Status since last LPCC WG

- Studies with 1/fb(7TeV) for all di-boson groups are published
- A common fitter is developed for both 1D 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/ZZγ/Zγγ)
- 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:

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

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

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

\( g_1^V = k^V = 1 \), \( f_i^V = h_i^V = 0 \)
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

$$\alpha(\hat{s}) = \frac{\alpha_0}{(1 + \frac{\hat{s}}{\Lambda^2})^n}$$

$\alpha_0$: coupling value at low energy limit

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

$\Lambda$: scale of new physics

$n$: WW/WZ/Wγ coupling parameters, $n=2$;

ZZ coupling parameters, $n=3$;

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

**Limits in ATLAS are set in two scenarios**

- $\Lambda=1.5, 2, 3, 6$ TeV, preserves unitarity
- $\Lambda=\infty$, violates unitarity, no model assumptions
TGC signal modeling

In the effective Lagrangian approach

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

coefficients of the 2nd order polynomial is known dependency on the $\alpha$'s is specified

For the case of 2 new TGCs: $\alpha_1$ and $\alpha_2$

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

$F_{00}$ is SM contribution

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

* NLO event by event reweighting
  * WW – 3D reweighting (3HO)
  * 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)
  * $W\gamma/Z\gamma$ – 1D Histogram (MCFM)
Sensitive observables

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

* Sensitive observables
  - $p_T$ of $\Upsilon (W\Upsilon/Z\Upsilon)$
  - $p_T$ of (leading)Z ($WZ/ZZ$)
  - $p_T$ of leading lepton ($WW$)

* Binning

  The aTGCs affect the high part of the observables more
  $W\Upsilon/Z\Upsilon/ZZ$: use only the last 1 bin of their observables
  $WW/WZ$: use several bins
Fitting Methods

- Construct Poisson likelihood function with aTGC parameters $x$ and nuisance parameters $\beta$.

$$L(\tilde{x}, \tilde{\beta}) = \prod_{i=1}^{m} \text{Poisson}(N_{obs}^i N_{sig}^i (\tilde{x}) \times (1 + \beta_i) + N_{bkg}^i \times (1 + \beta_{i+n}))$$

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:

\[ L_{\text{profile}}(\bar{x}) = \max_{\beta} [L(\bar{x}, \hat{\beta}) \times \exp\left(-\frac{1}{2} \beta_i (C_{ij})^{-1} \beta_j \right)] \]

Define profile likelihood ratio \[ R(\bar{x}) = \frac{L_{\text{prof}}(\bar{x})}{\max[L_{\text{prof}}(\bar{x}')]}. \]

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

- Interval I is computed to satisfy
  \[ \int_{\bar{x} \in I} L_{m \arg}(\bar{x}) = 0.95 \quad L_{m \arg}(\bar{x}) \geq L_{m \arg}(\bar{y}) \text{ for } \forall \bar{x} \in I \text{ and } \forall \bar{y} \notin I \]
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
  - **WZ**
    - PLB 709(2012) 314-357
  - **WY/ZY**
    - PLB
  - **ZZ**

* **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 WWY aTGC vertex
- Limits set using leading lepton $p_T$ spectrum
- $\Delta \log L$ limits set using LEP aTGC scenario (some other scenarios are also included)
Current status and results (3)

* 5/fb WW results

95% C.L Limits at different scenarios

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Parameter</th>
<th>Expected (Λ = 6 TeV)</th>
<th>Observed (Λ = 6 TeV)</th>
<th>Expected (Λ = ∞)</th>
<th>Observed (Λ = ∞)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LEP</td>
<td>ΔκZ</td>
<td>-0.043, 0.039</td>
<td>-0.045, 0.044</td>
<td>-0.039, 0.039</td>
<td>-0.043, 0.043</td>
</tr>
<tr>
<td></td>
<td>λZ = λγ</td>
<td>0.060, 0.062</td>
<td>0.062, 0.065</td>
<td>0.060, 0.056</td>
<td>0.062, 0.050</td>
</tr>
<tr>
<td></td>
<td>Δδγ1</td>
<td>-0.034, 0.002</td>
<td>-0.036, 0.006</td>
<td>-0.038, 0.047</td>
<td>-0.039, 0.052</td>
</tr>
<tr>
<td>HISZ</td>
<td>ΔκZ</td>
<td>-0.040, 0.054</td>
<td>-0.039, 0.057</td>
<td>-0.037, 0.054</td>
<td>-0.036, 0.057</td>
</tr>
<tr>
<td></td>
<td>λZ = λγ</td>
<td>-0.064, 0.062</td>
<td>-0.066, 0.065</td>
<td>-0.061, 0.060</td>
<td>-0.063, 0.063</td>
</tr>
<tr>
<td></td>
<td>Δκγ</td>
<td>-0.055, 0.059</td>
<td>-0.061, 0.093</td>
<td>-0.057, 0.080</td>
<td>-0.061, 0.083</td>
</tr>
<tr>
<td>Equal Couplings</td>
<td>λZ = λγ</td>
<td>-0.000, 0.002</td>
<td>-0.002, 0.006</td>
<td>-0.000, 0.056</td>
<td>-0.002, 0.050</td>
</tr>
</tbody>
</table>

Limits assuming no relationships among parameters

10-10-2012 LPCC
* 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/ZY 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

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