Triple Gauge Boson Couplings in ATLAS

LPCC EWK WG

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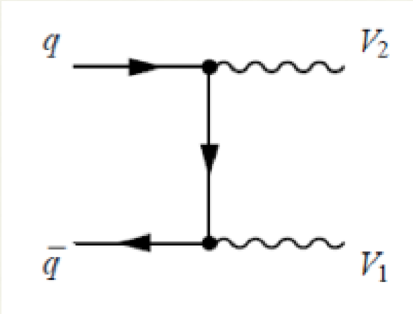
Status since last LPCC WG

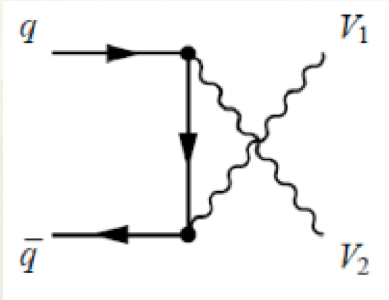
- Studies with 1/fb(7TeV) for all di-boson groups are published
- A common fitter is developed for both1D and 2D limit setting
- WW&WZ group have their public results with 5/fb (7TeV) ; results from other groups would be public soon

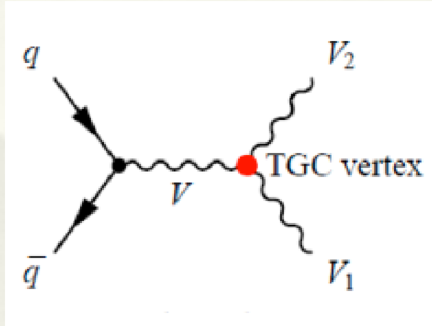
Outline

- TGC overview
- Study models
- Methods
- Current status and results
- Future plans

Motivation







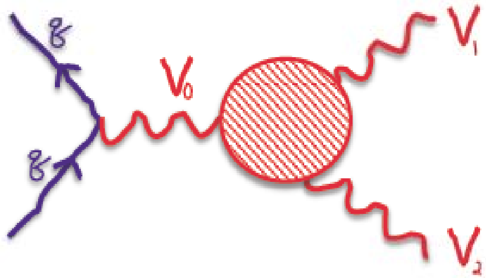
- The standard model of electroweak interactions permits gauge bosons (*Z, W, and γ) to self-interact via trilinear gauge boson* vertices.
- Neutral couplings are forbidden at tree level (ZZZ/ZZϒ/Zϒϒ)
- Other couplings are not yet well measured

A precise measurement of TGC

- A stringent test of the SM
- A sensitive probe to new physics

➡ New, heavy particles that couple to vector bosons compositeness of the bosons

Effective Lagrangian Approach



Express model independent triple gauge couplings as parameters in effective Lagrangian:

$$\frac{\mathcal{L}_{WWV}}{g_{WWV}} = i\left[g_1^V(W^\dagger_{\mu\nu}W^\mu V^\nu - W_{\mu\nu}W^{\dagger\mu}V^\nu) + \kappa^V W^\dagger_\mu W_\nu V^{\mu\nu} + \frac{\lambda^V}{m_W^2}W^\dagger_{\rho\mu}W^\mu_\nu V^{\nu\rho}\right] \quad \text{(WW, WZ)}$$

$$\mathcal{L}_{VZZ} = -\frac{e}{M_Z^2}\left[f_4^V(\partial_\mu V^{\mu\beta})Z_\alpha(\partial^\alpha Z_\beta) + f_5^V(\partial^\sigma V_{\sigma\mu})\tilde{Z}^{\mu\beta}Z_\beta\right] \quad \text{(ZZ)}$$

Many independent parameters

f_5^V, h_3^V and h_4^V are CP conserved

f_4^V, h_1^V and h_2^V are CP violated

By requiring CP invariance, less parameters are considered

In SM $g_1^V=k^V=1$, $f_i^V=h_i^V=0$

Cutoff scale/Form Factor

- With non-SM coupling, the amplitudes for gauge boson pair production grow with energy($\sqrt{s}$)
- Tree-level unitarity is violated at very high energy
- To avoid this, an effective Cutoff scale, is introduced

$$\alpha(\hat{s}) = \frac{\alpha 0}{(1+\hat{s}/\Lambda^2)^n}$$

$\alpha 0$: coupling value at low energy limit

$\sqrt{\hat{s}}$: invariant mass of the vector-boson pair

Λ: scale of new physics

n: WW/WZ/WΥ coupling parameters, n=2;

ZZ coupling parameters, n=3;

ZΥ coupling parameters, n=3 for h_3^V, n=4 for h_4^V

Limits in ATLAS are set in two scenarios

- ✓ Λ=1.5, 2, 3,6TeV, preserves unitarity
- ✓ $\Lambda = \infty$, violates unitarity, no model assumptions

TGC signal modeling

In the effective *L*agrangian approach

- New triple gauge-boson vertex operators are added linearly to the standard model term, parameterized with a new TGC, α_i
- the cross section (or Matrix Element - ME) is an exact bilinear form - quadratic function of the α's

coefficients of the 2nd order polynomial is known ⟺ **dependency on the α 's is specified**

For the case of 2 new TGCs: α_1 and α_2

$$ME = [1\ \alpha_1\ \alpha_2] \begin{bmatrix} F_{00} & F_{01} & F_{02} \\ 0 & F_{11} & F_{12} \\ 0 & 0 & F_{22} \end{bmatrix} \begin{bmatrix} 1 \\ \alpha_1 \\ \alpha_2 \end{bmatrix}$$

F_{00} is SM contribution

Matrix F_{ij} can be obtained from simulation with several different approaches

- NLO event by event reweighting
  - WW – 3D reweighting (BHO)
  - WZ – full dimension (MC@NLO 4.07)
- LO Event by Event reweighting
  - ZZ – full dimension, LO with one real emission jet (Bella/Hansen)
- Grid parameterization (Tevatron method)
  - Wγ/Zγ – 1D Histogram (MCFM)

Sensitive observables

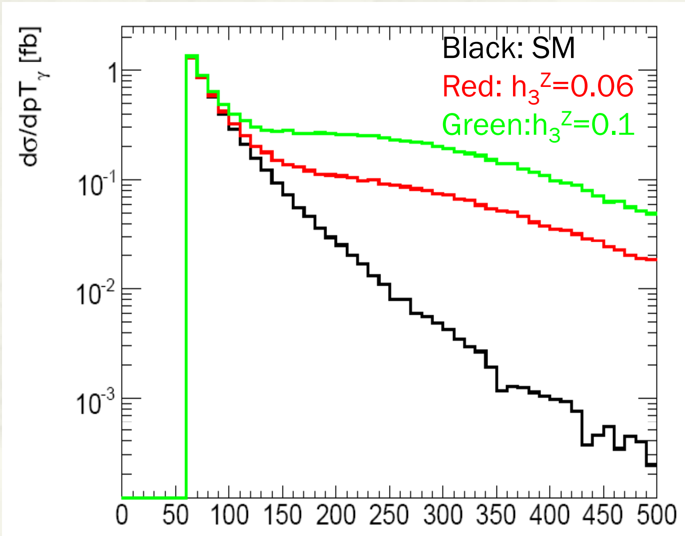
- The presence of aTGCs will affect the production cross-section of di-boson processes;
- Also has an important impact on the behavior of some measured observables.

- Sensitive observables
  - pT of ϒ (Wϒ/Z ϒ)
  - pT of (leading)Z (WZ/ZZ)
  - pT of leading lepton(WW)
- Binning

The aTGCs affect the high part of the observables more

Wϒ/Zϒ/ZZ: use only the last 1 bin of their observables

WW/WZ: use several bins



pT of ϒ/GeV

Fitting Methods

- Construct Poisson likelihood function with aTGC parameters x and nuisance parameters β)

$$L(\vec{x},\vec{\beta}) = \prod_{i=1}^{m} Poisson\left(N^{i}_{obs} N^{i}_{sig}(\vec{x}) \times (1+\beta_i) + N^{i}_{bkg} \times (1+\beta_{i+n})\right)$$

The likelihood function for the TGC determination is a product of the Poisson probability distribution with Gaussian terms (G) representing each of the nuisance parameters

- Several limit setting approaches
  - Profile likelihood “delta-log likelihood” method: ZZ
  - Frequentist limits: WZ
  - Bayesian likelihood limits: WW/Wγ/Zγ

Profile likelihood ratio

Profile likelihood ratio with Gaussian constraints on nuisance parameters:

$$L_{profile}(\vec{x}) = \max_{\beta}[L(\vec{x},\vec{\beta}) \times \exp[-\frac{1}{2}\beta_i (C_{ij})^{-1}\beta_j]$$

Define profile likelihood ratio $R(\vec{x}) = \frac{L_{prof}(\vec{x})}{\max[L_{prof}(\vec{x}')]}$

Two statistical approaches using ratio:

- -ln R(x) = 1.92 gives approximate 95% limit
  - delta log-likelihood method
  - fast, but coverage not guaranteed
- Frequentist limits use R as ranking function

Frequentist and Bayesian limits

Frequentist Limits

- Compute frequentist limits by Neyman construction
  - For each hypothetical value of aTGC parameter, generate a large number of pseudo experiments
  - observed number of events drawn randomly from Poisson distribution
  - Central value of nuisance parameters from Gaussian distribution
  - If > 95% of pseudo experiments have larger ratio than actual experiment did, the aTGC value is rejected at 95% CL
- Guarantees statistical coverage
- CPU intensive

Bayesian Limits

- Marginalize the nuisance parameters by integrating over them with Gaussian PDF

$$L_{m\,\arg}(\vec{x}) = \int_{-\infty}^{\infty} L(\vec{x},\vec{\beta}) \times \exp[-\frac{1}{2}\beta_i (C_{ij})^{-1}\beta_j] d^{2m}\vec{\beta}$$

- Interval I is computed to satisfy

$$\frac{\int_{\vec{x}\in I} L_{m\,\arg}(\vec{x})}{\int_{-\infty}^{\infty} L_{m\,\arg}(\vec{x})} = 0.95 \qquad L_{m\,\arg}(\vec{x}) \geq L_{m\,\arg}(\vec{y})\ for\ ^{\forall}\vec{x} \in I\ and\ ^{\forall}\vec{y} \notin I$$

Treatment of systematics

- Nuisance parameters with Gaussian constraints in likelihood function
- Full correlated between uncertainties across channels and bins

Sources of systematics

- Luminosity
- Electron / muon / MEt reconstruction
- Trigger efficiency
- PDFs
- Theoretical uncertainty on diboson production cross section
- Renormalization/factorization scale
- Data driven background estimates

Current status and results (1)

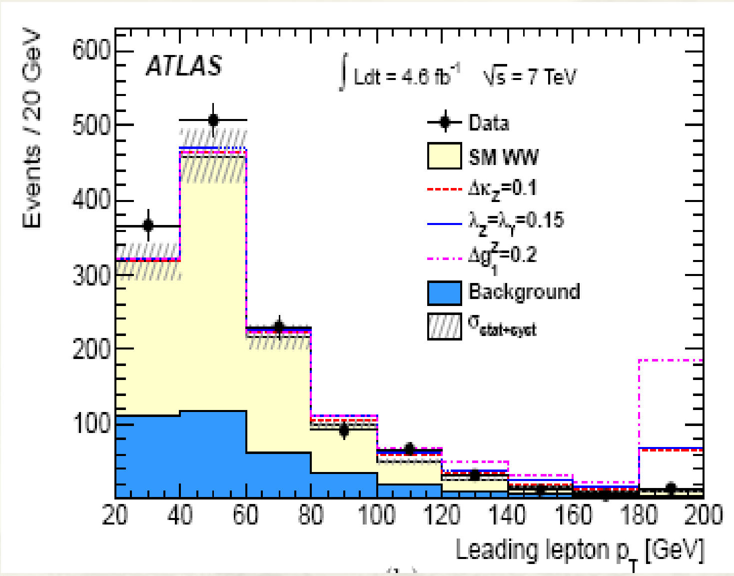
- ATLAS has TGC results in all channels published with 1/fb
  - ◆WW
    PLB
    arXiv:1203.6232[hep-ex]
  - ◆WZ
    PLB 709(2012) 314-357
  - ◆Wϒ/Zϒ
    PLB
    arXiv:1205.2531[hep-ex]
  - ◆ ZZ
    PRL 108, 041804(2012)
- ATLAS WZ&WW group have their public TGC results with 5/fb
  - ◆ WZ
    submit to EPJC   arXiv:1208.1390
  - ◆ WW
    To be submitted to PRD
- A common fitter is developed
  - ◆ defined input data format (ASCII text)
  - ◆ 1D: ΔlogL method, frequentist method, Bayesian method
  - ◆ 2D: ΔlogL method, frequentist method
- Other di-boson groups

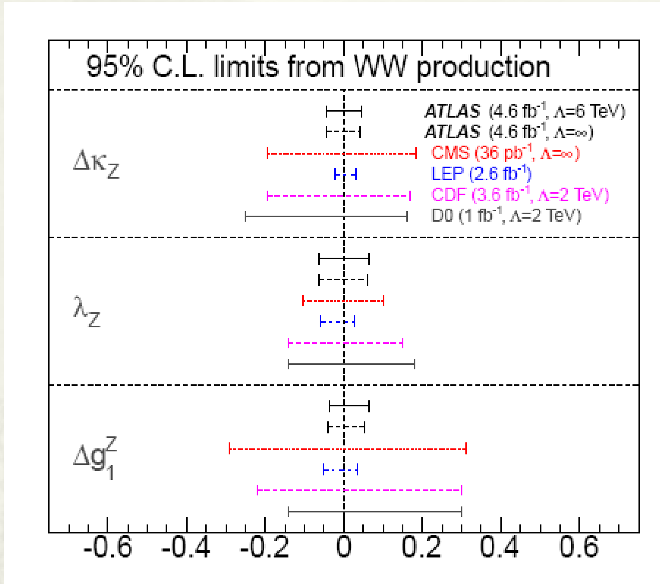
Applied the common fitter: Results approved in ATLAS SM group, coming soon

2D limits/limits from differential distributions

Current status and results (2)

* 5/fb WW results



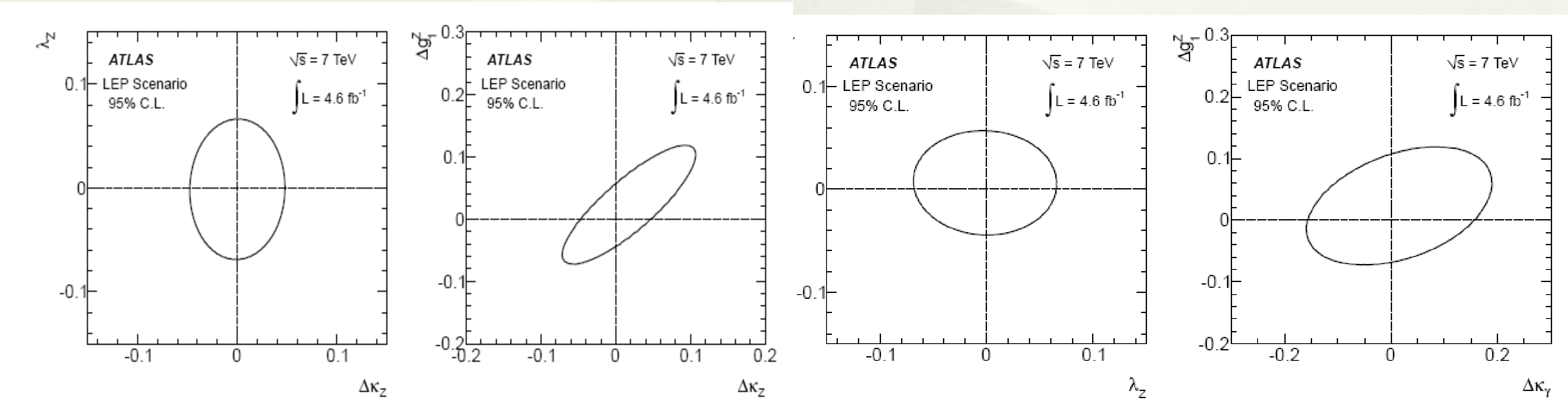


WW limit

- Sensitive to WWZ and WWϒ aTGC vertex
- Limits set using leading lepton p_T spectrum
- ΔLogL limits set using LEP aTGC scenario(some other scenarios are also included)

Current status and results (3)

- 5/fb WW results



Scenario	Parameter	Expected ($\Lambda = 6$ TeV)	Observed ($\Lambda = 6$ TeV)	Expected ($\Lambda = \infty$)	Observed ($\Lambda = \infty$)
LEP	$\Delta\kappa_Z$	$[-0.043, 0.040]$	$[-0.045, 0.044]$	$[-0.039, 0.039]$	$[-0.043, 0.043]$
	$\lambda_Z = \lambda_\gamma$	$[-0.060, 0.062]$	$[-0.062, 0.065]$	$[-0.060, 0.056]$	$[-0.062, 0.059]$
	Δg_1^Z	$[-0.034, 0.062]$	$[-0.036, 0.066]$	$[-0.038, 0.047]$	$[-0.039, 0.052]$
HISZ	$\Delta\kappa_Z$	$[-0.040, 0.054]$	$[-0.039, 0.057]$	$[-0.037, 0.054]$	$[-0.036, 0.057]$
	$\lambda_Z = \lambda_\gamma$	$[-0.064, 0.062]$	$[-0.066, 0.065]$	$[-0.061, 0.060]$	$[-0.063, 0.063]$
Equal Couplings	$\Delta\kappa_Z$	$[-0.058, 0.089]$	$[-0.061, 0.093]$	$[-0.057, 0.080]$	$[-0.061, 0.083]$
	$\lambda_Z = \lambda_\gamma$	$[-0.060, 0.062]$	$[-0.062, 0.065]$	$[-0.060, 0.056]$	$[-0.062, 0.059]$

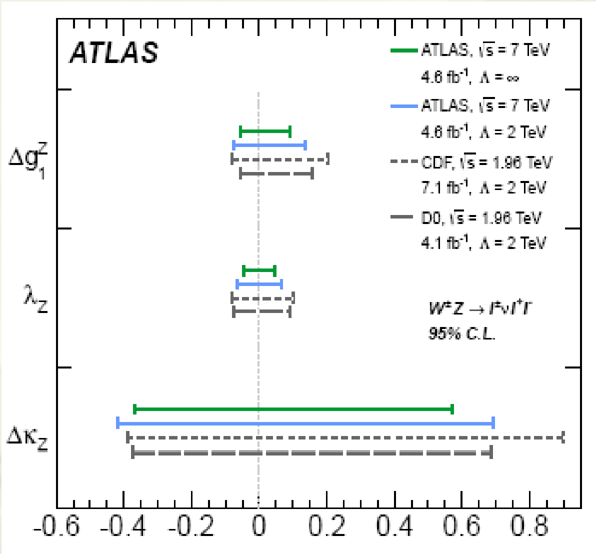
95% C.L Limits at different scenarios

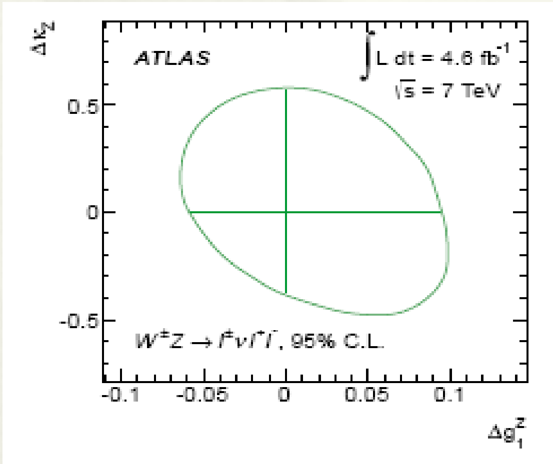
Parameter	Expected ($\Lambda = \infty$)	Observed ($\Lambda = \infty$)
$\Delta\kappa_Z$	$[-0.077, 0.086]$	$[-0.078, 0.092]$
λ_Z	$[-0.071, 0.069]$	$[-0.074, 0.073]$
λ_γ	$[-0.144, 0.135]$	$[-0.152, 0.146]$
Δg_1^Z	$[-0.449, 0.546]$	$[-0.373, 0.562]$
$\Delta\kappa_\gamma$	$[-0.128, 0.176]$	$[-0.135, 0.190]$

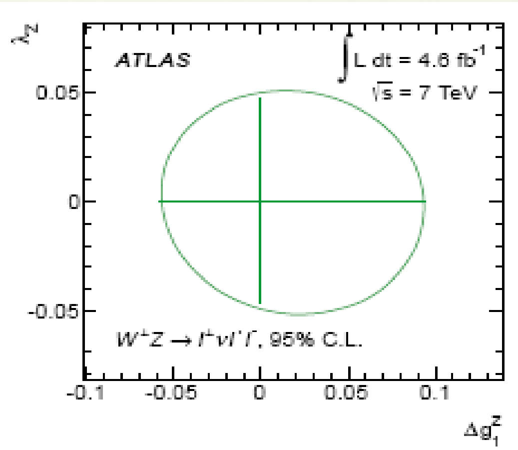
Limits assuming no relationships among parameters

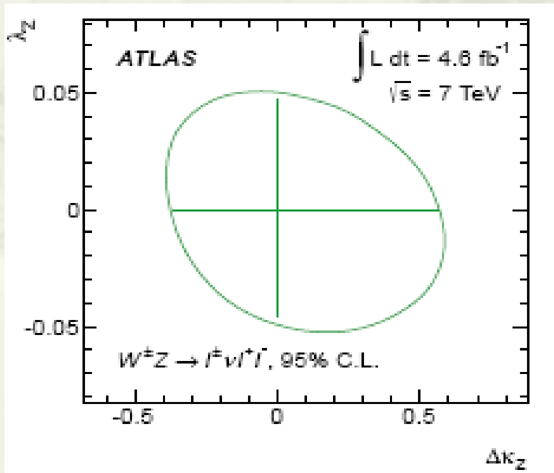
Current status and results (4)

* 5/fb WZ results





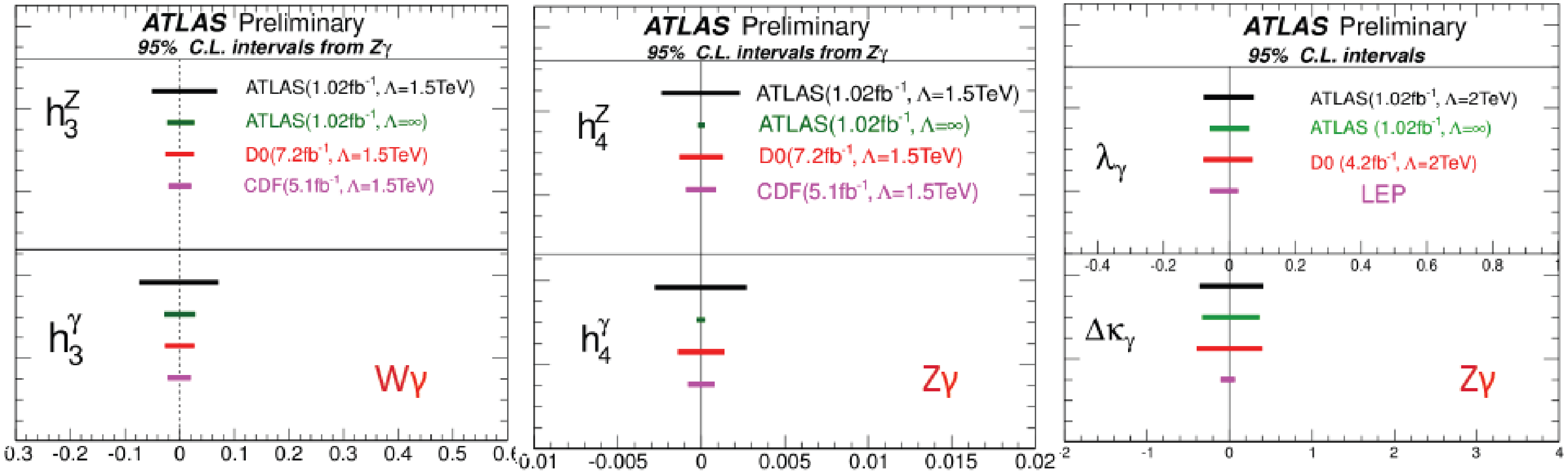




- Analysis sensitive to WWZ vertex
- Limits are extracted with 7 pT(Z) bins
- Frequentist limits set
- 5/fb limits are much more improved comparing to 1/fb limits

Current status and results (5)

* 1/fb W/ZΥ results

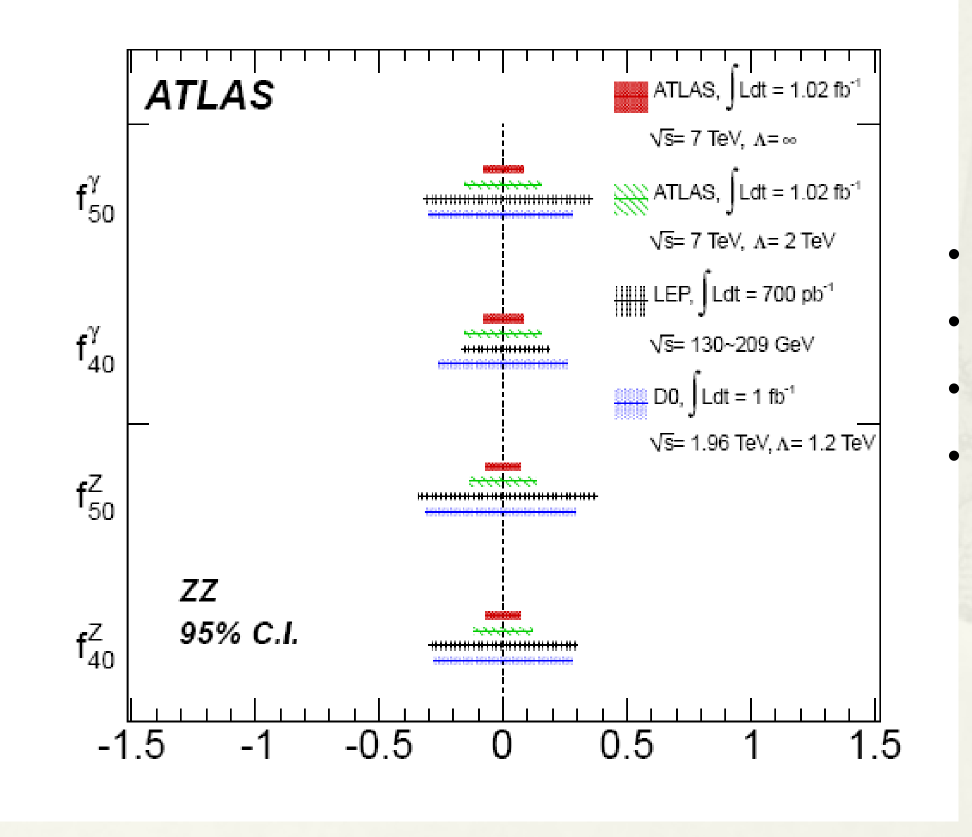


Wγ, Zγ limits

- Wγ analysis sensitive to WWγ aTGC vertex
- Zγ analysis sensitive to Zγγ and ZZγ aTGC vertices
- Limits extracted using exclusive fiducial cross-section (no jets) in high E_t^γ regime
    - E_t^γ > 100 GeV for Wγ
    - E_t^γ > 60 GeV for Zγ
- Bayesian likelihood limits set

Current status and results (6)

* 1/fb ZZ results



- Analysis sensitive to ZZγ and ZZZ aTGC vertices
- Limits extracted using observed event yield
- Profile likelihood limits set
- These limits are comparable with, or are more stringent than, those derived from measurements at LEP and the Tevatron.

Future plans

- 7 TeV

  limits from all di-boson group will be ready soon

  - common fitter
  - 2D limits
  - Differential distributions

- 8TeV
  - Limits as function of Λ
  - Combined limits among different di-boson channels
  - Combined limits with CMS?
  - More development on the common tools?