Quartic Gauge Boson Coupling Results from the LHC

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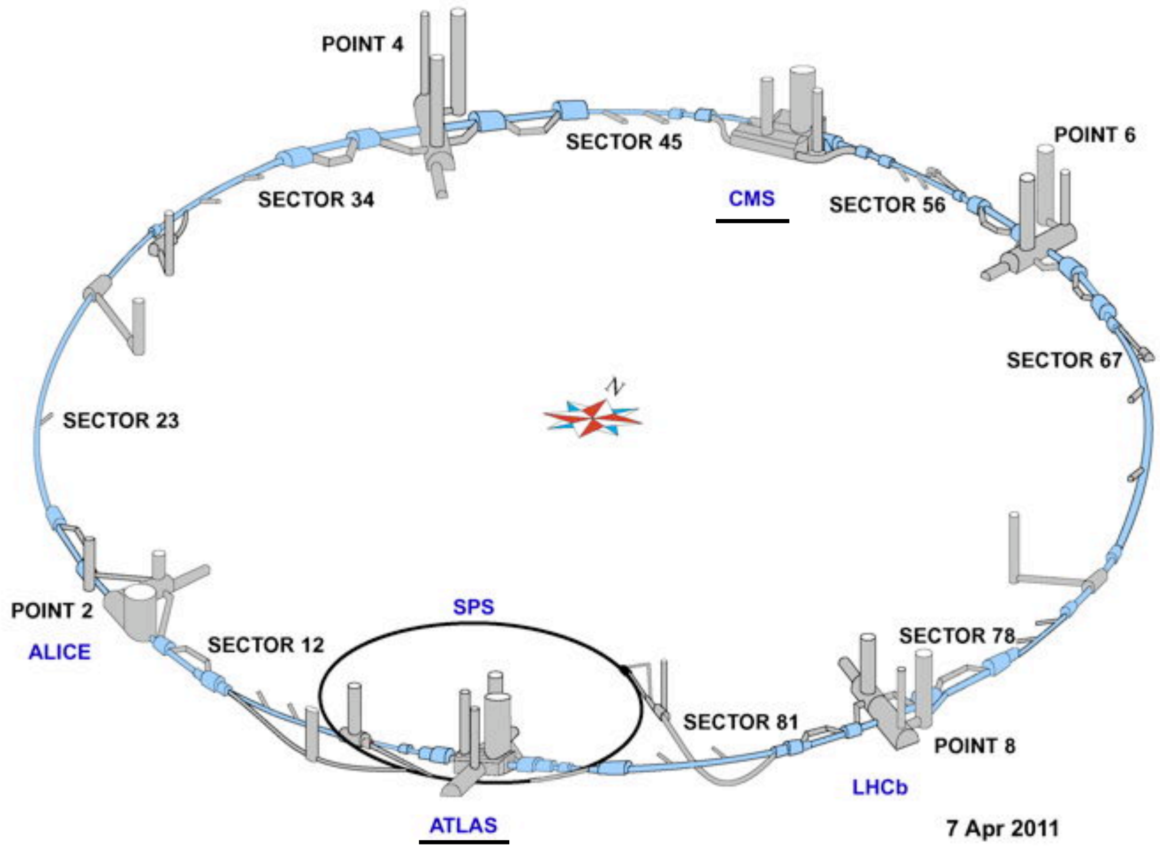
Large Hadron Collider



Measurements made using proton-proton collisions at the Large Hadron Collider. The LHC's two general discovery detectors are the **ATLAS** and **CMS** experiments.

Quartic Gauge Coupling (QGC) studies utilize the 2012 $\sqrt{s}$ **= 8 TeV** (20.3 fb^{-1} ATLAS 19.4 fb^{-1} CMS) data still place the most stringent limits on new physics.

Quartic Gauge Couplings

The Standard Model (SM) predicts the self interactions of the vector gauge bosons, **γ, $W^{\pm}$, Z,** and requires the presence of **Quartic Gauge Couplings**.

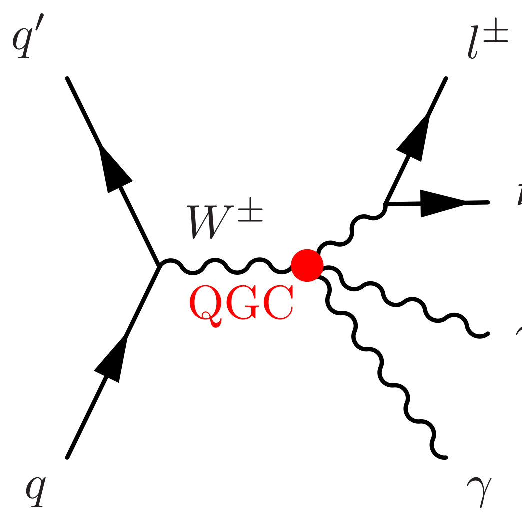
$$\mathcal{L} = -\frac{1}{4} W^{a\dagger}_{\mu\nu} W^{\mu\nu}_{a} - \frac{1}{4} B_{\mu\nu} B^{\mu\nu}$$

SU(2)$_L$ x U(1)$_Y$ Lagrangian

$$W^{a}_{\mu\nu} = \partial_\mu W^{a}_{\nu} - \partial_\nu W^{a}_{\mu} - g f_{abc} W^{b}_{\mu} W^{c}_{\nu}$$

Non-abelian Term

Neutral Quartic Vertices (ie ZZ$\gamma\gamma$) are forbidden by the SM



SM predicts value of the coupling strength

Deviation from the SM prediction is a clear sign of **new physics.**

Effective Field Theories

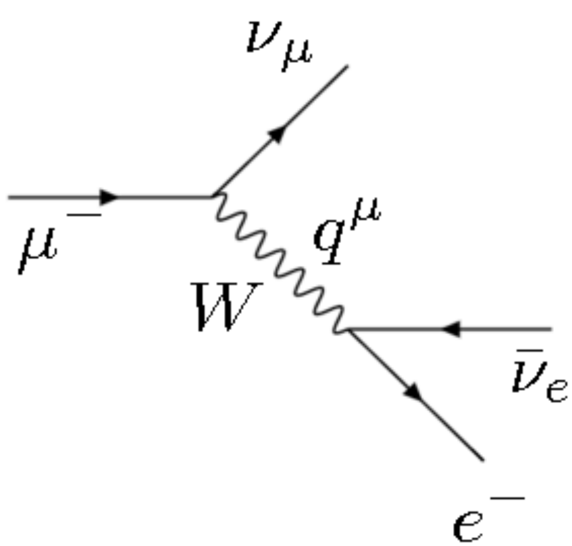
Anomalous QGCs are modeled with **Effective Field Theories** (EFT). **EFT** approximate new physics through higher mass dimension operators divided by powers of an energy scale, Λ:

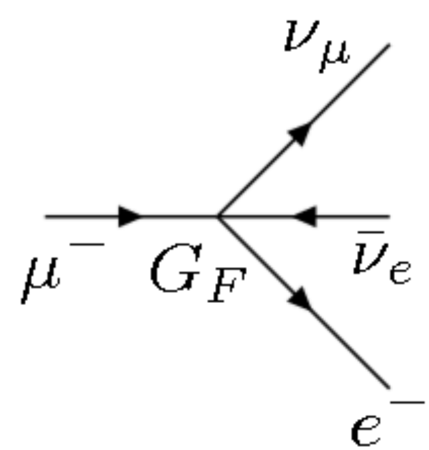
For **aQGC**, **dimension-8** is the lowest order of "purely" quartic gauge interactions. **18** possible operators exist. AQGCs manifest as an excess of events at high Q^2.

$$\mathcal{L}_{\mathrm{aQGC}} = \mathcal{L}_{\mathcal{SM}} + \sum_i \frac{f_i}{\boxed{\Lambda^4}} \mathcal{O}_i + \ldots$$

Example: The Fermi Theory of weak interactions is an **EFT** useful at energies, $q \ll m_W$ (Λ).

$$\mathcal{M} = \frac{g^2}{8}\left[\bar{\psi}\gamma^\mu(1-\gamma^5)\psi\right]\frac{g_{\mu\nu} - \frac{q_\mu q_\nu}{m_W^2}}{q^2 - m_W^2}\left[\bar{\psi}\gamma^\nu(1-\gamma^5)\psi\right] \longrightarrow \mathcal{M} = \frac{G_F}{\sqrt{2}}\boxed{\left[\bar{\psi}\gamma^\mu\psi\right]\left[\bar{\psi}\gamma_\mu\psi\right]}$$ **Dim-6** †





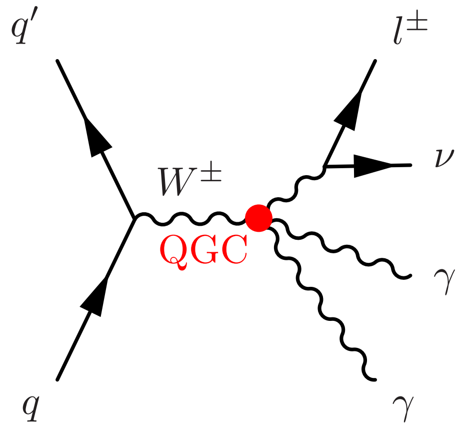
$$G_F = \frac{\sqrt{2}g^2}{8m_W^2}$$

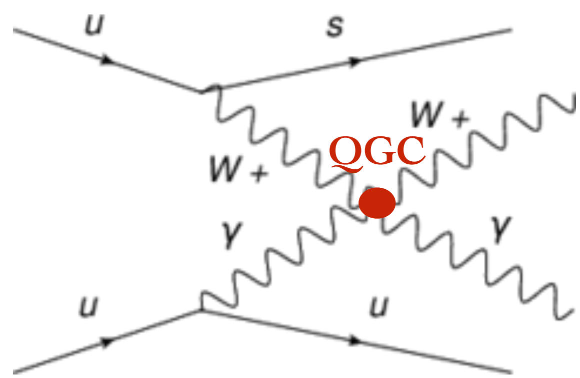
Can experimentally measure G_F from muon's lifetime.

†Original Fermi model was pure vector

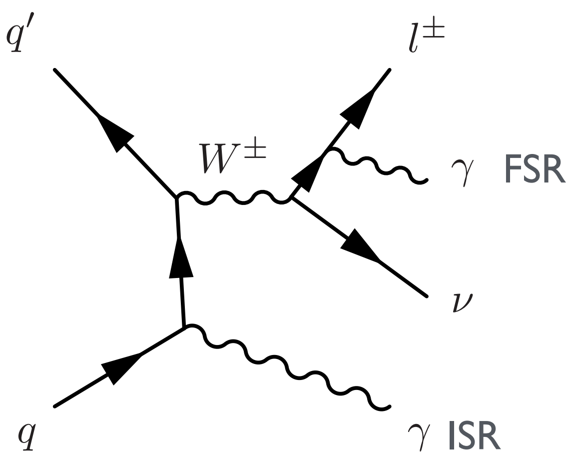
Final States

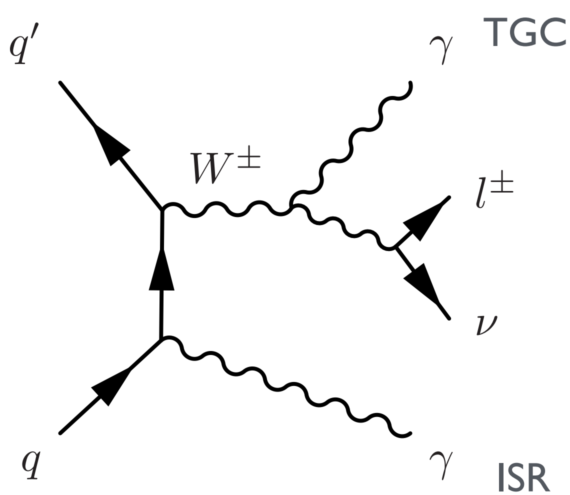
QGC studies measure **triboson production** or diboson production through **vector boson scattering (VBS),** looking for leptonic decays of the W,Z and in the case of **VBS** the presence of two separated jets.

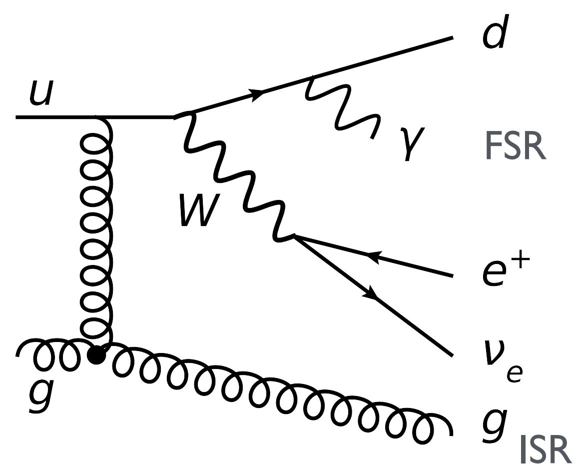




Additional non-**QGC** Feynman diagrams also contribute to these final states. There are contributions from **Initial State Radiation** (ISR), **Final State Radiation** (FSR), and **Triple Gauge Couplings** (TGC).



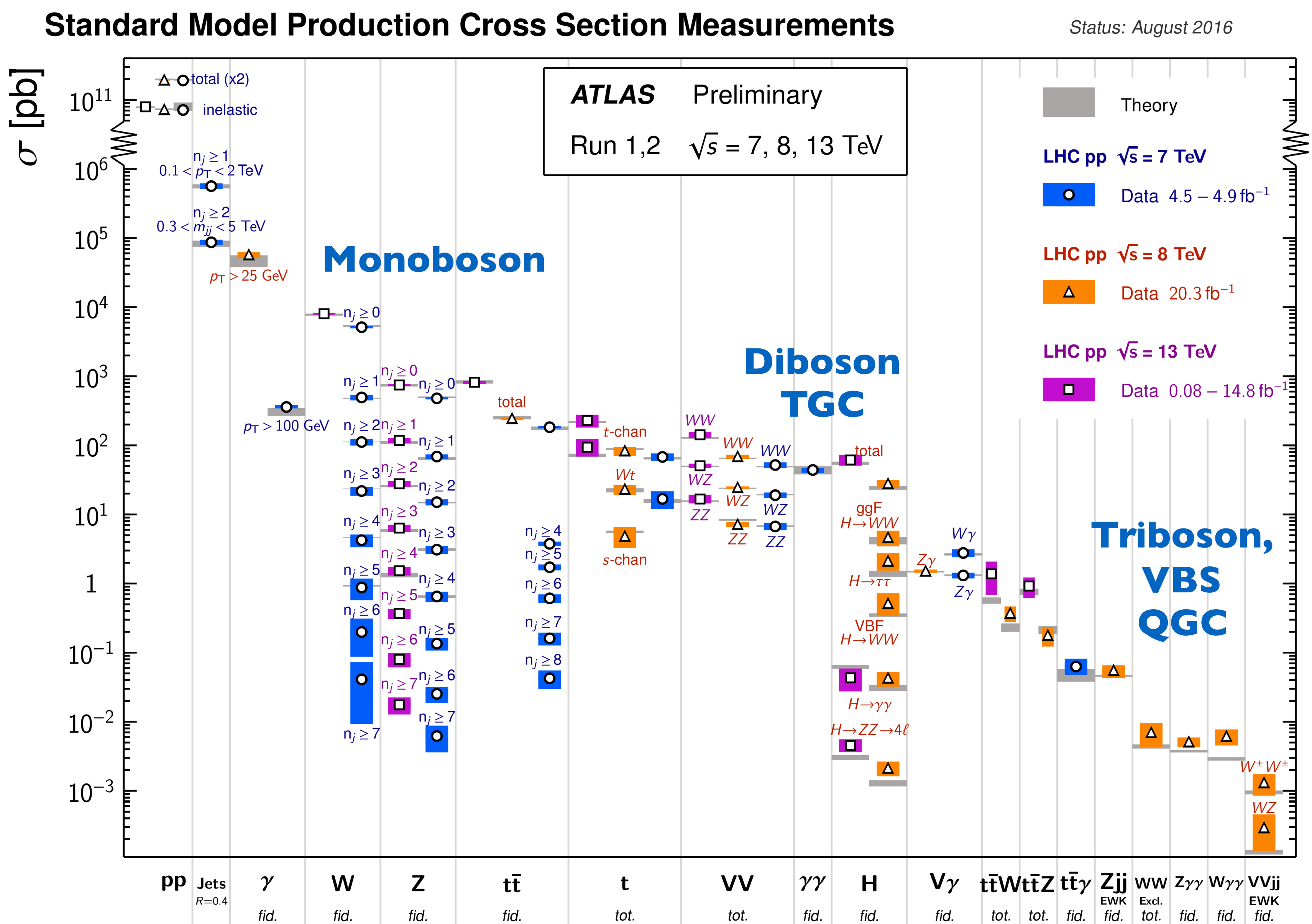




†Illustrative subset of the possible non-QGC diagrams, all must be considered.

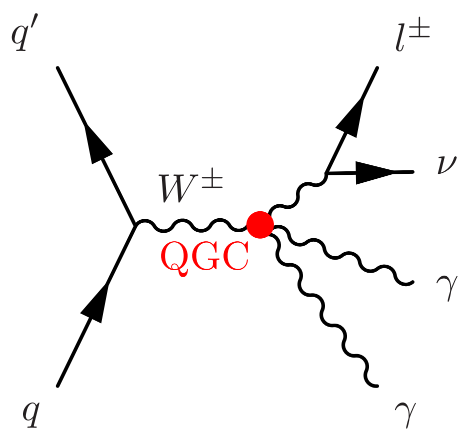
Production Cross Sections

Triboson production and VBS are **rare** SM processes just becoming accessible at the LHC.



These multiboson processes are backgrounds to Higgs measurements and new physics searches.

$W\gamma\gamma$

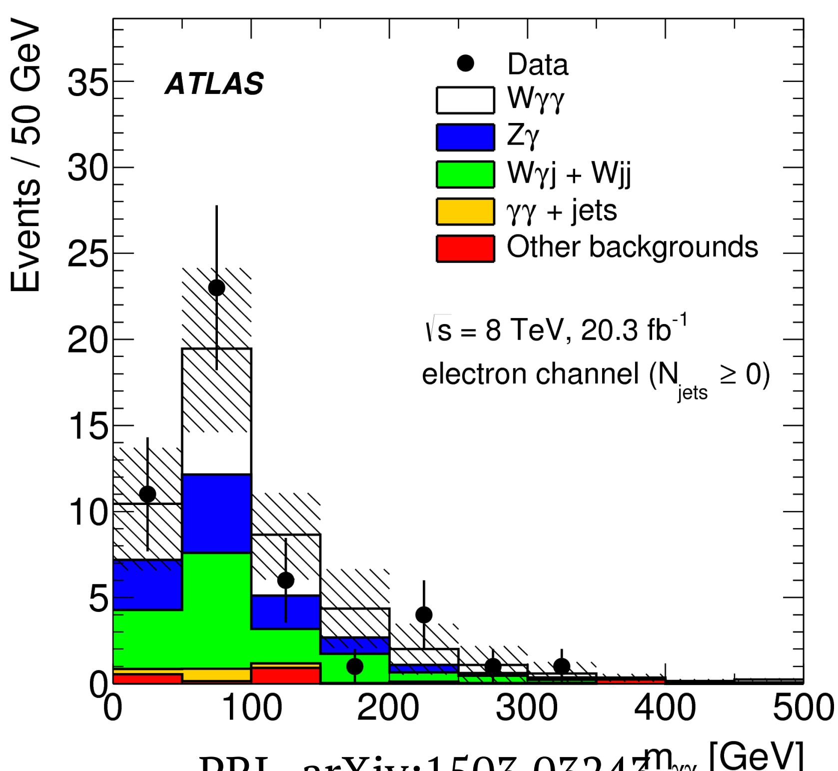


For ATLAS (CMS)

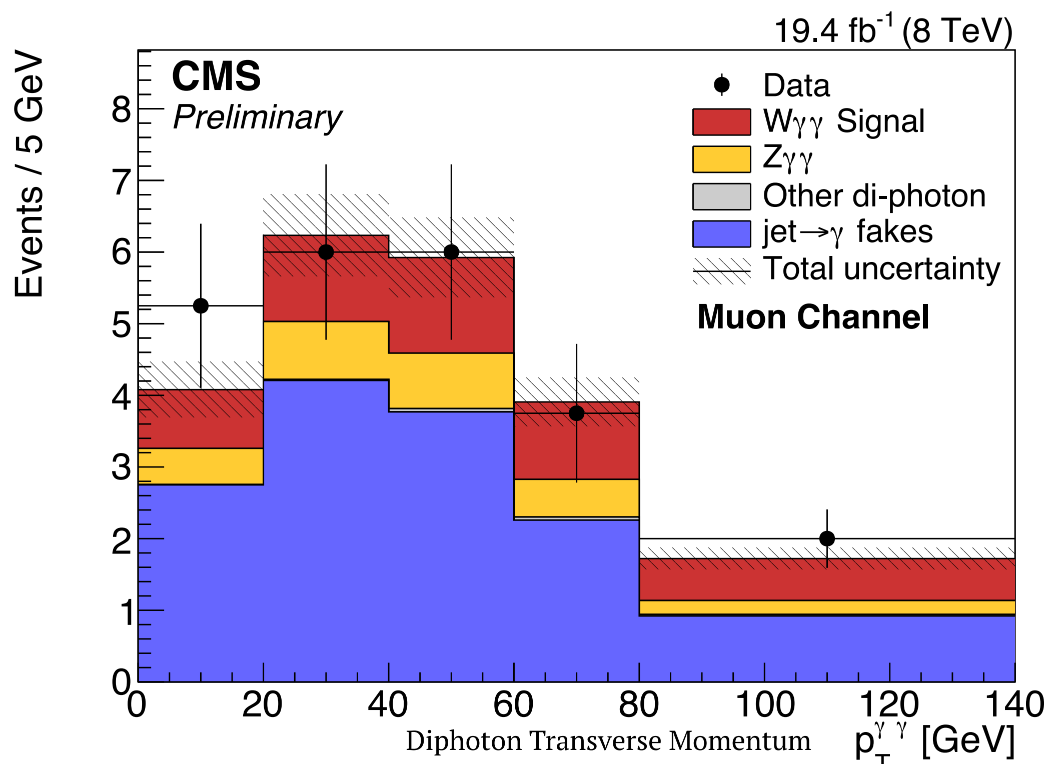
- Trigger on single electron, muon
- 2 photons p_T > 20 (25) GeV
- $m_T(\ell, E_T^{miss})$ > 40 (40) GeV

$$m_{\mathrm{T}} = \sqrt{2E_T^{\ell}E_{\mathrm{T}}^{\mathrm{miss}}\left(1-\cos\left(\Delta\phi\left(E_T^{\ell}, E_{\mathrm{T}}^{\mathrm{miss}}\right)\right)\right)}$$

Significance: 3σ (2.4σ)



PRL, arXiv:1503.03243



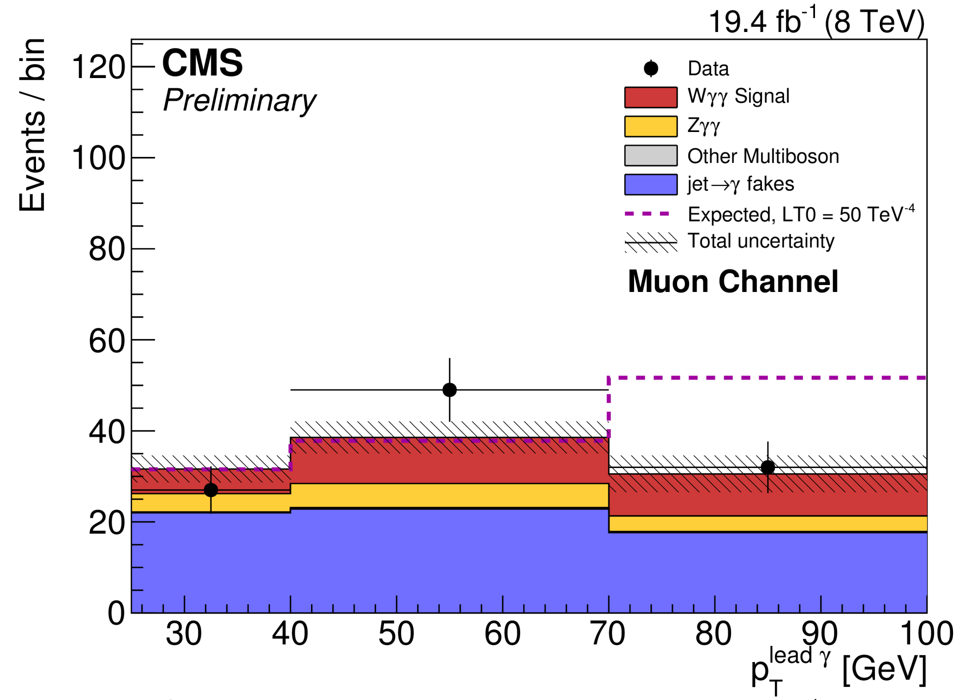
CMS-PAS-SMP-15-008

Strategy for Limit Setting

Triboson and VBS studies use a similar limit setting strategy.

Select subregion with a kinematic variable sensitive to aQGC, ie lead photon $p_T > 70$ GeV.

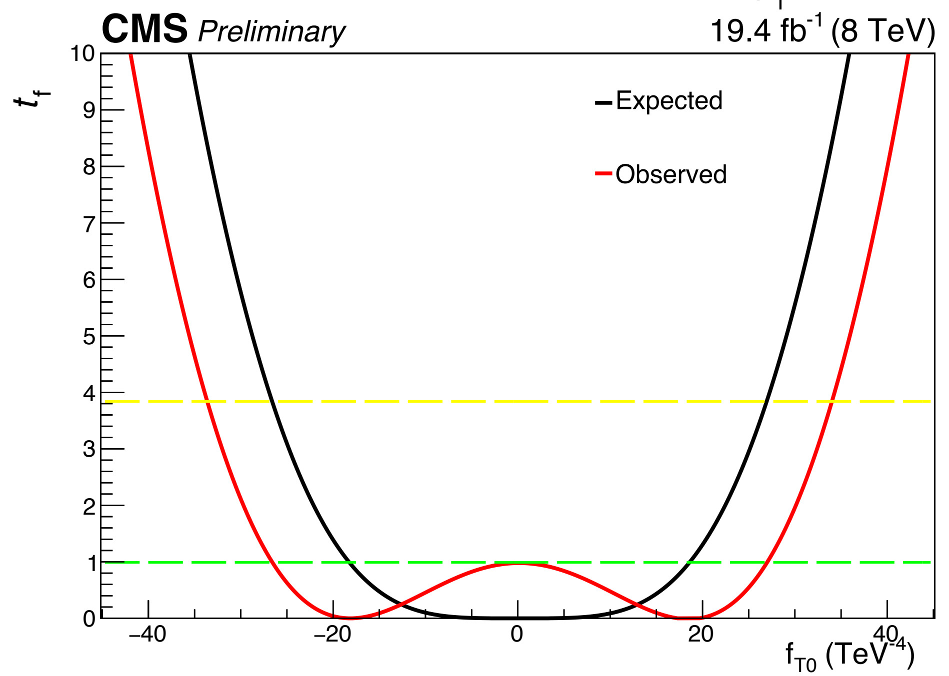
Determine 95% confidence level using ratio of likelihoods test statistic, t_f, behaves asymptotically as a $\chi 2$ distribution.



$$t_f = -2 \ln \frac{L(f, \hat{\hat{\theta}})}{L(\hat{f}, \hat{\theta})}$$

← Likelihood for specific f

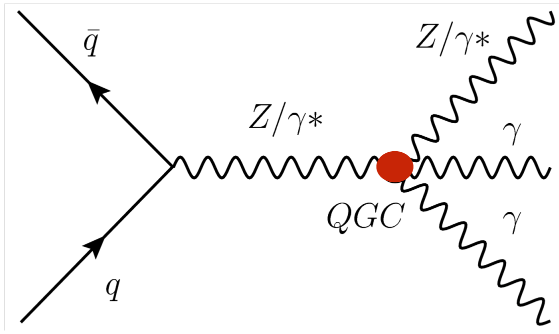
← Likelihood for best fit f



Limits for $W\gamma\gamma$

Expected Limits (TeV^{-4})	Observed Limits (TeV^{-4})
$-30.5 < \frac{f_{T0}}{\Lambda^4} < 31.1$	$-37.5 < \frac{f_{T0}}{\Lambda^4} < 38.1$
$-36.9 < \frac{f_{T1}}{\Lambda^4} < 37.5$	$-46.1 < \frac{f_{T1}}{\Lambda^4} < 46.9$
$-83.2 < \frac{f_{T2}}{\Lambda^4} < 83.2$	$-103 < \frac{f_{T2}}{\Lambda^4} < 103$
$-623 < \frac{f_{M2}}{\Lambda^4} < 603$	$-751 < \frac{f_{M2}}{\Lambda^4} < 729$
$-1080 < \frac{f_{M3}}{\Lambda^4} < 1110$	$-1290 < \frac{f_{M3}}{\Lambda^4} < 1340$

$Z\gamma\gamma$



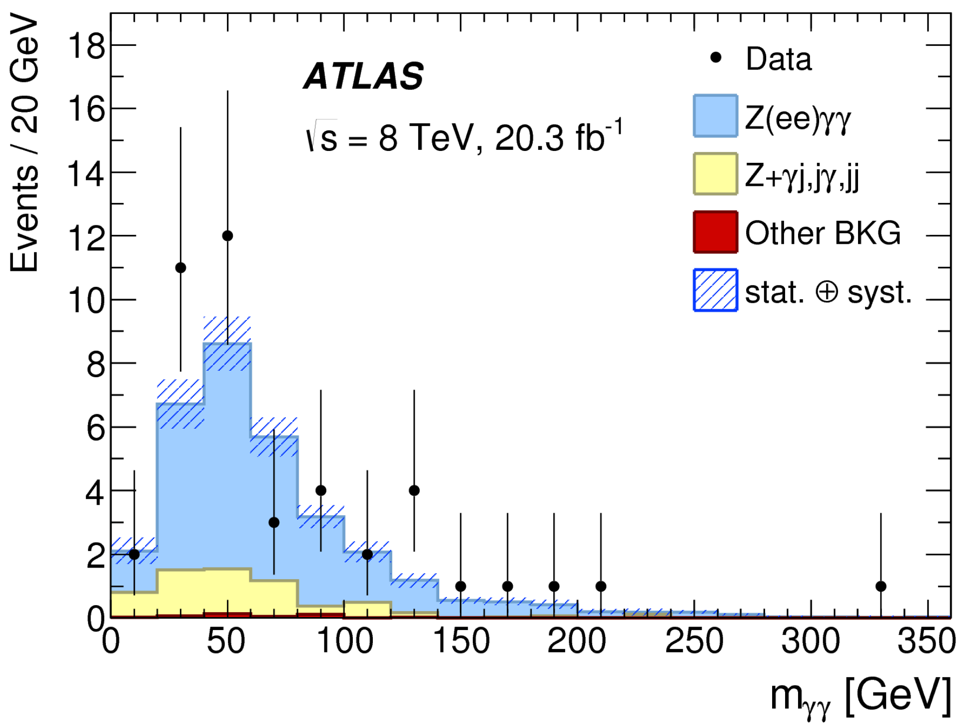
(Neutral QGC forbidden by SM)

For ATLAS (CMS)

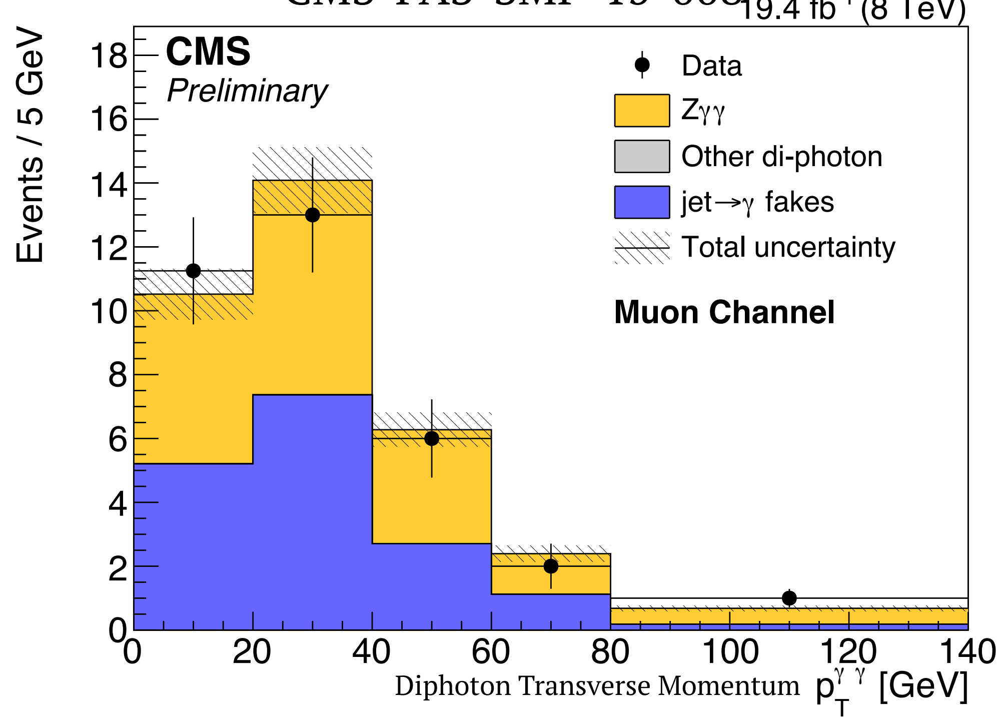
- Trigger on two electrons or muons, or photon for ATLAS νν channel
- 2 photons p_T > 15 (15), 22 GeV
- $M_{\ell\ell}$ > 40 (40) GeV , E_T^{Miss} > 110 GeV

Significance: 6.3σ (5.9σ)

PRD, arXiv:1604.05232

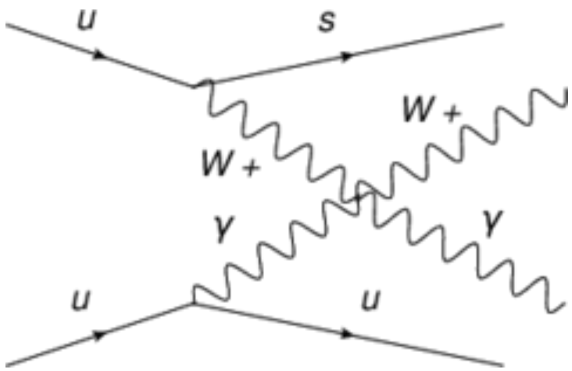


CMS-PAS-SMP-15-008



ATLAS sets limits using an aQGC region with $m_{\gamma\gamma}$ > 200 GeV, for νν channel $m_{\gamma\gamma}$ > 300 GeV

Wγ + 2 jets (VBS)



Optimized VBS Selection

- $\Delta |\eta(j_1,j_2)| > 2.4$
- $M_{jj} > 700$ GeV
- $\Delta |\phi(W\gamma,jj)| > 2.6$
- Zeppenfeld variable

$$|y_{W\gamma} - (y_{j1} + y_{j2})/2| < 0.6$$

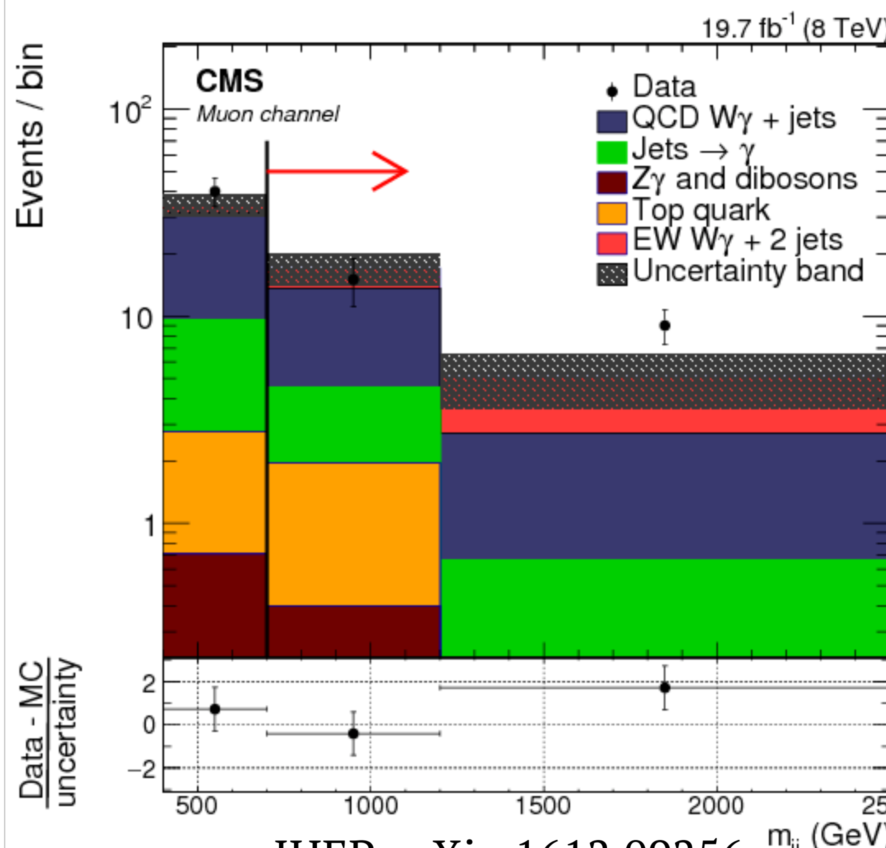
arXiv:9605444

AQGC region requires photon $p_T > 200$ GeV

For CMS

- Trigger on single electron, muon
- Lead, sublead jet $p_T > 40, 30$ GeV
- Photon $p_T > 22$ GeV
- $m_T(\ell, E_T^{miss}) > 30$ GeV

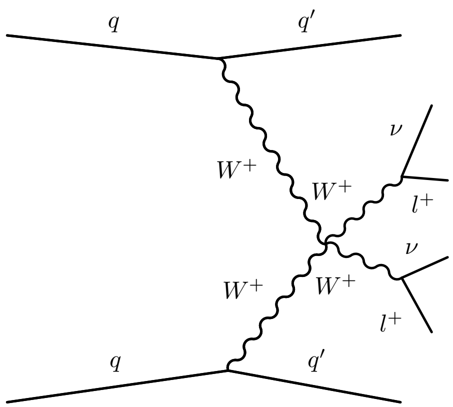
Significance: 2.7σ



JHEP, arXiv:1612.09256

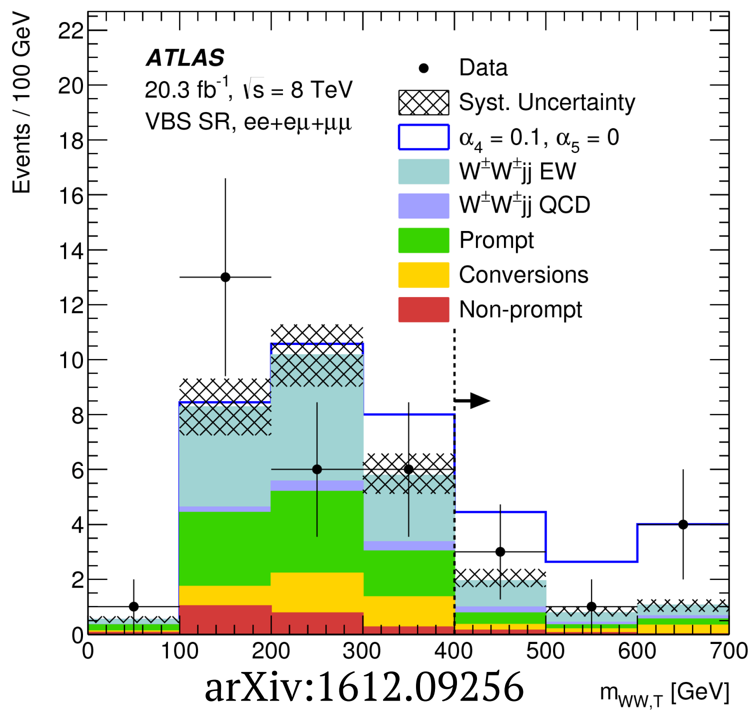
$W^\pm W^\pm jj$ (Same Sign)

Same sign WW production requires a hadron collider.

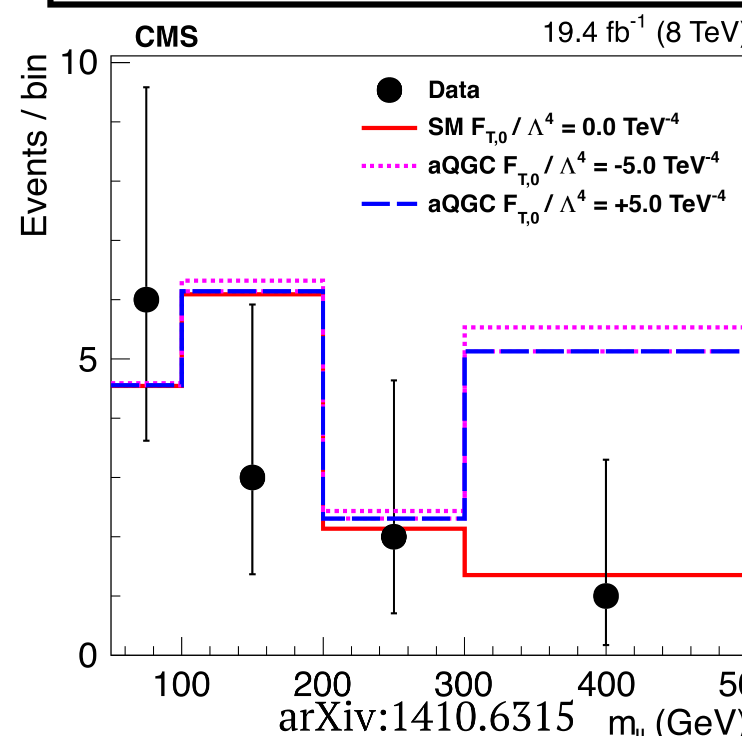


- Two leptons with the same electric charge: $e^\pm e^\pm$, $e^\pm \mu^\pm$, $\mu^\pm \mu^\pm$
- $E_T^{miss} > 40$ (40) GeV
- $M_{jj} > 500$ (500) GeV
- $\Delta\,|\eta(j_1,j_2)| > 2.4$ (2.5)

Significance: 3.6σ (2.0σ)



arXiv:1612.09256



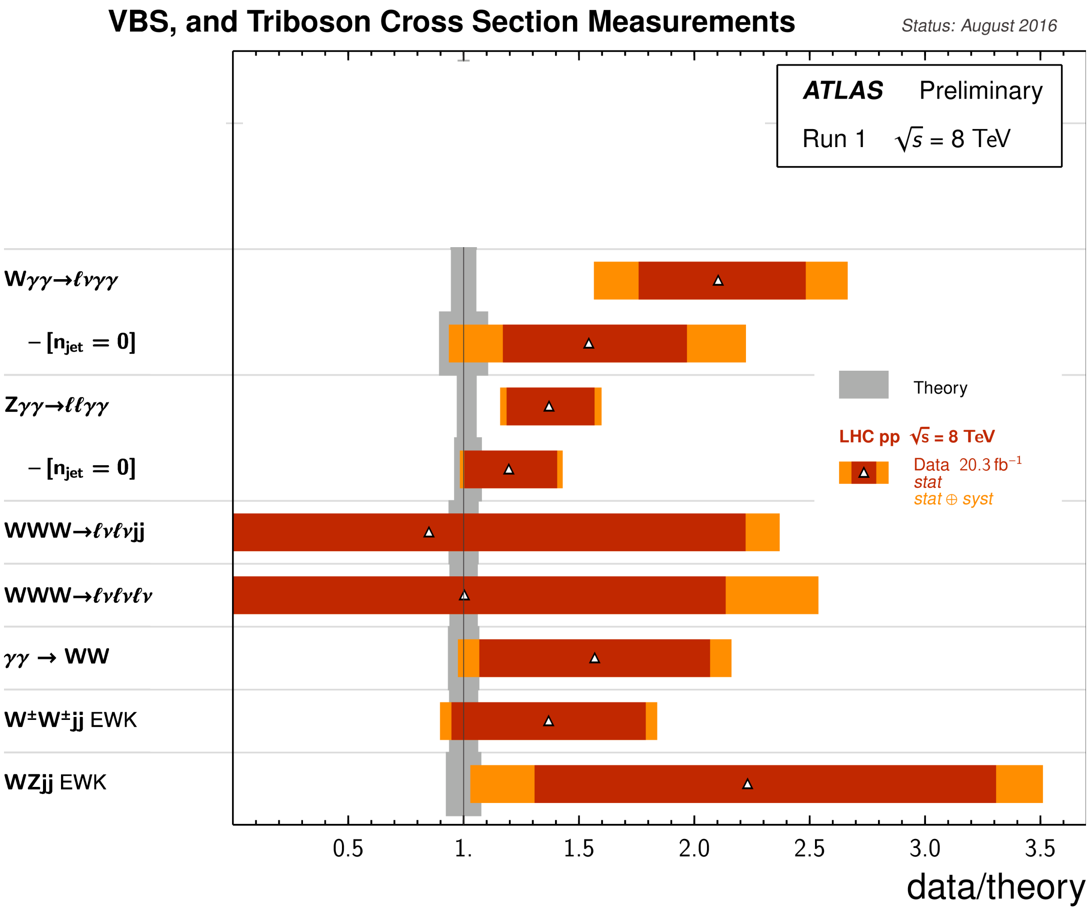
arXiv:1410.6315

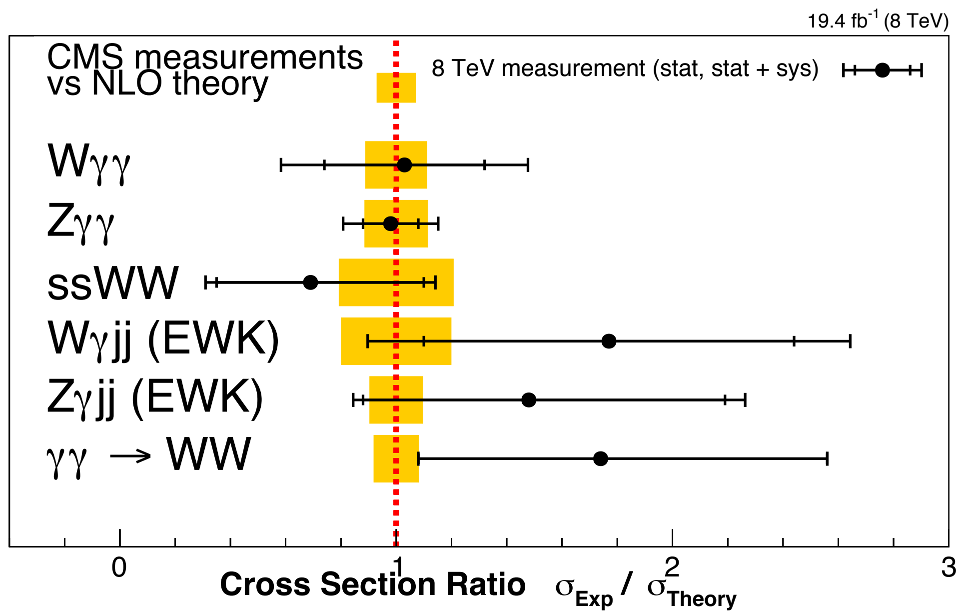
Limit setting: ATLAS utilizes WW transverse mass estimate, $m_{WW,T} = \sqrt{\left(\mathbf{P}_{\ell_1} + \mathbf{P}_{\ell_2} + \mathbf{P}_{E_T^{miss}}\right)^2}$, while CMS utilizes m_{ll}.

($m_{WWT} > 400$ GeV)

Comparison to Theory

The electron and muon channels are combined into a single cross-section measurements. Experimental results are in agreement with the NLO theory predictions.





Taken from ATLAS public results, twiki.cern.ch/twiki/bin/view/AtlasPublic/StandardModelPublicResults

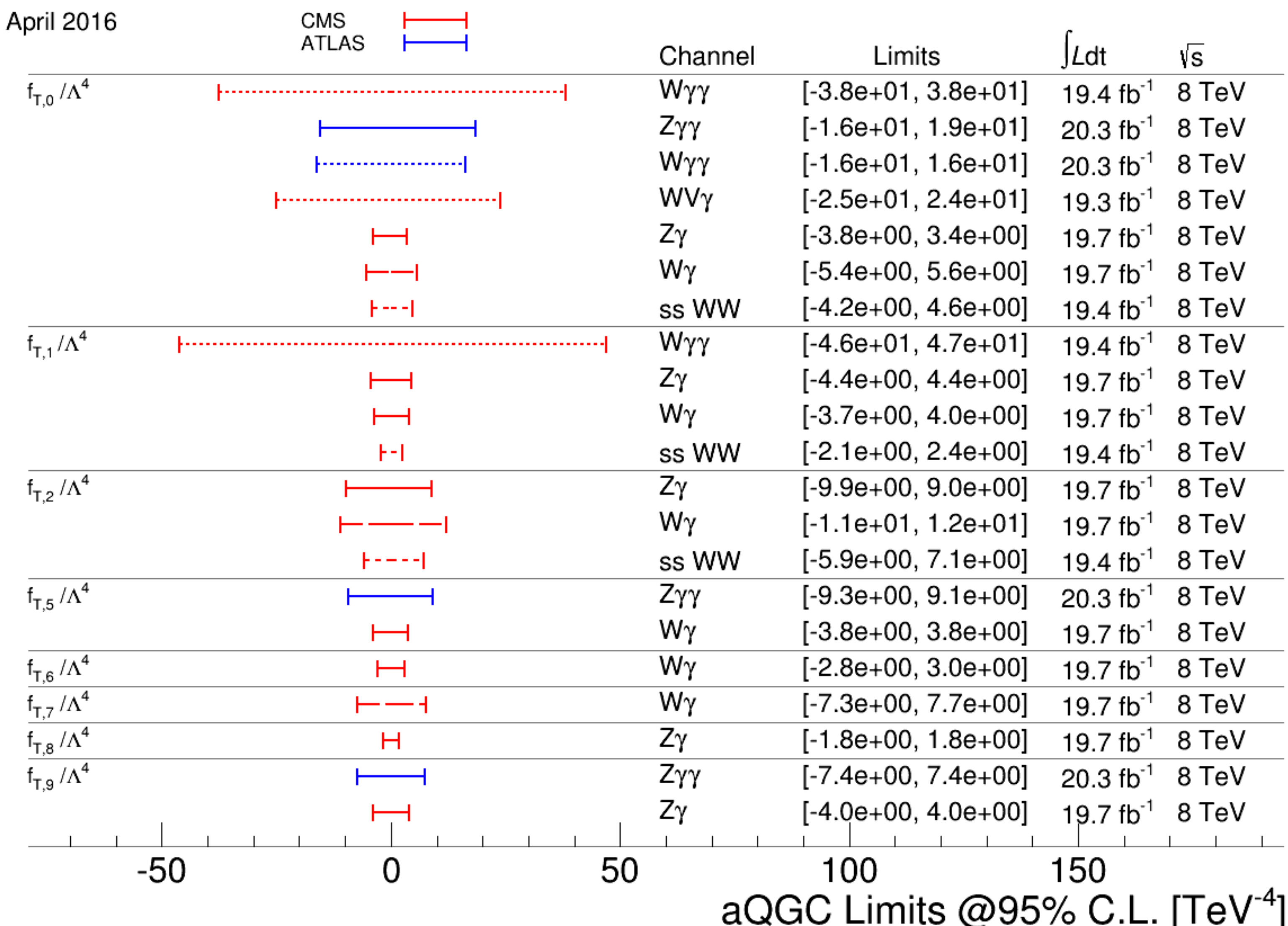
Taken from CMS-PAS -SMP-14-018, CMS-PAS-SMP-14-011, JHEP arXiv1604.04464

Summary of Limits

EFT are often constrained by multiple channels, useful for differentiating potential signal.

Summaries taken from: twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMPaTGC

Transverse Parameters

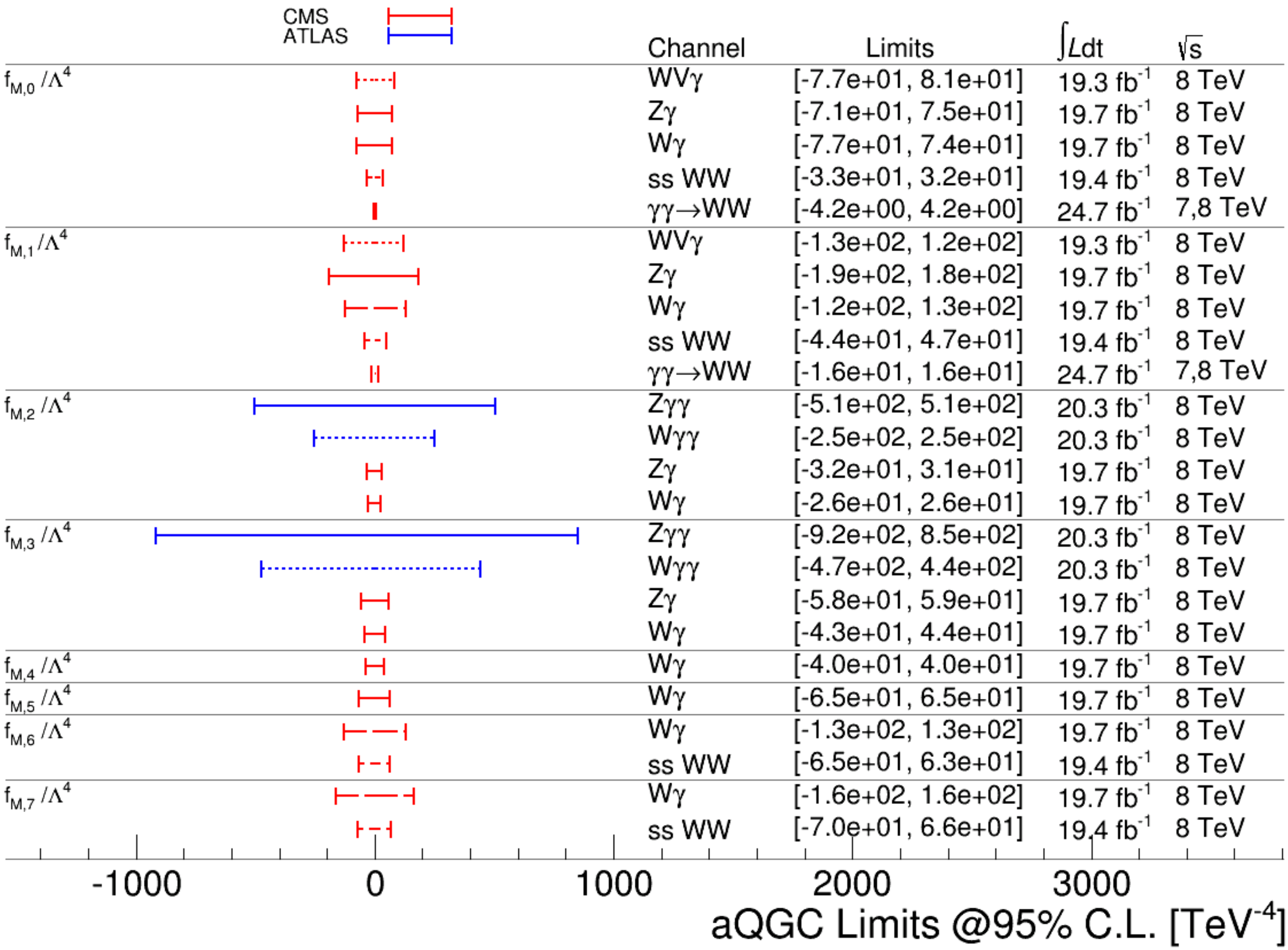


†Couplings are defined following the Eboli et. al convention,

Summary of Limits

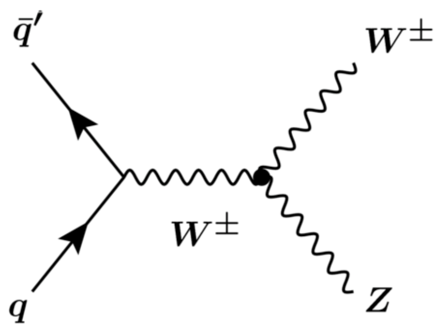
From: twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMPaTGC

Longitudinal and Mixed-Transverse Parameters



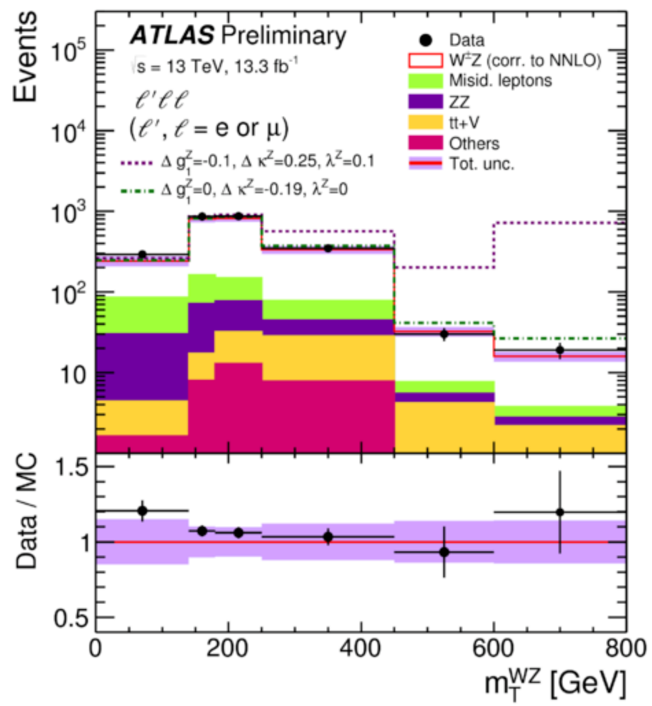
†Couplings are defined following the Eboli et. al convention,

Looking Forward



New data: Last summer ATLAS used partial 2016 dataset (13.3 fb^{-1}) to measured WZ production at $\sqrt{s}$ = 13 TeV. Limits placed on aTGC (Dim-6 EFT).

ATLAS-CONF-2016-043



Comparison of 8 TeV and 13 TeV Limits

8 TeV

EFT coupling	Expected [TeV^{-2}]	Observed [TeV^{-2}]
c_W/Λ^2	[−3.7 ; 7.6]	[−4.3 ; 6.8]
c_B/Λ^2	[−270 ; 180]	[−320 ; 210]
c_{WWW}/Λ^2	[−3.9 ; 3.8]	[−3.9 ; 4.0]

13 TeV

Coupling	Expected [TeV^{-2}]	Observed [TeV^{-2}]
c_W/Λ^2_{NP}	[-4.1; 7.6]	[-3.8; 8.6]
c_B/Λ^2_{NP}	[-261; 193]	[-280; 163]
c_{WWW}/Λ^2_{NP}	[-3.6; 3.4]	[-3.9; 3.7]

Limits are as good as or surpass previous 8 TeV results. With 36 fb^{-1} of integrated luminosity in the full 2016 dataset, new QGC studies should surpass current bounds and potentially discover new physics.

Summary

- Triboson production and VBS are accessible at the LHC.
- Fiducial cross-section measurements agree with SM predictions.
- Dim-8 EFT used to search for aQGC in the electroweak sector, $\sqrt{s} = 8$ TeV results are currently the most constraining.
- Excitement for new results and increased sensitivity with the 2016 data!

Backup Slides

Likelihood

For likelihood, observed number of events follows a Poisson distribution. Product over channels and detector regions.

SM signal **Estimated Background**

$$\mathcal{L}(f) = \prod_{i=1}^{nbins} Pois(x_i|\mu(f) \cdot s_i(\theta) + b_i(\theta)) \times P_n(\theta)$$

Observed Events **aQGC/SM ratio** **Nuisance Parameters**

Dim-8 EFT

	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

$$\mathcal{L}_{S,0} = \left[(D_\mu\Phi)^\dagger D_\nu\Phi\right] \times \left[(D^\mu\Phi)^\dagger D^\nu\Phi\right]$$

$$\mathcal{L}_{S,1} = \left[(D_\mu\Phi)^\dagger D^\mu\Phi\right] \times \left[(D_\nu\Phi)^\dagger D^\nu\Phi\right]$$

$$\mathcal{L}_{M,0} = \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right] \times \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right]$$

$$\mathcal{L}_{M,1} = \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\nu\beta}\right] \times \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right]$$

$$\mathcal{L}_{M,2} = \left[B_{\mu\nu}B^{\mu\nu}\right] \times \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right]$$

$$\mathcal{L}_{M,3} = \left[B_{\mu\nu}B^{\nu\beta}\right] \times \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right]$$

$$\mathcal{L}_{M,4} = \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu} D^\mu\Phi\right] \times B^{\beta\nu}$$

$$\mathcal{L}_{M,5} = \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu} D^\nu\Phi\right] \times B^{\beta\mu}$$

$$\mathcal{L}_{M,6} = \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu}\hat{W}^{\beta\nu} D^\mu\Phi\right]$$

$$\mathcal{L}_{M,7} = \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu}\hat{W}^{\beta\mu} D^\nu\Phi\right]$$

$$\mathcal{L}_{T,0} = \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right] \times \mathrm{Tr}\left[\hat{W}_{\alpha\beta}\hat{W}^{\alpha\beta}\right]$$

$$\mathcal{L}_{T,1} = \mathrm{Tr}\left[\hat{W}_{\alpha\nu}\hat{W}^{\mu\beta}\right] \times \mathrm{Tr}\left[\hat{W}_{\mu\beta}\hat{W}^{\alpha\nu}\right]$$

$$\mathcal{L}_{T,2} = \mathrm{Tr}\left[\hat{W}_{\alpha\mu}\hat{W}^{\mu\beta}\right] \times \mathrm{Tr}\left[\hat{W}_{\beta\nu}\hat{W}^{\nu\alpha}\right]$$

$$\mathcal{L}_{T,5} = \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right] \times B_{\alpha\beta}B^{\alpha\beta}$$

$$\mathcal{L}_{T,6} = \mathrm{Tr}\left[\hat{W}_{\alpha\nu}\hat{W}^{\mu\beta}\right] \times B_{\mu\beta}B^{\alpha\nu}$$

$$\mathcal{L}_{T,7} = \mathrm{Tr}\left[\hat{W}_{\alpha\mu}\hat{W}^{\mu\beta}\right] \times B_{\beta\nu}B^{\nu\alpha}$$

$$\mathcal{L}_{T,8} = B_{\mu\nu}B^{\mu\nu}B_{\alpha\beta}B^{\alpha\beta}$$

$$\mathcal{L}_{T,9} = B_{\alpha\mu}B^{\mu\beta}B_{\beta\nu}B^{\nu\alpha}$$