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EPS HEP 2015

Measurement of anomalous triple and quartic gauge couplings at CMS

Senka Đurić
(University of Wisconsin-Madison)

On behalf of the CMS Collaboration

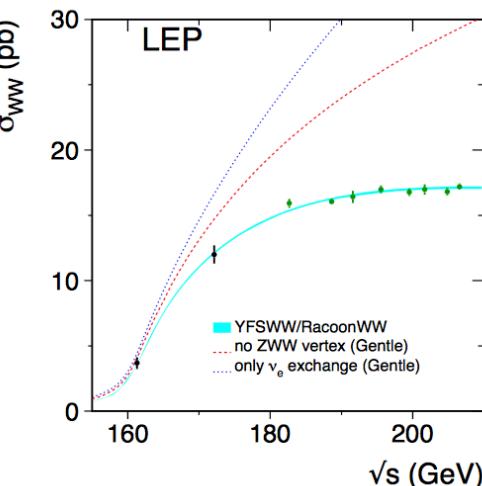
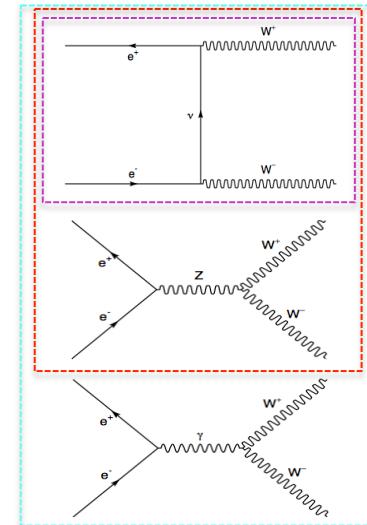


Vector boson couplings in SM

Triple and quartic vector boson couplings

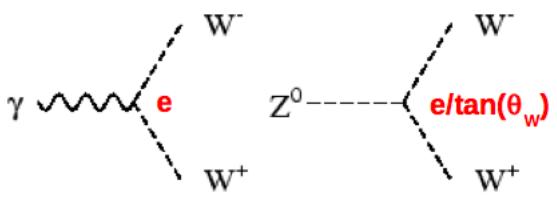
- Fundamental prediction of Standard Model (SM)
- Consequence of the non-Abelian nature of the $SU(2)_L \times U(1)_Y$ gauge theory
- Have exact values in SM!

LEP2 confirmed the presence of the TGCs and the non-abelian structure of the $SU(2)_L \times U(1)_Y$ gauge symmetry

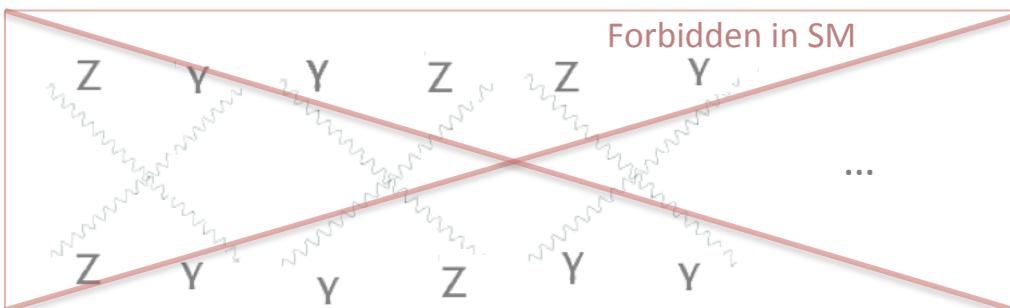
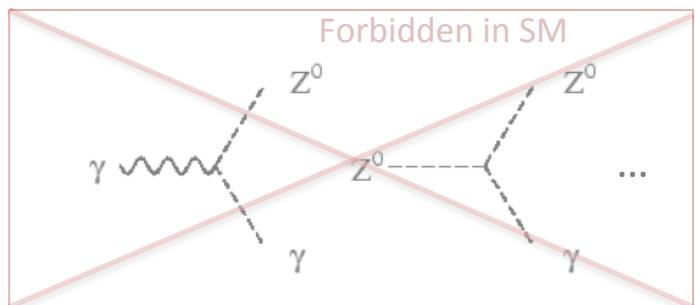
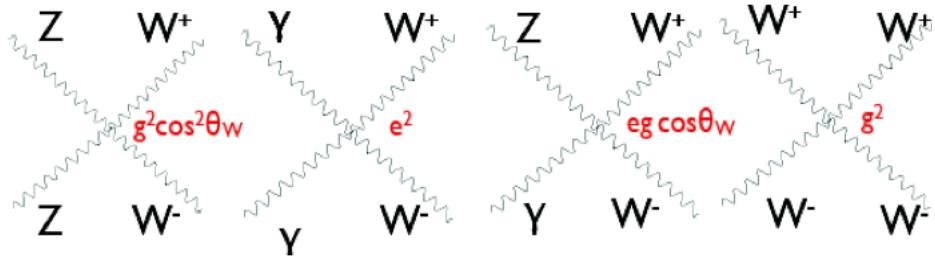


Phys. Rept. 532 (2013) 119

Triple gauge couplings (TGC)



Quartic gauge couplings (QGC)



Charged couplings are allowed at the tree level while neutral are forbidden in SM.

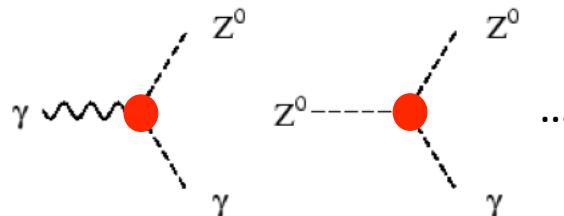
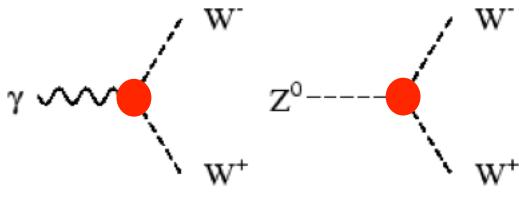
Deviation of vector boson couplings

Allowing vector boson couplings to vary away from SM values.

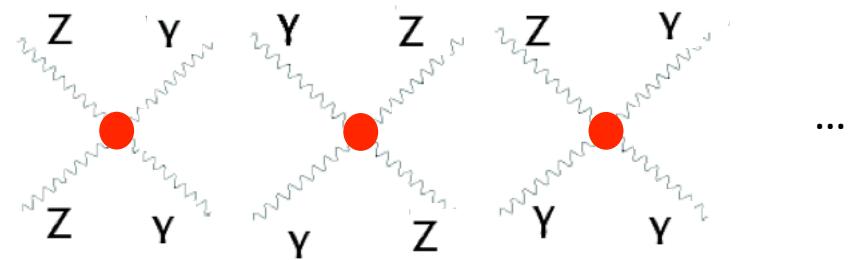
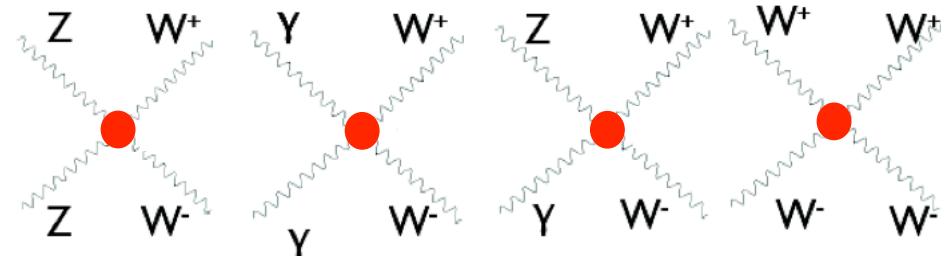
How to perform a measurement?

- Anomalous couplings contributions to gauge couplings have to be parametrized
- Ideally: performing global fit to all parameters → too many independent variables
- **Need to apply assumptions (physically motivated) to reduce the number of parameters to measure**

Anomalous Triple gauge couplings (aTGC)



Anomalous Quartic gauge couplings (aQGC)



Charged couplings are allowed at the tree level while neutral are forbidden in SM.

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)

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

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

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

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

- **Effective Lagrangian approach='phenomenological Lagrangian'** (WW analyses)

$$\mathcal{L}_{SM} \longrightarrow \mathcal{L}_{WWV} = -ig_{WWV} \left\{ g_1^V (W_{\mu\nu}^+ W^{-\mu} V^\nu - W_\mu^+ V_\nu W^{-\mu\nu}) + \kappa_V W_\mu^+ W_\nu^- V^{\mu\nu} + \frac{\lambda_V}{m_W^2} W_{\mu\nu}^+ W^{-\nu\rho} V_\rho^\mu - ig_5^V \epsilon^{\mu\nu\rho\sigma} [W_\mu^+ (\partial_\rho W_\nu^-) - (\partial_\rho W_\mu^+) W_\nu^-] V_\sigma \right\},$$
Phys. Rev. D41 (1990) 2113

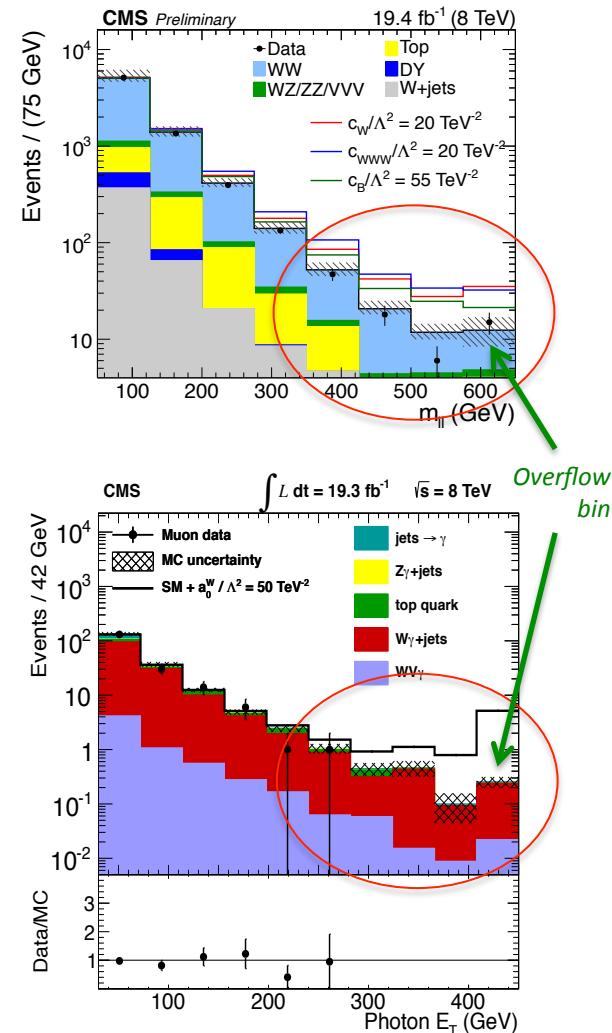
- **Effective Field Theory (EFT) approach** (WW analysis, VBF analyses and triboson analyses)

$$\mathcal{L}_{SM} \longrightarrow \mathcal{L}_{eff} = \mathcal{L}_{SM} + \sum_{n=1}^{\infty} \sum_i \frac{c_i^{(n)}}{\Lambda^n} \mathcal{O}_i^{(n+4)}$$
Phys. Rev. D48 (1993) 2182

Anomalous coupling signature

- Anomalous couplings result in an **increase of cross section at high energies (\hat{S})** \rightarrow observables dependent on the invariant mass of the diboson system and the boson p_T are particularly sensitive (m_{VV} , m_{\parallel} , pT_V , pT_I , ...)
- 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)**
- In different analyses: different observables are the most sensitive
- **Sensitivity depends on absolute size of anomalous coupling signal, absolute size of expected background and uncertainties**
- Binning is optimized to reach highest expected sensitivity
- Fit is usually performed simultaneously on electron and muon channel
- **95% CL limits are set using statistics criteria:**
 - **“deltaNLL”**: fit on parameter values (=measurement)
 - **“CLs”**: in presented analysis fit is performed on signal strength on individual parameter values, testing each point individually

$$CL_s = \frac{p_{s+b}}{1-p_b}$$



How to measure anomalous couplings (signal model)



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Lagrangian is linear in anomalous coupling parameters (α)

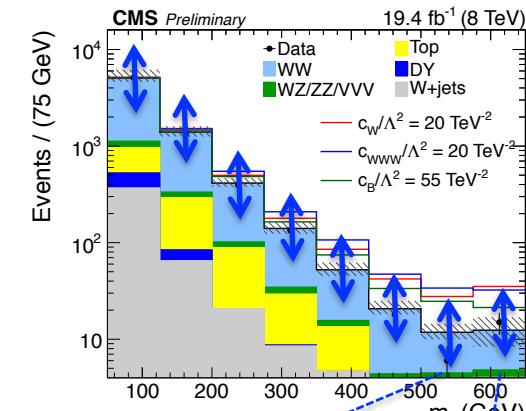
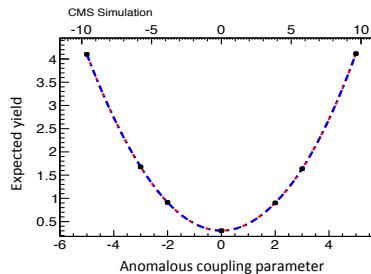
$$\sigma_{tot} \propto (\text{anomalous coupling parameter})^2 = \alpha^2 \sigma_{aC} + \alpha \sigma_{Int} + \sigma_{SM}$$

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

Building continuous signal model in parameter space:

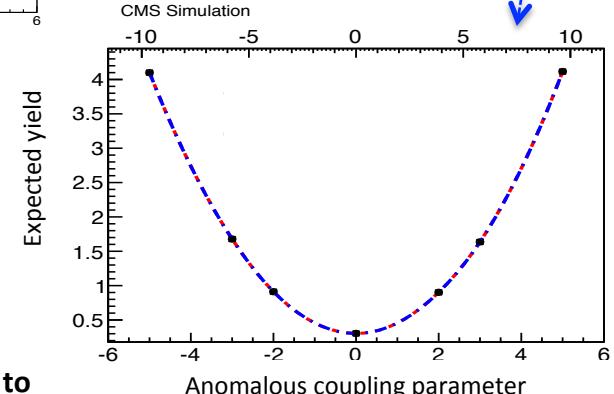
- Derive expected signal distributions for different parameter values
 - using simulated samples
 - or reweighting SM simulated sample with expected anomalous coupling contribution (ME reweighting or using anomalous coupling to SM ratio)
- Performing quadratic fit as a function of parameters in every observable bin
 - include effects from limited MC statistics and other uncertainties

... for every bin in observable ...



1D quadratic fit

1D Signal model



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

How to measure anomalous couplings (signal model)



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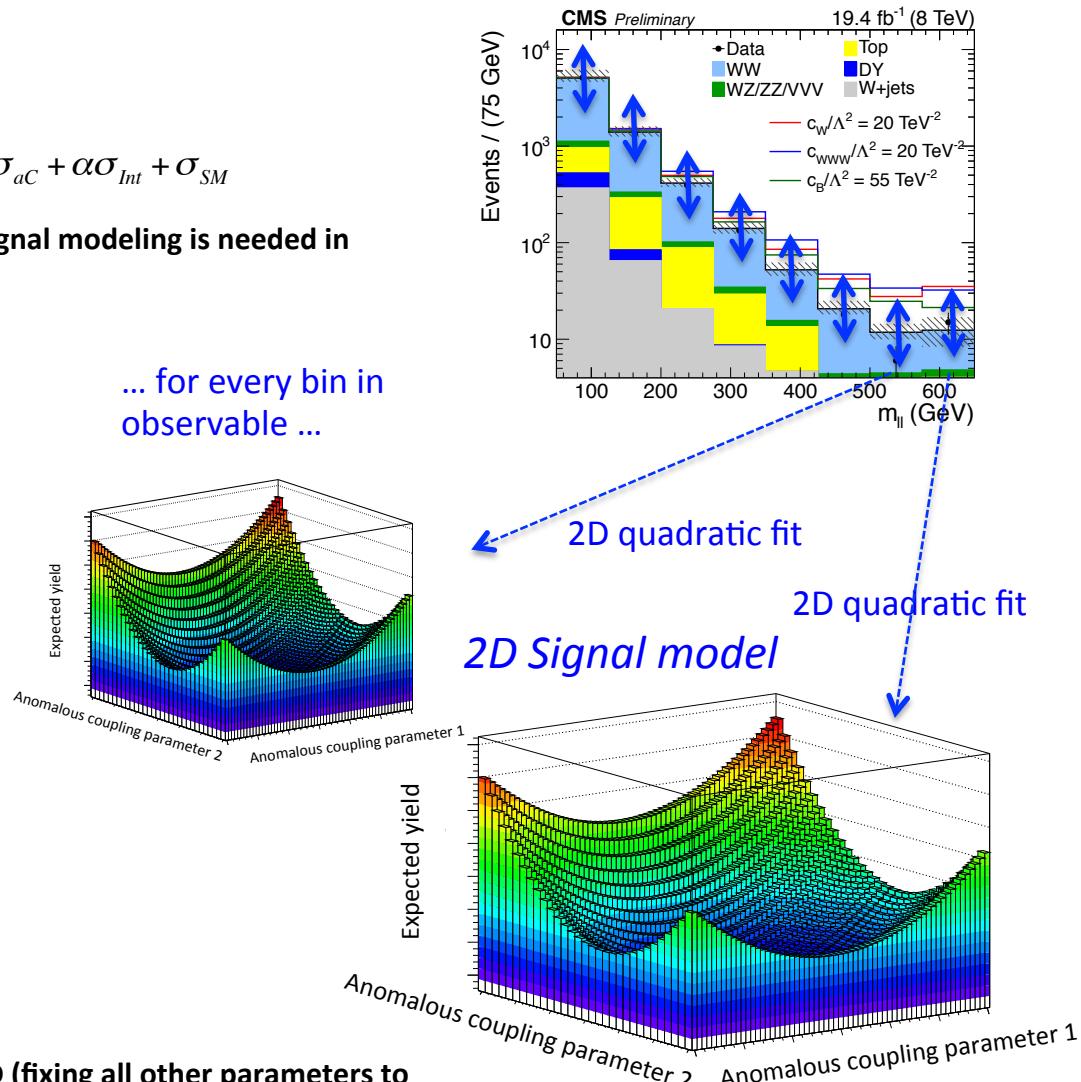
$$\sigma_{tot} \propto (\text{anomalous coupling parameter})^2 = \alpha^2 \sigma_{aC} + \alpha \sigma_{Int} + \sigma_{SM}$$

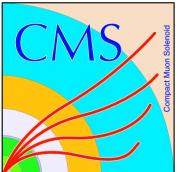
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 - include effects from limited MC statistics and other uncertainties

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





$W^+W^- \rightarrow l\nu l\nu$

8 TeV
19.4 fb^{-1}

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Effective field theory parametrization
“deltaNLL” limits

Selection:

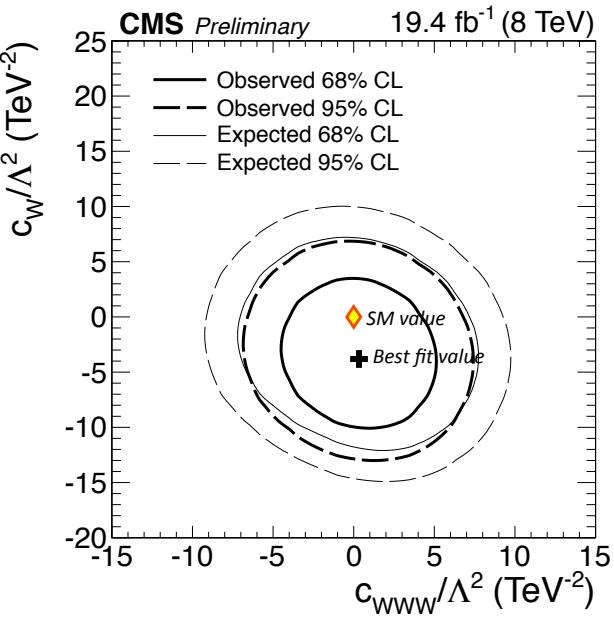
- 0 jet ($p_T > 30\text{ GeV}$, $|\eta| < 4.7$) requirement (to control background)
- $p_T(l) > 20\text{ GeV}$, MET $> 20\text{ GeV}$, $|m_{ll}-m_Z| > 15\text{ GeV}$, $p_T(l) > 30/45\text{ GeV}$ (DF/SF), $m_{ll} > 12\text{ GeV}$, veto additional leptons

aTGC measurement:

- aTGC signal: Madgraph LO MC
- Limits derived from binned fit to $M(ll)$ distribution
- No significant deviation in the high $M(ll)$ tail \rightarrow setting limits on parameters
- High $M(ll)$ tail is SM signal process dominated ($pp \rightarrow W^+W^-$)

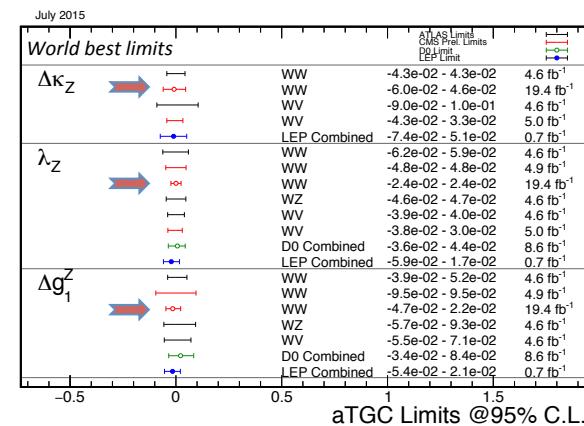
Limits are statistics dominated.

Expected limit = limits that we would set if there are no anomalous couplings
 \rightarrow signal process is SM



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EPS HEP 2015



Submitted to EPJC

arXiv.1507.03268

CERN-PH-EP-2015-122

<http://arxiv.org/abs/1205.4231v1>

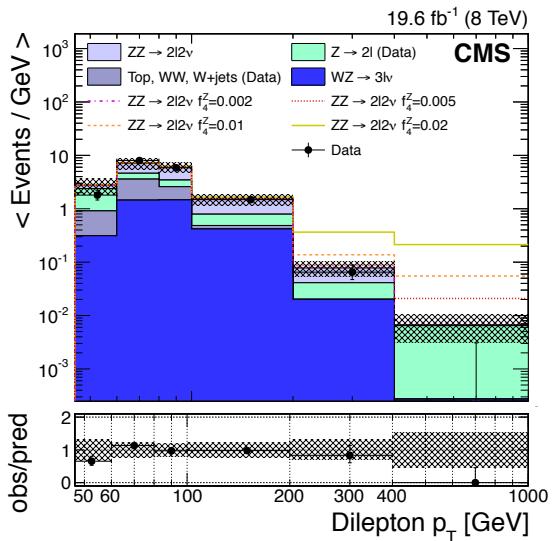
ZZ->4l & ZZ->2l2v



8+7 TeV
19.4+5.1 fb^{-1}

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Effective vertex parametrization
“deltaNLL” limits



Selection (2l2v):

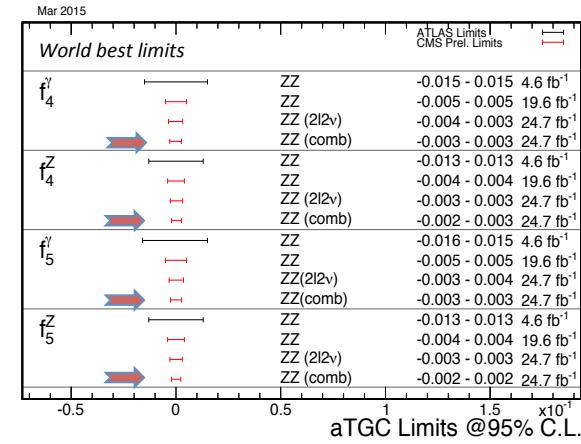
- 0 jet ($p\text{T}>30\text{GeV}$) requirement (to control background)
- Opposite sign same flavor pair in Zmass window
- $p\text{T}(l)>20\text{GeV}$, $p\text{T}(ll)>45\text{GeV}$, third lepton veto
- Large MET, MET and dilepton pT balanced

aTGC measurement:

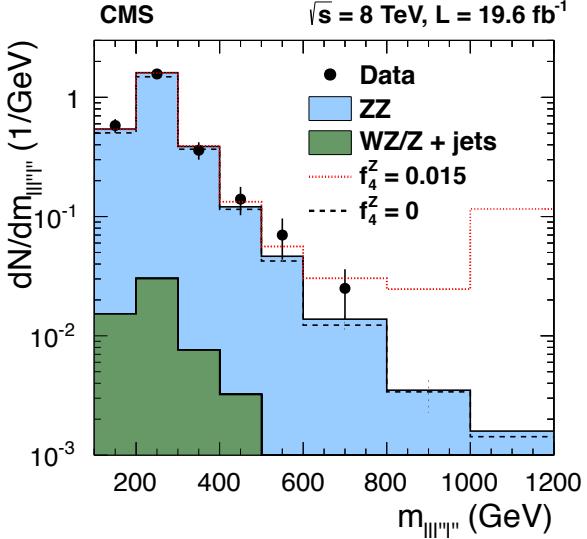
- aTGC signal: Sherpa MC
- Limits derived from binned fit to $p\text{T}(ll)$ distribution
- No significant deviation in the high $p\text{T}(ll)$ tail → setting limits on parameters

Limits are statistics dominated.

Largest systematic uncertainty in ZZ->2l2v is theoretical (MG vs Sherpa).



This result includes NLO QED corrections!



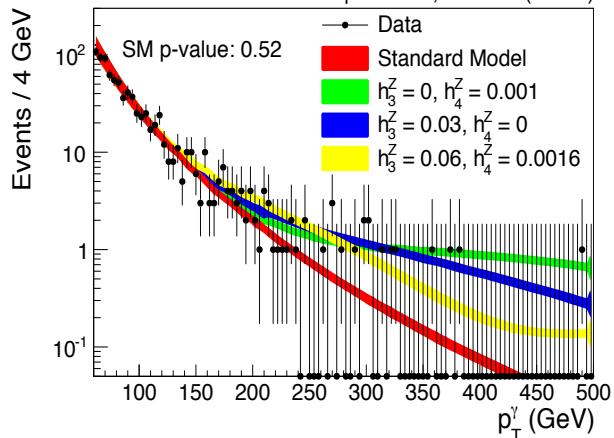
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EPS HEP 2015

Submitted to EPJC

arXiv.1503.05467

CERN-PH-EP-2015-029



Selection:

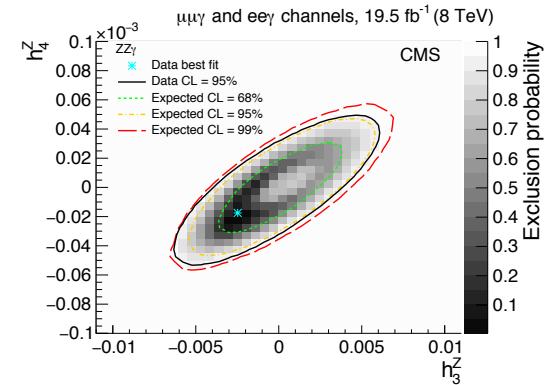
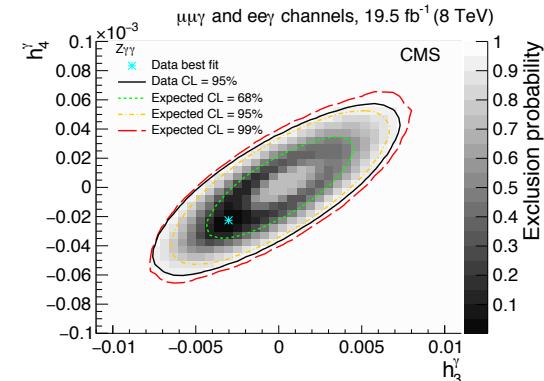
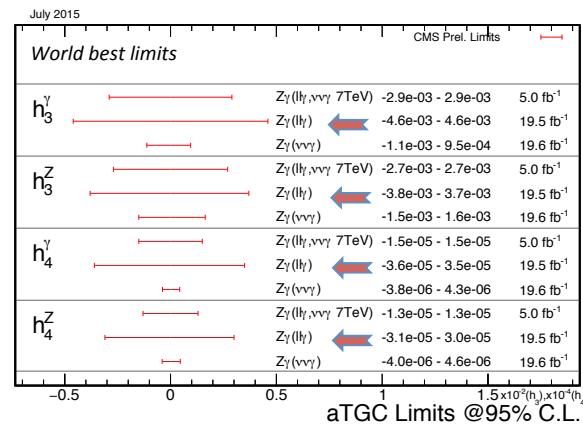
- Two isolated leptons $pT(l) > 20\text{GeV}$
- Opposite sign same flavor pair with $M(l\bar{l}) > 50\text{GeV}$
- Isolated photon $pT(\gamma) > 15\text{GeV}$

aTGC measurement:

- aTGC signal: MCFM
- Limits derived from binned fit to $\text{ET}(\gamma)$ distribution
- No significant deviation in the high $\text{ET}(\gamma)$ tail \rightarrow setting limits on parameters
- High $\text{ET}(\gamma)$ tail is SM signal process dominated

Limits are statistics dominated.

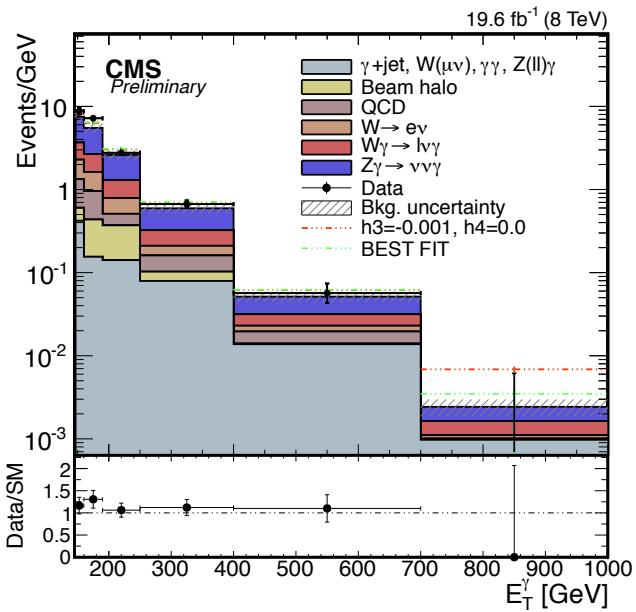
Limits are set by fitting each parameter point individually \rightarrow not a measurement of parameter value but limit setting on every point in parameter space!



Z γ ->vvv γ

8 TeV
19.4 fb $^{-1}$

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Larger branching ratio then Z γ ->l $\gamma\gamma$ => access to higher ET tail

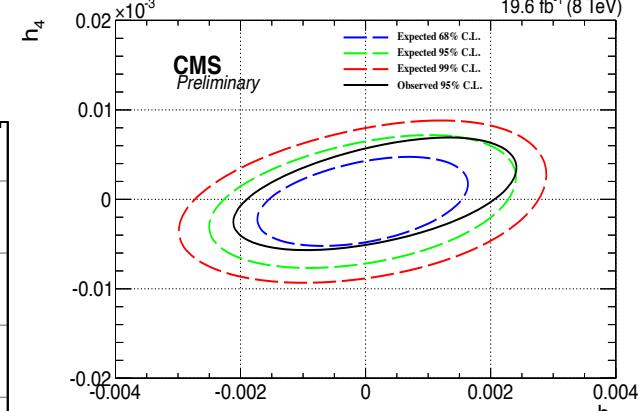
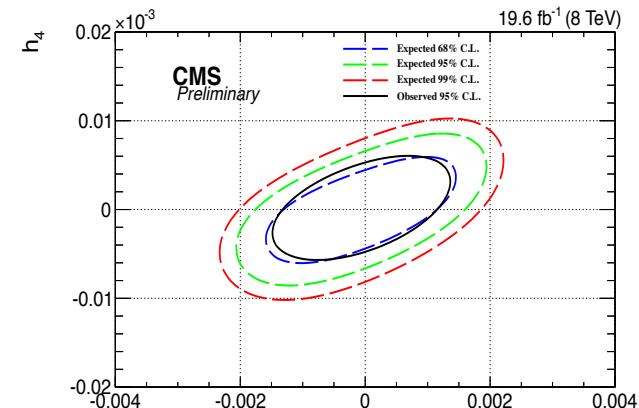
Selection:

- High MET (>140 GeV)
- Photon with large pT (>145 GeV)
- Lepton veto ($pT > 10$ GeV)

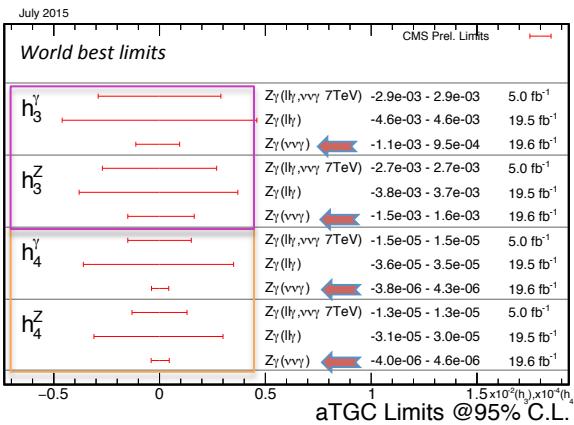
aTGC measurement:

- aTGC signal: Sherpa
- Limits derived from binned fit to ET(γ) distribution
- No significant deviation in the high ET(γ) tail \rightarrow setting limits on parameters

Limits are statistics dominated.

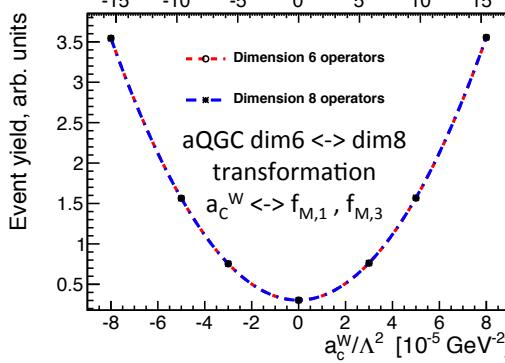
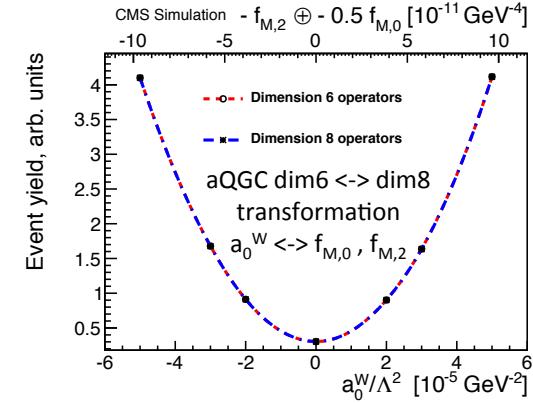
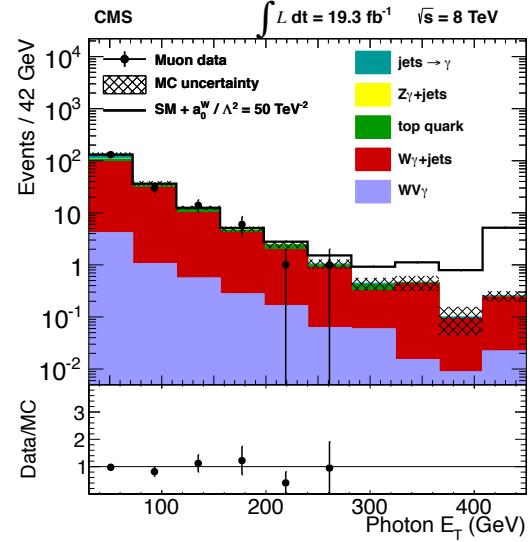
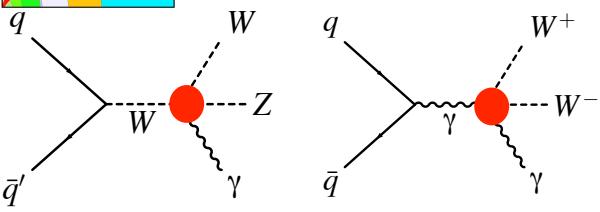


			Increase of NP effects with s
Z γ	h_3	dim6	$\sim s^{3/2}$ Slower improvement
	h_4	dim8	$\sim s^{5/2}$ Fast improvement



WW γ ->lvjj γ

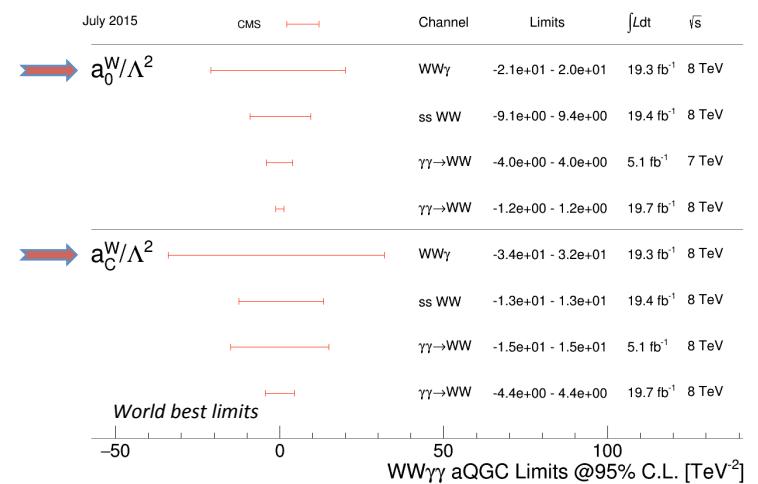
 8 TeV
19.4 fb $^{-1}$

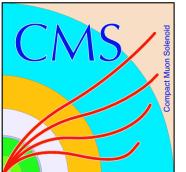
 Effective field theory parametrization
CL_S limits

Selection:

- MET>35GeV
- Isolated leptons pT(l)>25/30GeV muons/electrons
- At least two jets (pT>30GeV), b-jet veto
- Isolated photon ET(γ)>30GeV
- 70<|mjj|<100GeV
- MT(W)>30GeV, |M_{γe}-M_Z|>10GeV

aTGC measurement:

- aTGC signal: aMC@NLO
- Limits derived from binned fit to ET(γ) distribution
- No significant deviation in the high tail → setting limits on parameters

Limits are statistics dominated.


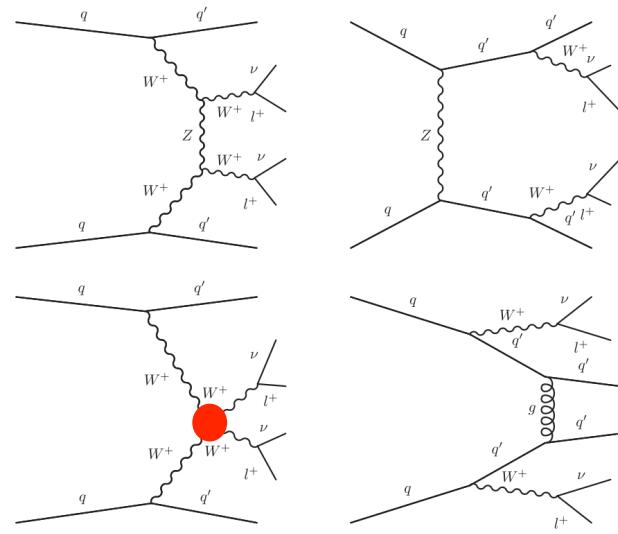


$W^\pm W^\pm \rightarrow l\nu l\nu$ EWK

8 TeV
19.3 fb^{-1}



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Selection:

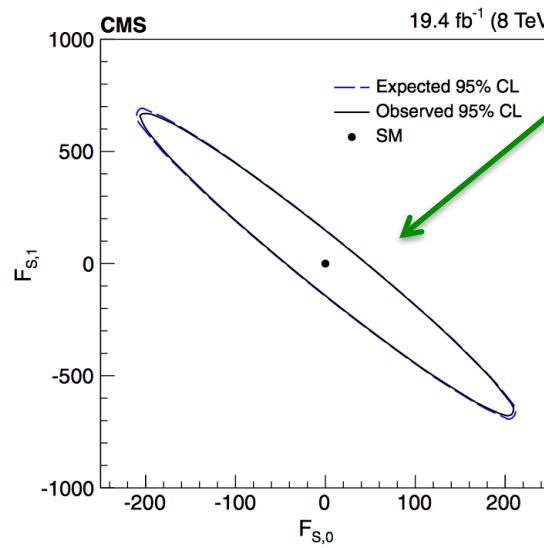
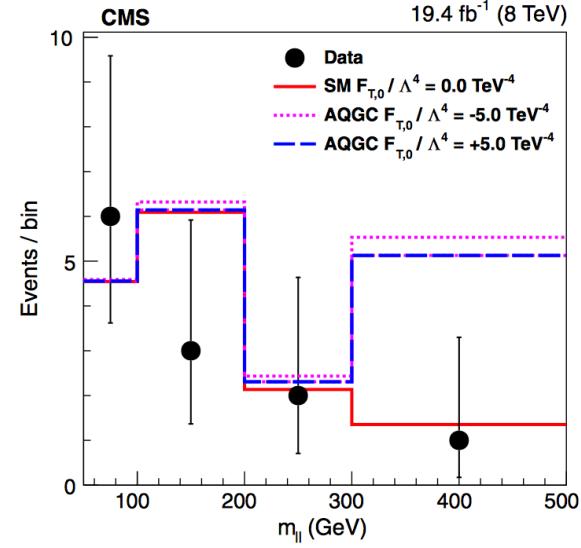
- Same-sign WW to reduce the background
- Two isolated leptons $pT(l) > 20\text{GeV}$, third lepton veto
- At least two jets ($pT > 30\text{GeV}$), top jet veto
- VBF topology: $m_{jj} > 500\text{GeV}$, $|\Delta\eta_{jj}| > 2.5$
- $M_{ll} > 50\text{GeV}$, Z mass window veto, MET $> 40\text{GeV}$

Effective field theory parametrization
“deltaNLL” limits

aTGC measurement:

- aTGC signal: LO Madgraph
- WZ EWK is a part of the background \rightarrow effect of possible aQGC on the WZ process in the signal region is negligible
- Limits derived from binned fit to $M(ll)$ distribution
- No significant deviation in the high tail \rightarrow setting limits on parameters

Limits are statistics dominated.



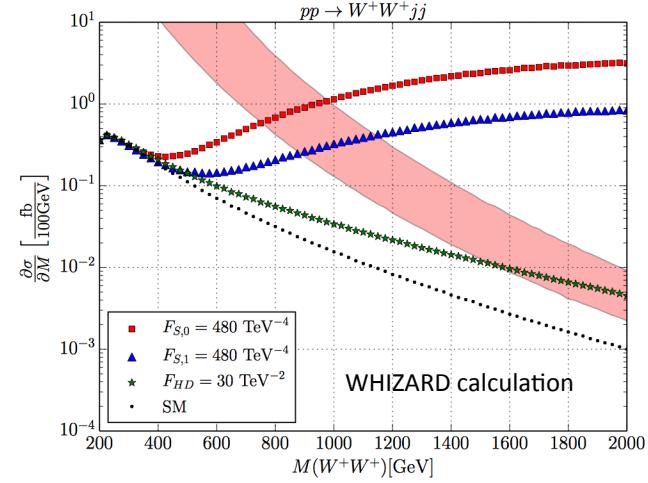
Linear combination of operators $F_{S,0}$ and $F_{S,1}$
leads to increase of cross section.

	July 2015	CMS	Channel	Limits	$\int L dt$	\sqrt{s}
a_W^W/Λ^2			$WW\gamma$	$-2.1e+01 - 2.0e+01$	19.3 fb^{-1}	8 TeV
			$ssWW$	$-9.1e+00 - 9.4e+00$	19.4 fb^{-1}	8 TeV
			$YY\rightarrow WW$	$-4.0e+00 - 4.0e+00$	5.1 fb^{-1}	7 TeV
			$YY\rightarrow WW$	$-1.2e+00 - 1.2e+00$	19.7 fb^{-1}	8 TeV
a_C^W/Λ^2			$WW\gamma$	$-3.4e+01 - 3.2e+01$	19.3 fb^{-1}	8 TeV
			$ssWW$	$-1.3e+01 - 1.3e+01$	19.4 fb^{-1}	8 TeV
			$YY\rightarrow WW$	$-1.5e+01 - 1.5e+01$	5.1 fb^{-1}	8 TeV
			$YY\rightarrow WW$	$-4.4e+00 - 4.4e+00$	19.7 fb^{-1}	8 TeV
World best limits						
WWγγ aQGC Limits @95% C.L. [TeV ⁻²]						

Question of unitarity

- Any non-zero value of anomalous coupling will lead to tree-level unitarity violation at sufficiently high energy
- At these high energies we will not have an effective theory (that we see at energies where we perform the measurement) but full New Physics theory that conserves unitarity
- Unitarity is preserved with applying (arbitrary) form-factor

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



<https://whizard.hepforge.org>

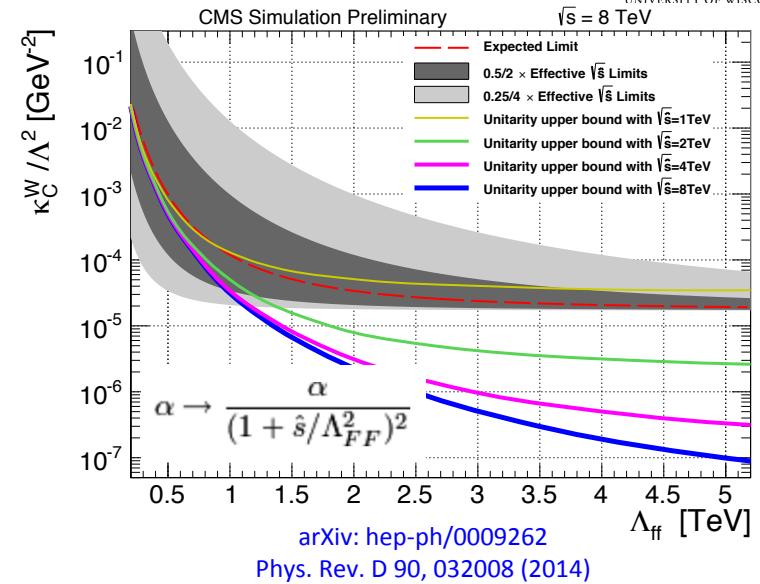
We will never observe the unitarity violation! However measurement can be “over-sensitive” if using models that break the unitarity for signal model building.

In CMS we have been setting limits without the use of form-factor, equivalent to $\Lambda_{FF}=\infty$.

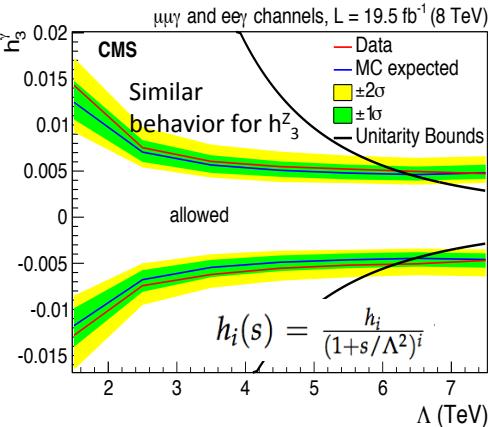
Unitarity of measured anomalous coupling limits

QGC (WV γ ->lvjj γ)

- Limits with form factor of $\Lambda_{FF} > \sim 4$ TeV give results similar to $\Lambda_{FF} = \infty$ (no form-factor)
- Effective field theory terms violate unitarity at parameter values close to the measured limits
- **For the case of dipol form factor neutral WW γ Z/ γ results are in the unitarity violating regime**



Phys. Rev. D30 (1984) 1513



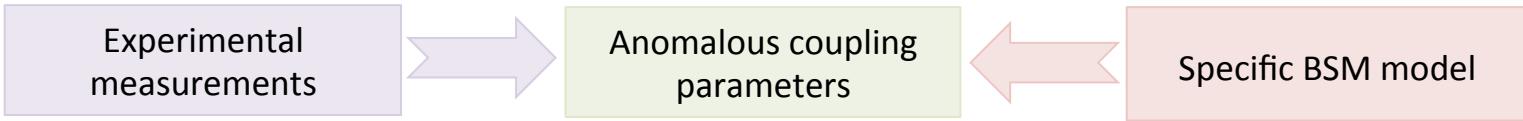
Neutral TGC

- Limits with form factor of $\Lambda_{FF} > \sim 3$ TeV give results similar to $\Lambda_{FF} = \infty$ (no form-factor)
- **Neutral TGC (Z γ Z/ γ and ZZZ/ γ) results are close to unitarity bound for limits from Z γ ->ll γ , but in unitarity non-violating regime for limits from Z γ ->vv γ**

Charged TGC

- Observed limits are 2 orders of magnitude smaller than the unitarity bound -> **results are in the unitarity non-violating regime**

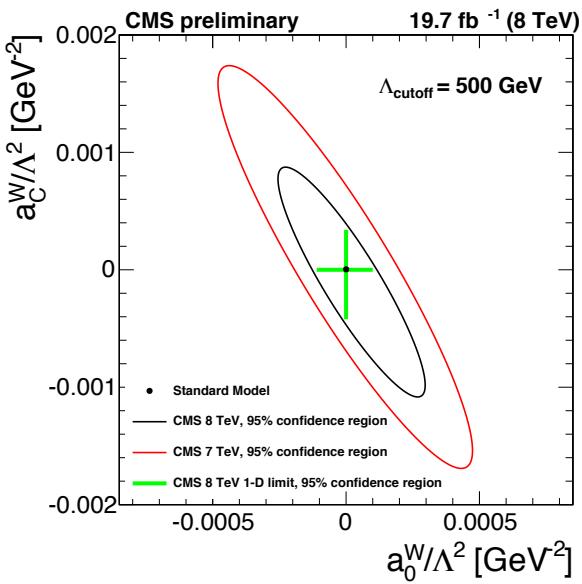
Conclusion



- Diboson and triboson channels are good indirect probes of new physics with anomalous coupling measurement
- **Anomalous couplings measurement is model independent search for new physics**
- Vector boson anomalous triple and quartic couplings were measured in many diboson and triboson channels with CMS detector
- **Limits on parameters are best, or close to, best world limits**
- Lagrangian, vertex function and EFT approaches were used to parametrize anomalous couplings → moving to EFT approach for future measurements
- Sensitivity to anomalous couplings is in high pT and mass tail
 - **Limits are statistics dominated**
 - Important to include higher order corrections into signal model for future measurements
- Anomalous coupling signal increases with energy → data at 13 TeV will soon give even better results
- Several parameters give signal in both diboson and higgs channels → simultaneous fit can be performed
- Future combination of limits between ATLAS and CMS for extra sensitivity

CMS SMP public results: <https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMP>
<http://cms-results.web.cern.ch/cms-results/public-results/publications/>

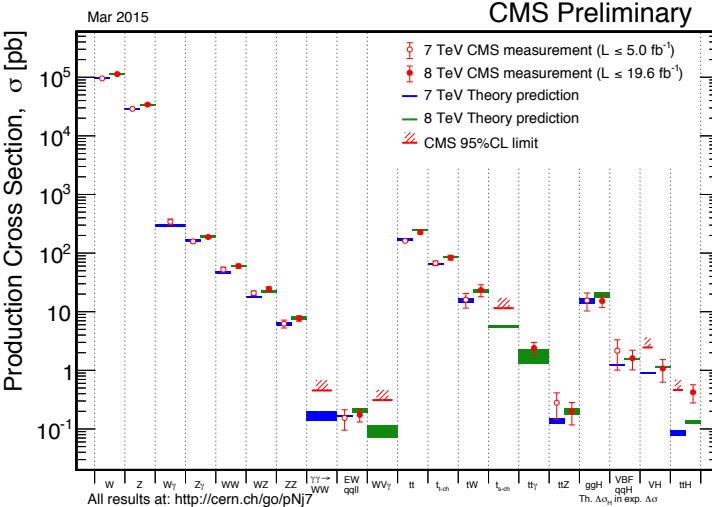
Related talks



Thursday 23 July 2015
Top and Electroweak Physics

12:24 Exclusive $W+W-$ production measured with the CMS experiment and constraints on Anomalous Quartic Gauge Couplings

JEITLER, Manfred



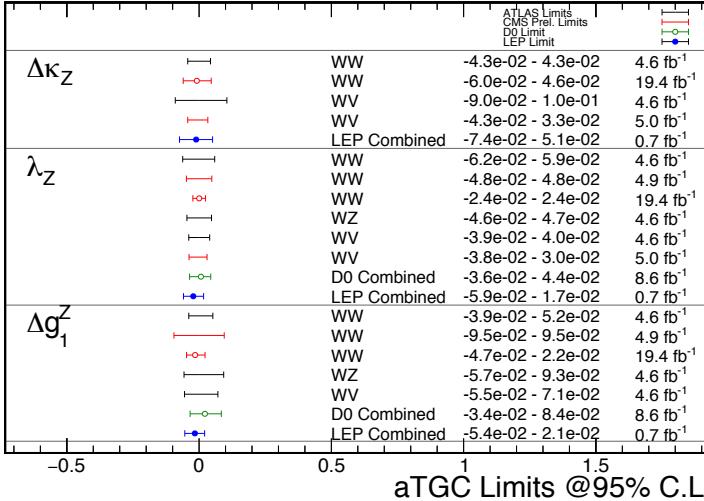
Friday 24 July 2015
Top and Electroweak Physics

15:24 Multiboson production at CMS

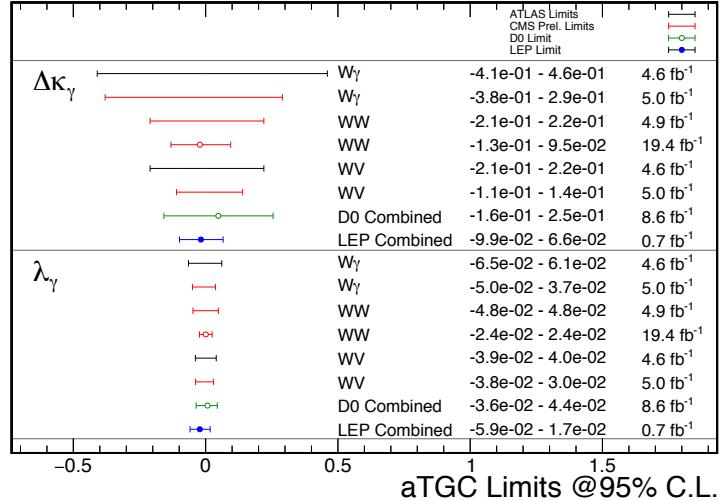
DUDERO, Phillip Russell

aTGC public results

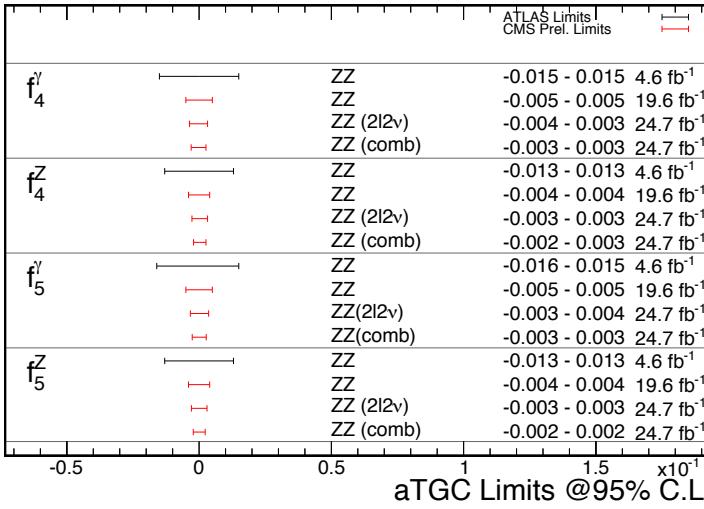
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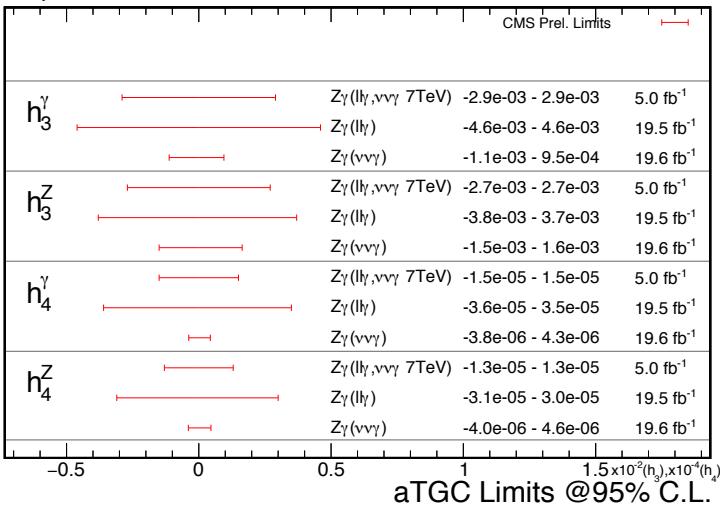
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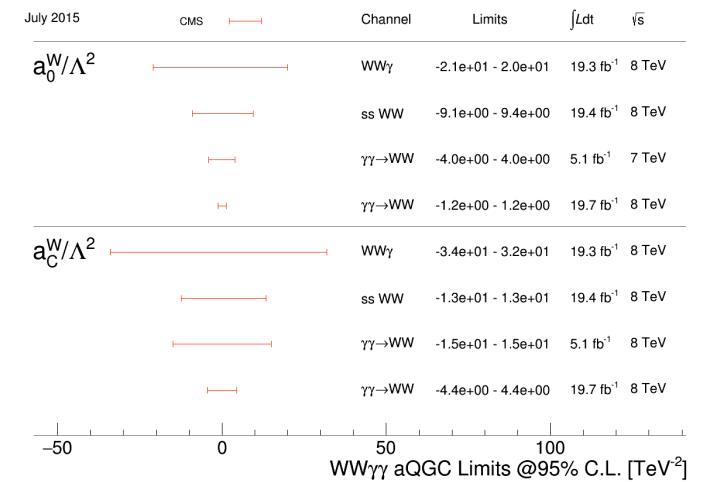
July 2015



aQGC public results

Observed Limits	Expected Limits
$-21 \text{ (TeV}^{-2}) < a_0^W / \Lambda^2 < 20 \text{ (TeV}^{-2})$	$-24 \text{ (TeV}^{-2}) < a_0^W / \Lambda^2 < 23 \text{ (TeV}^{-2})$
$-34 \text{ (TeV}^{-2}) < a_C^W / \Lambda^2 < 32 \text{ (TeV}^{-2})$	$-37 \text{ (TeV}^{-2}) < a_C^W / \Lambda^2 < 34 \text{ (TeV}^{-2})$
$-25 \text{ (TeV}^{-4}) < f_{T,0} / \Lambda^4 < 24 \text{ (TeV}^{-4})$	$-27 \text{ (TeV}^{-4}) < f_{T,0} / \Lambda^4 < 27 \text{ (TeV}^{-4})$
$-12 \text{ (TeV}^{-2}) < \kappa_0^W / \Lambda^2 < 10 \text{ (TeV}^{-2})$	$-12 \text{ (TeV}^{-2}) < \kappa_0^W / \Lambda^2 < 12 \text{ (TeV}^{-2})$
$-18 \text{ (TeV}^{-2}) < \kappa^W / \Lambda^2 < 17 \text{ (TeV}^{-2})$	$-19 \text{ (TeV}^{-2}) < \kappa^W / \Lambda^2 < 18 \text{ (TeV}^{-2})$

Observed Limits	Expected Limits
$-77 \text{ (TeV}^{-4}) < f_{M,0} / \Lambda^4 < 81 \text{ (TeV}^{-4})$	$-89 \text{ (TeV}^{-4}) < f_{M,0} / \Lambda^4 < 93 \text{ (TeV}^{-4})$
$-131 \text{ (TeV}^{-4}) < f_{M,1} / \Lambda^4 < 123 \text{ (TeV}^{-4})$	$-143 \text{ (TeV}^{-4}) < f_{M,1} / \Lambda^4 < 131 \text{ (TeV}^{-4})$
$-39 \text{ (TeV}^{-4}) < f_{M,2} / \Lambda^4 < 40 \text{ (TeV}^{-4})$	$-44 \text{ (TeV}^{-4}) < f_{M,2} / \Lambda^4 < 46 \text{ (TeV}^{-4})$
$-66 \text{ (TeV}^{-4}) < f_{M,3} / \Lambda^4 < 62 \text{ (TeV}^{-4})$	$-71 \text{ (TeV}^{-4}) < f_{M,3} / \Lambda^4 < 66 \text{ (TeV}^{-4})$





Backup



Multiboson production at CMS

$pp \rightarrow WW, WZ, Z\gamma, W\gamma, WV\gamma \dots$ at $\sqrt{s}=7$ TeV and 8 TeV



WISCONSIN
UNIVERSITY OF WISCONSIN-MADISON

Multiboson (diboson and triboson) production at CMS

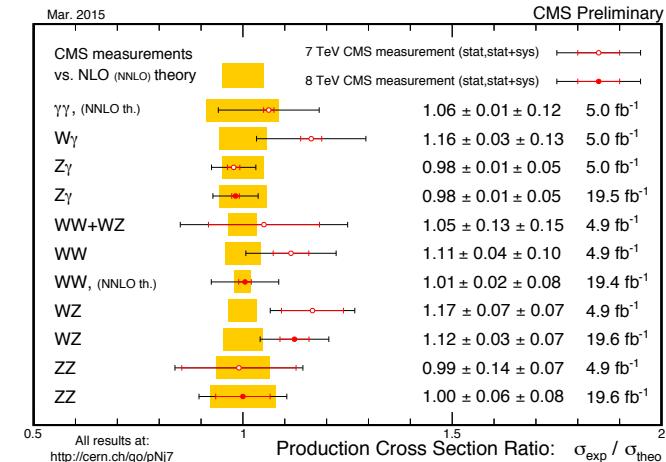
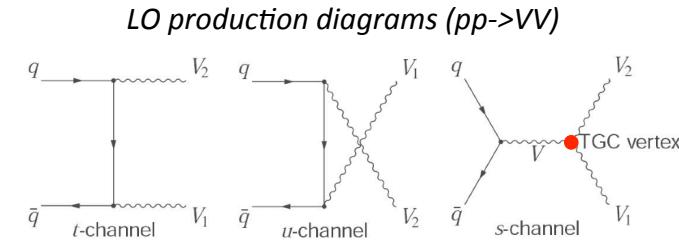
- Important test of the Standard Model
- Large cross section of multiboson production at LHC in pp collisions at center of mass energy of 7 and 8 TeV
- Clean signature and small branching ratio for vector bosons decaying leptonically
- Not clean signature but large branching ratio for hadronic decays
- Backgrounds for New Physics and Higgs measurements

Sensitive to theoretical calculation

- Large NLO QCD corrections at high \sqrt{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
- Anomalies in vector boson couplings = indirect search for New Physics



In most CMS multiboson analysis together with cross section measurement we measure anomalous gauge couplings

Anomalous coupling parametrizations: EFT summary



dim6 operators and vertices (aTGC and aQGC)

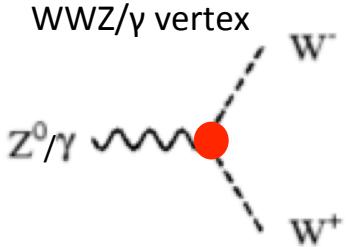
	\mathcal{O}_{WWW}	\mathcal{O}_{WW}	\mathcal{O}_W	\mathcal{O}_{BB}	\mathcal{O}_B	$\mathcal{O}_{\tilde{B}}$	$\mathcal{O}_{\tilde{B}B}$	$\mathcal{O}_{\tilde{W}W}$	$\mathcal{O}_{\tilde{W}WW}$	$\mathcal{O}_{\tilde{D}W}$
WWZ	✗		✗		✗	✗			✗	✗
WWA	✗		✗		✗	✗			✗	✗
ZZH		✗	✗	✗		✗	✗	✗		
WWH		✗	✗						✗	
AAH		✗		✗			✗	✗		
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
$\mathcal{O}_{S,0/1}$	✓	✓	✓						
$\mathcal{O}_{M,0/1/6/7}$	✓	✓	✓	✓	✓	✓	✓		
$\mathcal{O}_{M,2/3/4/5}$		✓	✓	✓	✓	✓	✓		
$\mathcal{O}_{T,0/1/2}$	✓	✓	✓	✓	✓	✓	✓	✓	✓
$\mathcal{O}_{T,5/6/7}$		✓	✓	✓	✓	✓	✓	✓	✓
$\mathcal{O}_{T,8/9}$			✓			✓	✓	✓	✓

Anomalous coupling parametrizations (aTGC)

Using additional assumptions to reduce the number of parameters



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)

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

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

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

valid for: $\sqrt{s} \ll \Lambda$

SU(3)xSU(2)xU(1) invariance by construction

Λ is large, of the order of the scale of New Physics

terms suppressed 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

Translation between
two approaches:

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

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

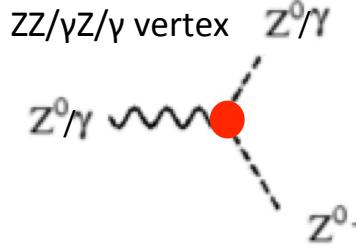
$$\begin{aligned}\mathcal{O}_{WWW} &= \text{Tr}[W_{\mu\nu} W^{\nu\rho} W_\rho^\mu] \\ \mathcal{O}_W &= (D_\mu \Phi)^\dagger W^{\mu\nu} (D_\nu \Phi) \\ \mathcal{O}_B &= (D_\mu \Phi)^\dagger B^{\mu\nu} (D_\nu \Phi)\end{aligned}$$

'HISZ' parametrization

channel	couplings	parametrization	parameters	Dimensionality of operator
WW	ZWW, γ WW	Effective Lagrangian	$\Delta \kappa$	dim4
	ZWW, γ WW		λ	dim6
	ZWW		Δg_z^1	dim4
	ZWW, γ WW	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



EFFECTIVE VERTEX PARAMETRIZATION

add higher order operators that respect symmetries

Nucl. Phys. B282 (1987) 253

Assumptions Zy channel: CP conservation

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

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

Assumptions ZZ channel: Electromagnetic gauge invariance

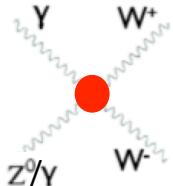
(Hagiwara *et al.*, Nucl.Phys.B282:253,1987)

$$\begin{aligned} \Gamma_{Z_1 Z_2 V}^{\alpha\beta\mu} = & i e \frac{q_V^2 - m_V^2}{m_Z^2} \{ f_4^V (q_V^\alpha g^{\beta\mu} + q_V^\beta g^{\mu\alpha}) \\ & + f_5^V \epsilon^{\alpha\beta\mu\rho} (q_{Z_1\rho} - q_{Z_2\rho}) \} \end{aligned}$$

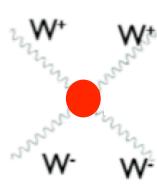
channel	couplings	parametrization	parameters	Dimensionality of operator
Zy	ZZ γ , γ Z γ	Effective vertex	h_3	dim6
			h_4	dim8
ZZ	ZZZ, γ ZZ		f_4	dim6
			f_5	dim6

Anomalous coupling parametrizations (aQGC)

$\gamma Z/\gamma WW$ 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.

Assumptions: CP conservation

NON-LINEAR FORMALISM (also used by LEP) [arXiv: hep-ph 9908254](https://arxiv.org/abs/hep-ph/9908254)

- 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:
 $a_0^W/\Lambda^2, a_c^W/\Lambda^2, \kappa_0^W/\Lambda^2, \kappa_c^W/\Lambda^2, \dots$

LINEAR FORMALISM

- 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 \rightarrow these are better measured
- Lowest independent aQGC operators (not affecting aTGC) are dim8 \rightarrow **used for aQGC measurements**

[arXiv: hep-ph 0606118](https://arxiv.org/abs/hep-ph/0606118)

Translation between two approaches:

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

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

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

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

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

channel	couplings	parametrization	parameters	Dimensionality of operator
WW γ	WW $\gamma\gamma$	Effective field theory	$a_0^W/\Lambda^2, a_c^W/\Lambda^2, \dots$	dim6
	WWZ γ		$\kappa_0^W/\Lambda^2, \kappa_c^W/\Lambda^2, \dots$	dim6
	WW $\gamma\gamma$, WWZ γ		$f_{T,0}/\Lambda^4, f_{M,0}/\Lambda^4, f_{M,1}/\Lambda^4, \dots$	dim8
WW EWK	WWWW		$f_{S,0}/\Lambda^4, f_{S,1}/\Lambda^4, f_{M,0}/\Lambda^4, \dots$	dim8

Question of unitarity

- Any non-zero value of anomalous coupling will lead to tree-level unitarity violation at sufficiently high energy
- At these high energies we will not have an effective theory (that we see at energies where we perform the measurement) but full New Physics theory that conserves unitarity

Effective Lagrangian and effective vertex formulation

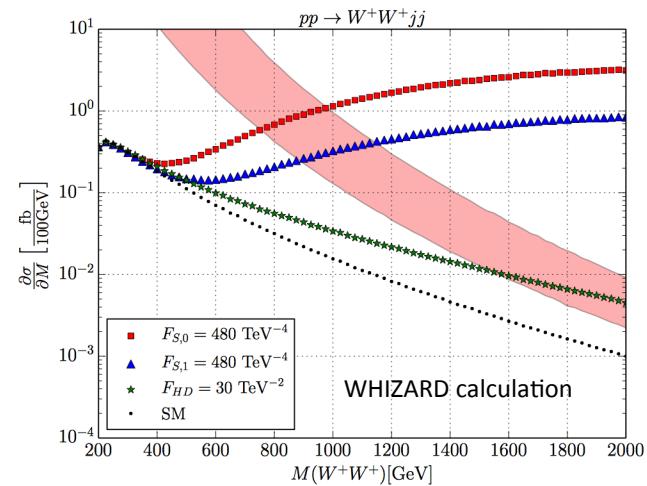
- Unitarity is preserved with applying a form-factor
 - Adding two new parameters and assuming their values a-priori: Λ_{FF} (form factor scale) and n
 - Form factor structure comes from New Physics structure
 - Form factor structure is unknown a-priori, so it is arbitrary

Effective field theory formulation

- Already has a scale (new physics scale Λ)
- Usually no need of form-factor

We will never observe the unitarity violation! However measurement can be “over-sensitive” if using models that break the unitarity for signal model building.

In CMS we have been setting limits without the use of form-factor, equivalent to $\Lambda_{FF}=\infty$.



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

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

Translation between formulations possible only for no form-factor approach!

CMS detector

HCAL $|\eta| < 5$
ECAL $|\eta| < 3.0$
Tracker $|\eta| < 2.5$
Muons $|\eta| < 2.4$

Pixels
 Tracker
ECAL
 HCAL
 Solenoid
 Steel Yoke
 Muons

