|<3$)

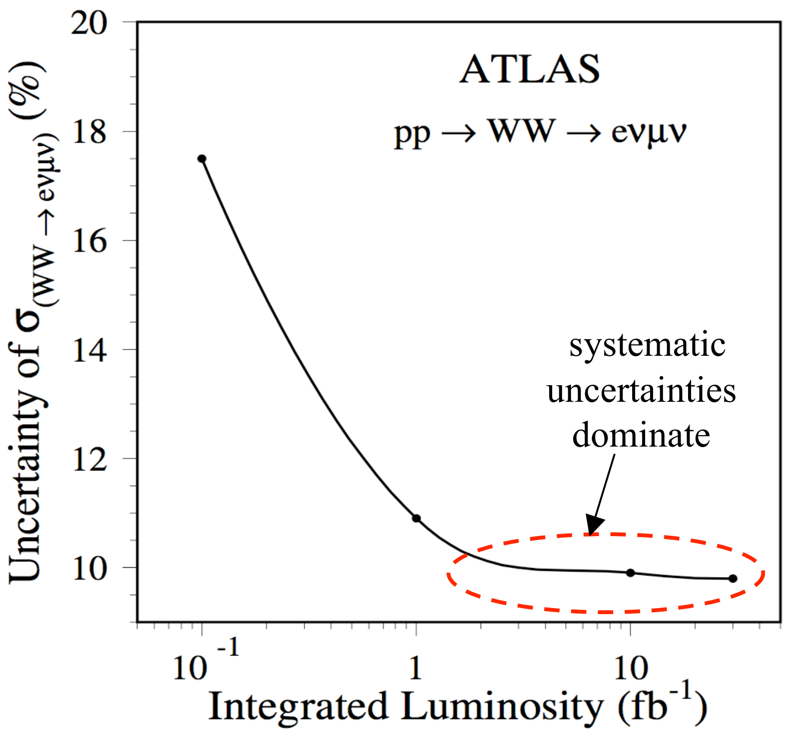
Production Cross Section at LHC



- W,Z production cross section increase by ~2X from $\sqrt{s}$=7 TeV to 14 TeV

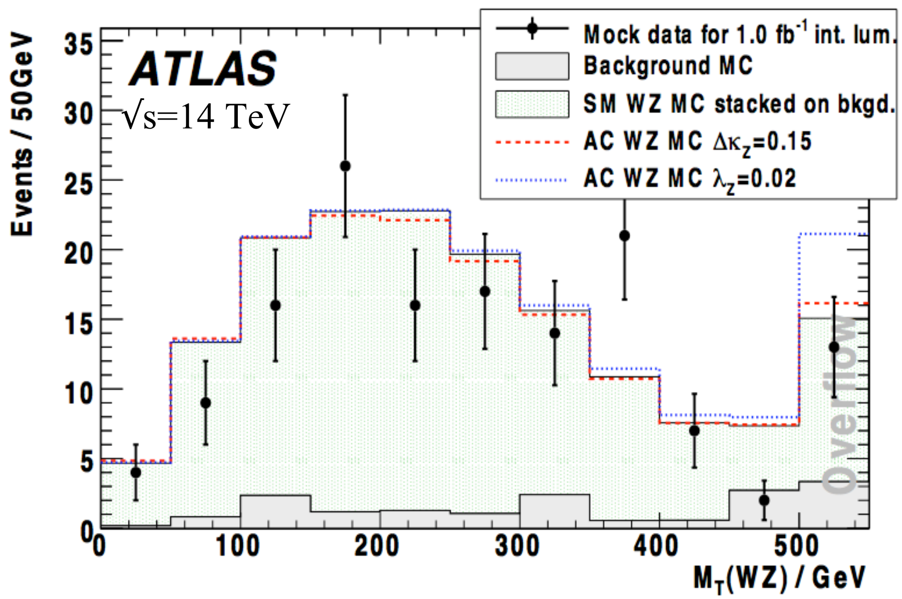
WW→*lνlν*

- Cross section uncertainties estimated ~20-30% @ L~100 pb^{-1}
- Expect uncertainties to improve with more data



WWZ Anomalous TGC in WZ Analysis

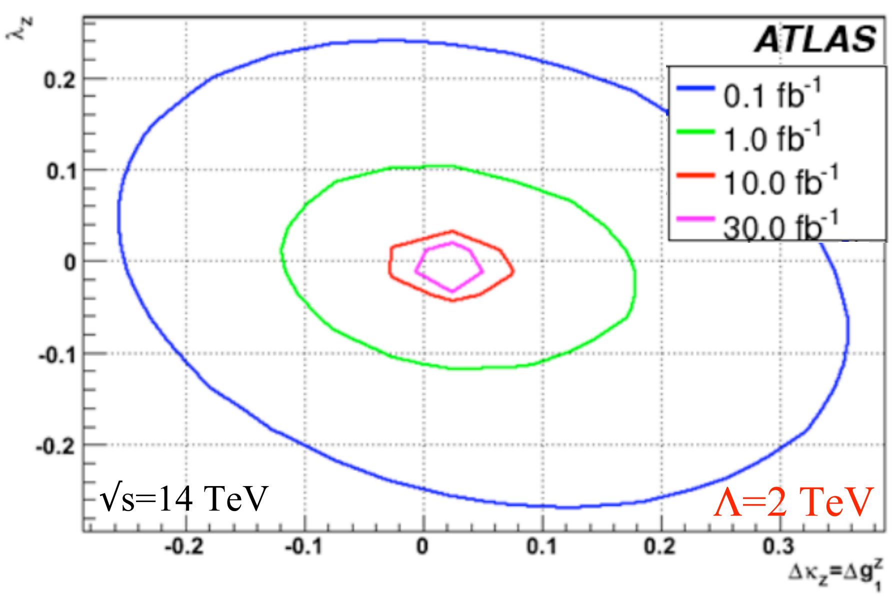
- $M_T(WZ)$ and $P_T(Z)$ spectra are fit to extract WWZ anomalous parameters at 95% C.L.



1-D anomalous coupling sensitivity interval :

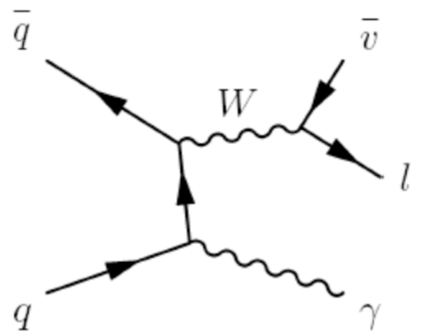
$\int L$ (fb^{-1})	0.1	1.0	10.0	30.0
$\Delta\kappa_Z$	[-0.440 , 0.609]	[-0.203 , 0.339]	[-0.095 , 0.222]	[-0.080 , 0.169]
λ_Z	[-0.062 , 0.056]	[-0.028 , 0.024]	[-0.015 , 0.013]	[-0.012 , 0.008]
Δg^Z_1	[-0.063 , 0.119]	[-0.021 , 0.054]	[-0.011 , 0.034]	[-0.005 , 0.023]

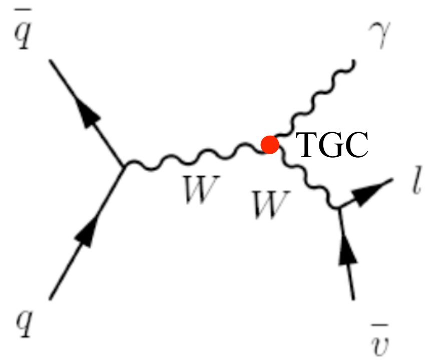
Λ=2 TeV



- 2-D anomalous TGC limit:
- Assume: $\Delta\kappa_Z=\Delta g^Z_1$

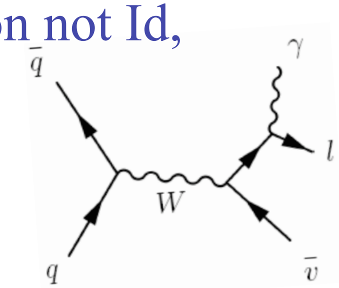
Wγ→*l*νγ





- Wγ measurement can probe WWγ TGC
- Events selected with 1 isolated lepton (e,μ) , 1 isolated photon, large E_T^{miss}

- **Main background:**
  - W+jets (jet fakes as γ)
  - Z+γ/jets (one lepton not Id, jet mis-Id as γ)
  - W+γ (γ from FSR)

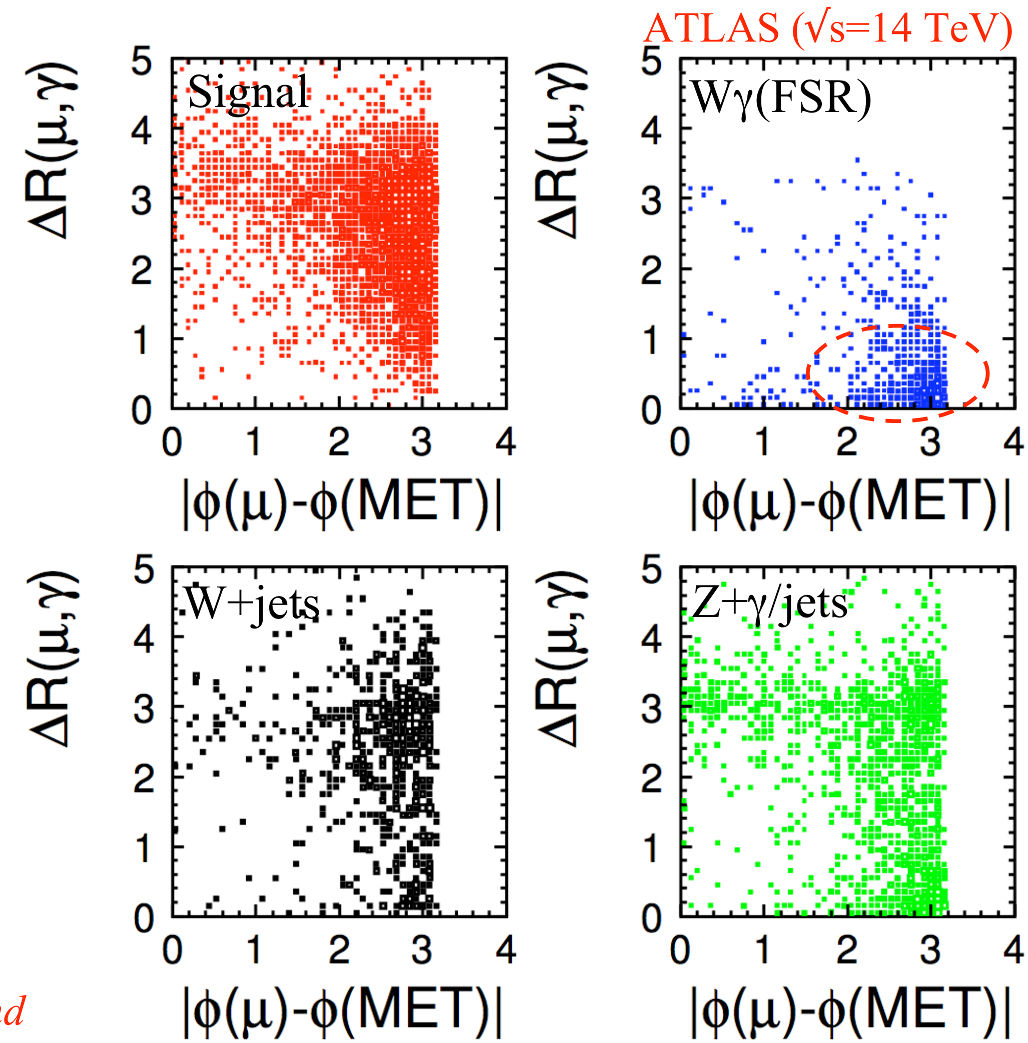


<u>**ATLAS:**</u>

- Train BDT to discriminate Wγ signal from background

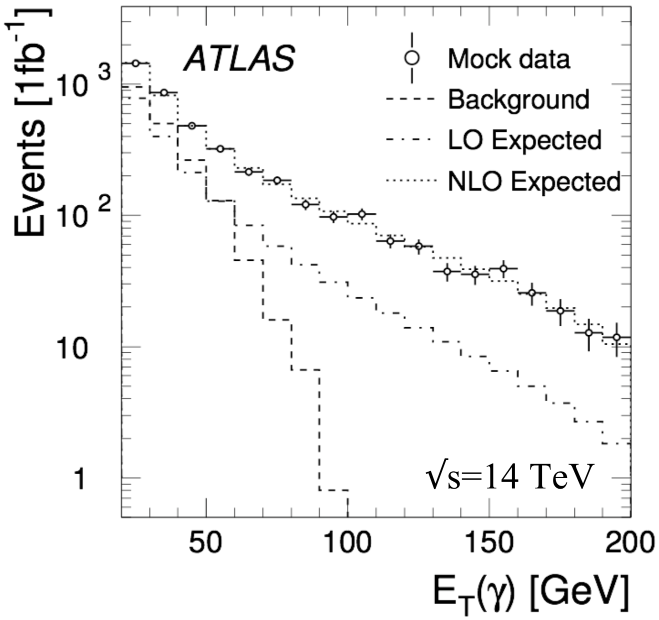
√s=14 TeV, L=1 fb^{-1}	#signal	#bkg
$l = e$	1604	1183
$l = \mu$	2166	1342

Still can achieve S/√B>~10 at √s=7 TeV, for L=0.1 fb^{-1}, if assume both signal and background scale by ~0.5 going from √s=14 TeV to 7 TeV



WWγ Anomalous TGC in Wγ Analysis

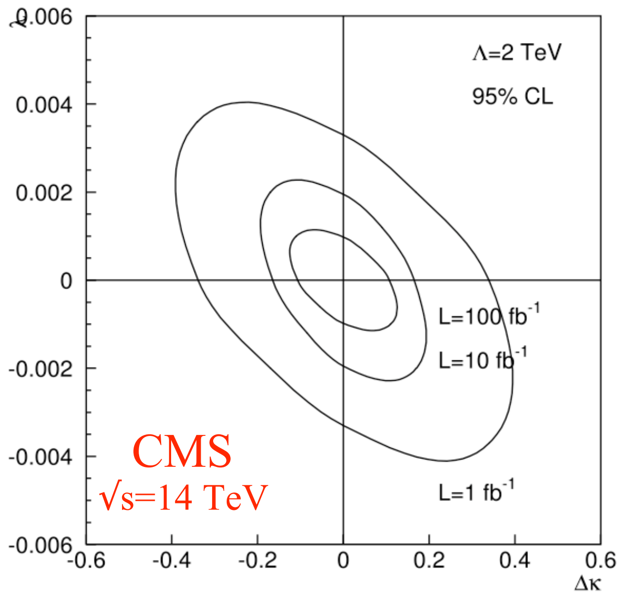
- $E_T(\gamma)$ distribution is used to determine the WWγ anomalous parameters at 95% C.L.



1-D anomalous coupling sensitivity interval

(ATLAS, √s=14 TeV, Λ=2 TeV)

	$W(\ell\nu)\gamma$		
	$1\ fb^{-1}$	$10\ fb^{-1}$	$30\ fb^{-1}$
λ_γ	[-0.09, 0.04]	[-0.05, 0.02]	[-0.02,0.01]
$\Delta\kappa_\gamma$	[-0.43, 0.20]	[-0.26, 0.07]	[-0.11,0.05]



2-D anomalous TGC limit from CMS:

- @ $L=100\ fb^{-1}$, Λ=2 TeV
  - $|\Delta\kappa_\gamma| < 0.1$
  - $|\lambda_\gamma| < 0.009$