TGC measurements

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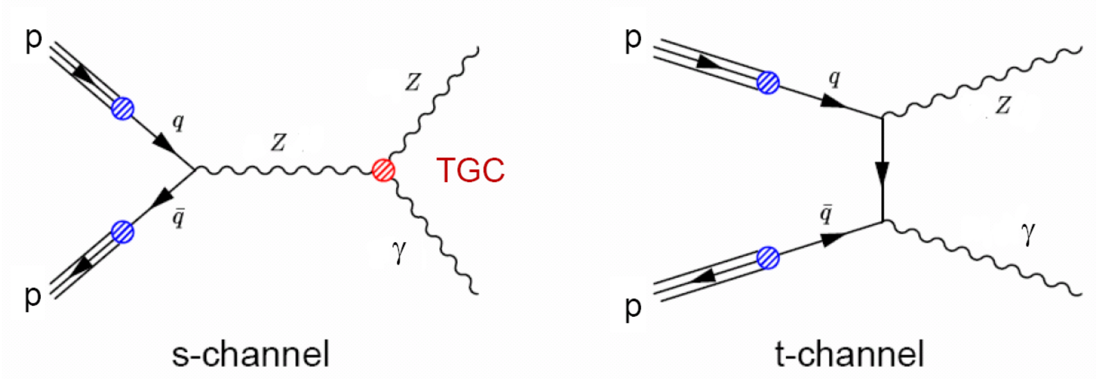
Introduction

- Anomalous triple gauge couplings (aTGC) represent new interaction vertices or corrections to existing ones between SM electroweak bosons. This modifies the expected production rate of dibosons, **e.g. Z+photon production**:
- 

- Introduced via effective Lagrangians:

$$\mathcal{L}_{ZZ\gamma} = \frac{-e}{m_Z^2}\Big[h_1^Z(\partial^\sigma Z_{\sigma\mu})Z_\beta F^{\mu\beta} + h_3^Z(\partial_\sigma Z^{\sigma\rho})Z^\alpha \tilde{F}_{\rho\alpha}$$
$$+\frac{h_2^Z}{m_Z^2}\left[\partial_\alpha\partial_\beta(\Box + m_Z^2)Z_\mu\right] Z^\alpha F^{\mu\beta} + \frac{h_4^Z}{2m_Z^2}\left[(\Box + m_Z^2)\partial^\sigma Z^{\rho\alpha}\right] Z_\sigma \tilde{F}_{\rho\alpha}\Big]$$

- Differential cross section has quadratic dependence on aTGCs. I.e. for only one coupling:

$$\mathrm{d}\sigma = F_0 + h\cdot F_1 + h^2\cdot F_2 \qquad \text{where } F_0 = \mathrm{d}\sigma_{\mathrm{SM}}$$

- Form factor introduced to preserve partial wave unitarity:

$$h(\hat{s}) = \frac{h_0}{(1+\hat{s}/\Lambda^2)^n}$$

Latest results in ATLAS

- **aTGCs in WZ production:** $WZ \to lll\nu \qquad l = \{e, \mu\}$

$$\{\, \Delta g_1^Z \,,\ \Delta\kappa_Z \,,\ \lambda_Z \,\} \equiv \{\, 1 - g_1^Z \,,\ 1 - \kappa_Z \,,\ \lambda_Z \,\} = \{\, 0 \,,\ 0 \,,\ 0 \,\}_{\mathrm{SM}}$$

- Limits obtained using total number of observed events
  - Too small statistics for differential measurement
  - 95% CI with profile likelihood test
- Dependency on aTGCs modeled with MC@NLO v4.0
  - Modeled at MC generator level and then subjected to full detector simulation.
- Limits for each coupling assumes all other couplings at their SM values.
- Form factor (dipole):

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

  - Cutoff scale at 2 TeV and infinity (2 TeV ensures unitarity for expected yield).
  - n=2

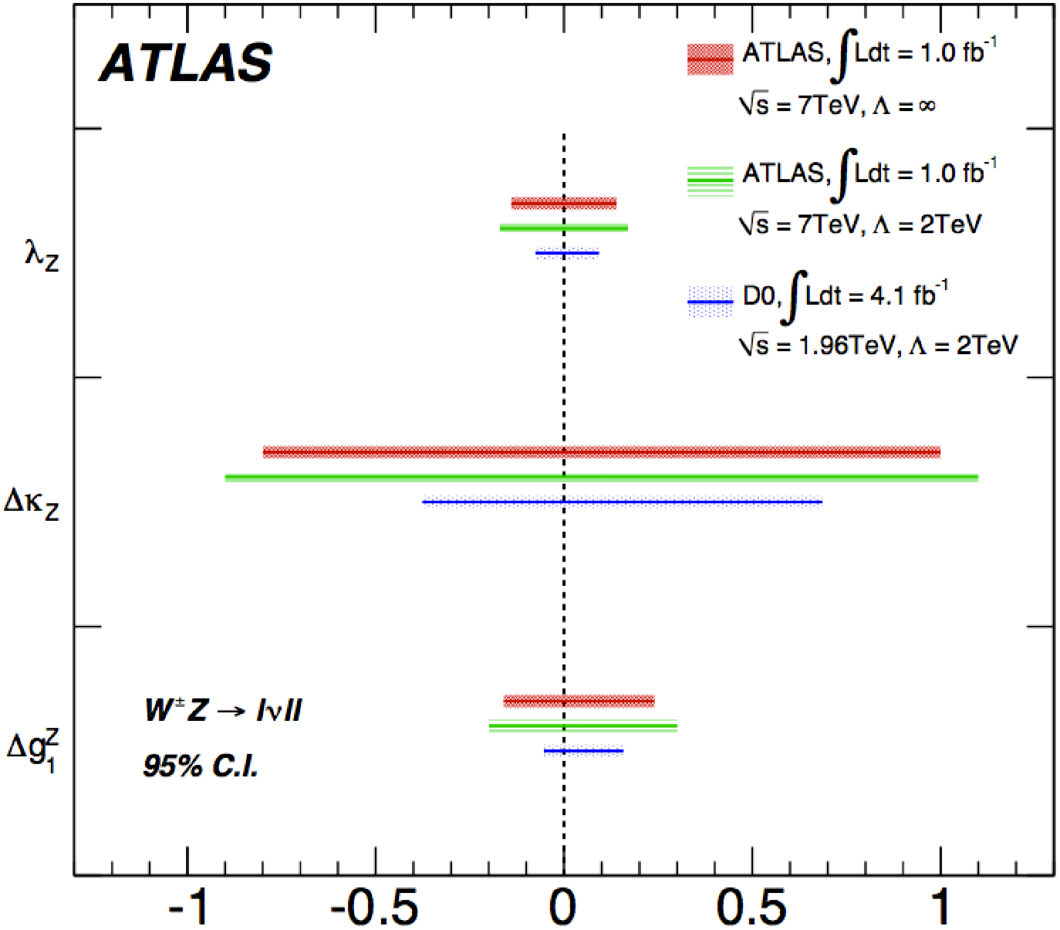
Latest results in ATLAS

- **aTGCs in WZ production:**

  Comparison with other experiments

Coupling	Observed ($\Lambda = 2$ TeV)	Observed ($\Lambda = \infty$)	Expected ($\Lambda = \infty$)
Δg_1^Z	$[-0.20, 0.30]$	$[-0.16, 0.24]$	$[-0.12, 0.20]$
$\Delta\kappa_Z$	$[-0.9, 1.1]$	$[-0.8, 1.0]$	$[-0.6, 0.8]$
λ_Z	$[-0.17, 0.17]$	$[-0.14, 0.14]$	$[-0.11, 0.11]$

Table 3: Observed and expected 95% C.I. for the anomalous couplings Δg_1^Z, $\Delta\kappa_Z$, and λ_Z. Expected experimental limits assume SM values.



Latest results in ATLAS

- **aTGCs in ZZ production:** $ZZ \to llll \qquad l = \{e, \mu\}$

$$\{\ f_4^\gamma\ ,\ f_4^Z\ ,\ f_5^\gamma\ ,\ f_5^Z\ \}\ =\ \{\ 0\ ,\ 0\ ,\ 0\ ,\ 0\ \}_{\mathrm{SM}}$$

- Limits obtained using total number of observed events
  - Too small statistics for differential measurement
  - 95% CI with profile likelihood test
- Dependency on aTGCs modeled with SHERPA and Baur-Rainwater
  - Modeled after full detector simulation of SHERPA sample using LO ME (Baur-Rainwater) reweighting framework.
- Limits for each coupling assumes all other couplings at their SM values.
- Form factor (dipole):

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

  - Cutoff scales at 2 TeV and infinity (2 TeV ensures unitarity for expected yield).
  - n=3

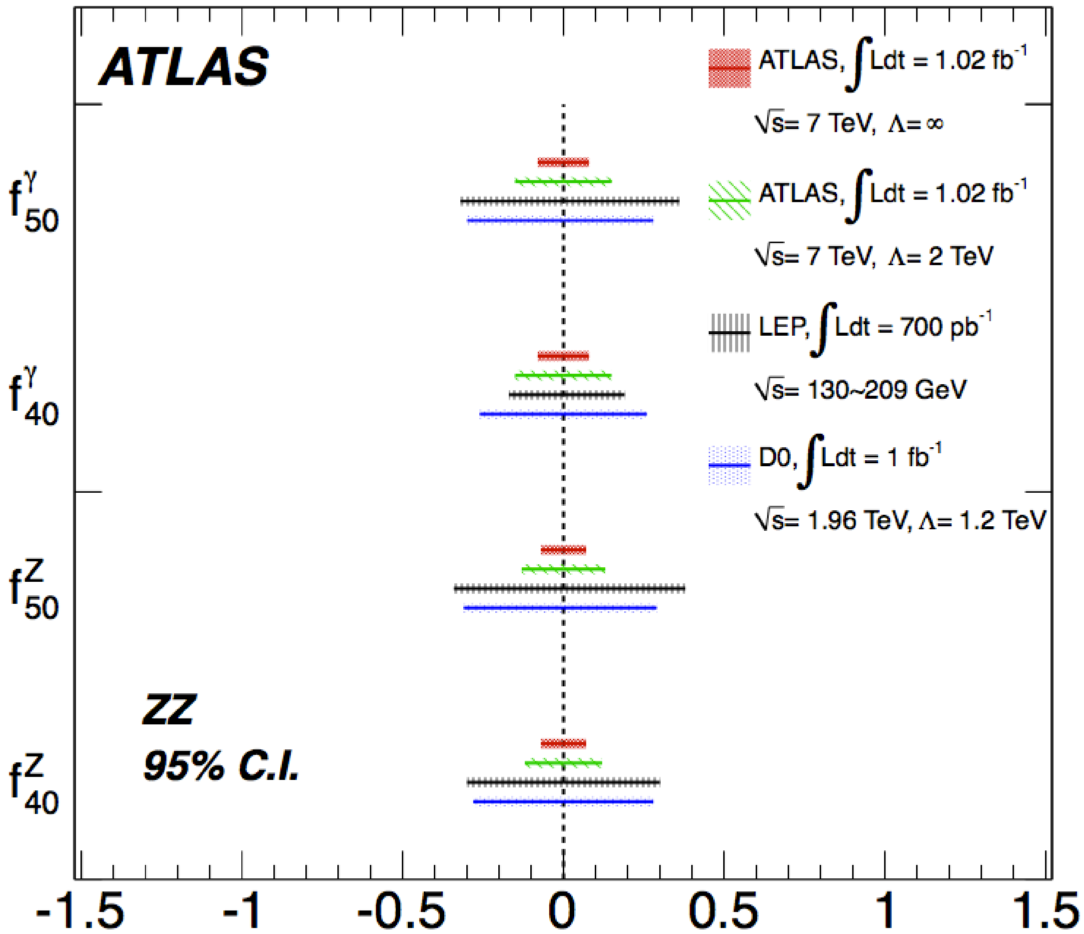
Latest results in ATLAS

- **aTGCs in ZZ production:**

  Comparison with other experiments

TABLE II. One dimensional 95% confidence intervals for anomalous neutral gauge boson couplings, where the limit for each coupling assumes the other couplings fixed at their Standard Model value. Limits are presented for form factor scales of $\Lambda = 2$ TeV and $\Lambda = \infty$ and include both statistical and systematic uncertainties; the statistical uncertainties are dominant.

Λ	f_{40}^{γ}	f_{40}^{Z}	f_{50}^{γ}	f_{50}^{Z}
2 TeV	$[-0.15, 0.15]$	$[-0.12, 0.12]$	$[-0.15, 0.15]$	$[-0.13, 0.13]$
∞	$[-0.08, 0.08]$	$[-0.07, 0.07]$	$[-0.08, 0.08]$	$[-0.07, 0.07]$



MC needs for TGC limit extraction

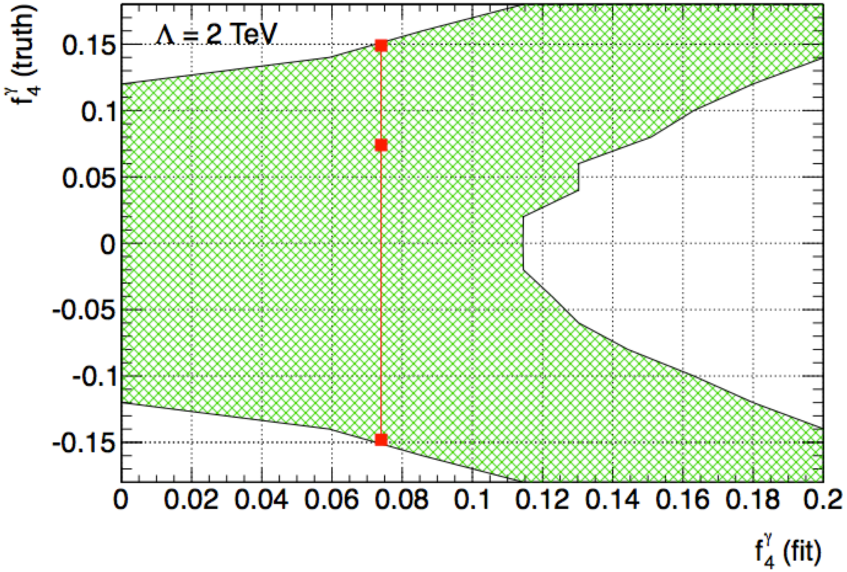
- Monte Carlo generators used for public results:
  - WZ : MC@NLO v4.0 (NLO in QCD)
  - ZZ : SHERPA (LO) reweighted with Baur-Rainwater (LO)
- Monte Carlo generators that include aTGCs:
  - MC@NLO v4.0
    - aTGCs for WZ (**CP cons.**)
  - SHERPA
    - aTGCs for all diboson processes (**CP cons.** + **CP viol.**)
  - MCFM v6.1
    - aTGCs for WZ, WW, Wγ (**CP cons.**), Zγ (**CP cons.** + **CP viol.**).
  - BHO
    - aTGCs for all diboson processes, except for ZZ. CTGCs (**CP cons.**), NTGCs (**CP cons.** + **CP viol.**).
  - POWHEG BOX
    - aTGCs for WW and WZ (**CP cons.**).
- EW corrections...?

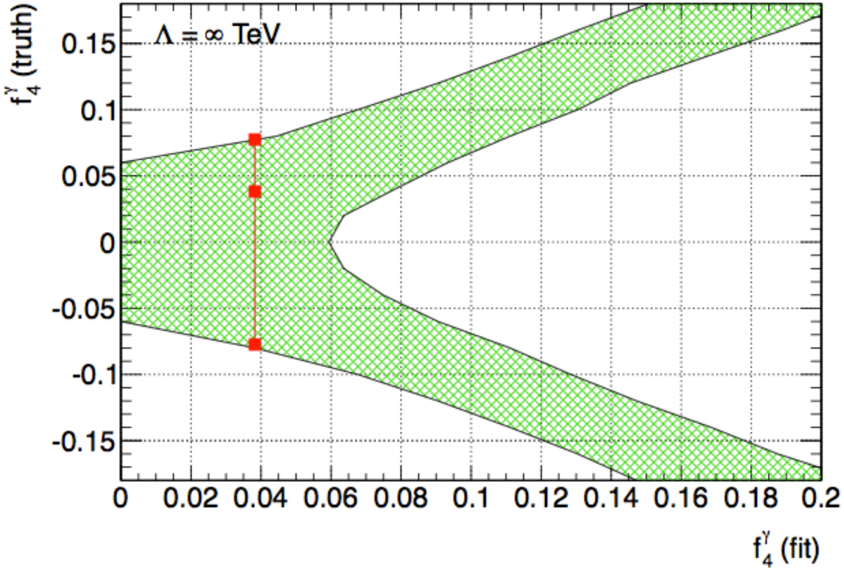
Fitting techniques

- Frequentist approach (both WZ and ZZ):
  - Profile likelihood
  - Neyman construction

    (likelihood ratio ordered –

    Feldman-Cousins)
  - 95% C.I.





EXAMPLE

- So far only single parameter limits.
- Future prospects for limit setting:
  - 2D and 3D contour limits
  - Combine channels:
    - Zγ + ZZ
    - WW+Wγ and WW+WZ
  - Choice of form factor?

Form factor

- **Effective Lagrangians:**
  - The original purpose of aTGCs is an effective Lagrangian for a multiboson interaction expansion in $1/\Lambda^2$:

$$\mathcal{L}_{\text{eff}} = \sum_{d=4}^{\infty} \frac{1}{\Lambda^{d-4}} \mathcal{L}_d = \mathcal{L}_4 + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \ldots$$

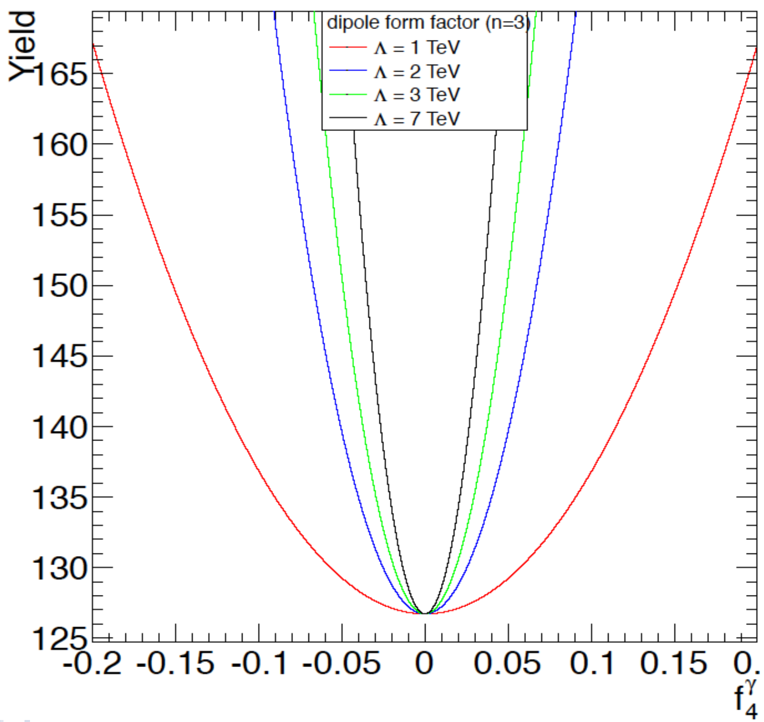
  - With

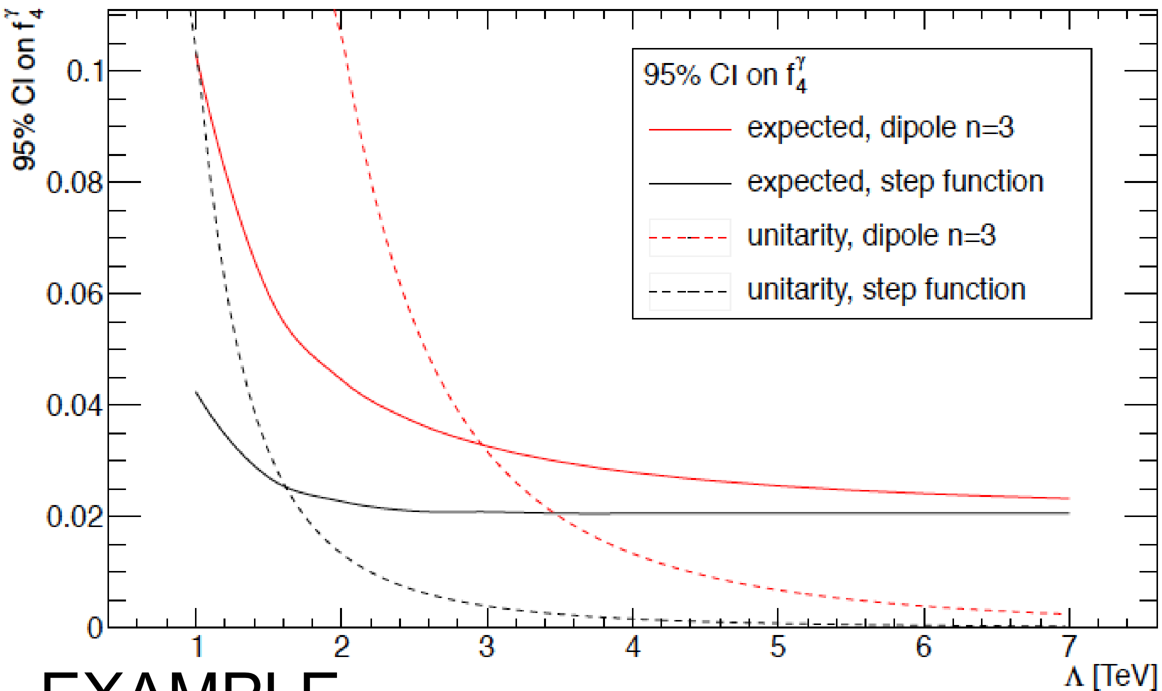
$$\mathcal{L}_i = \sum_j \alpha_{ij} \mathcal{O}_{ij}$$

  - Where Λ is the scale of new physics. (Note: only one Λ!)
  - Standard "two parameter" problem – Λ and α.
  - By construction, (truncated) effective Lagrangians violate unitarity at some scale.
- Current approach of introducing dipole form factor to restore unitarity is ad-hoc and provides (if applied rigorously) different scales to each aTGC – *somewhat destroying the original idea*.
- Using different cutoff scales for different processes and re-determining the scale when more data becomes available makes it difficult to compare to previous results and to other experiments.
- Which cutoff should be used when combining different diboson channels?

Form factor

- **Follow-up on last meeting:**
  - It was discussed that limits could be given as function of Λ (step-function), thus providing results for several Λ scales.
  - Generator study: ZZ, f4G. Using dσ/dpT(Z). SHERPA events reweighted with Baur-Rainwater. Unitarity limits from U. Baur and D. Zeppenfeld, Phys. Lett. B 201 (1988) 383.





EXAMPLE

Form factor

- **Follow-up on last meeting:**
  - From the perspective of effective Lagrangians, there should be one common Λ scale for all diboson processes.
  - Why should unitarity dictate the scale of new physics scale Λ in our model?
  - Do we have a prior for Λ? (...SM breaks down at ~1 TeV).
  - By construction, it is expected that effective Lagrangians violate unitarity at some point. Do we even need form factors?
  - Standard contact interactions do not care about unitarity. Why should we?
  - Predefined fixed set of Λ to set limits – which values?
    - Facilitate combination at current and future energies.
  - Choice of form factor – dipole vs. step function.
  - Use-cases from theory?
  - Currently, ATLAS gives results for
    - Λ that restores unitarity
    - no form factor.