Latest results on anomalous gauge couplings in ATLAS

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June 15, 2015
PHOTON2015, Novosibirsk

Probing the Standard Model at the Large Hadron Collider

At the LHC:
Probing the Standard Model by measuring processes containing the predicted interactions

Electroweak sector:

- Interaction of fermions through gauge bosons
- Non-Abelian nature of $SU(2)_L \times U(1)_Y$ allows for self-interactions of the gauge bosons

$\Rightarrow$ Triple and quartic gauge interactions

Allowed are vertices with charged gauge couplings: WWZ, $WW\gamma$, $WWWW$, $WWZZ$, $WWZ\gamma$, $WW\gamma\gamma$

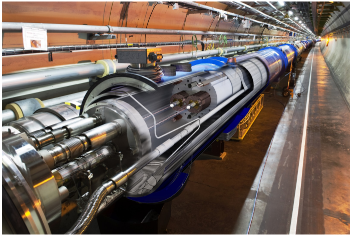
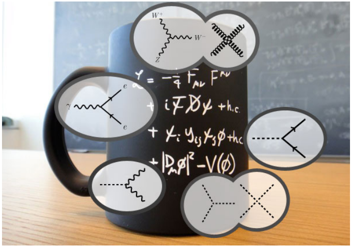


Image: CERN



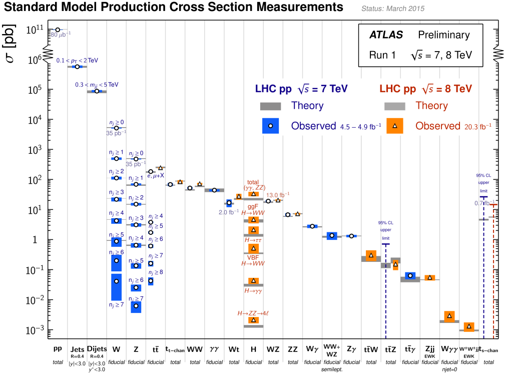
http://www.quantumdiaries.org

The case for an effective field theory

LHC measurements:

well described by the SM

BUT:
open questions remain
→ DARK MATTER?
→ HIERARCHY PROBLEM?
→ HIGGS PROPERTIES?
...



Goal: Assess contributions of new physics

- Quantify deviations from SM (for search or exclusion)

... in a model independent way

... interpret deviations in terms of models

→ effective field theory

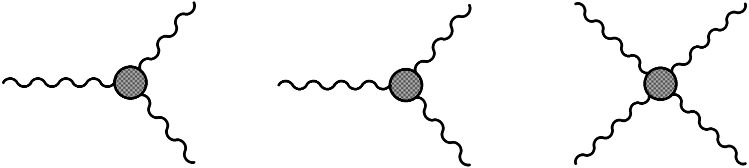
Effective field theory with anomalous gauge couplings

Introduce additional operators $\mathcal{O}$ of higher dimension (d) and add to SM-Lagrangian:

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \sum_d \sum_i \frac{c_i^{(d)}}{\Lambda^{d-4}} \mathcal{O}_i^{(d)}$$

Λ: scale of new physics

⇒ anomalous triple and quartic gauge couplings in the effective Lagrangian
⇒ lead to increase in total and differential cross sections



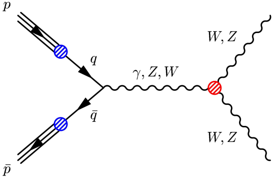
charged TGC   neutral TGC   QGC

Resulting amplitudes need to be **unitarized**

Experimental strategy

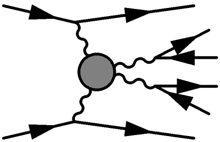
Measurements provide the opportunity to assess compatibility of anomalous couplings models with data

Diboson production



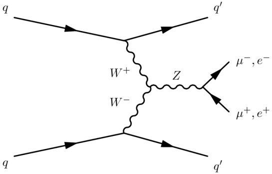
triple gauge couplings (neutral and charged)

Vector boson scattering



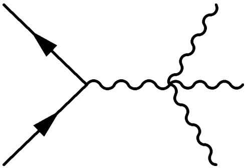
triple and quartic gauge couplings (with or without photons)

Vector boson fusion



triple gauge couplings (neutral and charged)

Triple boson production



quartic gauge couplings (with or without photons)

Triple gauge couplings

- SM: charged TGC; no neutral TGC
- BSM: modelled by **effective Lagrangian** with anomalous TGC parameters
  imposed constraints: C and P conservation, electromagnetic gauge invariance

5 charged couplings (cTGC):

$$\mathcal{L}_{WWV}/g_{WWV} = ig_1^V(W^\dagger_{\mu\nu}W^\mu V^\nu - W^\dagger_\mu V_\nu W^{\mu\nu}) + i\kappa_V W^\dagger_\mu V^{\mu\nu} + \frac{i\lambda_V}{m_W^2} W^\dagger_{\lambda\mu} W^\mu_\nu V^{\nu\lambda}$$

$g_1^Z, \kappa_Z, \kappa_\gamma, \lambda_Z$, and λ_γ

SM case:
$g_1^Z = \kappa_Z = \kappa_\gamma = 1$;
$\lambda_Z = \lambda_\gamma = 0$

8 neutral couplings (nTGC):

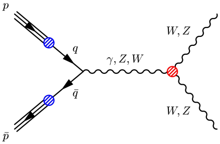
$$\mathcal{L}_{ZZV} = -\frac{e}{m_Z^2}[f_4^V(\partial_\mu V^{\mu\beta})Z_\alpha(\partial^\alpha Z_\beta) + f_5^V(\partial^\sigma V_{\sigma\mu})\tilde{Z}^{\mu\beta}Z_\beta]$$

$h_3^V, h_4^V, f_4^V, f_5^V$ with $V = Z, \gamma$

all $h_i^V = 0$ in SM

Several **scenarios** constrain the dependencies to reduce the number of free parameters
e.g. LEP scenario: $\Delta\kappa_\gamma = (\cos^2\theta_W/\sin^2\theta_W)(\Delta g_1^Z - \Delta\kappa_Z)$ and $\lambda_Z = \lambda_\gamma$

TGC in diboson production



Parameters' accessibility by channel:

aTGC vertex	parameters	channel
WWγ	$\lambda_\gamma, \Delta\kappa_\gamma$	WW, Wγ
WWZ	$\lambda_Z, \Delta\kappa_Z, \Delta g_1^Z$	WW, WZ
ZZγ	h_3^Z, h_4^Z	ZZ
Z$\gamma\gamma$	h_3^γ, h_4^γ	Zγ
ZγZ	f_4^Z, f_5^Z	Zγ
ZZZ	f_4^γ, f_5^γ	ZZ

Triple gauge couplings in WW, WZ production

- WW, WZ channels: sensitive to cTGC parameters $\lambda_Z, \Delta\kappa_Z, \Delta g_1^Z$
- 3 measurements:
  - $WW \to \ell\nu\ell\nu$
  - $WZ \to \ell\ell\nu$
  - $WV \to \ell\nu jj$

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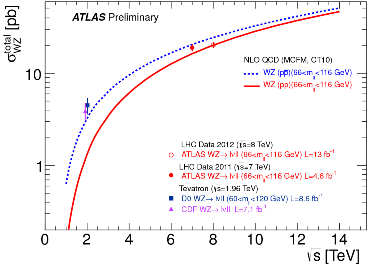
WW, WZ: Leptonic channels

Measurement of $W^\pm Z \to \ell^\pm \nu \ell^\pm \ell^\mp$ production

Event selection:
3 high-p_{T} isolated leptons,
large $E_{\mathrm{T}}^{\mathrm{miss}}$ and m_T^W

Backgrounds
Z+jets, top (fake leptons):
data-driven estimate
ZZ, W/Z + γ:
estimate from simulation



Measurement at $\sqrt{s} = 8\,\mathrm{TeV}$
(ATLAS-CONF-2013-021)

WW, WZ: Leptonic channels

Measurement of $W^+W^- \to \ell^+\nu\ell^-\bar{\nu}$ production

Event selection:

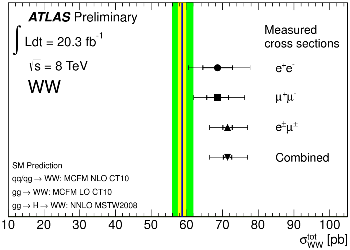
- 2 high-p_T isolated leptons, opposite charge
- Z-mass veto
- large E_T^{miss}, $E_{T,Rel}^{miss}$
- jet veto

Backgrounds

top (b-tagged):
data driven estimate

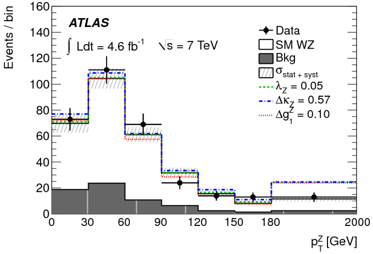
W+jets (fake leptons):
data driven

Z+jets:
transfer factor from control region



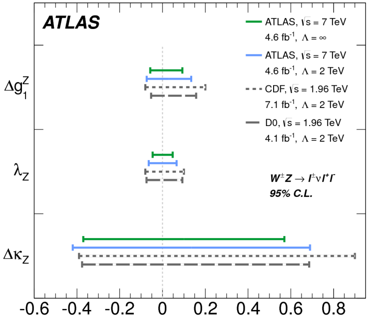
Measurement at $\sqrt{s} = 8$ TeV
(ATLAS-CONF-2014-033)

Limits on aTGC from $WZ \to \ell\ell\ell\nu$



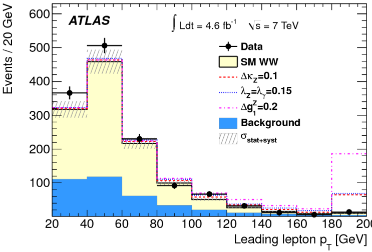
Extraction of aTGC limits from $p_{\mathrm{T}}(Z)$ spectrum

aTGC limits based on $\sqrt{s} = 7$ TeV measurement
Eur. Phys. J. C (2012) 72:2173

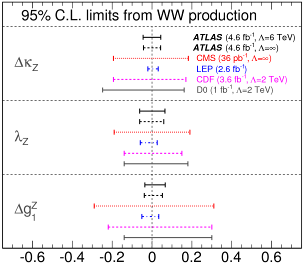


Limits on aTGC from $W^+W^- \to \ell^+\nu\ell^-\bar{\nu}$

aTGC limits
extracted from the p_{T} distribution of the highest-p_{T} charged lepton



Limits based on
$\sqrt{s} = 7\,\mathrm{TeV}$, $\mathcal{L} = 4.6\,\mathrm{fb}^{-1}$:
Phys.Rev. D87, 112001 (2013)

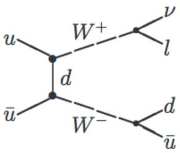


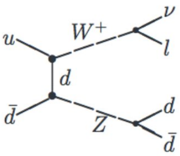
Limits on charged aTGC for WWZ and $WW\gamma$ (LEP scenario)

WW/WZ in the single lepton final state

$\sqrt{s} = 7\,\text{TeV}$, $\mathcal{L} = 4.7\,\text{fb}^{-1}$: JHEP01(2015)049

Semi-leptonic WW/WZ $\to \ell\nu qq'$





+larger branching ratio

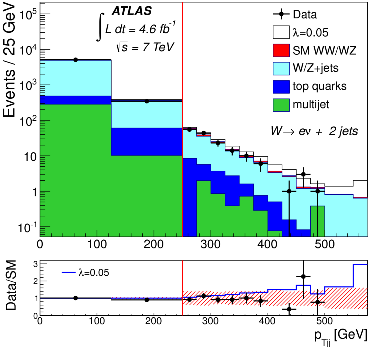
−large background from W/Z+jets

Event selection:
one high-p_{T} isolated lepton, $E_{\mathrm{T}}^{\mathrm{miss}}$, $m_T(\ell, E_{\mathrm{T}}^{\mathrm{miss}})$
2 jets, well separated

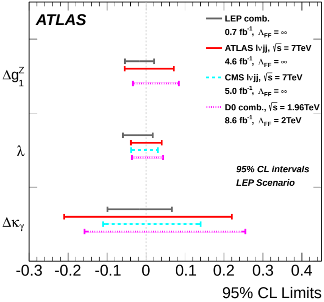
Dominating background ***W*/*Z*+jets**: Estimated from data

WW/WZ in the single lepton final state

$\sqrt{s} = 7\,\text{TeV}$, $\mathcal{L} = 4.7\,\text{fb}^{-1}$: JHEP01(2015)049



binned maximum-likelihood fit to the p_{Tjj} spectrum to extract aTGC limits



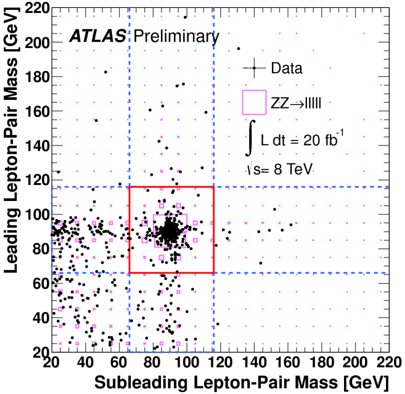
Limits on aTGC parameters in the LEP scenario

$ZZ \to 4\ell$

$\sqrt{s} = 8$ TeV. $\mathcal{L} = 20\,\text{fb}^{-1}$: ATLAS-CONF-2013-020

Event selection:
4 leptons very clean channel

- 4 isolated leptons
- combined to same-flavor, opposite charge pairs
- Z-mass window



Dominant background: $W^\pm/Z + X$ ($X = \gamma$ or jets - misidentified)
data-driven estimate

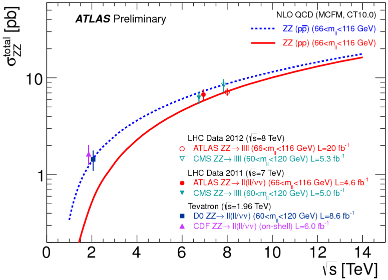
Signal yields:

Data events: **305**
Signal expectation: **292.5 $\pm$10.6**
Background expectation: **20.4 $\pm$ 5.8**

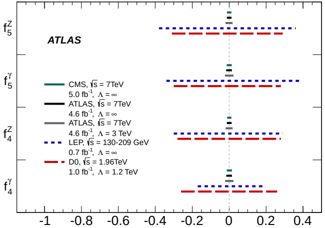
"golden channel"

$ZZ \to 4\ell$

$\sqrt{s} = 8\,\text{TeV}$, $\mathcal{L} = 20\,\text{fb}^{-1}$: ATLAS-CONF-2013-020



aTGC based on
$\sqrt{s} = 7\,\text{TeV}$, $\mathcal{L} = 1.02\,\text{fb}^{-1}$
(*Phys. Rev. Lett. 108 (2012) 041804*):
using total number of observed events



Limits on neutral aTGC

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$W\gamma$, $Z\gamma$

$\sqrt{s} = 7\,\text{TeV}$, $\mathcal{L} = 4.6\,\text{fb}^{-1}$: Phys. Rev. D 87, 112003 (2013)

Three decay channels: $W\gamma \to \ell\nu\gamma$, $Z\gamma \to \ell^+\ell^-\gamma$, $Z\gamma \to \nu\bar{\nu}\gamma$

$W\gamma \to \ell\nu\gamma$

1 high-p_T lepton,
1 high-E_T photon,
high E_T^miss,
high $m_T(\ell, E_\text{T}^\text{miss})$

$Z\gamma \to \ell^+\ell^-\gamma$

2 opp. charge, same flavor leptons,
high M_{ll},
1 high-E_T photon

$Z\gamma \to \nu\bar{\nu}\gamma$

1 very high-E_T photon ($E_T^\gamma > 100\,\text{GeV}$),
high E_T^miss
large $\Delta\Phi(E_\text{T}^\text{miss}, \gamma)$

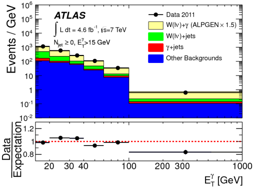
Limits on aTGC parameters set by fitting to the E_T^γ distributions

$W\gamma, Z\gamma$

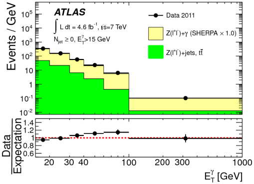
$\sqrt{s} = 7\,\text{TeV}$, $\mathcal{L} = 4.6\,\text{fb}^{-1}$: Phys. Rev. D 87, 112003 (2013)

Three decay channels: $W\gamma \to \ell\nu\gamma$, $Z\gamma \to \ell^+\ell^-\gamma$, $Z\gamma \to \nu\bar{\nu}\gamma$

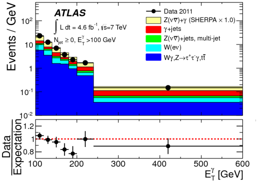
$W\gamma \to \ell\nu\gamma$



$Z\gamma \to \ell^+\ell^-\gamma$



$Z\gamma \to \nu\bar{\nu}\gamma$

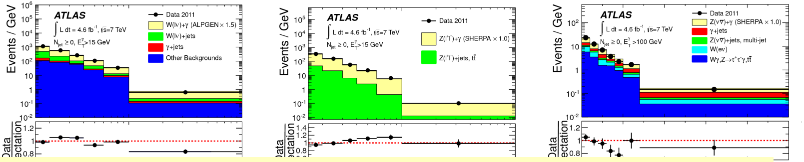


$W\gamma$, $Z\gamma$

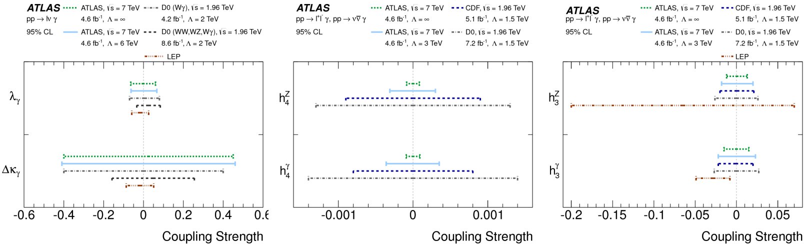
$\sqrt{s} = 7$ TeV, $\mathcal{L} = 4.6$,fb^{-1}: Phys. Rev. D 87, 112003 (2013)

Three decay channels: $W\gamma \to \ell\nu\gamma$, $Z\gamma \to \ell^+\ell^-\gamma$, $Z\gamma \to \nu\bar{\nu}\gamma$

$W\gamma \to \ell\nu\gamma$ | $Z\gamma \to \ell^+\ell^-\gamma$ | $Z\gamma \to \nu\bar{\nu}\gamma$



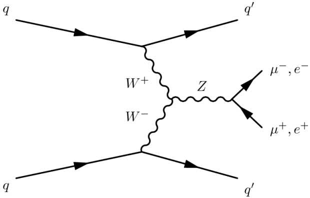
Limits on charged and neutral aTGCs:



Vector boson fusion to Z boson

$\sqrt{s} = 8\,\mathrm{TeV}$, $\mathcal{L} = 20\,\mathrm{fb}^{-1}$: JHEP04(2014)031

First ATLAS measurement of a **VBF** $\rightarrow$ **Vector Boson** process

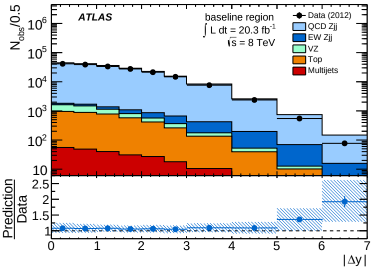


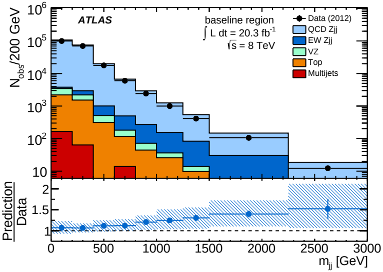
Selection

Z-boson candidate: $81 \leq m_{\ell\ell} \leq 101\,\mathrm{GeV}$

$p_\mathrm{T}(j1) > 55\,\mathrm{GeV}$, $p_\mathrm{T}(j2) > 45\,\mathrm{GeV}$, $M_{jj} > 250\,\mathrm{GeV}$

jet veto on jets with $p_\mathrm{T} > 25\,\mathrm{GeV}$ in rapidity gap of tagging jets



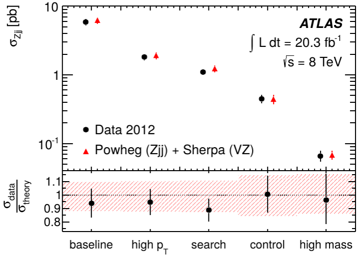


Extract electroweak component by a fit to the dijet invariant mass distribution

Vector boson fusion to Z boson

$\sqrt{s} = 8\,\text{TeV}$, $\mathcal{L} = 20\,\text{fb}^{-1}$: JHEP04(2014)031

Measurement:



search region: $M_{jj} > 1000\,\text{GeV}$

Limits on charged aTGC in the search region

aTGC	$\Lambda = 6$ TeV (obs)	$\Lambda = 6$ TeV (exp)	$\Lambda = \infty$ (obs)	$\Lambda = \infty$ (exp)
$\Delta g_{1,Z}$	$[-0.65, 0.33]$	$[-0.58, 0.27]$	$[-0.50, 0.26]$	$[-0.45, 0.22]$
λ_Z	$[-0.22, 0.19]$	$[-0.19, 0.16]$	$[-0.15, 0.13]$	$[-0.14, 0.11]$

Λ: scale of new physics in form-factor used for unitarization

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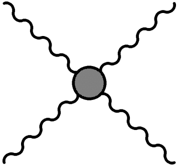
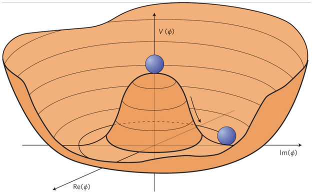
Quartic gauge couplings



Quartic gauge vertex



Quartic vertices with photons ($WW\gamma\gamma$, $WWZ\gamma$)

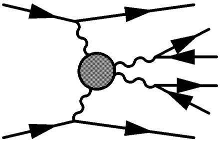
- Charged vertices with photons predicted by electroweak theory → no Higgs contributions → study gauge structure
- Neutral vertices: not allowed by the SM

Quartic vertices with massive electroweak gauge bosons ($WWWW$, $WWZZ$)

- Longitudinal degrees of freedom of electroweak gauge bosons are generated through the Higgs mechanism → study the electroweak symmetry breaking mechanism in addition to the electroweak gauge structure
- Neutral vertices: not allowed by the SM

Scattering of two like-charge W bosons

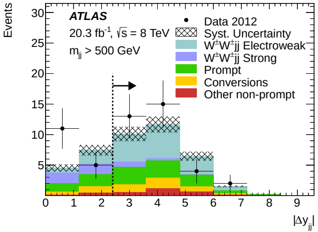
$\sqrt{s} = 8\,\text{TeV}$, $\mathcal{L} = 20\,\text{fb}^{-1}$:Phys. Rev. Lett. 113, 141803

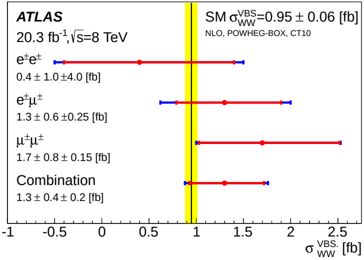


Electroweak production of $\ell^\pm \nu \ell^\pm \nu jj$

Selection:
$M_{jj} > 500$ GeV (inclusive region)
+ $\Delta Y(jj) > 2.4$ (VBS region)
Extract electroweak production of $W^\pm W^\pm jj$

$\Rightarrow$ First evidence of $W^\pm W^\pm$ scattering and $W^\pm W^\pm jj$ production





Scattering of two like-charge W bosons

Limits on anomalous quartic gauge coupling ($WWWW$ vertex)

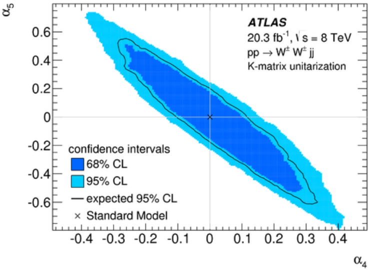
derived from fiducial cross sections
Electroweak chiral Lagrangian with the operators

$$\mathcal{L}_4 = \alpha_4(\mathrm{tr}[\mathbf{V}_\mu \mathbf{V}_\nu])^2$$

and

$$\mathcal{L}_5 = \alpha_5(\mathrm{tr}[\mathbf{V}_\mu \mathbf{V}^\mu])^2$$

with parameters α_4 and α_5,
unitarized using K-Matrix unitarization



One-dimensional limits at 95 % C.L. :

$$\alpha_4 \in [-0.14, 0.16]$$
$$\alpha_5 \in [-0.23, 0.24]$$

⇒ First limits on aQGC with massive electroweak vector bosons

- Scale of new physics [hep-ph:1307.8170]:

$$\Lambda \sim v/\sqrt{\alpha_i}$$

$$\Rightarrow \Lambda > 500 \ldots 650\,\mathrm{GeV}$$

$W\gamma\gamma$ production

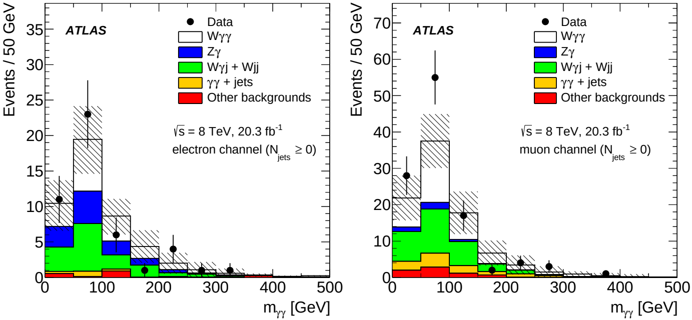
$\sqrt{s} = 8\,\text{TeV}$, $\mathcal{L} = 20\,\text{fb}^{-1}$: CERN-PH-EP-2015-009

Triple boson production with $W\gamma\gamma$ final state

Selection

lepton and E_T^{miss} from W decay
two isolated photons
$\Delta R(\ell, \gamma) > 0.7$
$m_T^W > 40\,\text{GeV}$ (Inclusive region)

Exclusive region: veto on additional jets with $p_T > 30\,\text{GeV}$



Invariant mass of the two photons in electron/muon channel

$W\gamma\gamma$ production

$\sqrt{s} = 8\,\text{TeV}$, $\mathcal{L} = 20\,\text{fb}^{-1}$: CERN-PH-EP-2015-009

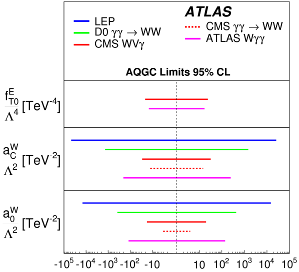
Measurement

	σ^{fid} [fb]	σ^{MCFM} [fb]
Inclusive ($N_{\text{jet}} \geq 0$)		
$\mu\nu\gamma\gamma$	$7.1\ ^{+1.3}_{-1.2}$ (stat.) ± 1.5 (syst.) ± 0.2 (lumi.)	2.90 ± 0.16
$e\nu\gamma\gamma$	$4.3\ ^{+1.8}_{-1.6}$ (stat.) $^{+1.9}_{-1.8}$ (syst.) ± 0.2 (lumi.)	
$\ell\nu\gamma\gamma$	$6.1\ ^{+1.1}_{-1.0}$ (stat.) ± 1.2 (syst.) ± 0.2 (lumi.)	
Exclusive ($N_{\text{jet}} = 0$)		
$\mu\nu\gamma\gamma$	3.5 ± 0.9 (stat.) $^{+1.1}_{-1.0}$ (syst.) ± 0.1 (lumi.)	1.88 ± 0.20
$e\nu\gamma\gamma$	$1.9\ ^{+1.4}_{-1.1}$ (stat.) $^{+1.1}_{-1.2}$ (syst.) ± 0.1 (lumi.)	
$\ell\nu\gamma\gamma$	$2.9\ ^{+0.8}_{-0.7}$ (stat.) $^{+1.0}_{-0.9}$ (syst.) ± 0.1 (lumi.)	

aQGC limits

Parameters a_c^W, a_0^W, and f_{T0}^E, unitarized by a form-factor

Limits on aQGC with photons derived from the number of events in the exclusive selection with additional requirement of $M_{\gamma\gamma} > 300\,\text{GeV}$



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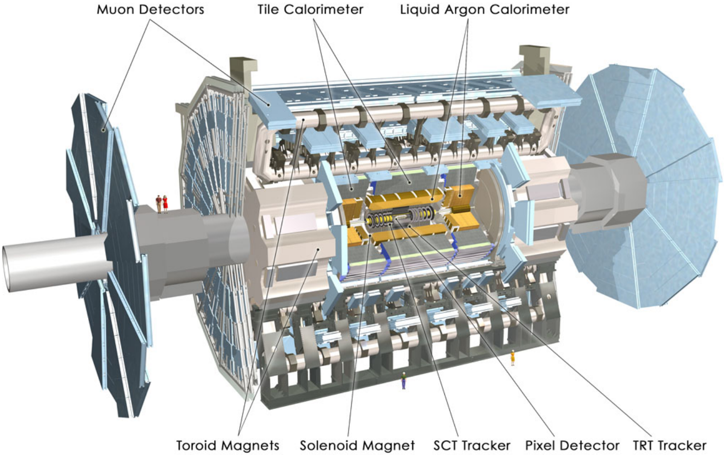
Conclusions

- Anomalous gauge couplings describe new physics contributions in the frame of an **effective field theory**
- Various di-boson, VBF, VBS, and tri-boson measurements at ATLAS have set limits on anomalous TGC and QGC
- Neutral and charge triple gauge couplings are accessible in di-boson production and vector boson fusion; **improvement of limits** compared to LEP and Tevatron in many cases
- Since recently, **quartic gauge couplings** with and without photons are accessible in vector boson scattering and triple gauge boson production at the LHC

BACKUP SLIDES

ATLAS detector

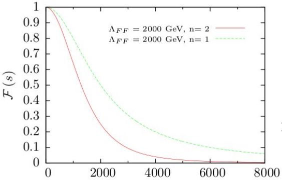


Need for Unitarization

Amplitudes with additional operators can **violate unitarity** ⇒ unitarize in order to retain physical events

Form factor unitarization

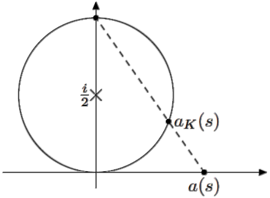
- apply **form factor** to coupling f as $f_i^V = f_{i,0}^V/(1+\hat{s}/\Lambda^2)^n$



O. Schlimpert, 2013

Unitarization with k-matrix method

- unitarization using K-MATRIX METHOD: projecting the amplitude on the Argand circle
- implemented in WHIZARD
- on a low-energy theorem amplitude, it acts as infinitely heavy resonance



Argand circle

TGC: LEP scenario

In order to reduce the number of free TGC parameters, different scenarios can be used:

Equal couplings scenario: WWZ and $WW\gamma$ couplings are equal

LEP scenario: $\Delta\kappa_\gamma = (\cos^2\theta_W/\sin^2\theta_W)(\Delta g_1^Z - \Delta\kappa_Z)$ and $\lambda_Z = \lambda_\gamma$ (motivated by $SU(2) \times U(1)$ gauge invariance)

HISZ scenario $\Delta g^Z = \Delta\kappa_Z/(\cos^2\theta_w - \sin^2\theta_W)$,
$\Delta\kappa_\gamma = 2\Delta\kappa_Z \cos^2\theta_W/(\cos^2\theta_w - \sin^2\theta_W)$, and $\lambda_Z = \lambda_\gamma$

Number of free parameters:
2 for "equal couplings" and HISZ scenarios, 3 for LEP' scenario

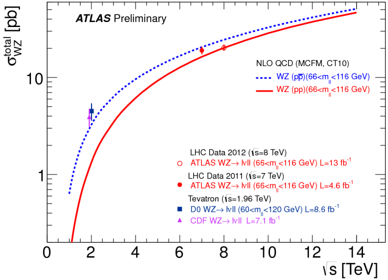
$WZ \to \ell\ell\ell\nu$

$\sqrt{s} = 8\,\text{TeV}$, $\mathcal{L} = 13\,\text{fb}^{-1}$: ATLAS-CONF-2013-021

Event selection:
3 high-p_{T} isolated leptons, large $E_{\mathrm{T}}^{\mathrm{miss}}$ and m_T^W

Backgrounds

Z+jets, top:	data-driven (fake leptons)
ZZ, W/Z + γ:	from simulation



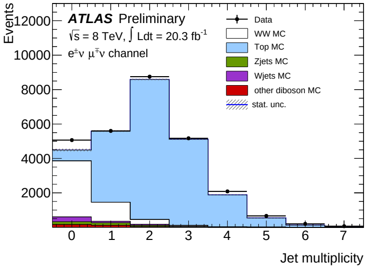
Measured total cross section:
$\sigma =$
$20.3^{+0.8}_{-0.7}(\text{stat})\ ^{+1.2}_{-1.1}(\text{syst})\ ^{+0.7}_{0.6}(\text{lumi})\,\text{pb}$
Theory: $\sigma = 20.3 \pm 0.8\,\text{pb}$
Dominated by **systematics**

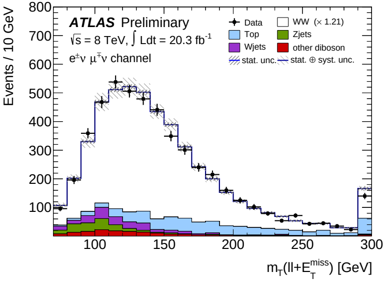
$W^+W^- \to \ell^+\nu\ell^-\bar{\nu}$

$\sqrt{s} = 8\,\text{TeV}$, $\mathcal{L} = 20.3\,\text{fb}^{-1}$: ATLAS-CONF-2014-033

Selection:

- 2 high-p_T isolated leptons (opposite charge)
- Z-veto to suppress Drell-Yan: $|m_{ll} - m_Z| > 15, 10\,\text{GeV}(ee, \mu\mu)$
- $E_{T,Rel}^{miss} > 45,45,25\,\text{GeV}(ee, e\mu, \mu\mu)$
  $$E_{T,Rel}^{miss} = \begin{cases} E_T^{miss} \cdot \sin\Delta\Phi, & \text{if } \Delta\Phi < \pi/2 \\ E_T^{miss}, & \text{if } \Delta\Phi \geq \pi/2 \end{cases}$$
- jet veto to suppress top background





$m_T(llE_T^{miss})$ in signal region

Background estimates

top	data-driven (b-tagged)
W+jets	data-driven (fakes)
Drell-Yan	transfer-factor Drell-Yan control region