Multi-Boson results and anomalous couplings at the LHC



Marc-André Pleier

 $S\Lambda$





Stress-testing the Standard Model at the LHC, KITP, May 27 2016







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Run II Results

First 13 TeV multi-V results available...



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... but nothing on anomalous couplings so far

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Introduction

- Vector boson self-interactions in the SM: study processes including triple and quartic gauge couplings (TGCs and QGCs)
 - Measurements allow precision tests of SM predictions @ (N)NLO
 - "Model-independent" probe for new phenomena
 - QGC processes are just being established new territory!
 - Multi-boson production is important background for other processes
- Experimental access to probe for aGCs:
 - aTGCs: VBF Vjj and VV production
 - aQGCs: VBS VVjj and VVV production
 - Datasets so far: 7 TeV: ~5/fb, 8 TeV: ~20/fb, 13 TeV: ~3/fb in 2015
 - Rely mainly on leptonic W/Z decay channels to allow signal extraction from large BG (ℓ = e or μ)
 - Experimental signature: isolated high p_T leptons/photons, MET if v present, "tagging jets" if VBF/VBS

Recent VBF/VV results

Recent VV results

Overview of studied aTGCs:

Coupling	Parameters	Channel	r all
$\overline{WW\gamma}$	$\Delta \kappa_{\gamma}, \lambda_{\gamma}$	$WW, W\gamma, { m VBF-}W$	i foi
WWZ	$\Delta g_1^Z, \Delta \kappa_Z, \lambda_Z$	WW, WZ, VBF-W, VBF-Z	ion
$Z\gamma\gamma$	h_3^γ, h_4^γ	$Z\gamma$	ctat
$Z\gamma Z$	h_3^Z,h_4^Z	$Z\gamma$	the
$ZZ\gamma$	f_4^γ, f_5^γ	$ZZ = f_A^V$ violate CP	[ex
ZZZ	f_4^Z, f_5^Z	ZZ	SN

- Experimental access: aTGCs modify total production rate as well as event kinematics
 - Use cross-section measurement or kinematics to constrain aTGCs
- A suppression factor depending on a scale Λ ensures conservation of unitarity (divergent xsecs at high \sqrt{s}):

$$\lambda(\hat{s}) = rac{\lambda_0}{(1+\hat{s}/\Lambda^2)^n}$$

these parameters

$Z\gamma \rightarrow \ell \ell \gamma$, $\nu \nu \gamma @ 8 \text{ TeV}$

arXiv:1604.05232

• $e^+e^- / \mu^+ \mu^-$ or MET plus isolated photon(s)

***** Early NNLO fully differential <u>calculation for $Z\gamma$ </u> in 2013



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WW $\rightarrow \ell \nu \ell \nu @$ 8 TeV

arXiv:1603.01702

- ◆ 2 isolated leptons (e or µ) of opposite charge, MET, no jets (CMS: ≤ 1 jets)
- qq, gg, gg(H) production mechanisms (CMS subtracts gg(H))



Fully differential NNLO QCD Galculation just became available Marc-André Pleier Brookhaven National Laboratory

WW $\rightarrow \ell \nu \ell \nu @$ 8 TeV

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- ◆ 2 isolated leptons (e or µ) of opposite charge, MET, no jets (CMS: ≤ 1 jets)
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$WZ \rightarrow \ell \nu \ell \ell @ 8 \text{ TeV}$

PRD 93, 092004 (2016)

✤ 3 isolated leptons (e or µ), MET

Inclusive NNLO QCD calculation <u>recently became available</u>



Inclusive fiducial xsec precision: 4.2% ! Provided as well:

- Unfolded differential cross sections
- Ratio of W⁺Z, W⁻Z cross sections (also as function of kinematic vars)

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aTGC status



Most stringent limits on WWγ, WWZ from WZ and WW

aTGC Limits at 95% CL

aTGC status



- Most stringent limits on WWγ, WWZ from WZ and WW
- * Best constraints so far on $h_{3,4}^{\gamma,Z}$, driven by $\nu\nu\gamma$

aTGC status

Mar 2016		CMS						
		ATLAS		Channel	Limits	∫∠dt	√s	
f ^γ .				ZZ	[-1.5e-02, 1.5e-02]	4.6 fb ⁻¹	7 TeV	
4				ZZ	[-5.0e-03, 5.0e-03]	19.6 fb ⁻¹	8 TeV	
		—		ZZ (2l2v)	[-3.6e-03, 3.2e-03]	24.7 fb ⁻¹	7,8 TeV	
		—		ZZ (comb)	[-3.0e-03, 2.6e-03]	24.7 fb ⁻¹	7,8 TeV	
f				ZZ	[-1.3e-02, 1.3e-02]	4.6 fb ⁻¹	7 TeV	
-4		HI		ZZ	[-4.0e-03, 4.0e-03]	19.6 fb ⁻¹	8 TeV	
		—		ZZ (2l2v)	[-2.7e-03, 3.2e-03]	24.7 fb ⁻¹	7,8 TeV	
		— —–1		ZZ (comb)	[-2.1e-03, 2.6e-03]	24.7 fb ⁻¹	7,8 TeV	
f				ZZ	[-1.6e-02, 1.5e-02]	4.6 fb ⁻¹	7 TeV	
5		⊢1		ZZ	[-5.0e-03, 5.0e-03]	19.6 fb ⁻¹	8 TeV	
		F1		ZZ(2l2v)	[-3.3e-03, 3.6e-03]	24.7 fb ⁻¹	7,8 TeV	
		⊢−−− 1		ZZ(comb)	[-2.6e-03, 2.7e-03]	24.7 fb ⁻¹	7,8 TeV	
fz				ZZ	[-1.3e-02, 1.3e-02]	4.6 fb ⁻¹	7 TeV	
5		HI		ZZ	[-4.0e-03, 4.0e-03]	19.6 fb ⁻¹	8 TeV	
		⊢−−−− 1		ZZ (2l2v)	[-2.9e-03, 3.0e-03]	24.7 fb ⁻¹	7,8 TeV	
				ZZ (comb)	[-2.2e-03, 2.3e-03]	24.7 fb ⁻¹	7,8 TeV	
-0.	02	0		0.02	0.04 aTGC Lim	its @95	0.06 % C.I.	

- Most stringent limits on WWγ, WWZ from WZ and WW
- Best constraints so far on $h_{3,4}^{\gamma,Z}$, driven by $\nu\nu\gamma$
- * Constraints on $f_{3,4}^{\gamma,Z}$ driven by $\ell\ell\nu\nu$
- First ATLAS/CMS aTGC combination to be released soon!

Recent VBS/VVV results

VBS/VVV Production and aQGCs

Overview of studied aQGCs:

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

Vertex-specific conversions from WHIZARD α_4, α_5 exist, e.g. for WWWW:

$$\alpha_4 = \frac{f_{S,0}}{\Lambda^4} \frac{v^4}{8}, \alpha_4 + 2 \cdot \alpha_5 = \frac{f_{S,1}}{\Lambda^4} \frac{v^4}{8}$$

- Experimental access: aQGCs modify total production rate as well as event kinematics
 - Use cross-section measurement or kinematics to constrain aQGCs
- A suppression factor depending on a scale Λ ensures conservation of unitarity (divergent xsecs at high \sqrt{s}):

$$\lambda(\hat{s}) = rac{\lambda_0}{(1+\hat{s}/\Lambda^2)^n}$$

$\gamma\gamma \rightarrow WW$

arxiv:1604.04464

✤ eµ pair with large pT, no other charged particles @ vertex

* First evidence for signal combining 7, 8 TeV data: 3.4 σ



aQGC limits placed using dilepton pT distribution

No tag jets -> suppressed WWWW, WWZZ, WWZγ contribs

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$Z\gamma\gamma \rightarrow \ell\ell\gamma\gamma, \nu\nu\gamma\gamma$

arXiv:1604.05232

- Signal @ >5 σ . NLO prediction is still state-of-the-art for signal!



$Z\gamma\gamma \rightarrow \ell\ell\gamma\gamma, \nu\nu\gamma\gamma$

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Signal @ >5 σ . NLO prediction is still state-of-the-art for signal!



Exclusive high-mγγ fiducial xsecs used for aQGC limits

WZjj $\rightarrow \ell \nu \ell \ell j$ j @ 8 TeV

PRD 93, 092004 (2016)

- ★ 3 isolated leptons (e or μ), MET, \geq two jets
- **VBS**/aQGC additional selection on m_{ii} , $\Delta \Phi(W,Z)$, $\Sigma |p_T(\ell)|$



WZjj $\rightarrow \ell \nu \ell \ell j$ @ 8 TeV

PRD 93, 092004 (2016)

- ★ 3 isolated leptons (e or μ), MET, \geq two jets
- ♦ VBS/aQGC additional selection on m_{ii} , $\Delta \Phi$ (W,Z), Σ | $p_T(\ell)$ |



 measured fiducial xsec in aQGC phase space used for limits
 Conversion α_{4,5} to f_{s0,1} after k-matrix unitarisation (proof, anyone?) Marc-André Pleier

aQGC limits

Different processes give access to different aQGCs

- Trend that exclusive outperforms VBS, which is better than VVV
- Different parametrizations/unitarisation => no fair comparison

April 2016	CMS			C
	ATLAS	Channel	Limits	J <i>L</i> dt √s
f _{M,0} /Λ ⁴	<u>}</u> ∤	WVγ	[-7.7e+01, 8.1e+01]	19.3 fb ⁻¹ 8 TeV
	⊢-I	Zγ	[-7.1e+01, 7.5e+01]	19.7 fb ⁻¹ 8 TeV
	⊢	Wγ	[-7.7e+01, 7.4e+01]	19.7 fb ⁻¹ 8 TeV
	H	ss WW	[-3.3e+01, 3.2e+01]	19.4 fb ⁻¹ 8 TeV
	L. L	γγ→WW	[-4.2e+00, 4.2e+00]	24.7 fb ⁻¹ 7,8 Te
$f_{M,1}/\Lambda^4$	I	WVγ	[-1.3e+02, 1.2e+02]	19.3 fb ⁻¹ 8 TeV
	⊢−−−−	Zγ	[-1.9e+02, 1.8e+02]	19.7 fb ⁻¹ 8 TeV
	⊢− +	Wγ	[-1.2e+02, 1.3e+02]	19.7 fb ⁻¹ 8 TeV
	F-I	ss WW	[-4.4e+01, 4.7e+01]	19.4 fb ⁻¹ 8 TeV
	Н	γγ→WW	[-1.6e+01, 1.6e+01]	24.7 fb ⁻¹ 7,8 Te
$f_{M,2}/\Lambda^4$		Ζγγ	[-5.1e+02, 5.1e+02]	20.3 fb ⁻¹ 8 TeV
	h	Wγγ	[-2.5e+02, 2.5e+02]	20.3 fb ⁻¹ 8 TeV
	н	Zγ	[-3.2e+01, 3.1e+01]	19.7 fb ⁻¹ 8 TeV
	н	Ŵγ	[-2.6e+01, 2.6e+01]	19.7 fb ⁻¹ 8 TeV
$f_{M,3}/\Lambda^4$		- Ζγγ	[-9.2e+02, 8.5e+02]	20.3 fb ⁻¹ 8 TeV
		Wγγ	[-4.7e+02, 4.4e+02]	20.3 fb ⁻¹ 8 TeV
	н	Zγ	[-5.8e+01, 5.9e+01]	19.7 fb ⁻¹ 8 TeV
	н	Wγ	[-4.3e+01, 4.4e+01]	19.7 fb ⁻¹ 8 TeV
$f_{M,4} / \Lambda^4$	Н	Wγ	[-4.0e+01, 4.0e+01]	19.7 fb ⁻¹ 8 TeV
$f_{M.5}/\Lambda^4$	H	Wγ	[-6.5e+01, 6.5e+01]	19.7 fb ⁻¹ 8 TeV
$f_{M,6}/\Lambda^4$	⊢ −+	Wγ	[-1.3e+02, 1.3e+02]	19.7 fb ⁻¹ 8 TeV
	F-1	ss WW	[-6.5e+01, 6.3e+01]	19.4 fb ⁻¹ 8 TeV
$f_{M,7}/\Lambda^4$	⊢	Wγ	[-1.6e+02, 1.6e+02]	19.7 fb ⁻¹ 8 TeV
		ss WW	[-7.0e+01, 6.6e+01]	19,4 fb ⁻¹ 8 TeV
-1	000 0	1000	2000	3000
		aQC	GC Limits @95	% C.L. [TeV

aQGC limits

Different processes give access to different aQGCs

- Trend that exclusive outperforms VBS, which is better than VVV
- Different parametrizations/unitarisation => no fair comparison

4pril 2016	CIVIS			c	
		Channel	Limits	J <i>L</i> dt	√s
$f_{T,0} / \Lambda^4$		Wγγ	[-3.8e+01, 3.8e+01]	19.4 fb ⁻¹	8 TeV
	F	Ζγγ	[-1.6e+01, 1.9e+01]	20.3 fb ⁻¹	8 TeV
		Wγγ	[-1.6e+01, 1.6e+01]	20.3 fb ⁻¹	8 TeV
	I	WVγ	[-2.5e+01, 2.4e+01]	19.3 fb ⁻¹	8 TeV
	H	Ζγ	[-3.8e+00, 3.4e+00]	19.7 fb ⁻¹	8 TeV
	⊢−−− I	Wγ	[-5.4e+00, 5.6e+00]	19.7 fb ⁻¹	8 TeV
	F1	ss WW	[-4.2e+00, 4.6e+00]	19.4 fb ⁻¹	8 TeV
$f_{T,1}/\Lambda^4$		Wγγ	[-4.6e+01, 4.7e+01]	19.4 fb ⁻¹	8 TeV
	H	Ζγ	[-4.4e+00, 4.4e+00]	19.7 fb ⁻¹	8 TeV
	H	Wγ	[-3.7e+00, 4.0e+00]	19.7 fb ⁻¹	8 TeV
	F-I	ss WW	[-2.1e+00, 2.4e+00]	19.4 fb ⁻¹	8 TeV
$f_{T,2}/\Lambda^4$		Ζγ	[-9.9e+00, 9.0e+00]	19.7 fb ⁻¹	8 TeV
	⊢−−−− I	Wγ	[-1.1e+01, 1.2e+01]	19.7 fb ⁻¹	8 TeV
	HI	ss WW	[-5.9e+00, 7.1e+00]	19.4 fb ⁻¹	8 TeV
$f_{T,5} / \Lambda^4$		Ζγγ	[-9.3e+00, 9.1e+00]	20.3 fb ⁻¹	8 TeV
	н	Wγ	[-3.8e+00, 3.8e+00]	19.7 fb ⁻¹	8 TeV
$f_{T,6} / \Lambda^4$	H	Wγ	[-2.8e+00, 3.0e+00]	19.7 fb ⁻¹	8 TeV
$f_{T,7}/\Lambda^4$	⊢+	Wγ	[-7.3e+00, 7.7e+00]	19.7 fb ⁻¹	8 TeV
$f_{T,8}/\Lambda^4$	Н	Ζγ	[-1.8e+00, 1.8e+00]	19.7 fb ⁻¹	8 TeV
$f_{T,9}/\Lambda^4$	⊢I	Ζγγ	[-7.4e+00, 7.4e+00]	20.3 fb ⁻¹	8 TeV
	, , ,	Ζγ	[-4.0e+00, 4.0e+00]	19.7 fb ⁻¹	8 TeV
	-50 0 50	~		150	
		aQC	3C Limits @95	% C.L.	llev

aQGC limits

Different processes give access to different aQGCs

- Trend that exclusive outperforms VBS, which is better than VVV
 - Different parametrizations/unitarisation => no fair comparison April 2016 CMS ATLAS Limits ٧s Channel $f_{T,0}/\Lambda^4$ B.8e+011 8 TeV 8e+01 8 TeV re, TeV WV₂ [-2.5e+01, 2.4e+01] 19.3 fb⁻¹ 8 TeV [-3.8e+00, 3.4e+00] 19.7 fb⁻¹ 8 TeV [-5.4e+00, 5.6e+00]19.7 fb⁻¹ 8 TeV [-4.2e+00, 4.6e+00] ww 19.4 fb⁻¹ 8 TeV $f_{T,1}/\Lambda^4$ Wγγ [-4.6e+01-4-7e+01] 19.4 fb⁻¹ 8 TeV Zγ 9.7 fb⁻¹ 8 TeV Wγ 8 TeV 8 TeV ss WW $f_{T,2}$ Zγ 8 TeV Wγ 8 TeV ss WW B TeV Ζγγ f_{T,5} / A 8 TeV Wγ 8 TeV Wγ $f_{T.6} / \Lambda^4$ 8 TeV $f_{T,7}/\Lambda^4$ Wγ 8 TeV $f_{T,8}/\Lambda^4$ Zγ 8 TeV Ζγγ 8 TeV f_{T.9} / fb⁻¹ Zγ 8 TeV -50 50 100 150 0 aQGC Limits @95% C.L. [TeV-4]

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16/20

Putting it all together...



EFT Limit Combinations

\clubsuit Higgs analyses now also moving away from μ, κ & towards EFT

- First(?) example: ATLAS Hγγ PLB 753, 69 (2016)
- Combining constraints from
 - Higgs/SM in ATLAS
 - ATLAS and CMS
 - LHC and beyond (<u>e.g. B-meson observables</u>)
- Some ingredients: agree on
 - common basis, modeling choices, unitarisation method if needed, tools
 - common binning, treatment of correlations, signal/background (H/VV)
 - Smaller scale "testbench" before moving to "global fit"
 - Best observable (ŝ sensitive)?
 Current sensitivity more from normalization than shape...

In addition/alternatively,

- Provide unfolded measurements w/ correlation matrix instead?
- Provide N-dimensional limits with correlation matrix

Summary

- Harvest of Run I analyses still ongoing establishing new processes.
- Run 2 will provide access to more processes (VBS, VVV), and more stringent limits!
- Starting to prepare for combinations of limits
- THANK YOU to the MC generator + HO correction community
 - NNLO QCD predictions are very important for multi-V
 - HO EWK corrections as well, particularly for aGC limits
- Current "state of the art" ATLAS MC in multi-bosons: see "<u>Multi-Boson Simulation for 13 TeV ATLAS Analyses</u>"
 - Mix and match in modelling: PDF, ME, scales, PS, EW scheme, HO corrs

 lots of combinations, some of which will be sub-optimal
- Wishlist:
 - NNLO (multi-leg) QCD + NLO EWK + PS event generation. ③
 - Re-weighting functionality for PDFs, scales, EFTs/aGCs

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Outlook

August 24th to August 26th 2016:



https://agenda.hep.wisc.edu/event/965/