LHC EWWG di-boson, discussion on aGC for Run II

Measurements of Multiboson Interactions at LHC Introduction

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On behalf of the ATLAS and CMS Collaborations

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Introduction

- LHC EWK WG workshop to discuss anomalous vector boson coupling measurements for LHC Run II

- **The goal is to get a useful input and recommendations from theory side for ATLAS and CMS experimentalist that are planning to work on anomalous coupling vector boson measurements with Run II data**

Multiboson production at LHC

Multiboson (diboson and triboson) production at LHC

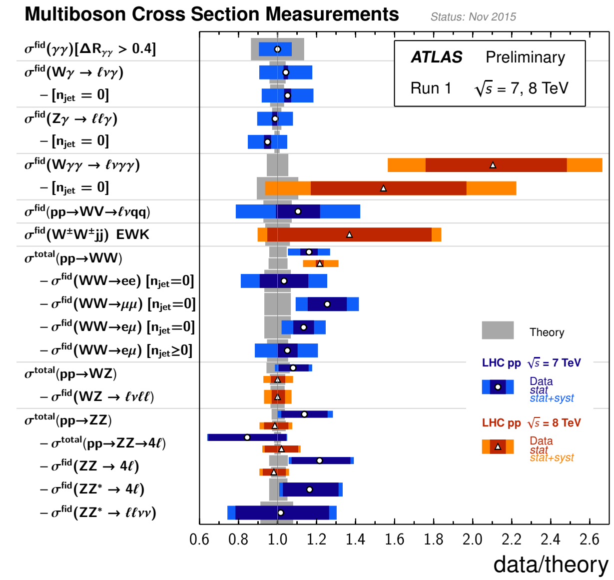
- Important test of the Standard Model
- Large cross section of multiboson production at LHC in pp collisions
- Backgrounds for New Physics and Higgs measurements

Sensitive to theoretical calculation

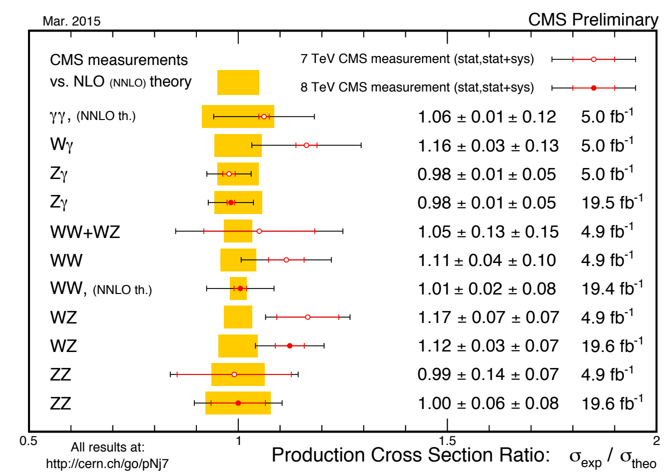
- Large NLO QCD corrections at high √s
- Non-negligible NNLO QCD and NLO QED corrections

Sensitive to new physics

- New particles decaying to vector bosons: W’, Z’, …
- Anomalies in vector boson scattering
- **<u>Anomalies in vector boson couplings (aGC) = indirect search for New Physics</u>**



<u>In most multiboson analysis together with cross section measurement ATLAS and CMS measure anomalous gauge couplings</u>

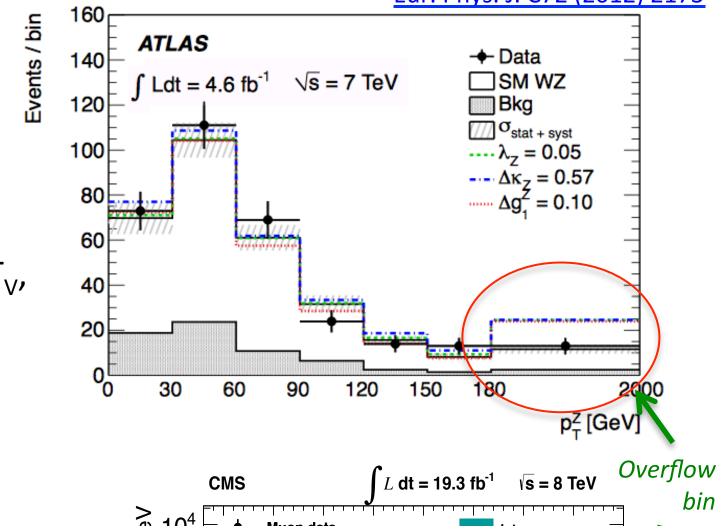


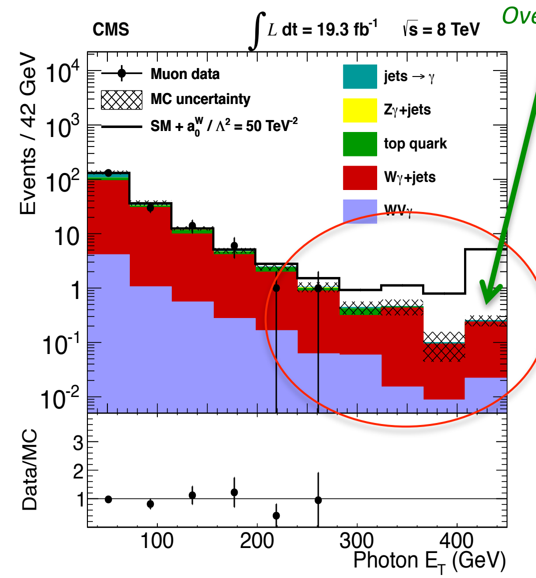
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots, cms-results.web.cern.ch/cms-results/public-results/publications/SMP

Anomalous coupling signature

- Anomalous couplings result in an **increase of cross section at high energies** $(\hat{s})$ -> observables dependent on the invariant mass of the diboson system and the boson p_T are particularly sensitive (m_{VV}, m_{ll}, pT_V, pT_l, …)
- Couplings are measured (or limits are set) by performing **binned fit in single sensitive observable**
- **Sensitivity mostly in highest bins**
  - **Last bin is always overflow bin**
  - **Limiting factor: observed statistics in the tail (primary) and systematic and statistical uncertainty on the signal model (secondary)**
- **Sensitivity depends on absolute size of anomalous coupling signal, absolute size of expected background and uncertainties**
- Binning is optimized to reach highest expected sensitivity

Eur. Phys. J. C72 (2012) 2173





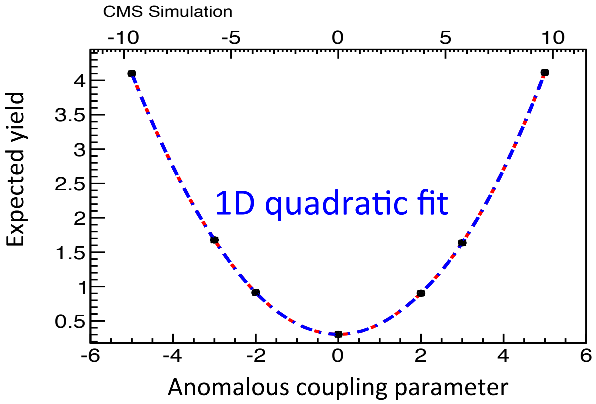
Phys. Rev. D 90, 032008 (2014)

How we measure anomalous couplings (signal model)

Cross section (yield) is a quadratic function of anomalous coupling parameters (α)

$$\sigma_{tot} \propto (\text{anomalous coupling parameter})^2 = \alpha^2\sigma_{aC} + \alpha\sigma_{Int} + \sigma_{SM} \quad (1)$$

signal contribution depends on pT, mass, … -> **different signal modeling in every bin in chosen observable**



Building continuous signal model in parameter space:

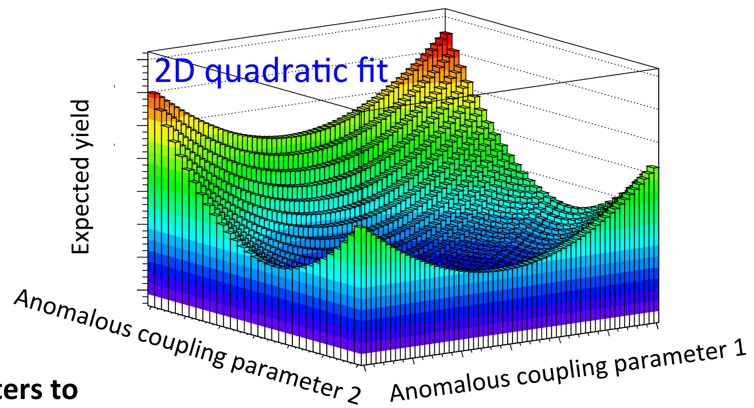
1. **Derive expected signal distributions for several different parameter values using MC generator by:**
   a) Generating several aGC points in the parameter space individually
   b) Generating one sample and reweighting to other a-priori defined aGC points
2. **Performing quadratic fit as a function of parameters in every observable bin**

➔ Parameters in (1)

OR:

Derive ME weights from MC generator

- Parameters in (1) directly from MC generator



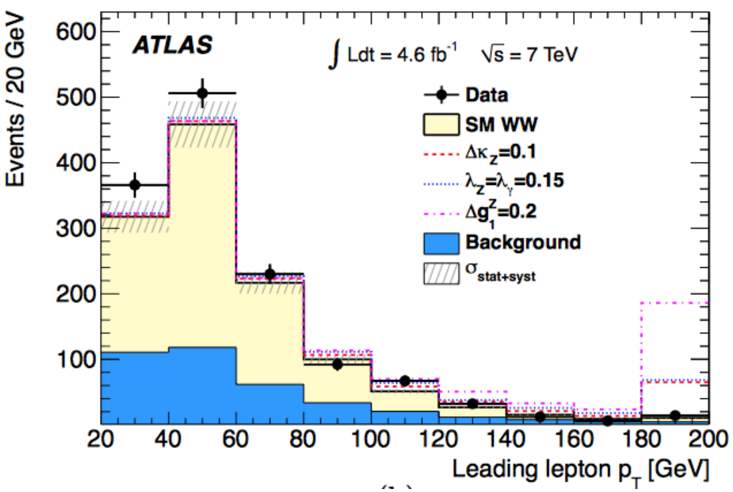
Measurement of parameters is performed in 1D and 2D (fixing all other parameters to SM value) by fitting parameters as parameters of interest

How we measure anomalous couplings (floating parameters)

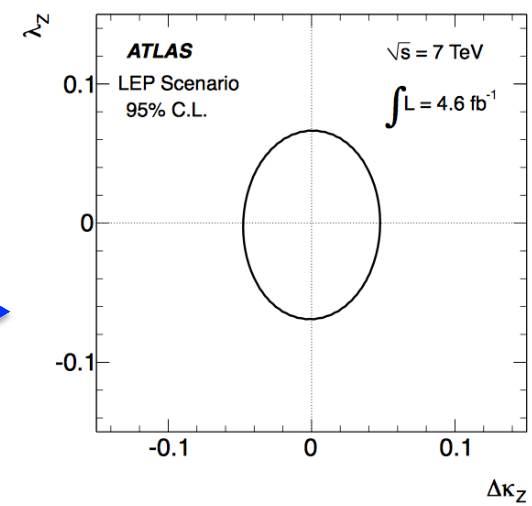
Both Collaborations report 1D and 2D limits.

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	$\Delta\kappa_Z$	$[-0.058, 0.089]$	$[-0.061, 0.093]$	$[-0.057, 0.080]$	$[-0.061, 0.083]$
	$\lambda_Z = \lambda_\gamma$	$[-0.060, 0.062]$	$[-0.062, 0.065]$	$[-0.060, 0.056]$	$[-0.062, 0.059]$

Fitting **single** parameter (1D) while **fixing all other to SM value**



Fitting **two** parameters (2D) simultaneously while **fixing all other to SM value**



Phys. Rev. D 87, 112001 (2013)

Form-factors and parametrizations summary

- In ATLAS limits are set for the case **with form-factor** (Λ=2-6TeV for aTGC and Λ~500GeV for aQGC) **and without form-factor** (equivalent to Λ=∞)
  - k-matrix unitarization for same-sign WW
- In CMS limits are set **without form-factors**

parametrization	**Charged TGC**	**Neutral TGC**	**aQGC**
ATLAS	Effective Lagrangian approach (“LEP”, HISZ, equal couplings) and EFT	Effective vertex approach	EFT Linear (dim 8) parametrization
CMS	Effective Lagrangian approach (“LEP”) and EFT		EFT Linear (dim 8) and EFT non-linear (dim 6) parametrization

Nucl. Phys. B282 (1987) 253, Phys. Rev. D41 (1990) 2113, Phys. Rev. D48 (1993) 2182

Plans for Run II

- Higher collision energy provides better sensitivity for anomalous couplings measurements
- Moving towards EFT approach for anomalous coupling parametrization…
- Combination of limits between ATLAS and CMS
- Combination of limits between multiboson and higgs analysis

✧ **As a result of discussions:**

Do we want to prepare the document with EWK LHC working group recommendations for anomalous coupling measurements for Run II?

- the example of the dark matter working group document "Dark Matter Benchmark Models for Early LHC Run-2 Searches: Report of the ATLAS/CMS Dark Matter Forum?" (http://arxiv.org/abs/1507.00966)
- goal of the document: summary of the parametrization, recommendations on the issue of unitarity, combination (with Higgs), signal modeling and MC generation

Questions from Run II analyzers (I/IV)

To guide discussions during following talks…

Anomalous couplings and EFT:

- the validity of the EFT interpretation of LHC results
  - how to ensure the validity of EFT in Run II measurements?
  - how precise a measurement must be so that limits on higher-dimensional operators can be interpreted as saying something general about new physics?
  - given a set of operators how precise our result has to be for each of these operators so that we can interpret the results as a limit on an EFT?

… specific recommendations for experimentalists to guide our publications plans

Questions from Run II analyzers (II/IV)

To guide discussions during following talks…

<u>Combination of limits between multiboson and higgs analysis</u>

- recommended basis and their availability in MC generators
- which parameters from which final states can be combined
- sensitive observables: shape or normalization only?

… specific recommendations for experimentalists to guide our publications plans

Questions from Run II analyzers (III/IV)

To guide discussions during following talks…

General

- What is the most complete set of parameters?
  - What is the appropriate parametrization of yield as a function of the parameters for variation of 1/2/3 parameters simultaneously?
  - simultaneous multidimensional fits vs single parameters fits. Are single parameter limits useful?
- Translation of specific BSM models to anomalous coupling parameters
- Physical interpretation of operators
- Use of unfolded distributions for anomalous coupling measurements. Inputs on the caveats of using unfolded spectra for setting limits on NP (the most useful kinematic quantities, minimising phase space extrapolations etc.)

… specific recommendations for experimentalists to guide our publications plans

Questions from Run II analyzers (IV/IV)

To guide discussions during following talks…

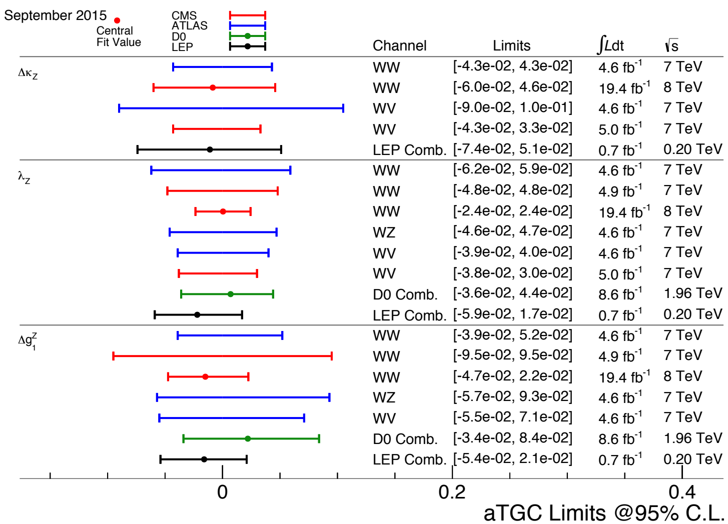
<u>General (NLO)</u>

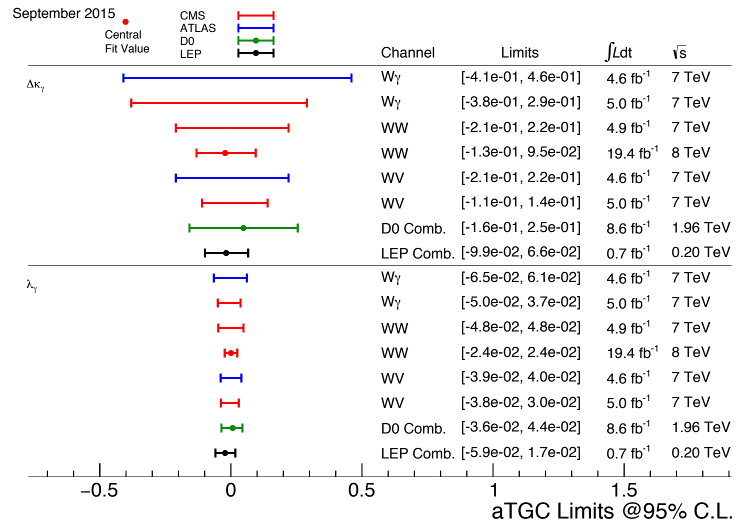
- **QCD NLO corrections for anomalous coupling**
  - if we are not using NLO QCD anomalous coupling calculation (using LO MC) is it safe to apply SM k-factor? Some preliminary studies show anomalous couplings have k-factors different from SM.
  - **NNLO QCD** corrections can be substantial in certain areas of the phase space. Should this be taken into account? Is it possible to get differential k-factors in variables of interest to aCs such as vector boson pT or m_VV?
- **Anomalous coupling MC reweighting tools**
  - LO QCD anomalous coupling reweighting is available in MG, what are the limitations and important points to know
  - Status and plans of NLO QCD anomalous coupling reweighting tools
- **QED NLO corrections for anomalous couplings are not available**
  - Is it safe to apply EWK correction for SM on anomalous couplings?
  - Recommendations to approximate the effect?
  - Should we use QED LO and asign systematic uncertainty?

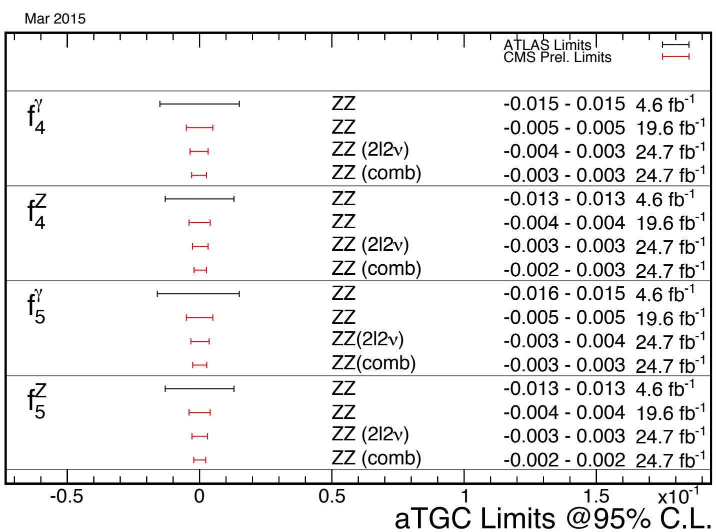
… specific recommendations for experimentalists to guide our publications plans

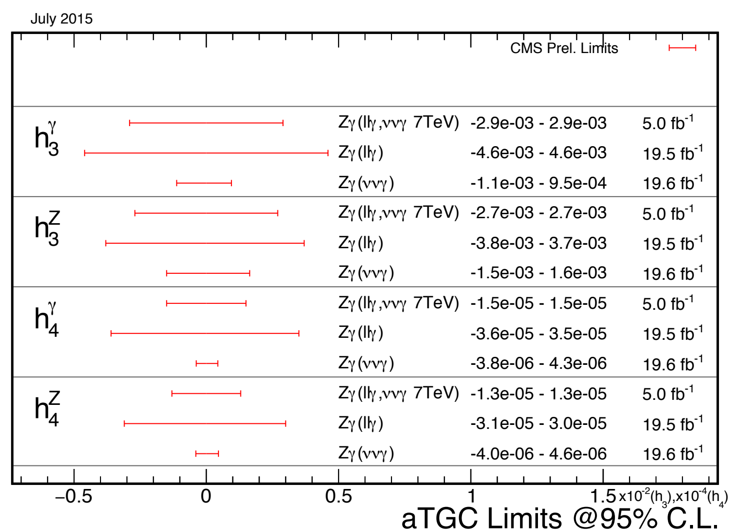
Backup

aTGC public results Run I summary



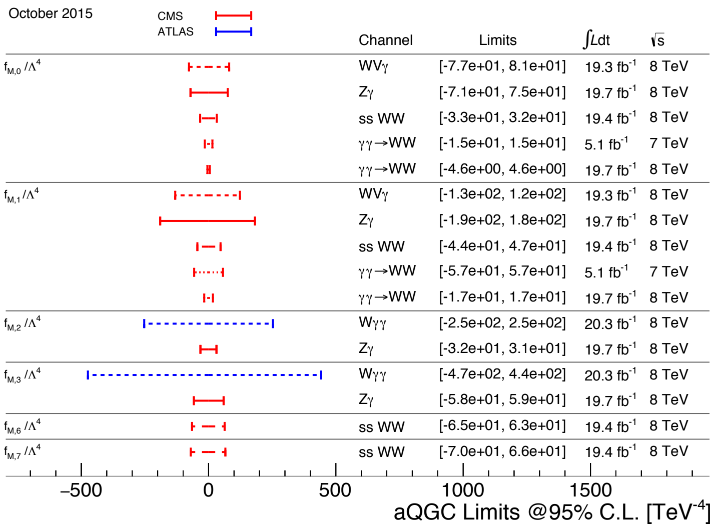


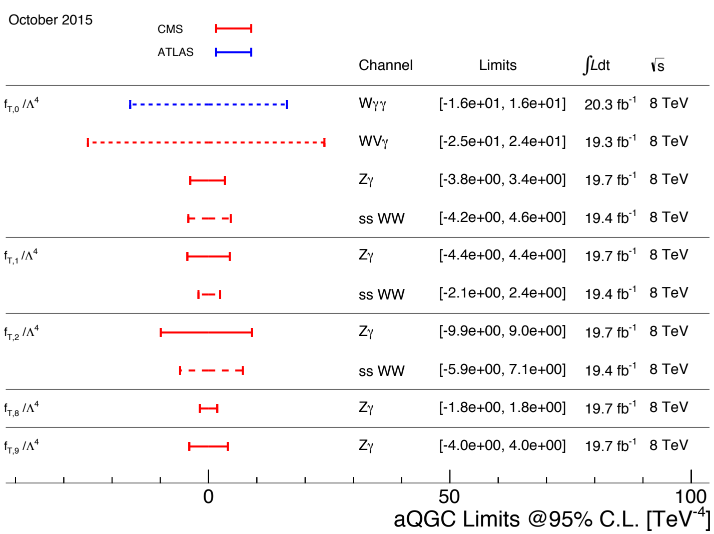


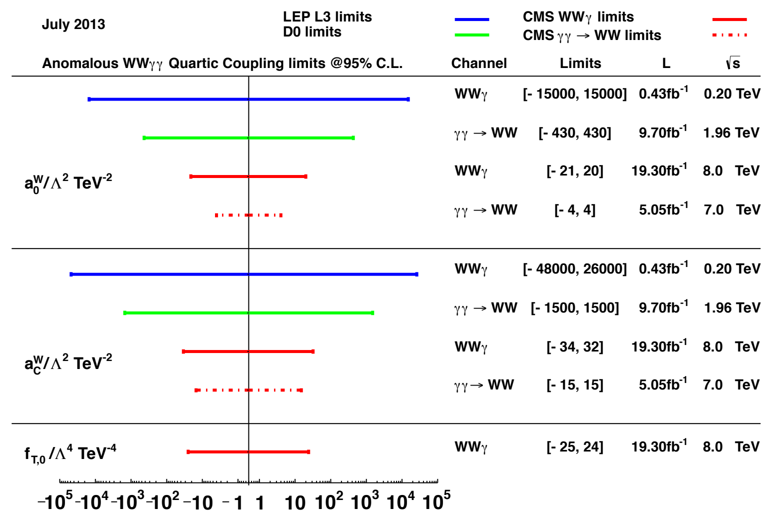


https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMPaTGC

aQGC public results Run I summary







https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMPaTGC

Anomalous couplings as search for New Physics?

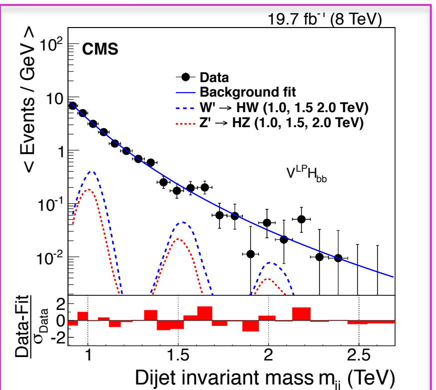
Two general ways to look for deviations from the SM:

a) Assume a specific model of New Physics: SUSY scenario, dark matter, … — Anomalous coupling measurement

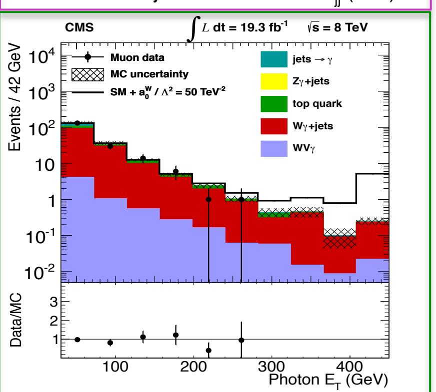
b) Look for model independent deviations and measure “the deviation from SM” (deviations still have to be parametrized)

And also choose between:

1. Looking for a peak in observed distribution — Anomalous coupling measurement
2. Looking for a deviation in the tails of observed distribution (broad deviation)



Submitted to JHEP
arXiv:1506.01443



Phys. Rev. D 90, 032008 (2014)

Lagrangian that we feel at low energies can be expressed as the SM + additional terms

- **Effective vertex approach** (used in ZZ and Zγ analyses) — Nucl. Phys. B282 (1987) 253

$$\Gamma^{\alpha\beta\mu}_{Z_1 Z_2 V} = i\, e \frac{q_V^2 - m_V^2}{m_Z^2} \left\{ f_4^V \left(q_V^\alpha\, g^{\beta\mu} + q_V^\beta\, g^{\mu\alpha}\right) + f_5^V\, \epsilon^{\alpha\beta\mu\rho}\left(q_{Z_1\rho} - q_{Z_2\rho}\right) \right\}$$

$$\Gamma^{\alpha\beta\mu}_{Z\gamma V} = i\, e \frac{q_V^2 - m_V^2}{m_Z^2} \left\{ h_1^V \left(q_\gamma^\mu g^{\alpha\beta} - q_\gamma^\alpha g^{\beta\mu}\right) + h_2^V \frac{q_V^\alpha}{m_Z^2}\left(q_\gamma q_V\, g^{\beta\mu} - q_\gamma^\mu\, q_V^\beta\right) + h_3^V\, \epsilon^{\alpha\beta\mu\rho}\, q_{\gamma\rho} + h_4^V \frac{q_V^\alpha}{m_Z^2}\, \epsilon^{\mu\beta\rho\sigma}\, q_{V\rho}\, q_{\gamma\sigma} \right\}$$

- **Effective Lagrangian approach=’phenomenological Lagrangian’** (WV analyses) — Phys. Rev. D41 (1990) 2113

$$\mathcal{L}_{SM} \longrightarrow \mathcal{L}_{WWV} = -ig_{WWV}\Big\{ g_1^V\left(W^+_{\mu\nu}W^{-\mu}V^\nu - W^+_\mu V_\nu W^{-\mu\nu}\right) + \kappa_V W^+_\mu W^-_\nu V^{\mu\nu} + \frac{\lambda_V}{m_W^2} W^+_{\mu\nu} W^{-\nu\rho} V_\rho{}^\mu - i g_5^V \epsilon^{\mu\nu\rho\sigma}\left[W^+_\mu(\partial_\rho W^-_\nu) - (\partial_\rho W^+_\mu)W^-_\nu\right]V_\sigma \Big\},$$

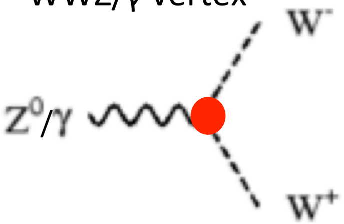
- **Effective Field Theory (EFT) approach** (WW analysis, VBF analyses and triboson analyses) — Phys. Rev. D48 (1993) 2182

$$\mathcal{L}_{SM} \longrightarrow \mathcal{L}_{eff} = \mathcal{L}_{SM} + \sum_{n=1}^{\infty}\sum_i \frac{c_i^{(n)}}{\Lambda^n}\mathcal{O}_i^{(n+4)}$$

Anomalous coupling parametrizations (aTGC)

Using additional assumptions to reduce the number of parameters

WWZ/γ vertex



Nucl. Phys. B282 (1987) 253.
Phys. Rev. D41 (1990) 2113

EFFECTIVE LAGRANGIAN PARAMETRIZATION

allow the couplings of SM operators to vary + add higher order operators that respect symmetries

(Hagiwara *et al.*, Nucl.Phys.B282:253,1987)

$$\begin{aligned}\Gamma^{\alpha\beta\mu}_{WWV} &= (1+\Delta g_1^V)[(q_1-q_2)^\mu g^{\alpha\beta} - q_1^\beta g^{\mu\alpha} + q_2^\alpha g^{\mu\beta}] \\ &+ (1+\Delta\kappa_V)[q_2^\alpha g^{\mu\beta} - q_1^\beta g^{\mu\alpha}] \\ &+ \frac{\lambda_V}{m_W^2}(q_1-q_2)^\mu\,[\frac{s}{2}g^{\alpha\beta} - q_2^\alpha q_1^\beta] \\ &+ i\, g_5^V\, \epsilon^{\mu\alpha\beta\rho}\,(q_1-q_2)_\rho\end{aligned}$$

Assumptions (14->3 independent parameters):
Electromagnetic gauge invariance, C and P conservation, Lagrangian SU(2)XU(1) invariant

$$\Delta g_1^Z = \Delta\kappa_Z + \tan^2\theta_W \Delta\kappa_\gamma \qquad \Delta g_1^Z = g_1^Z - 1,\ \Delta\kappa_{\gamma,Z} = \kappa_{\gamma,Z} - 1$$

valid for: $\sqrt{s} << \Lambda$
SU(3)xSU(2)xU(1) invariance by construction
Λ is large, of the order of the scale of New Physics
terms supressed by $\propto \frac{\sqrt{s}}{\Lambda}$
only the first terms are relevant
O_i are operator of (energy) "dimension n"
c_i are adimensional couplings of order ~ 1
allows systematic calculation of higher order corrections

EFFECTIVE FIELD THEORY PARAMETRIZATION

infinite sum of (non-renormalizable) Lagrangians:

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \sum_{n=1}^{\infty}\sum_i \frac{c_i^{(n)}}{\Lambda^n}\mathcal{O}_i^{(n+4)}$$

Assumptions (5->3 independent parameters):
CP conservation

$$\begin{aligned}\mathcal{O}_{WWW} &= \mathrm{Tr}[W_{\mu\nu}W^{\nu\rho}W_\rho^\mu] \\ \mathcal{O}_W &= (D_\mu\Phi)^\dagger W^{\mu\nu}(D_\nu\Phi) \\ \mathcal{O}_B &= (D_\mu\Phi)^\dagger B^{\mu\nu}(D_\nu\Phi)\end{aligned}$$

'HISZ' parametrization

Translation betwen two approaches:

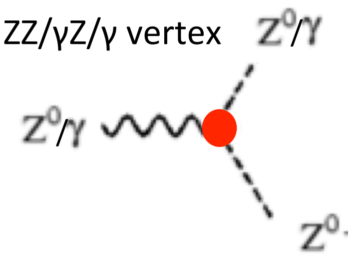
$$\begin{aligned}g_1^Z &= 1 + c_W\frac{m_Z^2}{2\Lambda^2} \\ \kappa_\gamma &= 1 + (c_W + c_B)\frac{m_W^2}{2\Lambda^2} \\ \kappa_Z &= 1 + (c_W - c_B\tan^2\theta_W)\frac{m_W^2}{2\Lambda^2} \\ \lambda_\gamma &= \lambda_Z = c_{WWW}\frac{3g^2m_W^2}{2\Lambda^2}\end{aligned}$$

channel	couplings	parametrization	parameters	Dimensionality of operator
WV	ZWW, γWW	Effective Lagrangian	$\Delta\kappa$	dim4
	ZWW, γWW		λ	dim6
	ZWW		Δg^1_Z	dim4
	ZWW, γWW	Effective field theory	c_{WWW}/Λ^2	dim6
			c_B/Λ^2	dim6
			c_W/Λ^2	dim6

Anomalous coupling parametrizations (aTGC)

Using additional assumptions to reduce the number of parameters

ZZ/γZ/γ vertex



EFFECTIVE VERTEX PARAMETRIZATION

add higher order operators that respect symmetries

Nucl.Phys. B282 (1987) 253

Assumptions Zγ channel: CP conservation

(Hagiwara *et al.*, Nucl.Phys.B282 (1987) 253 (+ missing "*i*" factor))

$$\Gamma^{\alpha\beta\mu}_{Z\gamma V} = i\, e \frac{q_V^2 - m_V^2}{m_Z^2} \{ h_1^V \, (q_\gamma^\mu g^{\alpha\beta} - q_\gamma^\alpha g^{\beta\mu}) + h_2^V \frac{q_V^\alpha}{m_Z^2} (q_\gamma q_V \, g^{\beta\mu} - q_\gamma^\mu \, q_V^\beta) + h_3^V \, \epsilon^{\alpha\beta\mu\rho} \, q_{\gamma\rho} + h_4^V \frac{q_V^\alpha}{m_Z^2} \epsilon^{\mu\beta\rho\sigma} \, q_{V\rho} \, q_{\gamma\sigma} \}$$

Assumptions ZZ channel: Electromagnetic gauge invariance

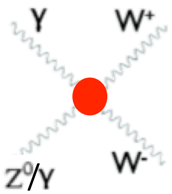
(Hagiwara *et al.*, Nucl.Phys.B282:253,1987)

$$\Gamma^{\alpha\beta\mu}_{Z_1 Z_2 V} = i\, e \frac{q_V^2 - m_V^2}{m_Z^2} \{ f_4^V \, (q_V^\alpha \, g^{\beta\mu} + q_V^\beta \, g^{\mu\alpha}) + f_5^V \, \epsilon^{\alpha\beta\mu\rho} \, (q_{Z_1\rho} - q_{Z_2\rho}) \}$$

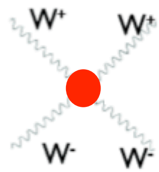
channel	couplings	parametrization	parameters	Dimensionality of operator
Zγ	ZZγ, γZγ	Effective vertex	h_3	dim6
			h_4	dim8
ZZ	ZZZ, γZZ		f_4	dim6
			f_5	dim6

Anomalous coupling parametrizations (aQGC)

γZ/γWW vertex



WWWW vertex



EFFECTIVE FIELD THEORY PARAMETRIZATION

add higher order operators that respect symmetries

Two formalisms are used in quartic coupling measurements: linear and non-linear formalism.

arXiv: hep-ph 9908254

Assumptions: CP conservation

NON-LINEAR FORMALISM (also used by LEP)

- Spontaneous symmetry breaking without a Higgs boson
- Non-decoupling: Valid below a ~3 TeV scale
- dim6 operators
- **Used for aQGC measurements for comparison with previous results**

Numerous operators:
a_0^W/Λ^2, a_C^W/Λ^2, κ_0^W/Λ^2, κ_C^W/Λ^2, …

Translation between two approaches:

$$\frac{a_0^W}{\Lambda^2} = -\frac{4M_W^2}{g^2}\frac{f_{M,0}}{\Lambda^4} - \frac{8M_W^2}{g'^2}\frac{f_{M,2}}{\Lambda^4},$$

$$\frac{a_C^W}{\Lambda^2} = \frac{4M_W^2}{g^2}\frac{f_{M,1}}{\Lambda^4} + \frac{8M_W^2}{g'^2}\frac{f_{M,3}}{\Lambda^4},$$

$$\frac{f_{M,0}}{\Lambda^4} = -\frac{g^4}{M_W^2}\frac{k_0^w}{\Lambda^2}, \qquad \frac{f_{M,1}}{\Lambda^4} = \frac{g^4}{M_W^2}\frac{k_c^w}{\Lambda^2}$$

$$\frac{f_{M,2}}{\Lambda^4} = -\frac{g^2 g'^2}{2M_W^2}\frac{k_0^b}{\Lambda^2}, \qquad \frac{f_{M,3}}{\Lambda^4} = \frac{g^2 g'^2}{2M_W^2}\frac{k_c^b}{\Lambda^2}$$

LINEAR FORMALISM arXiv: hep-ph 0606118

- Spontaneous symmetry breaking with a Higgs boson
- Decoupling: scale of New Physics is arbitrary large
- SM allowed vertices introduced at dim6
  - The same operators that affect aTGC -> these are better measured
  - Lowest independent aQGC operators (not affecting aTGC) are dim8 -> **used for aQGC measurements**

Numerous operators:
$f_{T,0}/\Lambda^4$, $f_{M,0}/\Lambda^4$, $f_{M,1}/\Lambda^4$, …

channel	couplings	parametrization	parameters	Dimensionality of operator
WVγ	WWγγ	Effective field theory	a_0^W/Λ^2, a_C^W/Λ^2, …	dim6
	WWZγ		κ_0^W/Λ^2, κ_C^W/Λ^2, …	dim6
	WWγγ, WWZγ		$f_{T,0}/\Lambda^4$, $f_{M,0}/\Lambda^4$, $f_{M,1}/\Lambda^4$, …	dim8
WW EWK	WWWW		$f_{S,0}/\Lambda^4$, $f_{S,1}/\Lambda^4$, $f_{M,0}/\Lambda^4$, …	dim8

Anomalous coupling parametrizations: EFT summary

dim6 operators and vertices (aTGC and aQGC)

	$\mathcal{O}_{WWW}$	$\mathcal{O}_{WW}$	$\mathcal{O}_{W}$	$\mathcal{O}_{BB}$	$\mathcal{O}_{B}$	$\mathcal{O}_{\tilde{B}}$	$\mathcal{O}_{\tilde{B}B}$	$\mathcal{O}_{\tilde{W}W}$	$\mathcal{O}_{\tilde{W}WW}$	$\mathcal{O}_{\tilde{D}W}$
WWZ	×		×		×	×			×	×
WWA	×		×		×	×			×	×
ZZH		×	×	×		×	×	×		
WWH		×	×					×		
AAH		×		×			×	×		
AZH		×	×	×	×	×	×	×		
WWWW	×		×						×	×
WWZZ	×		×						×	×
WWAA	×								×	×
WWAZ	×		×						×	×
WWHH		×	×					×		
ZZHH		×	×	×	×	×	×	×		
AZHH		×	×	×	×	×	×	×		
AAHH		×		×			×	×		

dim8 operators and vertices in linear parametrization (aQGC, no aTGC)

	WWWW	WWZZ	ZZZZ	WWAZ	WWAA	ZZZA	ZZAA	ZAAA	AAAA
$\mathcal{O}_{S,0/1}$	✓	✓	✓						
$\mathcal{O}_{M,0/1/6/7}$	✓	✓	✓	✓	✓	✓	✓		
$\mathcal{O}_{M,2/3/4/5}$		✓	✓	✓	✓	✓	✓		
$\mathcal{O}_{T,0/1/2}$	✓	✓	✓	✓	✓	✓	✓	✓	✓
$\mathcal{O}_{T,5/6/7}$		✓	✓	✓	✓	✓	✓	✓	✓
$\mathcal{O}_{T,8/9}$			✓			✓	✓	✓	✓