Triboson Results (CMS)

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on behalf of
The CMS Collaboration

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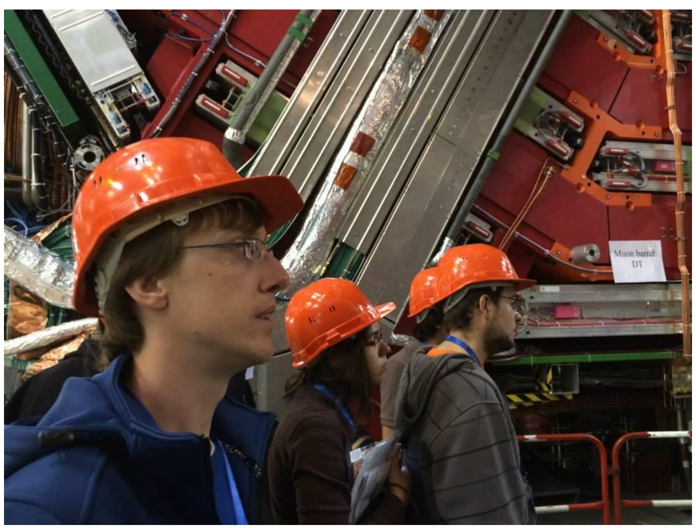
Overview

- Motivation
- Theoretical Details
- Experimental Details
- Results with 7/8 TeV Data
- Prospects for 13 TeV Data

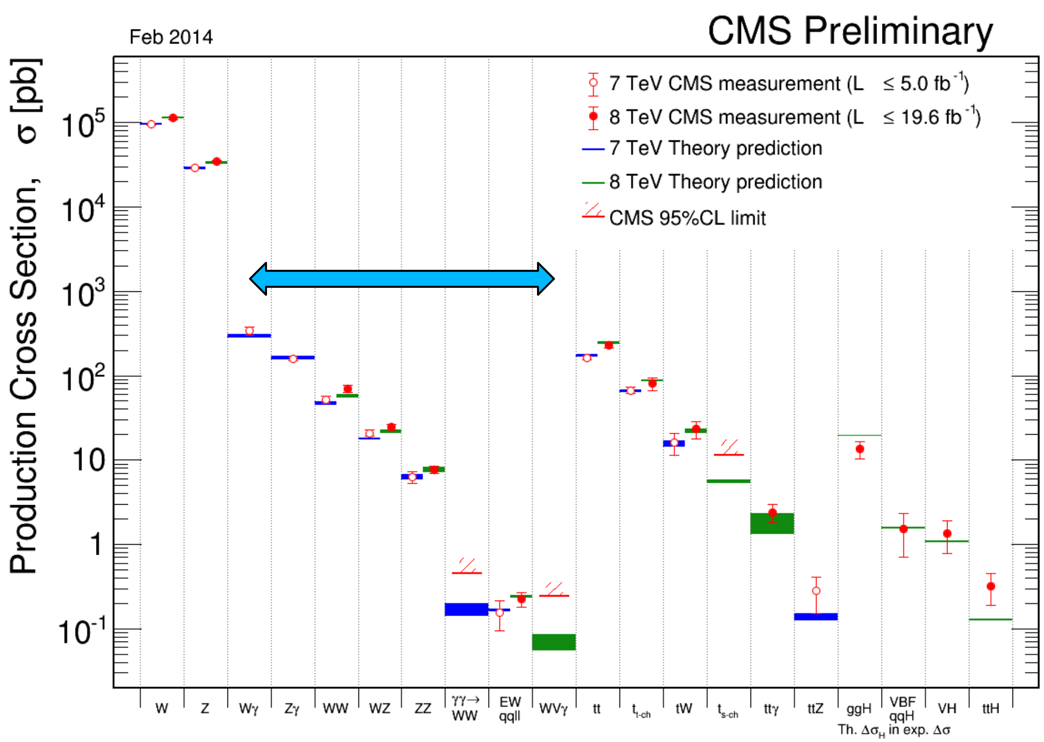


Motivation

Model-independent way to search for new physics

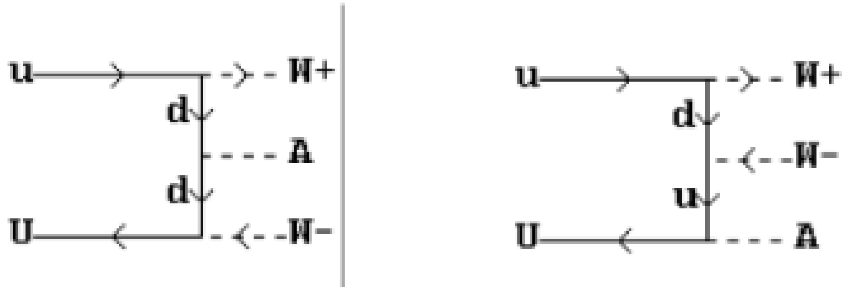
- Test of the standard model
- Anomalous coupling can enhance total cross sections and kinematics
  - *aTGC results*
  - *aQGC results*

Source: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMP

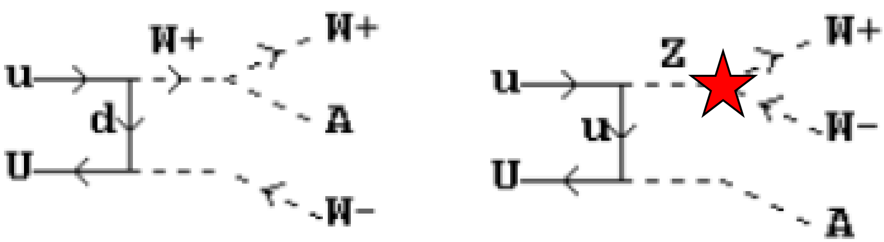


Theoretical Details

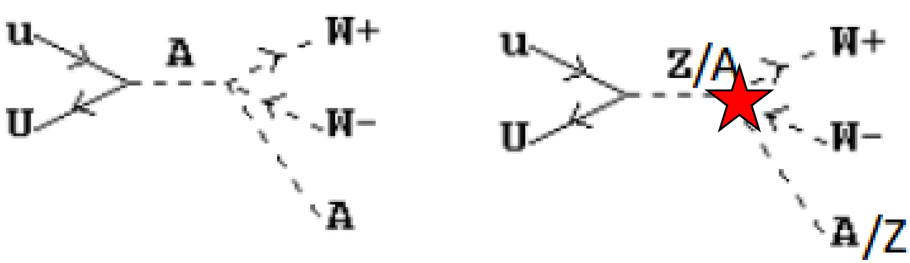
SM Multiboson Production



WVγ w/o multi-gauge boson interactions



Triple Gauge Coupling – WVγ



WWγγ WWZγ

Quartic Gauge Coupling - WWVγ

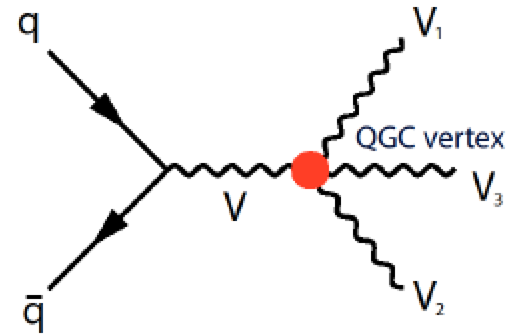
SM: K-Factor (WVγ analysis)

Phys. Rev. D 90, 032008 (2014)

- K-factor = NLO/LO ratio
  - *Applied as correction to SM yield to include NLO processes*
- aMC@NLO simulations for NLO contributions
- Study K-factor as function of photon p_T
  - *Distribution sensitive to aQGC*
  - *Linear within region of this analysis (p_T > 30 GeV)*
  - *Linear fit estimates K-factor = 2.1*
- Apply K-Factor to SM signal MC

aQGC Models

- Anomalous quartic gauge couplings
  - *Effective Field Theory approach*
  - *Assume $SU(2)_L$ x $U(1)_Y$ gauge invariance, C&P conservation, $SU(2)_C$ custodial symmetry*
- Previous work (non-linear realization, arXiv:hep-ph/0310141)
  - *Lowest order genuine quartic interaction: Dim. 6*
- Linear realization (arXiv:hep-ph/0606118)
  - *Lowest order genuine quartic interaction: Dim. 8*
- Non-linear Dim. 6 can be converted to Linear Dim. 8
  - *Not all Linear Dim. 8 can be converted to Non-linear Dim. 6*
- Sensitive observables: M^{VV}, p_T^{V}, etc.



http://feynrules.irmp.ucl.ac.be/wiki/AnomalousGaugeCoupling

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

aQGC Models

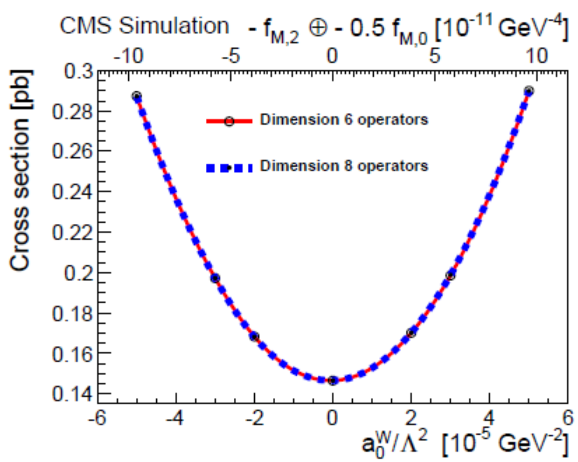
- Non-linear formalism (Dim. 6)

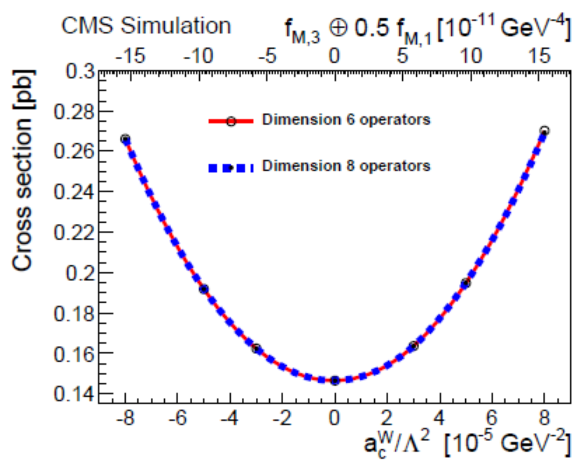
$$\mathcal{L}_{0,c} = \underbrace{\frac{k_0^{\gamma\gamma}}{\Lambda^2}\mathcal{W}_0^\gamma + \frac{k_c^{\gamma\gamma}}{\Lambda^2}\mathcal{W}_c^\gamma}_{WW\gamma\gamma} + \underbrace{\frac{k_0^W}{\Lambda^2}\mathcal{W}_0^Z + \frac{k_c^W}{\Lambda^2}\mathcal{W}_c^Z + \sum_{i=1,2,3}\frac{k_i^W}{\Lambda^2}\mathcal{W}_i^Z}_{WWZ\gamma}$$

WWγγ: a_0^W, a_c^W
WWZγ: k_0^W, k_c^W, k_i^W

- Linear formalism (Dim. 8)
  - *Transformations to Non-linear Dim. 6 terms possible:* $\frac{q_i}{\Lambda^4} = \frac{8a_i}{\Lambda^2 M_W^2}$

$$\mathcal{L}_{AQGC} = \underbrace{\frac{a_0^W}{4g^2}\mathcal{W}_0^\gamma + \frac{a_c^W}{4g^2}\mathcal{W}_c^\gamma}_{} + \underbrace{\sum_i k_i^W \mathcal{W}_i^Z + \mathcal{L}_{T,0} + \mathcal{L}_{T,1} + \mathcal{L}_{T,2}}_{}$$





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Simulation of aGC: Strategy

- Not realistic to produce samples for all aGC values
- 1-D Limits:
  - *Indentify aGC parameters to alter*
  - *Vary one parameter*
  - *Leave other parameters at SM values*
  - *Repeat for each parameter*
- Higher-D Limits:
  - *Vary n-parameters simultaneously*
  - *Leave other parameters at SM values*
  - *Repeat for each set of parameters*
- Observe kinematic distribution (photon E_T) for each aGC sample
  - *Determine aGC/SM yield ratio in distribution*
  - *Parameterize aGC/SM yield ratio over all aGC samples (quadratic polynomial)*
- Predict arbitrary aGC kinematic distribution

aQGC: K-Factor (WVγ analysis)

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- aQGC simulations contain SM events
- Weaker aQGC $\rightarrow$ SM-like K-Factor
- Stronger aQGC $\rightarrow$ Drell Yan-like K-Factor
- Dominate aQGC events in high E_T region
- Subtract SM contribution
  - *aQGC events remain*
  - *K-Factor of remaining events*

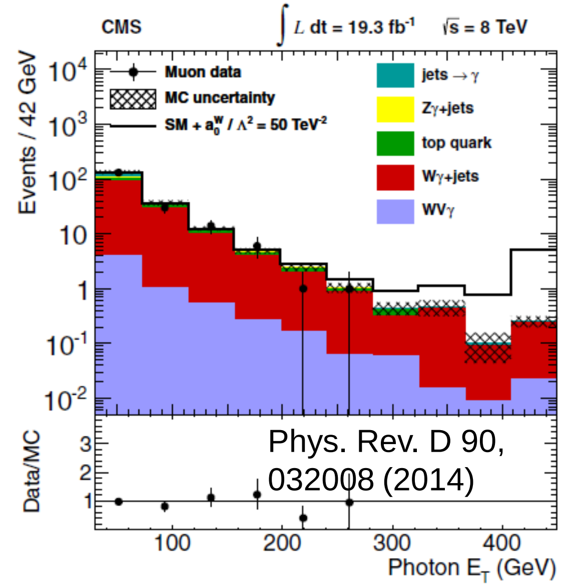
    (aQGC) ~ 1.2 (DY)
- Apply aQGC K-Factor

aQGC K-Factor ~ DY

Experimental Details

$WV\gamma \rightarrow$ lepton + jets + γ + $\not\!\!E_T$

- 8 TeV data from 2012
- One W boson decays leptonically
  - Lepton p_T > 25 GeV (μ), 30 GeV (e)
  - Lepton | η | < 2.1 (μ), 2.5 (e)
  - Missing E_T for the neutrinos > 35 GeV
  - m_T (leptonic W) > 30 GeV
- Other boson (W or Z) decays hadronically
  - Jet p_T > 30 GeV, | η | < 2.4
  - b-jets vetoed
- Photon pT > 30 GeV, | η | < 1.44
- Backgrounds:
  - $W\gamma$ + jets
  - Misidentified jet (fake photon)
- Upper cross section limit set



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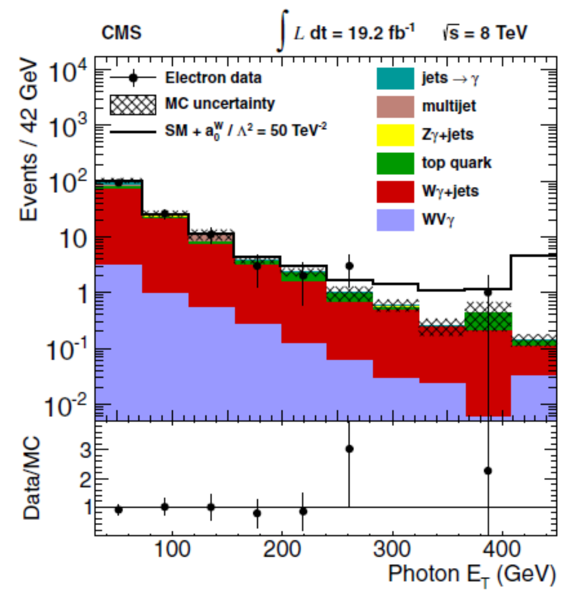
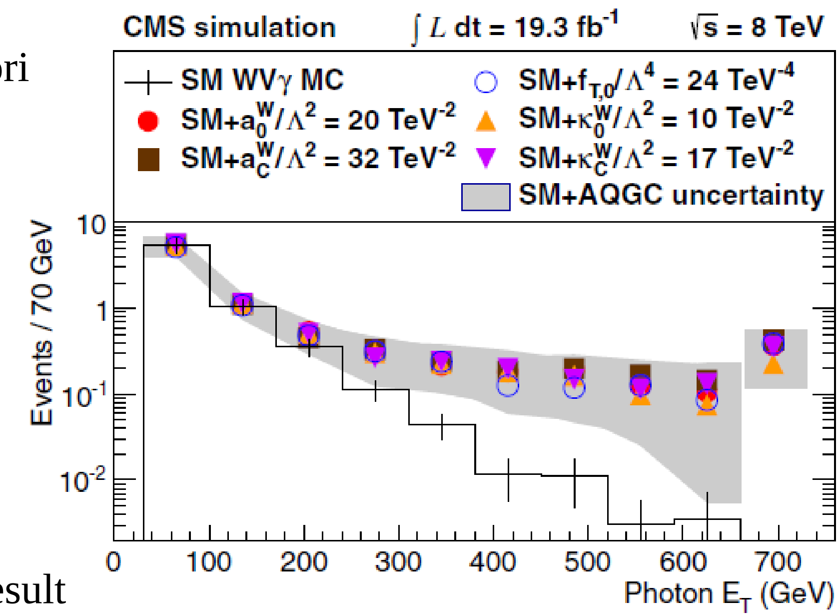


$WV\gamma \rightarrow$ lepton + jets + γ + $\not{E}_T$

- aQGC limits set without form factor
  - Dipole form factor could not conserve unitarity
  - Unitarity conserving new physics still possible with non-dipole form factor
    - Such new physics structure not known a priori
- Electron and muon channels separated
- Photon E_T used to set limits
- Upper limits set using profile likelihood asymptotic approximation method
  - Each channel provided as independent input
  - Combined statistically into final result
- Signal strength plotted over varying parameter values
  - Expected signal strength describes best possible result
  - Exclude regions below 1.0
  - 1-σ and 2-σ uncertainty bands included



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Results with 7/8 TeV Data

aQGC Limits

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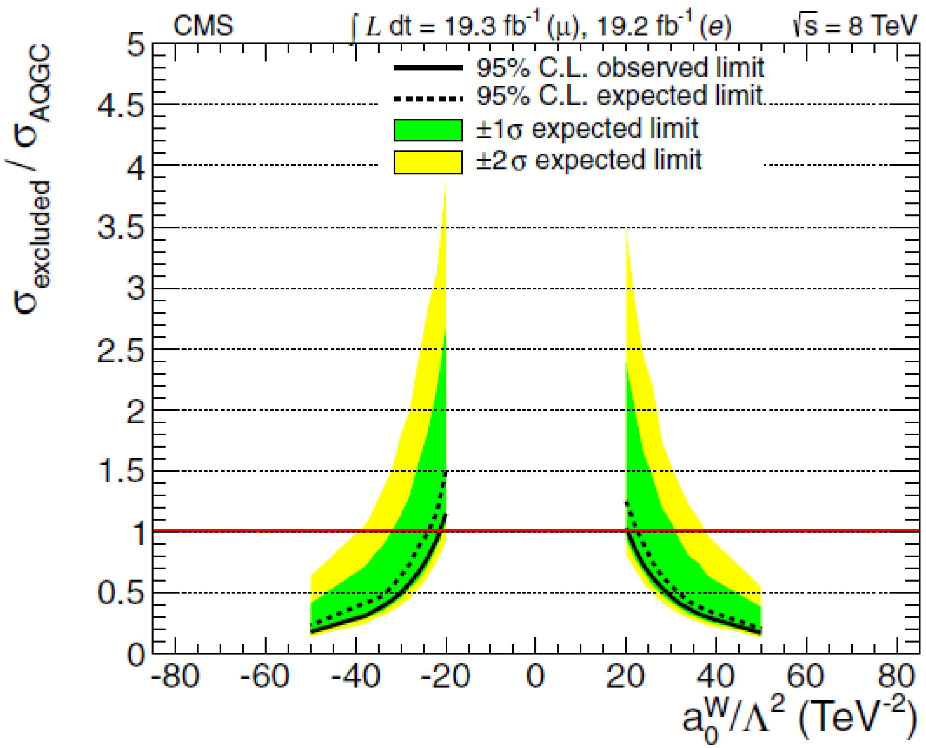
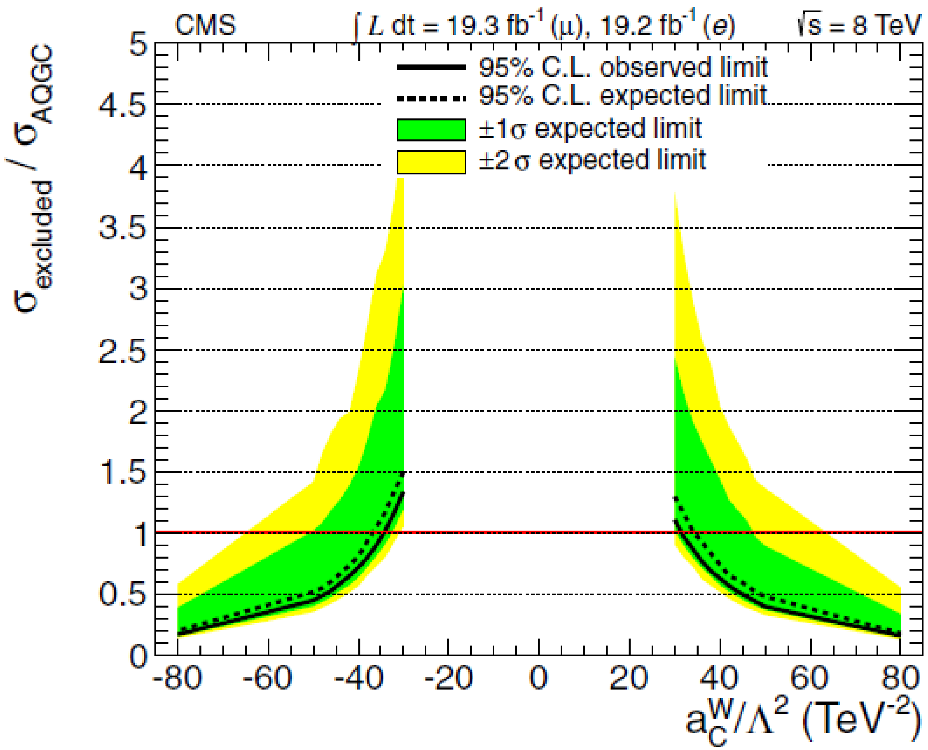


Observed Limits [TeV$^{-2,-4}$]	Expected Limits [TeV$^{-2,-4}$]
$-21 < a_0^W/\Lambda^2 < 20$	$-24 < a_0^W/\Lambda^2 < 23$
$-77 < f_{M,0}/\Lambda^4 < 81$	$-89 < f_{M,0}/\Lambda^4 < 93$
$-39 < f_{M,2}/\Lambda^4 < 40$	$-44 < f_{M,2}/\Lambda^4 < 46$
(LEP Limits) $-2000 < a_0^W/\Lambda^2 < 2000$	
(JHEP 1307 (2013) 116: $\gamma\gamma\to WW$ Limits) $-2.8 < a_0^W/\Lambda^2 < 2.8$	

$$\mathcal{L}_{AQGC} = \underbrace{\boxed{\frac{a_0^W}{4g^2}\mathcal{W}_0^\gamma}}_{\text{WWAA}} + \underbrace{\frac{a_c^W}{4g^2}\mathcal{W}_c^\gamma + \sum_i k_i^W \mathcal{W}_i^Z + \mathcal{L}_{T,0} + \mathcal{L}_{T,1} + \mathcal{L}_{T,2}}_{\text{Set to Zero}}$$

aQGC Limits



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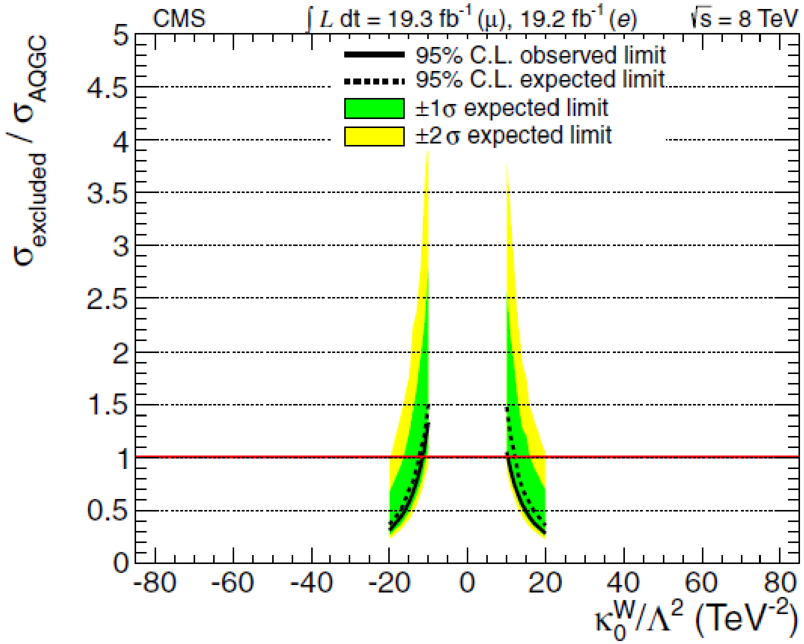
Observed Limits [$TeV^{-2,-4}$]	Expected Limits [$TeV^{-2,-4}$]
$-34 < a_C^W/\Lambda^2 < 32$	$-37 < a_C^W/\Lambda^2 < 34$
$-131 < f_{M,1}/\Lambda^4 < 123$	$-143 < f_{M,1}/\Lambda^4 < 131$
$-66 < f_{M,3}/\Lambda^4 < 62$	$-71 < f_{M,3}/\Lambda^4 < 66$
(LEP Limits) $-53000 < a_C^W/\Lambda^2 < 37000$	
(JHEP 1307 (2013) 116: $\gamma\gamma \to WW$ Limits) $-10.2 < a_C^W/\Lambda^2 < 10.2$	

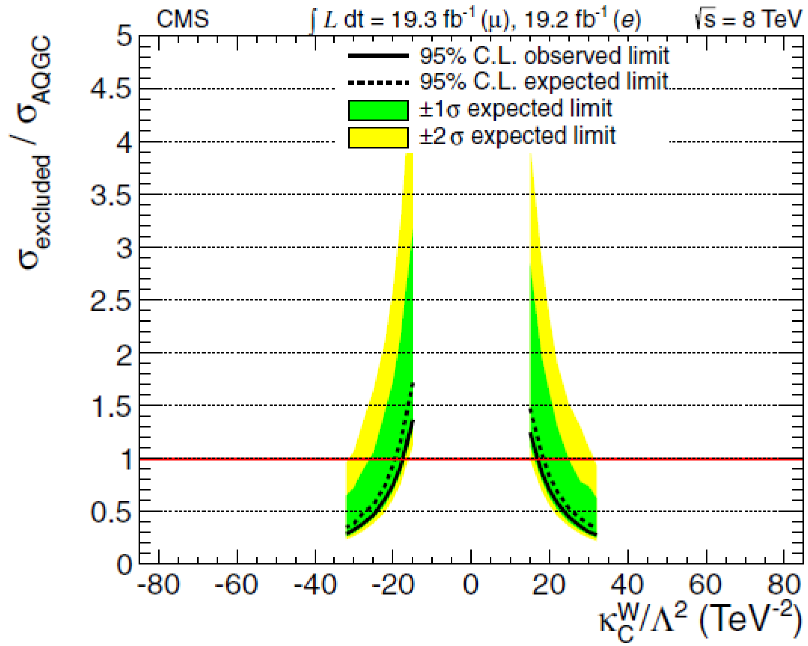
$$\mathcal{L}_{AQGC} = \underbrace{\frac{a_0^W}{4g^2}\mathcal{W}_0^\gamma}_{} + \boxed{\frac{a_c^W}{4g^2}\mathcal{W}_c^\gamma} + \underbrace{\sum_i k_i^W \mathcal{W}_i^Z + \mathcal{L}_{T,0} + \mathcal{L}_{T,1} + \mathcal{L}_{T,2}}_{}$$

WWAA

Set to Zero

aQGC Limits





Observed Limits [TeV^{-2}]	Expected Limits [TeV^{-2}]
$-12 < \kappa_0{}^W/\Lambda^2 < 10$	$-12 < \kappa_0{}^W/\Lambda^2 < 12$
$-18 < \kappa_C{}^W/\Lambda^2 < 17$	$-19 < \kappa_C{}^W/\Lambda^2 < 18$

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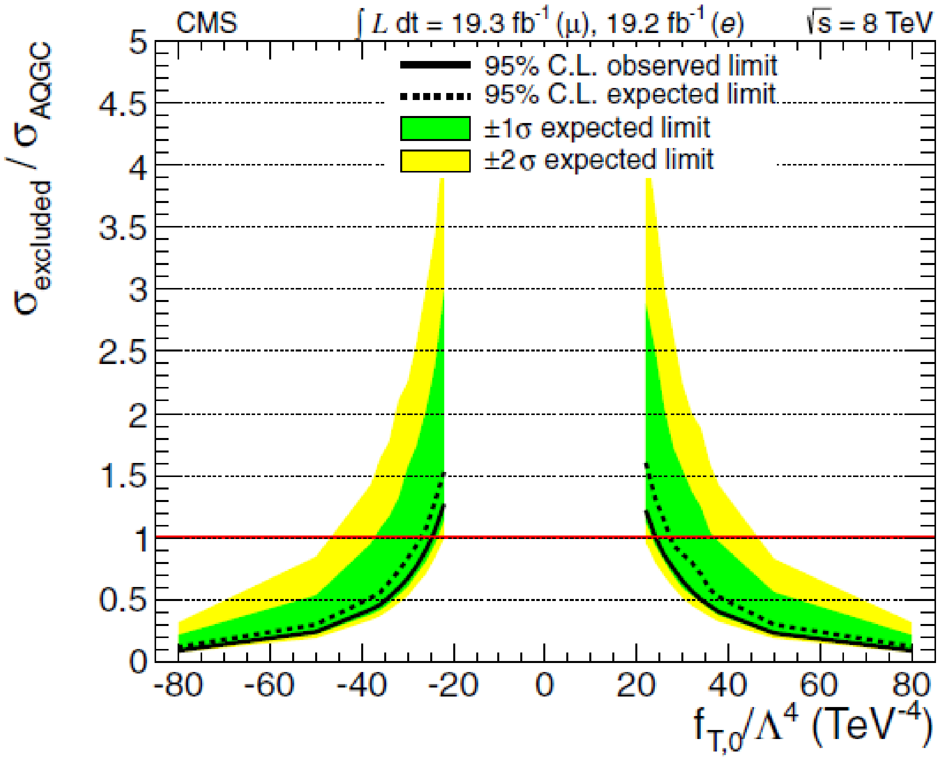
$$\mathcal{L}_{AQGC} = \frac{a_0^W}{4g^2}\mathcal{W}_0^\gamma + \frac{a_c^W}{4g^2}\mathcal{W}_c^\gamma + \underbrace{\boxed{\sum_i k_i^W \mathcal{W}_i^Z}}_{\text{WWZA}} + \underbrace{\mathcal{L}_{T,0} + \mathcal{L}_{T,1} + \mathcal{L}_{T,2}}_{\text{Set to Zero}}$$

aQGC Limits



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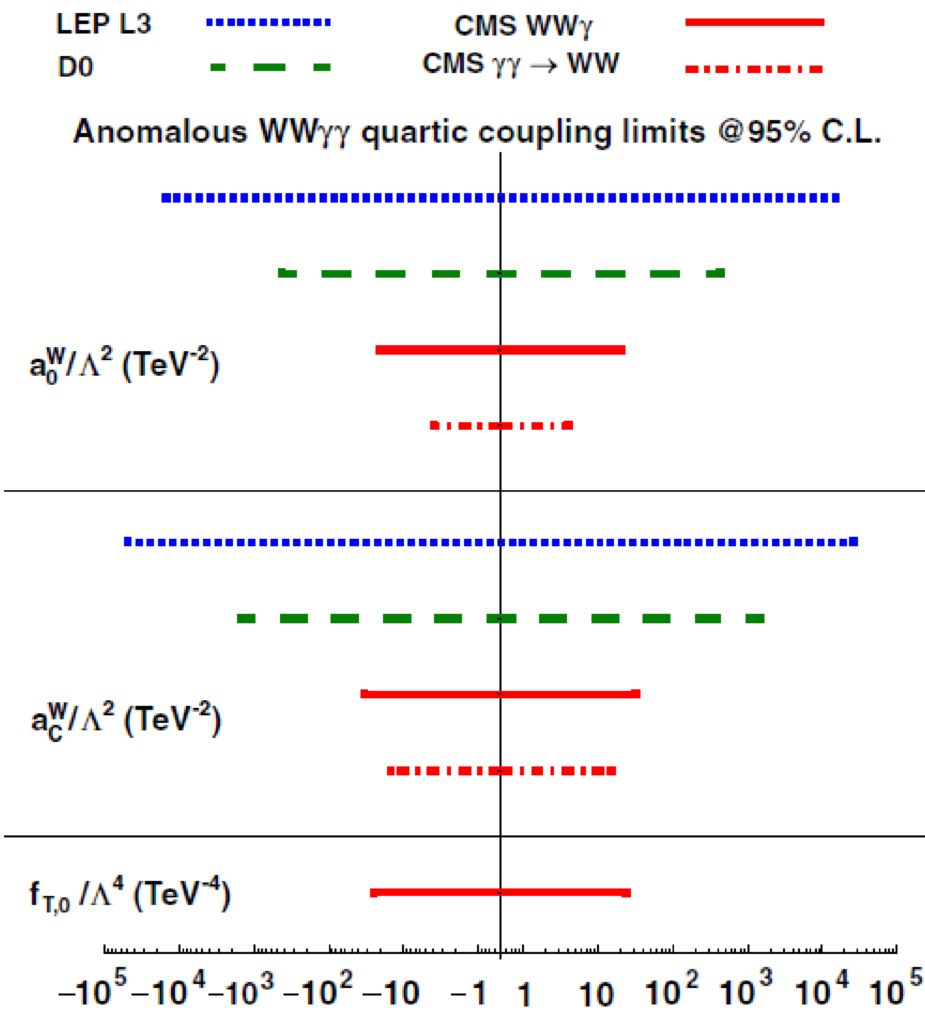
Observed Limits [TeV^{-4}]	Expected Limits [TeV^{-4}]
$-25 < f_{T,0}/\Lambda^4 < 24$	$-27 < f_{T,0}/\Lambda^4 < 27$

$$\mathcal{L}_{AQGC} = \frac{a_0^W}{4g^2}\mathcal{W}_0^\gamma + \frac{a_c^W}{4g^2}\mathcal{W}_c^\gamma + \sum_i k_i^W \mathcal{W}_i^Z + \boxed{\mathcal{L}_{T,0}} + \mathcal{L}_{T,1} + \mathcal{L}_{T,2}$$

WWAA

Set to Zero

aQGC Limits

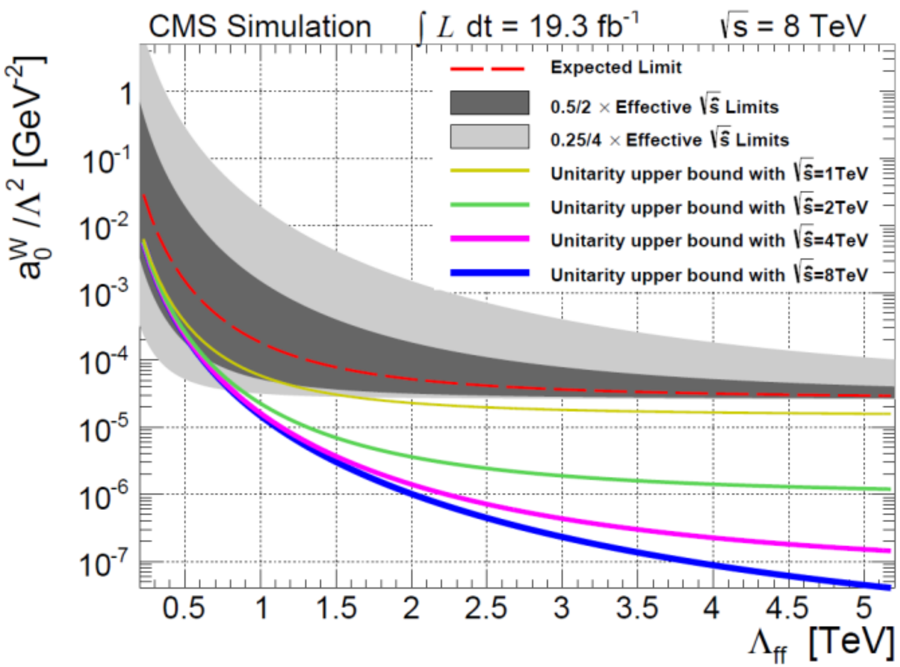


Coupling	Channel	Limits	$\int L\,dt$	$\sqrt{s}$
a_0^W/Λ^2 (TeV^{-2})	WWγ	[- 15000, 15000]	0.4fb^{-1}	0.20 TeV
	γγ → WW	[- 430, 430]	9.7fb^{-1}	1.96 TeV
	WWγ	[- 21, 20]	19.3fb^{-1}	8.0 TeV
	γγ → WW	[- 4, 4]	5.1fb^{-1}	7.0 TeV
a_C^W/Λ^2 (TeV^{-2})	WWγ	[- 48000, 26000]	0.4fb^{-1}	0.20 TeV
	γγ → WW	[- 1500, 1500]	9.7fb^{-1}	1.96 TeV
	WWγ	[- 34, 32]	19.3fb^{-1}	8.0 TeV
	γγ → WW	[- 15, 15]	5.1fb^{-1}	7.0 TeV
$f_{T,0}/\Lambda^4$ (TeV^{-4})	WWγ	[- 25, 24]	19.3fb^{-1}	8.0 TeV

Unitarity Violation

$$a_{0,c}^W \rightarrow \frac{a_{0,c}^W}{(1+\hat{s}/\Lambda_{ff}^2)^2}$$

- Form Factor dampens aQGC
  - *Used to conserve unitarity*
    - Little effect on low-energy events
    - Dampens high-energy events
  - *In non-unitary regime*
    - No matter the Form Factor choice



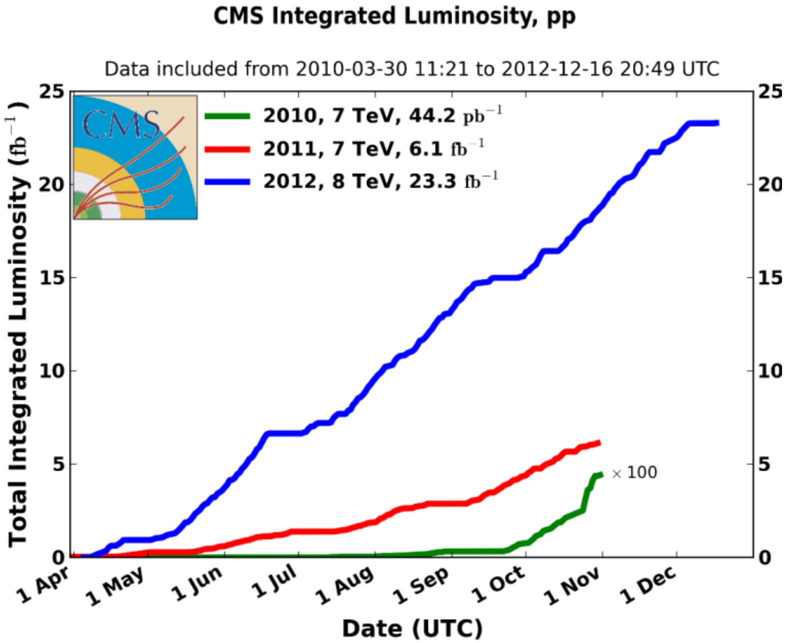
$$\frac{1}{N}\left(\frac{\alpha a s}{16}\right)^2\left(1-\frac{4M_W^2}{s}\right)^{1/2}\left(3-\frac{s}{M_W^2}+\frac{s^2}{4M_W^4}\right)\leq 1$$

2 → 2 Process Approximate Unitary Bound Equation from: arXiv: hep-ph 0912.5161

Prospects with 13 TeV Data

Run II is projected to achieve 13 TeV collisions

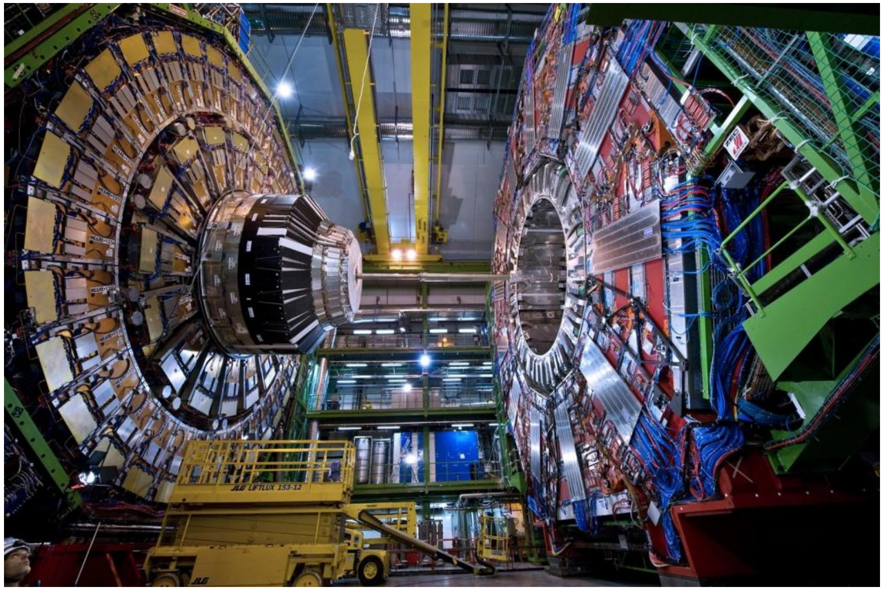
- Luminosity for 2012 data reached above 20 fb^{-1}
- In Run II we expect increase in number of observed triboson processes
- Expect enhanced sensitivity to aQGC in phase space of interest
  - High boson p_T regions



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

Summary

- Processes with triboson final states have been studied
  - Set upper SM cross section limits on WVγ
- aQGC studies have included linear formalism
- Contribution from aQGC is not observed to date
  - Limits agree with SM
  - Tighter aQGC limits set with 7/8 TeV data
- Unitarity violation considered
  - Dipole form factor
  - Various new physics scales
- 13 TeV data very promising for aQGC studies



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