Search for WWγ and WZγ Production and Anomalous Quartic Gauge Couplings in pp collisions at $\sqrt{s}$ = 8 TeV

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On behalf of CMS Collaboration

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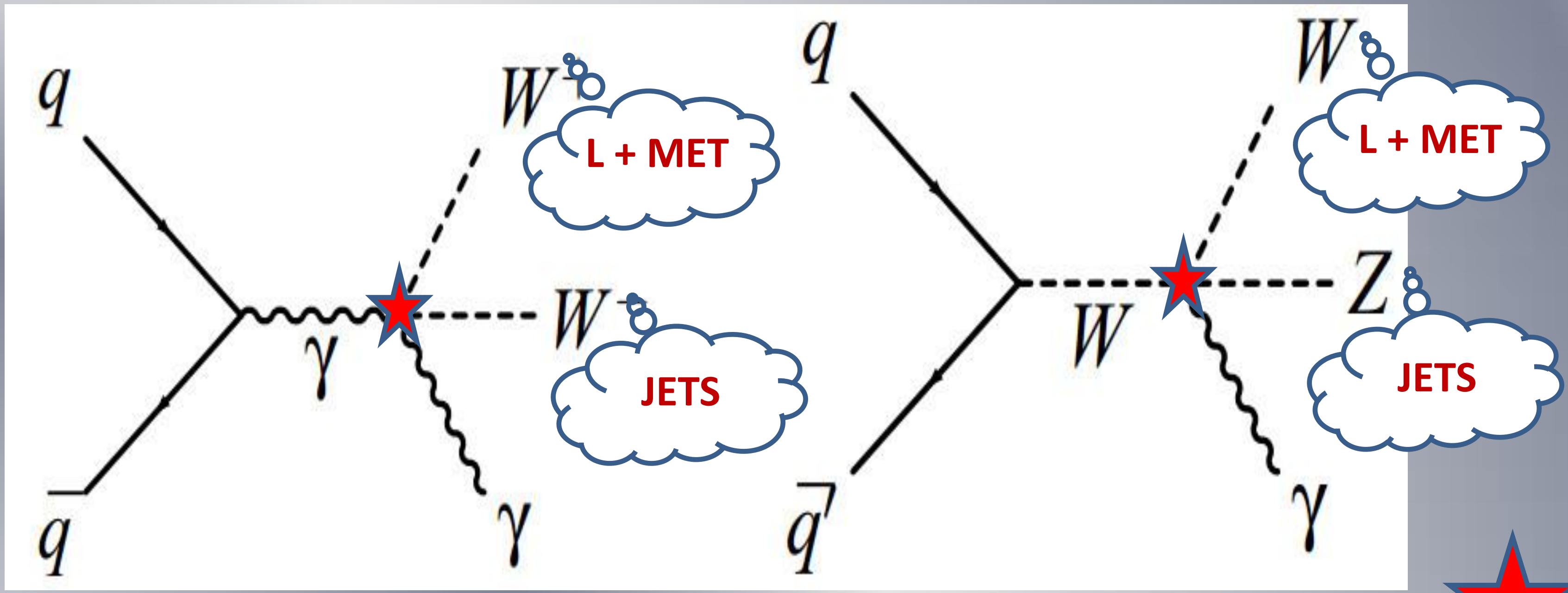
Gauge Boson Self-Interactions on Standard Model

From the non-abelian structure of SM gauge symmetry emerges naturally the **triple** and **quartic** gauge bosons vertex

$$
\begin{aligned}
\mathcal{L}_{GC_{SM}} = \; & i\frac{e}{\tan\theta_W}\left[(W^-_\mu W^+_\nu - W^-_\nu W^+_\mu)\partial^\mu Z^\nu + W^+_{\mu\nu}W^{-\mu}Z^\nu - W^-_{\mu\nu}W^{+\mu}Z^\nu\right] \\
& + ie\left[(W^-_\mu W^+_\nu - W^-_\nu W^+_\mu)\partial^\mu A^\nu + W^+_{\mu\nu}W^{-\mu}A^\nu - W^-_{\mu\nu}W^{+\mu}A^\nu\right] \\
& + \frac{e^2}{\tan^2\theta_W}(W^+_\mu W^-_\nu Z^\mu Z^\nu - W^+_\mu W^{-\mu} Z_\nu Z^\nu) \\
& + \frac{e^2}{\sin^2\theta_W}(W^+_\mu W^-_\nu A^\mu A^\nu - W^+_\mu W^{-\mu} A_\nu A^\nu) \\
& + \frac{e^2}{\tan\theta_W}\left[(W^+_\mu W^-_\nu (Z^\mu A^\nu + Z_\nu A^\nu) - 2W^+_\mu W^{-\mu} Z_\nu A^\nu\right] \\
& + \frac{e^2}{2\sin\theta_W}(W^+_\mu W^-_\nu W^{+\mu} W^{-\nu} - W^+_\mu W^-_\nu W^{+\nu} W^{-\mu})
\end{aligned}
$$

Detailed investigation of gauge boson self-interactions is crucial to test the SM gauge structure and explore new physics!

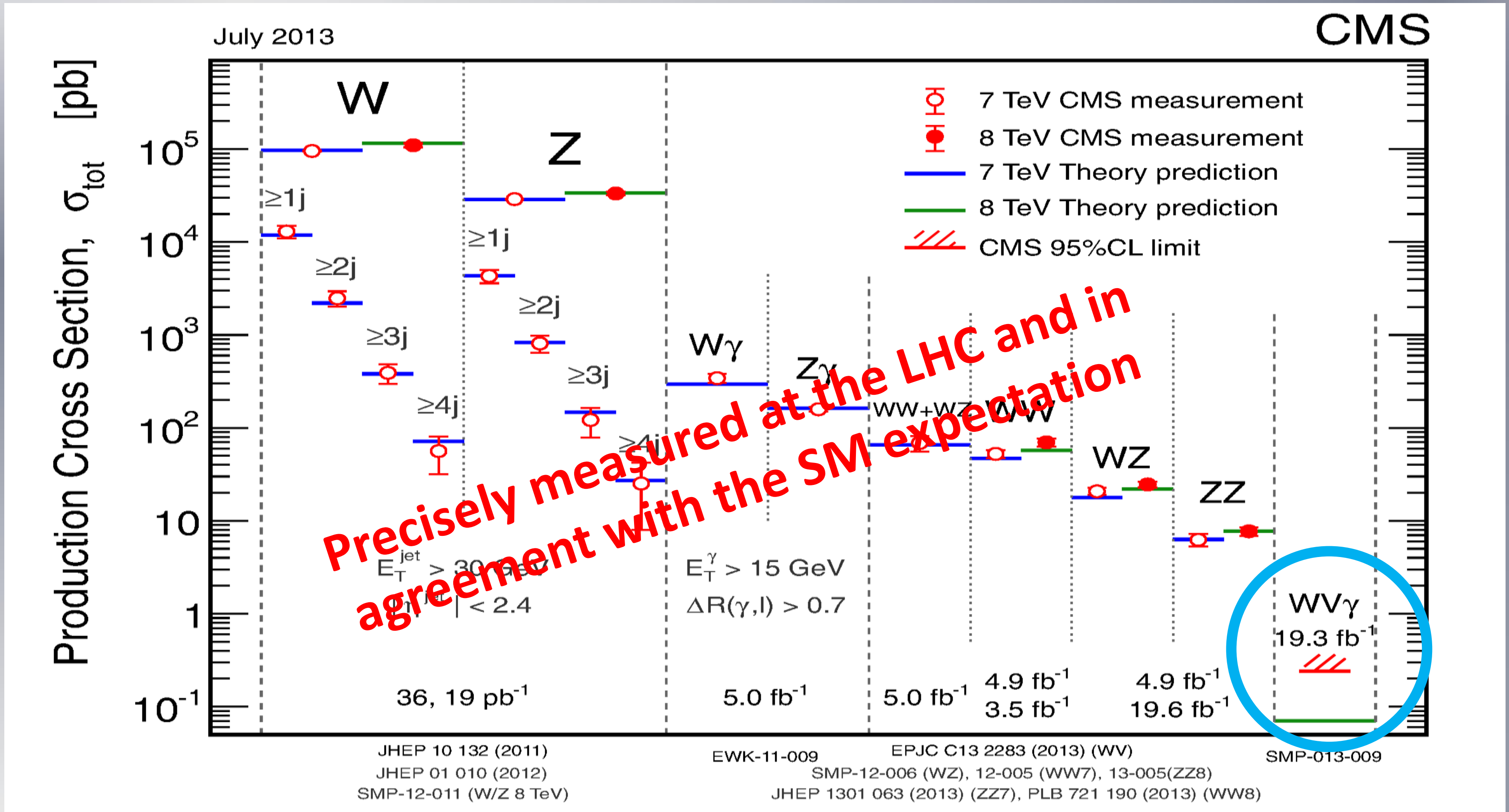
Self-Interactions through three gauge boson production channel



Three Gauge Boson Production is sensitive to the <u>Quartic Gauge Vertex</u>

Semileptonic decay mode has higher Branching Ratio

Overview of Gauge Boson Production Cross Section



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

WVγ Production Cross Section (expected @ NLO)

	Process	shape modeling	cross section [pb]
Signal	SM WW γ	MC	(NLO) 0.0582 ± 0.0138
	SM WZ γ	MC	(NLO) 0.0121 ± 0.0029
Backgrounds	W γ +Jets	MC	(data) 10.872 ± 0.087
	jet -> γ	data	data
	Z γ +Jets	MC	(LO) 0.632 ± 0.126
	$t\bar{t}\gamma$	MC	(LO) 0.615 ± 0.123
	Single Top + γ (inclusive)	MC	(NLO) 0.310 ± 0.011

- **p p collisions @ $\sqrt{s} = 8$ TeV ;**
- **Samples generated for PTγ > 10 GeV, |η | < 2.5**
- **2012 CMS Dataset with L = 19.3 fb-1;**
- **LO samples: Madgraph 5.1.3 and POWHEG; Pythia 6.426 (showering)**
- **NLO samples: aMC@NLO (K-factor 2.1)**

Physics Objects Reconstruction Selection Criteria

Leptons

Variable	Muons	Electrons
Single lepton trigger p_T threshold	>24 GeV	>27 GeV
$\|\eta\|$	< 2.1	< 2.5, excluding 1.44 < $\|\eta\|$ < 1.57
Missing transverse energy (MET)	> 35 GeV	> 35 GeV
$\Delta\varphi$(MET,jet)	>0.4	>0.4
W transverse mass (M_T)	> 30 GeV	> 30 GeV

Missing ET

Photon

Variable	Value
p_T threshold	>30 GeV
Photon $\|\eta\|$	< 1.44
Photon Isolation from jets Δ R	> 0.5
Photon Isolation from leptons Δ R	> 0.5

Physics Objects Reconstruction Selection Criteria (cont.)

Variable	Value
Anti-k_T clustering distance parameter R	0.5
at least 2 jets above p_T threshold	30 GeV
Jet $\|\eta\|$	< 2.4
Jet Isolation from leptons ΔR	> 0.3

Jets from PF algorithm

Additional selection requirements

Variable	Value
di-jet invariant mass (M_{jj})	$70 < M_{jj} < 100$ GeV
$\Delta\eta$ (jet 1,jet 2)	< 1.4
invariant mass of electron-photon pair $M_{e\gamma}$	$\|M_{e\gamma} - M_Z\| > 10$ GeV

Semileptonic decay mode cannot differentiate the two production processes WWγ and WZγ due to the detector di-jet mass resolution (≈ 10GeV) which is close to the mass difference between W and Z bosons. Therefore both channels were treated as a combined signal in this analysis.

Systematics Uncertanties

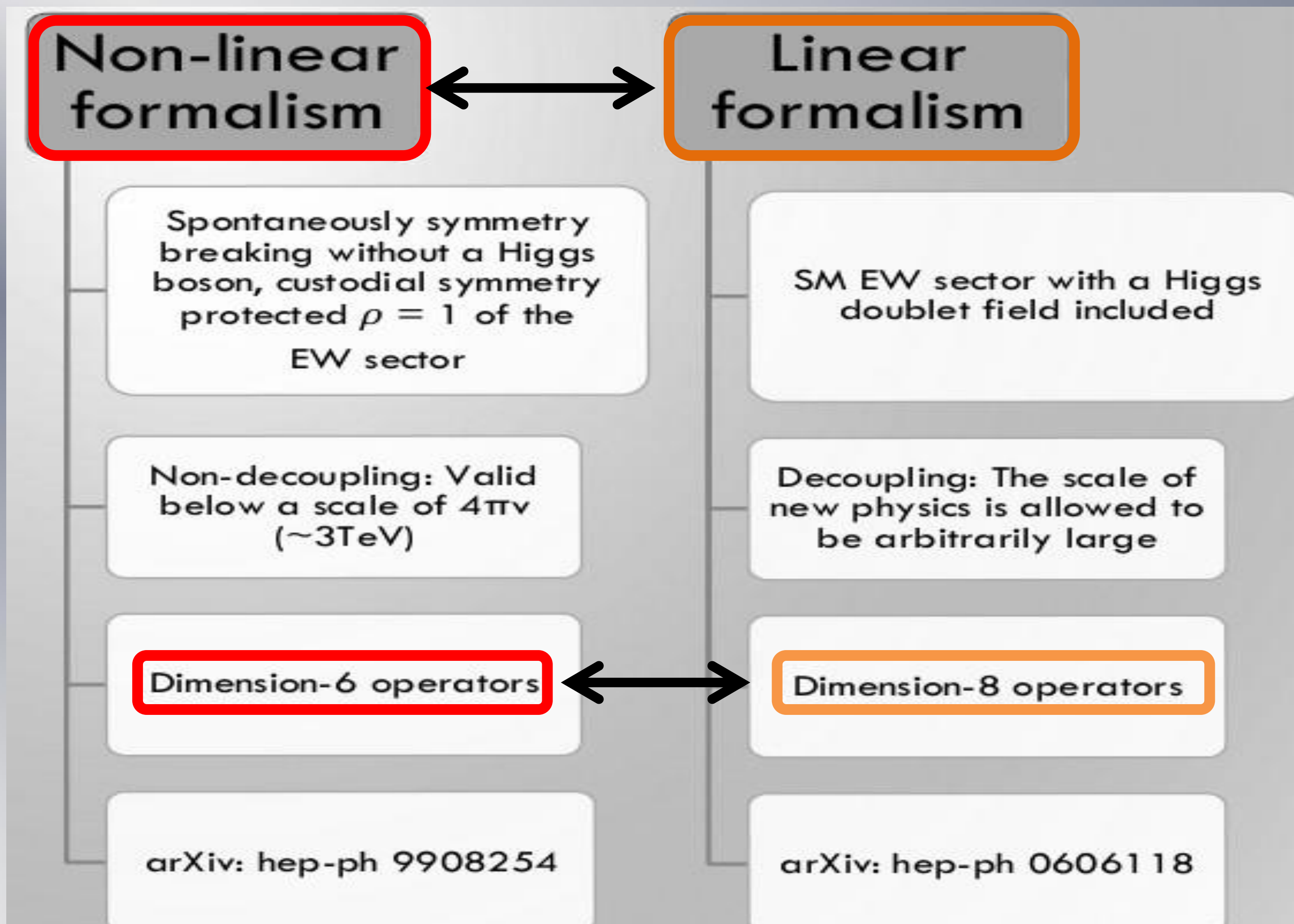
Source	Uncertainty
$W\gamma$ + Jets normalization	6.7%(mu), 7.9%(el)
jet -> γ	12% (30 GeV - 50 GeV)
	14% (50 GeV - 75 GeV)
	23% (75 GeV - 90 GeV)
	22% (90 GeV - 135 GeV)
	39% (> 135 GeV)
multijets	50%
Trigger Efficiency	1%
Lepton Selection Efficiency	2%
Jet Energy Resolution	1%
Jet Energy Scale	4.3%
Photon Energy Scale	1%
$\not{E}_T$	1%
Anti-b Tag ($t\bar{t}\gamma$)	11%
Anti-b Tag (single top + γ)	5%
Pileup modeling	1%
renormalization/factorization scale	23.4%
PDF	3.6%
Luminosity	4.4%

SM WVγ Cross Section Results

Process	muon channel number of events	electron channel number of events
W γ+jets	136.9 ± 3.5 ± 9.2 ± 0.0	101.6 ± 2.9 ± 8.0 ± 0.0
WV+jet, jet -> γ	33.1 ± 1.3 ± 4.6 ± 0.0	21.3 ± 1.0 ± 3.1 ± 0.0
MC $t\bar{t}\gamma$	12.5 ± 0.8 ± 2.9 ± 0.5	9.1 ± 0.7 ± 2.1 ± 0.4
MC single top	2.8 ± 0.8 ± 0.2 ± 0.1	1.7 ± 0.6 ± 0.1 ± 0.1
MC Z γ+jets	1.7 ± 0.1 ± 0.1 ± 0.1	1.5 ± 0.1 ± 0.1 ± 0.1
multijets	< 0.2± 0.0 ± 0.1 ± 0.0	7.2 ± 3.6 ± 3.6 ± 0.0
SM WW γ	6.3 ± 0.1 ± 1.5 ± 0.3	4.7 ± 0.1 ± 1.1 ± 0.2
SM WZ γ	0.6 ± 0.0 ± 0.1 ± 0.0	0.5 ± 0.0 ± 0.1 ± 0.0
Total predicted	193.9 ± 3.9 ± 10.8 ± 1.0	147.6 ± 4.8 ± 9.6 ± 0.7
Data	183	139

- **Cut & count approach based on selection criteria**
- **322 events observed in CMS 2012 data against 341.5 ± 15.8 events predicted.**
- **low statistics to measure the WVγ cross section**
- **an upper limit of 0.24 pb at 95%C.L. for WVγ with photon pT > 10 GeV at 8TeV with** $19.3 fb^{-1}$

"Genuine" Quartic Vertex with Higher Dimension Operators



Dimension 6 Anomalous Quartic Gauge Couplings

$$\mathcal{L}_{aQGC} = \frac{a_0^W}{4g^2}\mathcal{W}_0^\gamma + \frac{a_C^W}{4g^2}\mathcal{W}_c^\gamma + \sum_i \kappa_i^W \mathcal{W}_i^Z + \mathcal{L}_{T,0} + \mathcal{L}_{T,1} + \mathcal{L}_{T,2}$$

$$\mathcal{W}_0^\gamma = -\frac{e^2g^2}{2}F_{\mu\nu}F^{\mu\nu}W^{+\alpha}W^-_\alpha ,$$

$$\mathcal{W}_c^\gamma = -\frac{e^2g^2}{4}F_{\mu\nu}F^{\mu\alpha}(W^{+\nu}W^-_\alpha + W^{-\nu}W^+_\alpha)$$

LEP operators

$$\mathcal{W}_0^Z = -e^2g^2F_{\mu\nu}Z^{\mu\nu}W^{+\alpha}W^-_\alpha$$

$$\mathcal{W}_c^Z = -\frac{e^2g^2}{2}F_{\mu\nu}Z^{\mu\alpha}(W^{+\nu}W^-_\alpha + W^{-\nu}W^+_\alpha)$$

$$\mathcal{W}_1^Z = -\frac{e^2g^2}{2c_w s_w}F^{\mu\nu}(W^+_{\mu\nu}W^-_\alpha Z^\alpha + W^-_{\mu\nu}W^+_\alpha Z^\alpha)$$

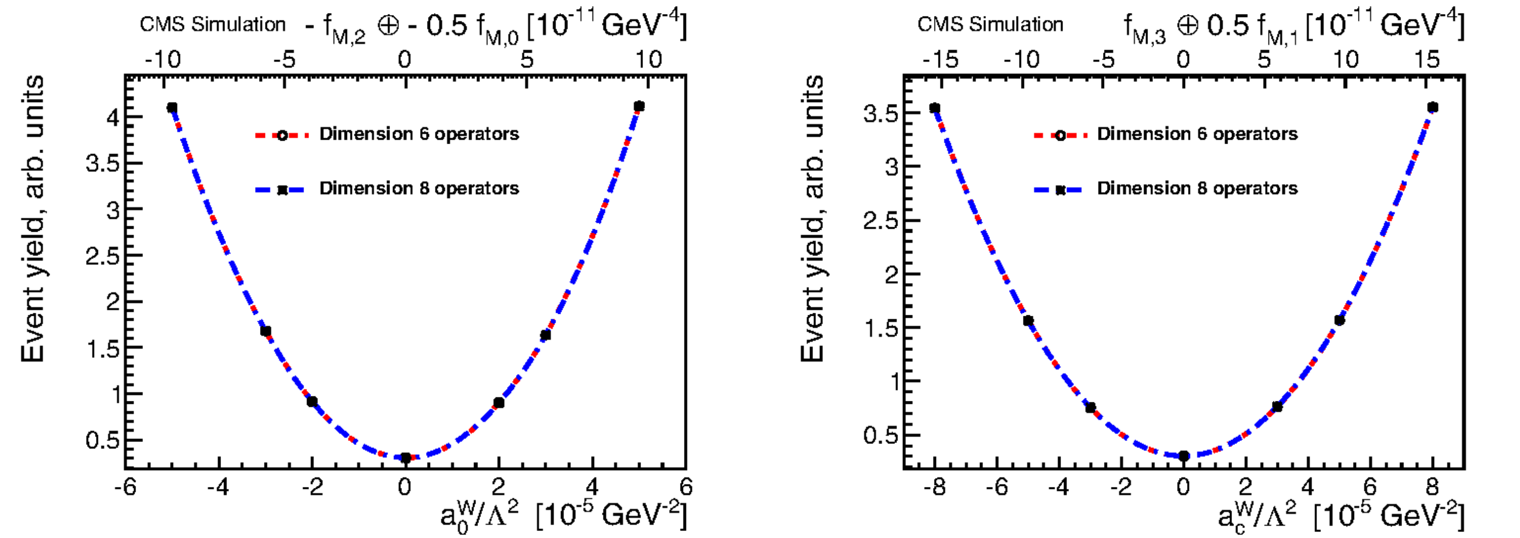
$$\mathcal{W}_2^Z = -\frac{e^2g^2}{2c_w s_w}F^{\mu\nu}(W^+_{\mu\alpha}W^{-\alpha}Z_\nu + W^-_{\mu\alpha}W^{+\alpha}Z_\nu)$$

$$\mathcal{W}_3^Z = -\frac{e^2g^2}{2c_w s_w}F^{\mu\nu}(W^+_{\mu\alpha}W^-_\nu Z^\alpha + W^-_{\mu\alpha}W^+_\nu Z^\alpha)$$

New

Dim6 ↔ Dim8 Anomalous Quartic Gauge Couplings

$$\mathcal{L}_{aQGC} = \frac{a_0^W}{4g^2}\mathcal{W}_0^\gamma + \frac{a_C^W}{4g^2}\mathcal{W}_c^\gamma + \sum_i \kappa_i^W \mathcal{W}_i^Z + \mathcal{L}_{T,0} + \mathcal{L}_{T,1} + \mathcal{L}_{T,2}$$



$$\frac{f_{M,0}}{\Lambda^4} = -\frac{g^4}{M_W^2}\frac{\kappa_0^w}{\Lambda^2}$$

$$\frac{f_{M,2}}{\Lambda^4} = -\frac{g^2 g'^2}{2M_W^2}\frac{\kappa_0^b}{\Lambda^2}$$

$$a_{0,c} = 4g^2(k_{0,c}^w + k_{0,c}^b + k_{0,c}^m)$$

$$\frac{f_{M,1}}{\Lambda^4} = \frac{g^4}{M_W^2}\frac{\kappa_c^w}{\Lambda^2}$$

$$\frac{f_{M,3}}{\Lambda^4} = \frac{g^2 g'^2}{2M_W^2}\frac{\kappa_c^b}{\Lambda^2}$$

Dimension 8 Anomalous Quartic Gauge Couplings

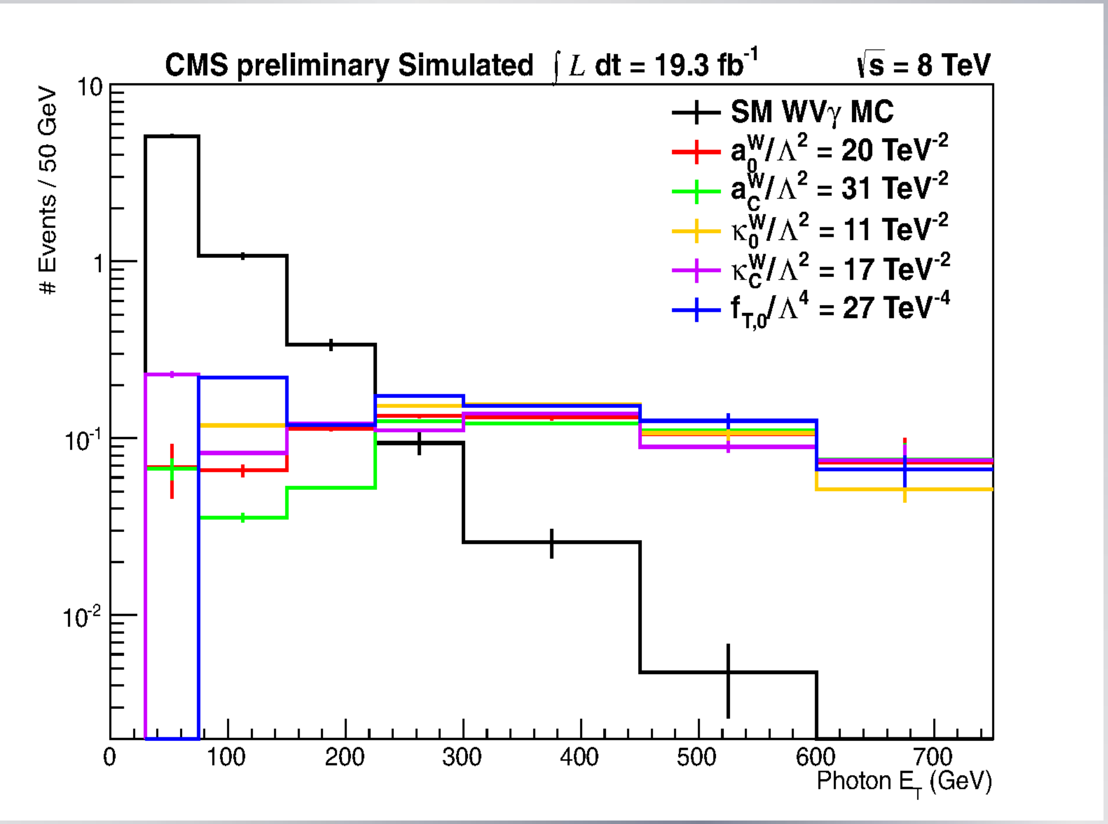
$$\mathcal{L}_{aQGC} = \frac{a_0^W}{4g^2}\mathcal{W}_0^\gamma + \frac{a_C^W}{4g^2}\mathcal{W}_c^\gamma + \sum_i \kappa_i^W \mathcal{W}_i^Z + \mathcal{L}_{T,0} + \mathcal{L}_{T,1} + \mathcal{L}_{T,2}$$

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

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

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

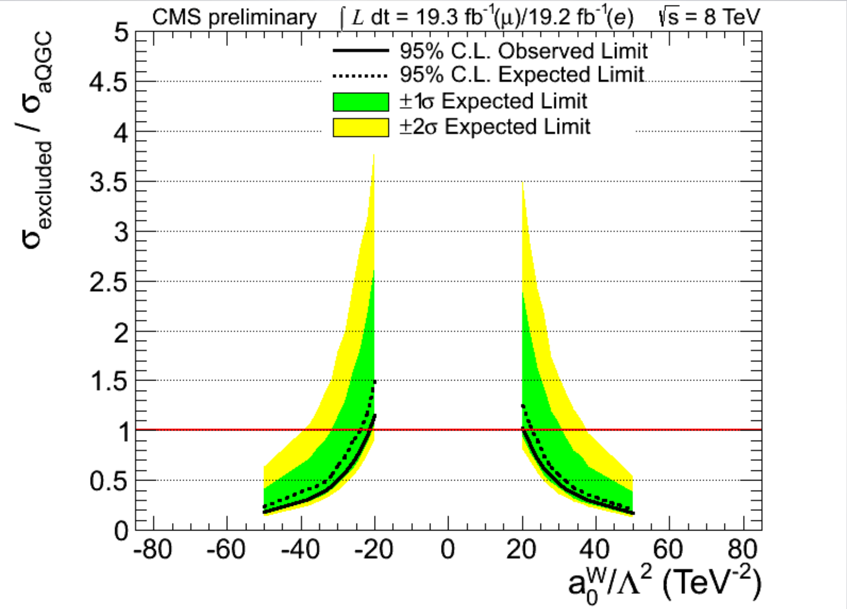
Setting Exclusion Limits for the aQGC's

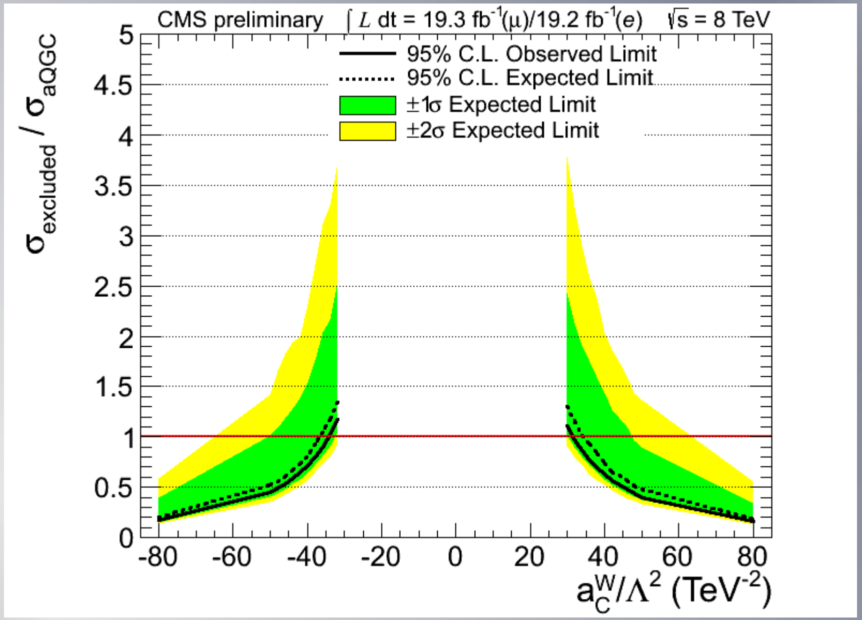


- PT distribution was used, after all selection criteria, as the observable to set limits on the aQGC parameters.

- Segregated by lepton flavor (independent inputs to the limit setter)

Exclusion Limits for Dim6 Anomalous Quartic Couplings (cont.)

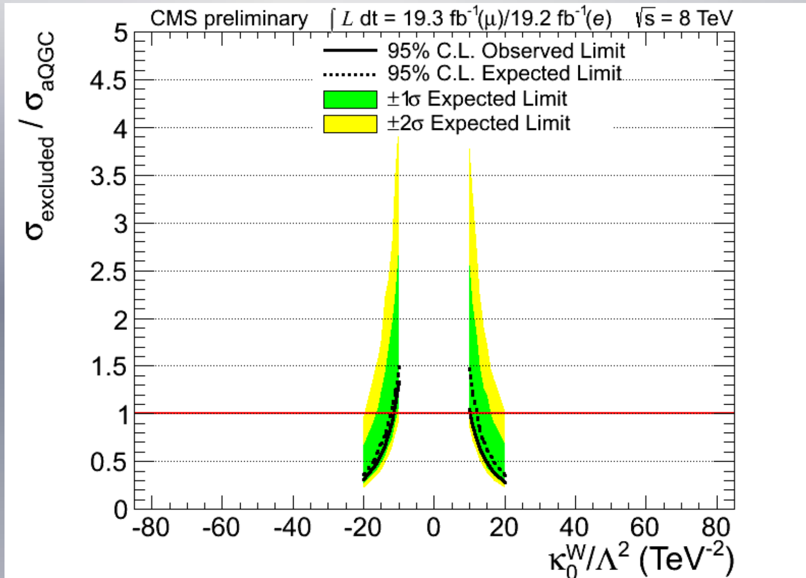


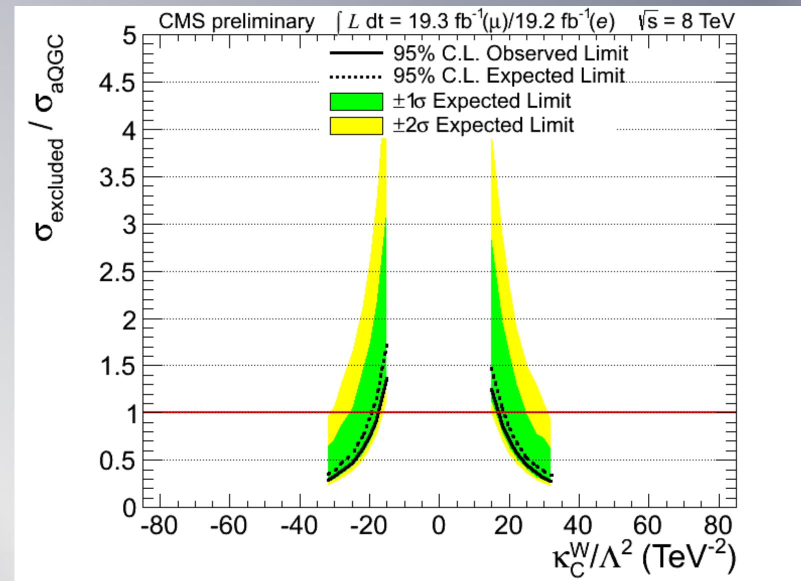


Observed Limits	Expected Limits
$-21\ (TeV^{-2}) < a_0^W / \Lambda^2 < 20\ (TeV^{-2})$	$-24\ (TeV^{-2}) < a_0^W / \Lambda^2 < 23\ (TeV^{-2})$
$-34\ (TeV^{-2}) < a_C^W / \Lambda^2 < 32\ (TeV^{-2})$	$-37\ (TeV^{-2}) < a_C^W / \Lambda^2 < 34\ (TeV^{-2})$

- **Exclusion limits for a0W and aCW parameters at 95%C.L., using photon pT as the observable**

Exclusion Limits for Dim6 Anomalous Quartic Couplings (cont.)





$-12\ (\mathrm{TeV}^{-2}) < \kappa_0^W / \Lambda^2 < 10\ (\mathrm{TeV}^{-2})$	$-12\ (\mathrm{TeV}^{-2}) < \kappa_0^W / \Lambda^2 < 12\ (\mathrm{TeV}^{-2})$
$-18\ (\mathrm{TeV}^{-2}) < \kappa^W / \Lambda^2 < 17\ (\mathrm{TeV}^{-2})$	$-19\ (\mathrm{TeV}^{-2}) < \kappa^W / \Lambda^2 < 18\ (\mathrm{TeV}^{-2})$

- **Exclusion limits for k0W and kCW parameters at 95%C.L., using photon pT as the observable.**

Exclusion Limits for Dim6 ⇔ Dim8 Anomalous Quartic Couplings

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

$$\frac{f_{M,0}}{\Lambda^4} = -\frac{g^4}{M_W^2}\frac{\kappa_0^w}{\Lambda^2}$$

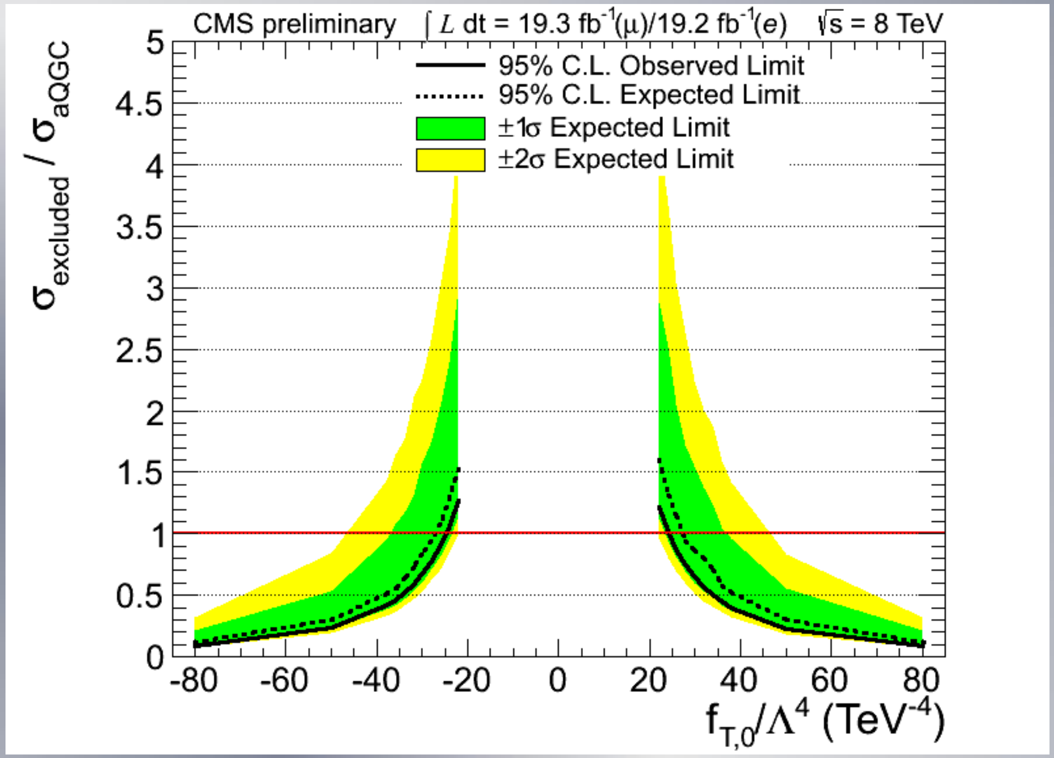
$$\frac{f_{M,2}}{\Lambda^4} = -\frac{g^2 g'^2}{2M_W^2}\frac{\kappa_0^b}{\Lambda^2}$$

$$\frac{f_{M,1}}{\Lambda^4} = \frac{g^4}{M_W^2}\frac{\kappa_c^w}{\Lambda^2}$$

$$\frac{f_{M,3}}{\Lambda^4} = \frac{g^2 g'^2}{2M_W^2}\frac{\kappa_c^b}{\Lambda^2}$$

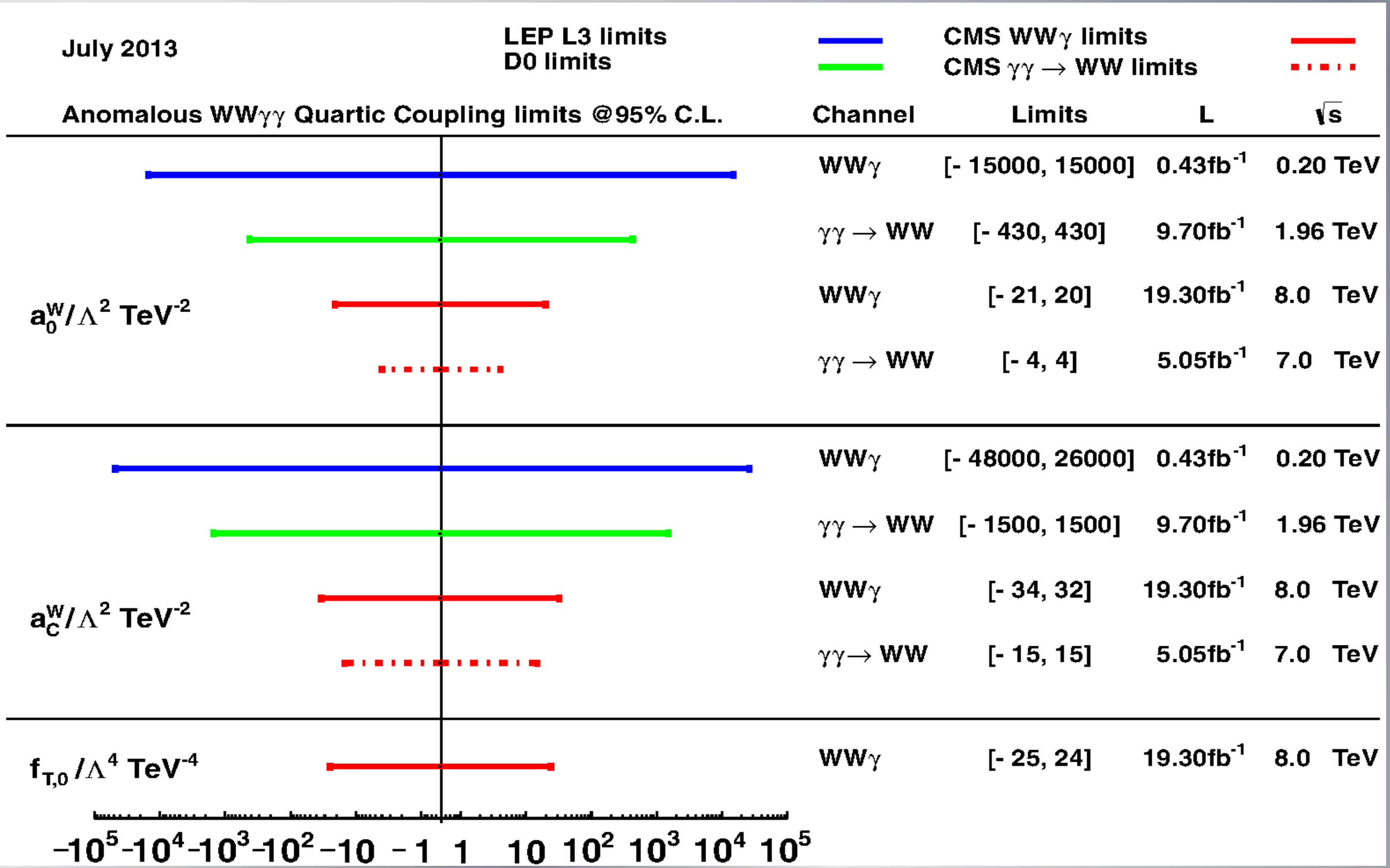
$$a_{0,c} = 4g^2\left(k_{0,c}^w + k_{0,c}^b + k_{0,c}^m\right)$$

Exclusion Limits for Dim8 Anomalous Quartic Couplings



$-25\ (\mathrm{TeV}^{-4}) < f_{T,0}/\Lambda^4 < 24\ (\mathrm{TeV}^{-4})$	$-27\ (\mathrm{TeV}^{-4}) < f_{T,0}/\Lambda^4 < 27\ (\mathrm{TeV}^{-4})$

Overview of Anomalous WWγγ Quartic Couplings @95% C.L.



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

Summing up...

- ✓ The WWγ and WZγ cross section measurement in pp collisions at $\sqrt{s} = 8$ TeV is **not accessible with the data collected in 2012 by the CMS detector**.

- ✓ It was only possible to set a one-sided upper limit on the cross section. For the amount of data presented here, **we set an upper limit of 0.24 pb at 95% C.L. for WVγ with photon pT > 10 GeV, which corresponds to 3.4 times the SM prediction.**

- ✓ **No evidence of anomalous WWγγ and WWZγ quartic gauge couplings was found**.

- ✓ 95% confidence level upper limits were obtained for several anomalous couplings. These are the **first ever limits on dim8 fT,0 and dim6 CP conserving couplings κ0W and κCW.**


THANK YOU!