LHC Results on VBS Di-boson Production and aQGCs

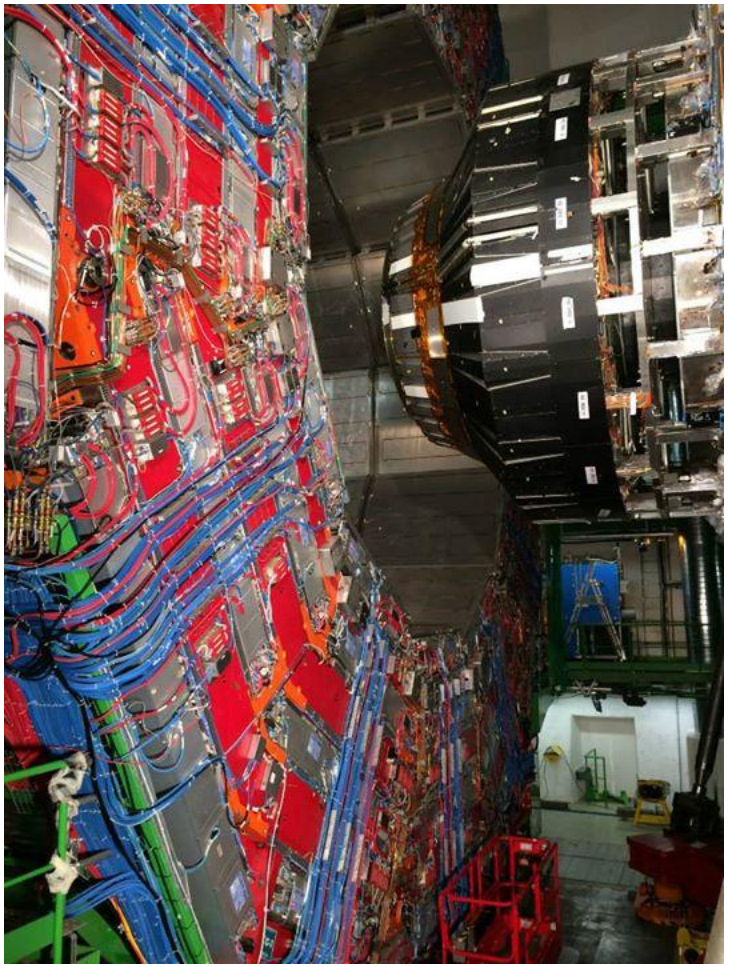
James Faulkner
On behalf of the CMS Collaboration

MBI 2016
24-26 August 2016
Madison, WI

TEXAS TECH UNIVERSITY

Overview:

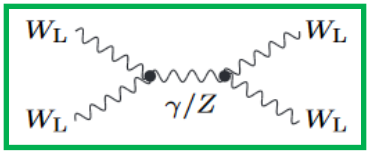
- Additional Info on VBS and aQGCs
- CMS Run I Analyses
- CMS Run II Prospects
- Limits on Anomalous Couplings
- Summary

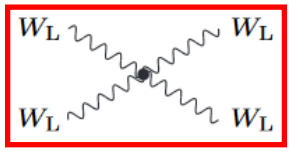


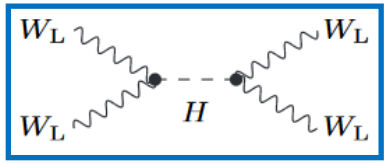
Vector Boson Scattering & Why We Care

Vector Boson Scattering:

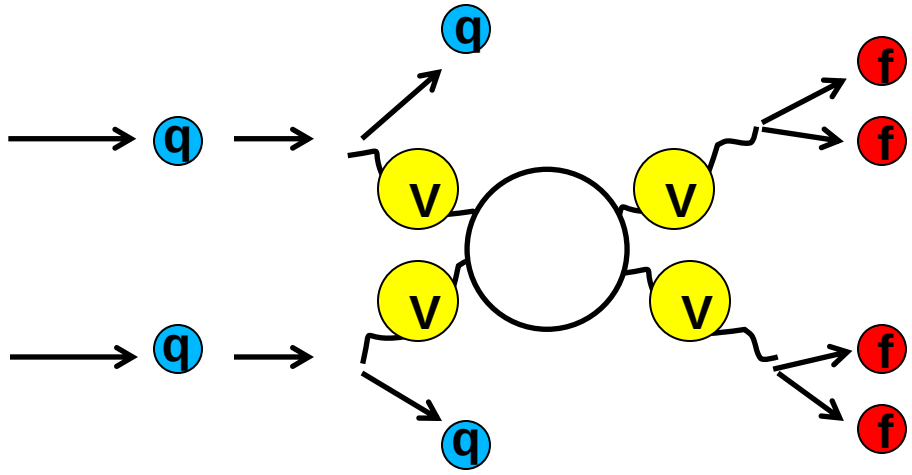
- Production involving scattering of massive vector bosons
  - Initiated by quarks radiating vector bosons
  - Produced via **Triple Gauge Coupling (TGC)**, **Quartic Gauge Coupling (QGC)**, or **Higgs exchange** in s- and t- channel
  - Final state bosons and jets in pure electroweak process
    - Two forward/backward jets at large |η|
    - Large separation in rapidity between jets
    - Large dijet invariant mass
    - Vector bosons' daughters in central region







Importance of VBS Measurements:



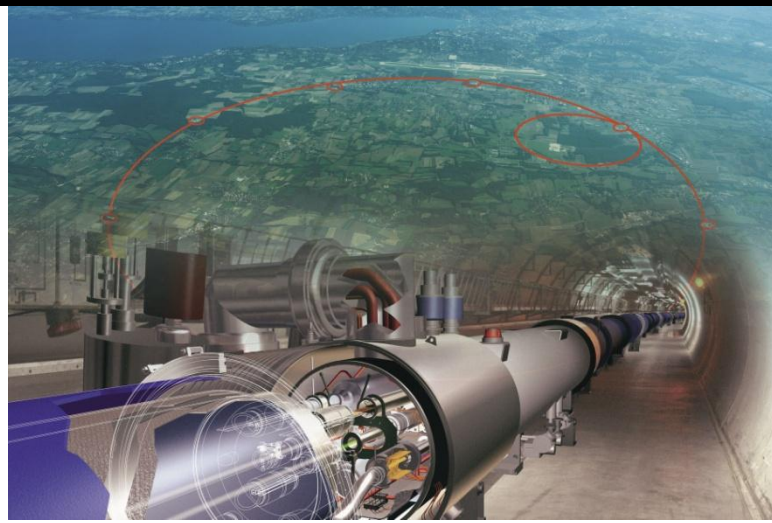
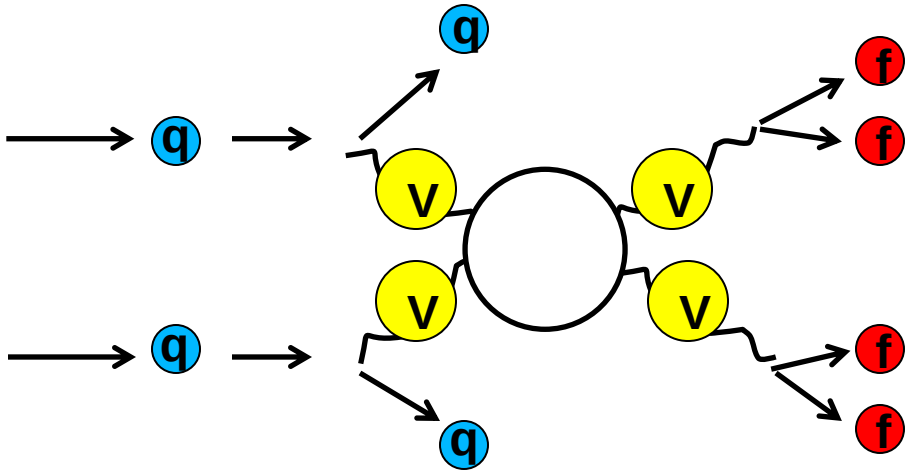


Image Source:
http://cms.web.cern.ch/sites/cms.web.cern.ch/files/styles/large/public/field/image/LHC_and_mountains-0503019-1-nice.jpg?itok=TzhBEw7i

- Another very precise SM measurement at the LHC
- Probe SM Electroweak Symmetry Breaking (EWSB)
- Test Higgs properties
  - Suppress scattering of longitudinal weak gauge bosons at high energies

Importance of VBS Measurements:



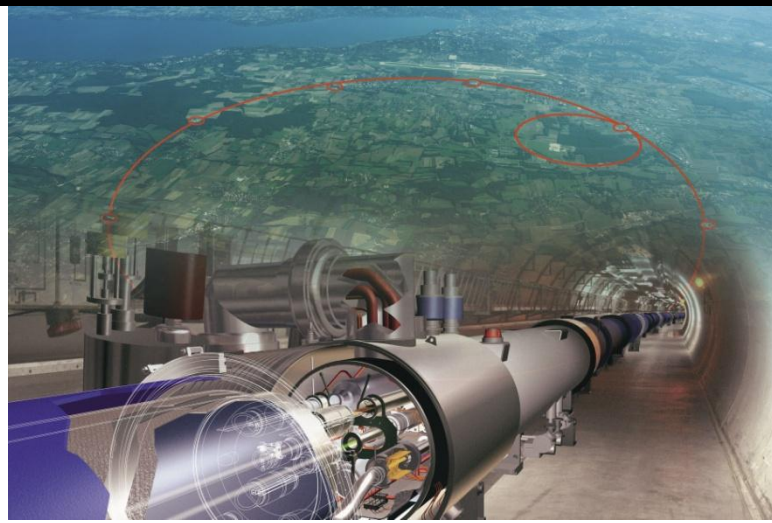


Image Source:
http://cms.web.cern.ch/sites/cms.web.cern.ch/files/styles/large/public/field/image/LHC_and_mountains-0503019-1-nice.jpg?itok=TzhBEw7i

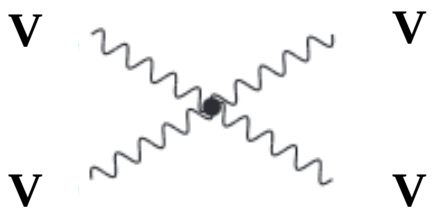
- Probe of new physics in electroweak sector
  - What alternative theory contributes to EWSB
  - Probe aTGCs/aQGCs

Anomalous
Quartic Gauge Couplings

Anomalous Quartic Gauge Couplings:

- Deviations from SM
- Effective Field Theory approach
  - Useful if no new light particles are discovered
  - Valid at scales much lower than that of new physics (Λ)
    - In phase space regions far from possible new resonance
  - Violates unitarity at higher energies (without K-matrix, Form Factors, etc.)

$$\mathcal{L}_{\mathcal{EFT}} = \mathcal{L}_{SM} + \sum_{d>4} \sum_{i} \frac{c_i}{\Lambda^{d-4}} \mathcal{O}_i$$



	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

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

Anomalous Quartic Gauge Couplings:

- Assume $SU(2)_L$ x $U(1)_Y$ gauge invariance, C&P conservation, $SU(2)_C$ custodial symmetry
- Linear realization (arXiv:hep-ph/0606118),
  - Lowest order genuine quartic interaction: Dim. 8
    - Following analyses assume no aTGC
    - Exclude lepton flavor violating terms (such as d = 5, 7)
- aGCs increase cross sections at high energies
  - Sensitive observables: M^{VV}, $p_T{}^V$, etc.

$$\mathcal{L}_{\mathcal{EFT}} = \mathcal{L}_{SM} + \sum_{d>4} \sum_{i} \frac{c_i}{\Lambda^{d-4}} \mathcal{O}_i$$

	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

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

CMS Run I Analyses

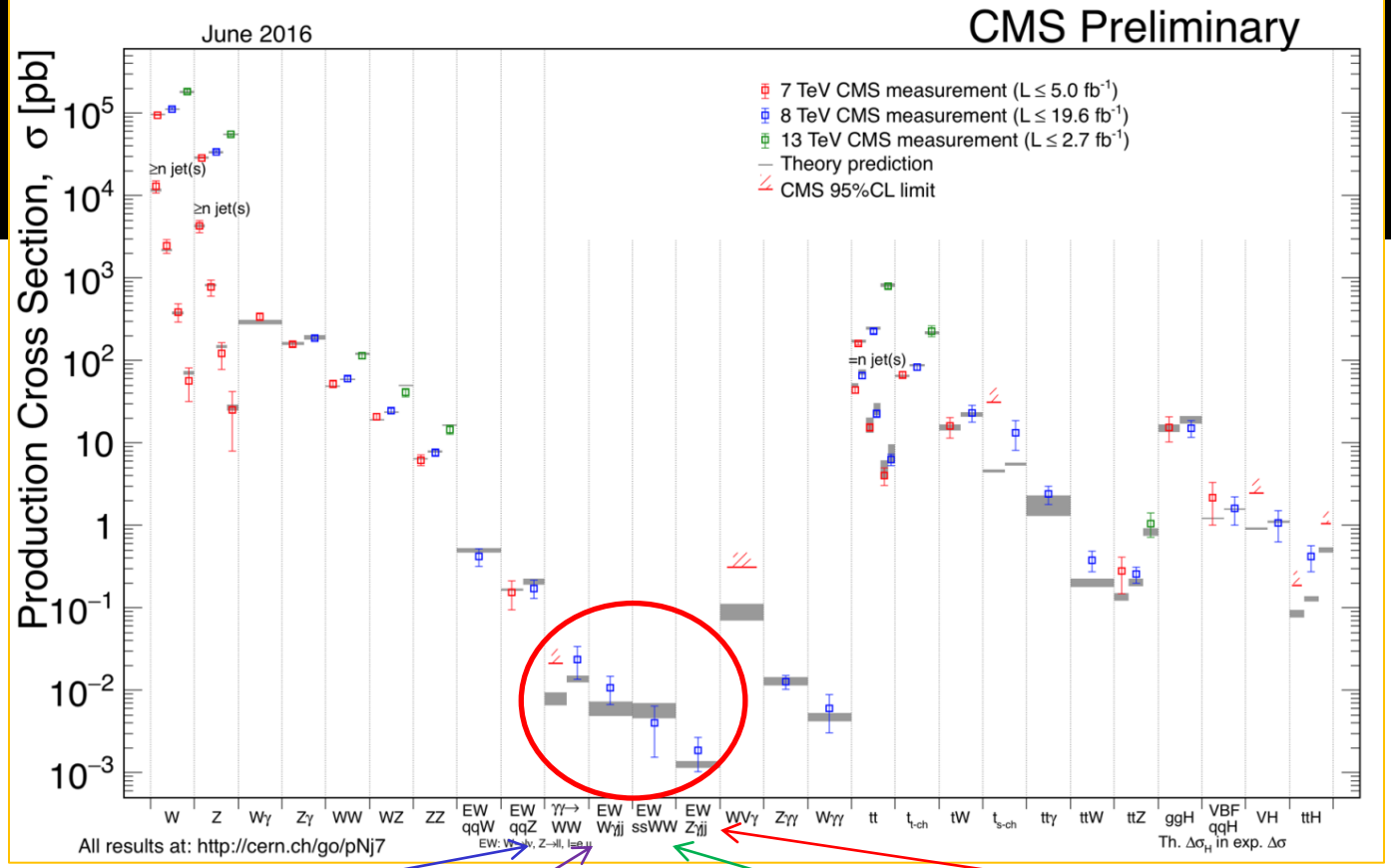
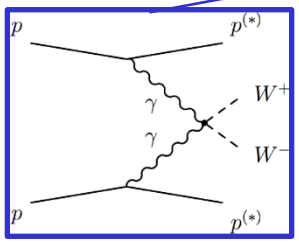
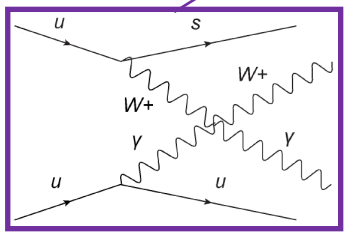


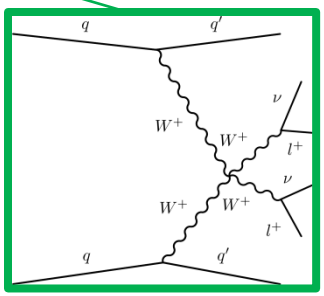
Image Source:
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsCombined



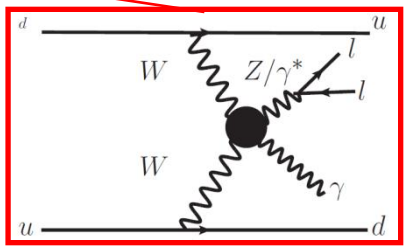
γγ → WW:
CMS-PAS-FSQ-13-008
arXiv 1604.04464



Wγjj:
CMS-PAS-SMP-14-011



Same-sign WW:
Phys. Rev. Lett. 114, 051801 (2015)



Zγjj:
CMS-PAS-SMP-14-018

Same-sign WW plus 2 Jets: P.R.L. 114, 051801 (2015)

$(\mu^{\pm}\mu^{\pm}, e^{\pm}e^{\pm}, \mu^{\pm}e^{\pm})$ + 2jets + $\not{E}_T$

*Allow τ-lepton decays to μ,e

$p_T^{lepton} > 20$ GeV, $|\eta^{lepton}| < 2.4(2.5)$

$\Delta R = 0.3$, $m_{ll} > 50$ GeV

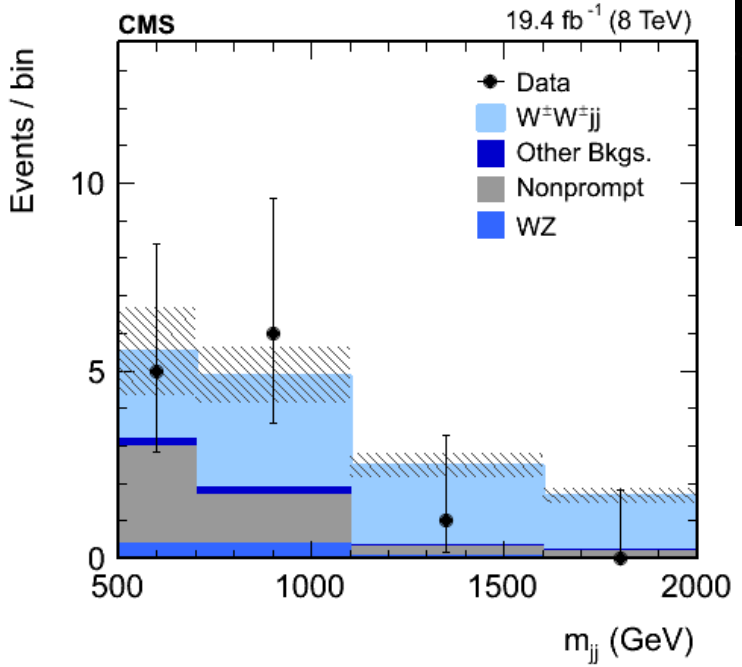
$|m_{ll} - m_Z| > 15$ GeV (el. ch.), $\not{E}_T > 40$ GeV

> 1 Anti-k_T jets ($R = 0.5$), $E_T^{jet} > 30$ GeV

$|\eta^{jet}| < 4.7$, $m_{jj} > 500$ GeV, $|\Delta\eta^{jj}| > 2.5$

Major Backgrounds:

Nonprompt leptons, WZ



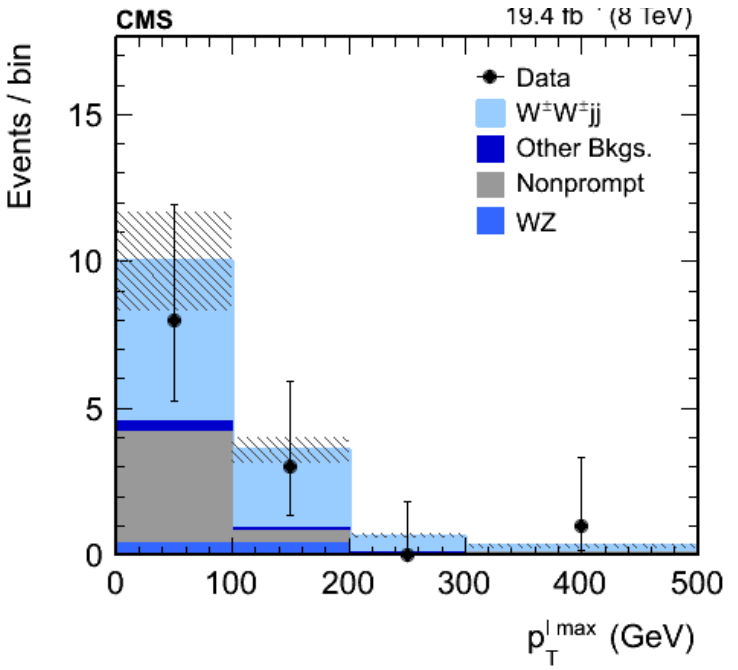
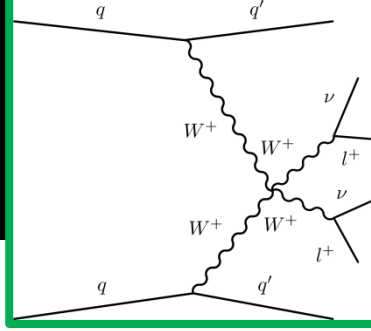


Image Source:
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMP13015

Same-sign WW plus 2 Jets: P.R.L. 114, 051801 (2015)

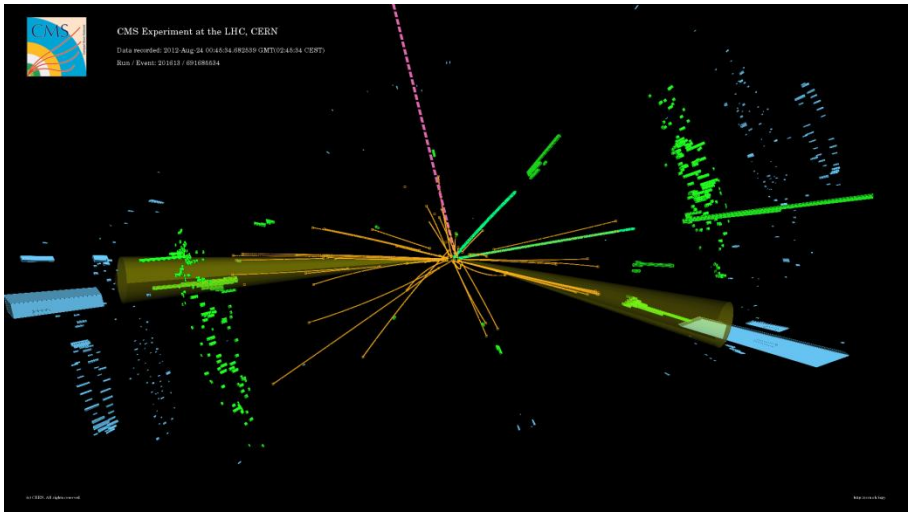


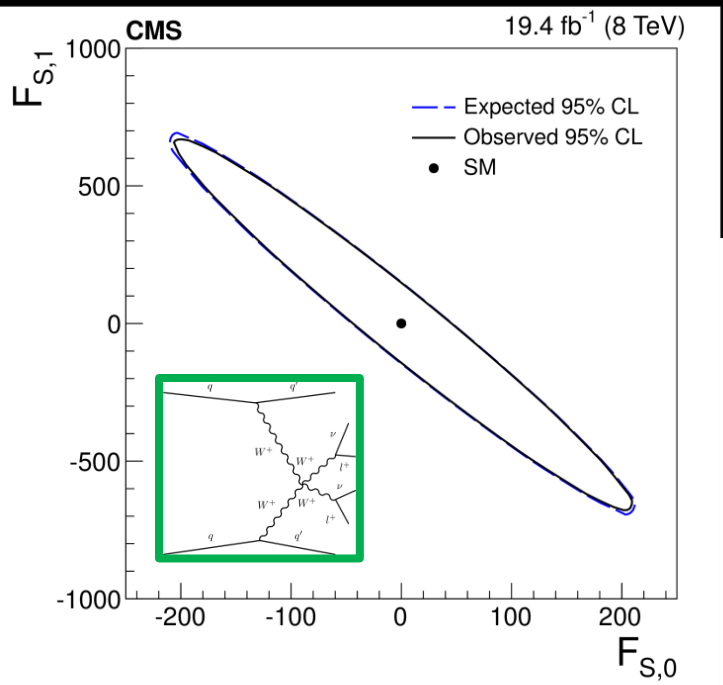
	Nonprompt	WZ	VVV	Wrong sign	WW DPS	Total bkg.	$W^{\pm}W^{\pm}jj$	Data
$\mu^{\pm}\mu^{\pm}$	2.1 ± 0.6	0.2 ± 0.1	0.1 ± 0.1	—	—	2.4 ± 0.6	3.0 ± 0.1	2
$e^{\pm}e^{\pm}$	0.6 ± 0.2	0.3 ± 0.1	0.1 ± 0.1	—	—	1.0 ± 0.2	1.4 ± 0.1	3
$e^{\pm}\mu^{\pm}$	1.5 ± 0.4	0.5 ± 0.1	0.1 ± 0.1	0.1 ± 0.1	0.1 ± 0.1	2.3 ± 0.5	4.5 ± 0.1	7
W^+W^+	2.1 ± 0.6	0.6 ± 0.1	0.2 ± 0.1	0.1 ± 0.1	0.1 ± 0.1	3.1 ± 0.6	7.1 ± 0.1	10
W^-W^-	2.1 ± 0.5	0.4 ± 0.1	0.1 ± 0.1	—	—	2.6 ± 0.5	1.8 ± 0.1	2
$W^{\pm}W^{\pm}$	4.2 ± 0.8	1.0 ± 0.1	0.3 ± 0.1	0.1 ± 0.1	0.1 ± 0.1	5.7 ± 0.8	8.9 ± 0.1	12

- Only statistical unc.'s listed above
- EWK+QCD contributions included in signal
  - EWK constitutes 85% - 90% of total signal
- Observed cross section x BR (fiducial) = $4.0^{+2.4}_{-2.0}\,(\text{stat})^{+1.1}_{-1.0}\,(\text{syst})$ fb
- Also measured σ(WZjj) x BR (fiducial) = $10.8 \pm 4.0\,(\text{stat}) \pm 1.3\,(\text{syst})$ fb

Image Source:
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMP13015

Same-sign WW plus 2 Jets: P.R.L. 114, 051801 (2015)





No Form Factor (etc.) applied

Operator coefficient	Exp. lower	Exp. upper	Obs. lower	Obs. upper	Unitarity limit
$F_{S,0}/\Lambda^4$	−42	43	−38	40	0.016
$F_{S,1}/\Lambda^4$	−129	131	−118	120	0.050
$F_{M,0}/\Lambda^4$	−35	35	−33	32	80
$F_{M,1}/\Lambda^4$	−49	51	−44	47	205
$F_{M,6}/\Lambda^4$	−70	69	−65	63	160
$F_{M,7}/\Lambda^4$	−76	73	−70	66	105
$F_{T,0}/\Lambda^4$	−4.6	4.9	−4.2	4.6	0.027
$F_{T,1}/\Lambda^4$	−2.1	2.4	−1.9	2.2	0.022
$F_{T,2}/\Lambda^4$	−5.9	7.0	−5.2	6.4	0.08

Most stringent limits to date

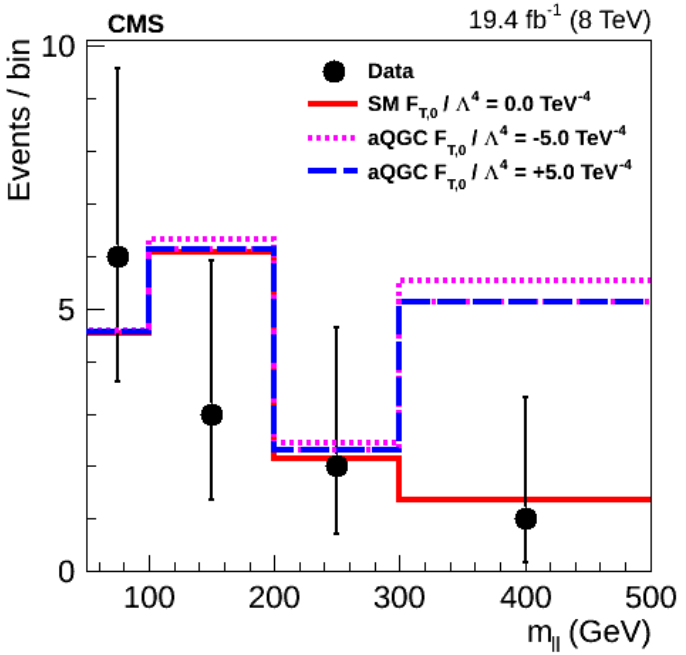


Image Source:
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMP13015

γγ→WW: CMS-PAS-FSQ-13-008 arXiv 1604.04464

* Accepted for publication in JHEP

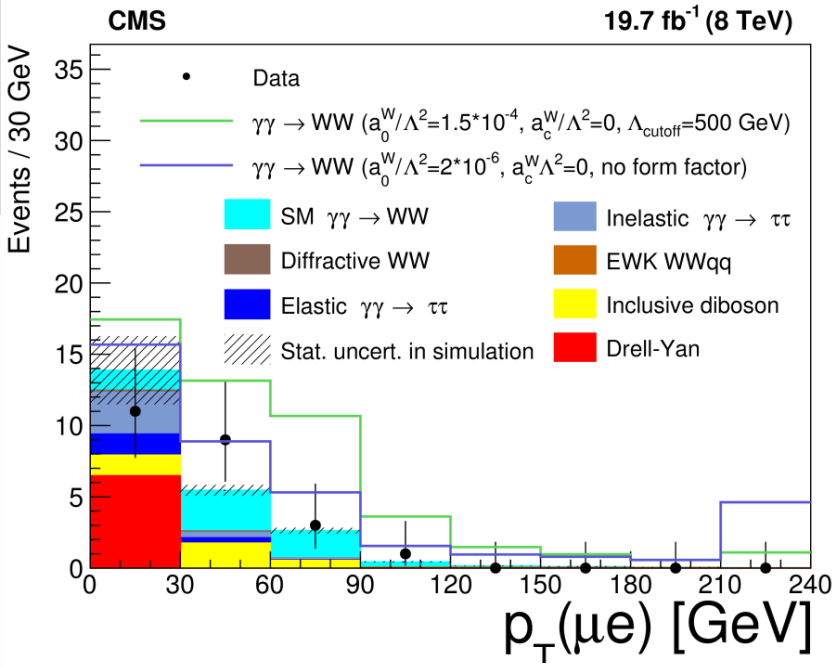
$p^{(*)}\mu^{\pm}e^{\mp}p^{(*)} + \not{E}_T$

*Protons remain intact or dissociate into undetected system

Allow τ-lepton decays to μ,e

$p_T^{lepton} > 20$ GeV, $p_T^{ll} > 30$ GeV
no additional tracks
$|\eta^{lepton}| < 2.4$

Major Background:
Inclusive Diboson



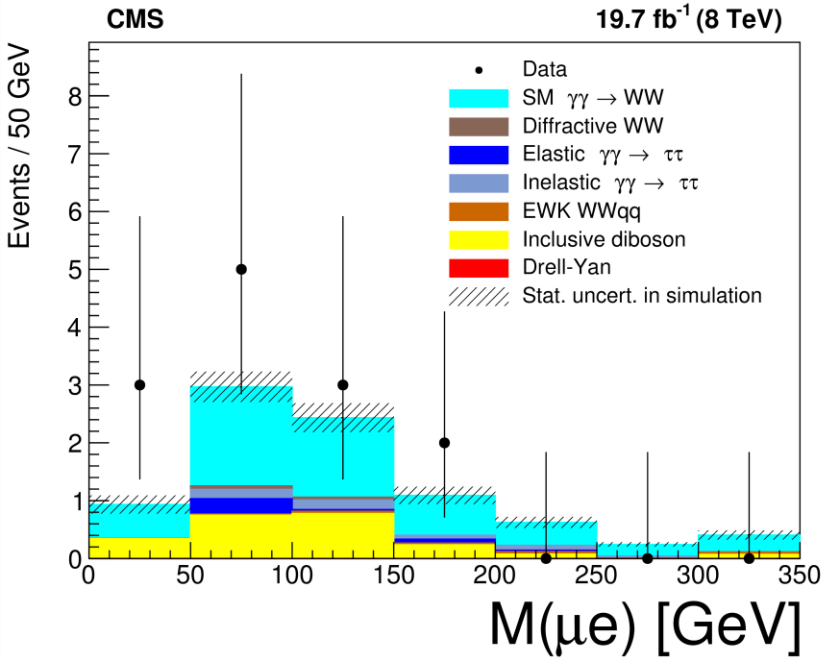
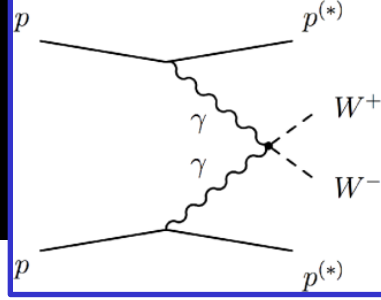


Image Source:
http://cms-results.web.cern.ch/cms-results/public-results/publications/FSQ-13-008/index.html

γγ→WW:
CMS-PAS-FSQ-13-008
arXiv 1604.04464

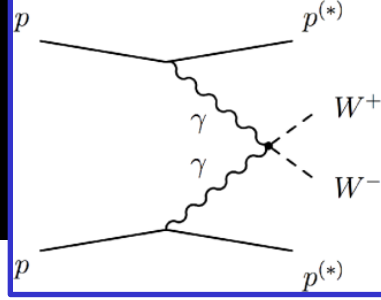


Selection step	Data	Exclusive $\gamma\gamma \to WW$	Total background	Inclusive diboson	Drell-Yan	$\gamma\gamma \to \tau\tau$	Other backgrounds
Trigger and Preselection	19406	26.9±0.2	22180±1890	1546±15	7093±75	18.1±0.8	13520±1890
$m(\mu^{\pm}e^{\mp}) > 20\,\text{GeV}$	18466	26.6±0.2	21590±1850	1507±15	7065±75	18.1±0.8	13000±1850
Muon and electron identification	6541	22.5±0.2	6640±93	1306±11	4219±58	12.6±0.7	1102±72
$\mu^{\pm}e^{\mp}$ vertex with no add. tracks	24	6.7±0.2	15.2±2.5	3.7±0.7	6.5±2.3	4.3±0.5	0.7±0.1
$p_T(\mu^{\pm}e^{\mp}) > 30\,\text{GeV}$	13	5.3±0.1	3.9±0.5	2.3±0.4	0.1±0.1	0.9±0.2	0.6±0.1

- Only statistical unc.'s listed above
- Vetoing additional tracks **drastically reduces backgrounds**
- Observed (Expected) Signal Significance: 3.4σ (2.8σ)

Image Source:
http://cms-results.web.cern.ch/cms-results/public-results/publications/FSQ-13-008/index.html

γγ→WW: CMS-PAS-FSQ-13-008 arXiv 1604.04464



- Combine 7 TeV and 8 TeV Analyses
- Set 2D limits on Dim. 6 aQGCs

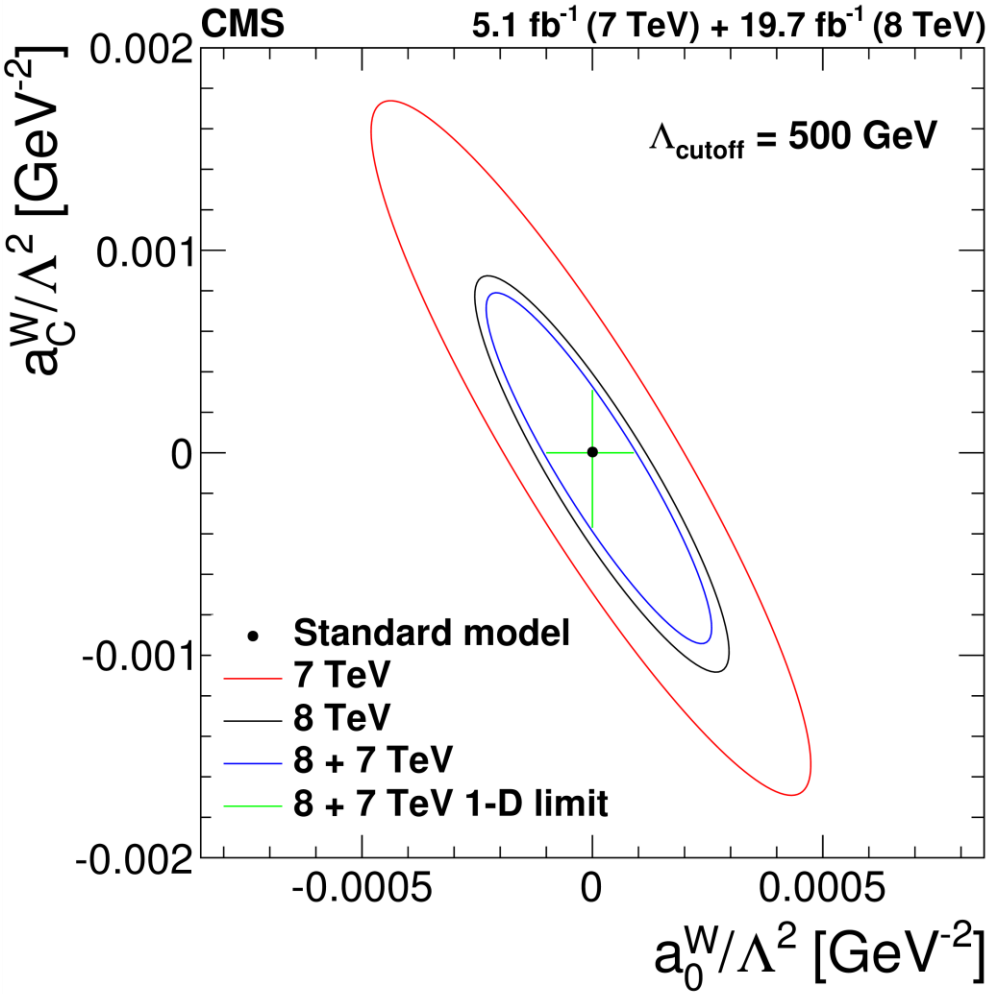


Image Source:
http://cms-results.web.cern.ch/cms-results/public-results/publications/FSQ-13-008/index.html

γγ→WW:
CMS-PAS-FSQ-13-008
arXiv 1604.04464

Dimension-6 AQGC parameter	7 TeV ($\times 10^{-4}$ GeV^{-2})	8 TeV ($\times 10^{-4}$ GeV^{-2})	7+8 TeV ($\times 10^{-4}$ GeV^{-2})
$a_0^W/\Lambda^2(\Lambda_{\text{cutoff}} = 500\,\text{GeV})$	$-1.5 < a_0^W/\Lambda^2 < 1.5$	$-1.1 < a_0^W/\Lambda^2 < 1.0$	$-0.9 < a_0^W/\Lambda^2 < 0.9$
$a_C^W/\Lambda^2(\Lambda_{\text{cutoff}} = 500\,\text{GeV})$	$-5 < a_C^W/\Lambda^2 < 5$	$-4.2 < a_C^W/\Lambda^2 < 3.4$	$-3.6 < a_C^W/\Lambda^2 < 3.0$
Dimension-8 AQGC parameter	7 TeV ($\times 10^{-10}$ GeV^{-4})	8 TeV ($\times 10^{-10}$ GeV^{-4})	7+8 TeV ($\times 10^{-10}$ GeV^{-4})
$f_{M,0}/\Lambda^4(\Lambda_{\text{cutoff}} = 500\,\text{GeV})$	$-5.7 < f_{M,0}/\Lambda^4 < 5.7$	$-3.8 < f_{M,0}/\Lambda^4 < 4.2$	$-3.4 < f_{M,0}/\Lambda^4 < 3.4$
$f_{M,1}/\Lambda^4(\Lambda_{\text{cutoff}} = 500\,\text{GeV})$	$-19 < f_{M,1}/\Lambda^4 < 19$	$-16 < f_{M,1}/\Lambda^4 < 13$	$-14 < f_{M,1}/\Lambda^4 < 12$
$f_{M,2}/\Lambda^4(\Lambda_{\text{cutoff}} = 500\,\text{GeV})$	$-2.8 < f_{M,2}/\Lambda^4 < 2.8$	$-1.9 < f_{M,2}/\Lambda^4 < 2.1$	$-1.9 < f_{M,2}/\Lambda^4 < 1.9$
$f_{M,3}/\Lambda^4(\Lambda_{\text{cutoff}} = 500\,\text{GeV})$	$-9.5 < f_{M,3}/\Lambda^4 < 9.5$	$-8.0 < f_{M,3}/\Lambda^4 < 6.5$	$-6.8 < f_{M,3}/\Lambda^4 < 5.7$
Dimension-6 AQGC parameter	7 TeV ($\times 10^{-6}$ GeV^{-2})	8 TeV ($\times 10^{-6}$ GeV^{-2})	7+8 TeV ($\times 10^{-6}$ GeV^{-2})
a_0^W/Λ^2 (no form factor)	$-4 < a_0^W/\Lambda^2 < 4$	$-1.2 < a_0^W/\Lambda^2 < 1.2$	$-1.1 < a_0^W/\Lambda^2 < 1.1$
a_C^W/Λ^2 (no form factor)	$-15 < a_C^W/\Lambda^2 < 15$	$-4.4 < a_C^W/\Lambda^2 < 4.4$	$-4.1 < a_C^W/\Lambda^2 < 4.1$
Dimension-8 AQGC parameter	7 TeV ($\times 10^{-12}$ GeV^{-4})	8 TeV ($\times 10^{-12}$ GeV^{-4})	7+8 TeV ($\times 10^{-12}$ GeV^{-4})
$f_{M,0}/\Lambda^4$ (no form factor)	$-15 < f_{M,0}/\Lambda^4 < 15$	$-4.6 < f_{M,0}/\Lambda^4 < 4.6$	$-4.2 < f_{M,0}/\Lambda^4 < 4.2$
$f_{M,1}/\Lambda^4$ (no form factor)	$-57 < f_{M,1}/\Lambda^4 < 57$	$-17 < f_{M,1}/\Lambda^4 < 17$	$-16 < f_{M,1}/\Lambda^4 < 16$
$f_{M,2}/\Lambda^4$ (no form factor)	$-7.6 < f_{M,2}/\Lambda^4 < 7.6$	$-2.3 < f_{M,2}/\Lambda^4 < 2.3$	$-2.1 < f_{M,2}/\Lambda^4 < 2.1$
$f_{M,3}/\Lambda^4$ (no form factor)	$-28 < f_{M,3}/\Lambda^4 < 28$	$-8.4 < f_{M,3}/\Lambda^4 < 8.4$	$-7.8 < f_{M,3}/\Lambda^4 < 7.8$

Most stringent limits to date

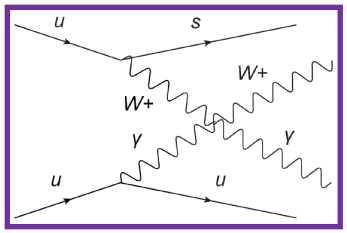
Image Source:
http://cms-results.web.cern.ch/cms-results/public-results/publications/FSQ-13-008/index.html

W γjj: CMS-PAS-SMP-14-011

μ(e) + γ+ $\not{E}_T$ + 2 jets

Allow τ-lepton decays to μ,e

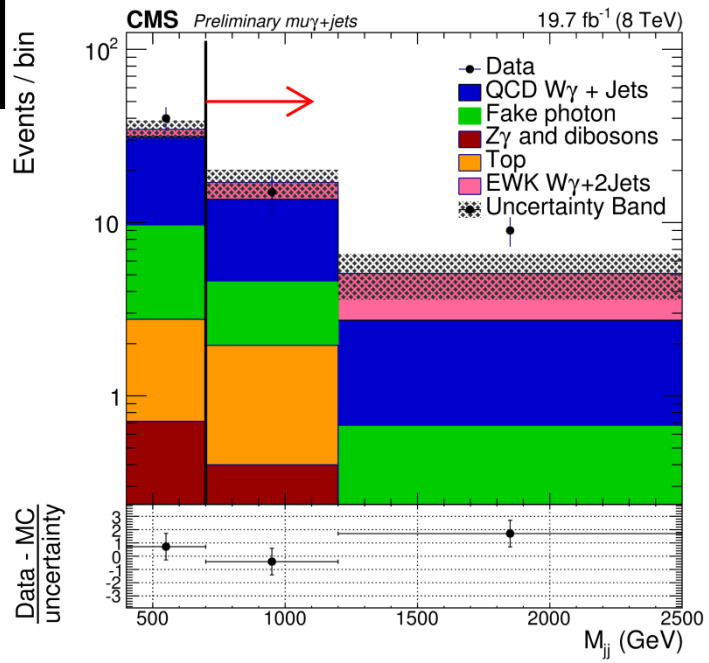
$$|y_{W\gamma} - (y_{j1} + y_{j2})/2.0| < 0.6,$$
$$|\Delta\phi_{W\gamma,dijet}| > 2.6,$$
$$p_T^{j1} > 30\ \text{GeV}, |\eta^{j1}| < 4.7,$$
$$p_T^{j2} > 30\ \text{GeV}, |\eta^{j2}| < 4.7,$$
$$M_{jj} > 700\ \text{GeV}, |\Delta\eta(j,j)| > 2.4,$$
$$p_T^{l} > 20\ \text{GeV}, |\eta^{l}| < 2.4,$$
$$p_T^{\gamma} > 20\ \text{GeV}, |\eta^{\gamma}| < 1.4442,$$
$$\not{E}_T > 20\ \text{GeV},$$
$$\Delta R_{j,j}, \Delta R_{l,j}, \Delta R_{\gamma,j}, \Delta R_{l,\gamma} > 0.4$$



Major Backgrounds:

QCD Wγ+jets, Fake Photons

Muon Channel



Electron Channel

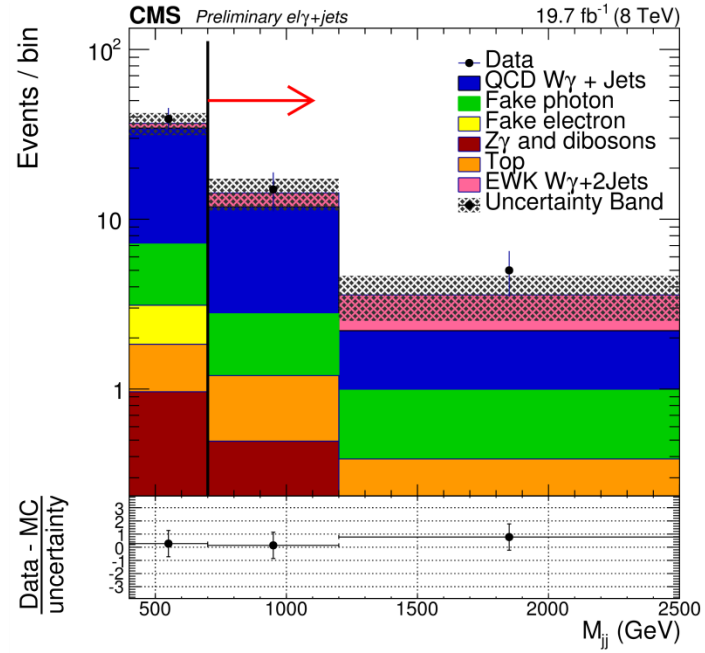
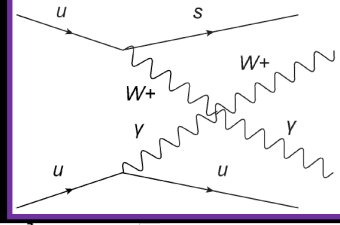
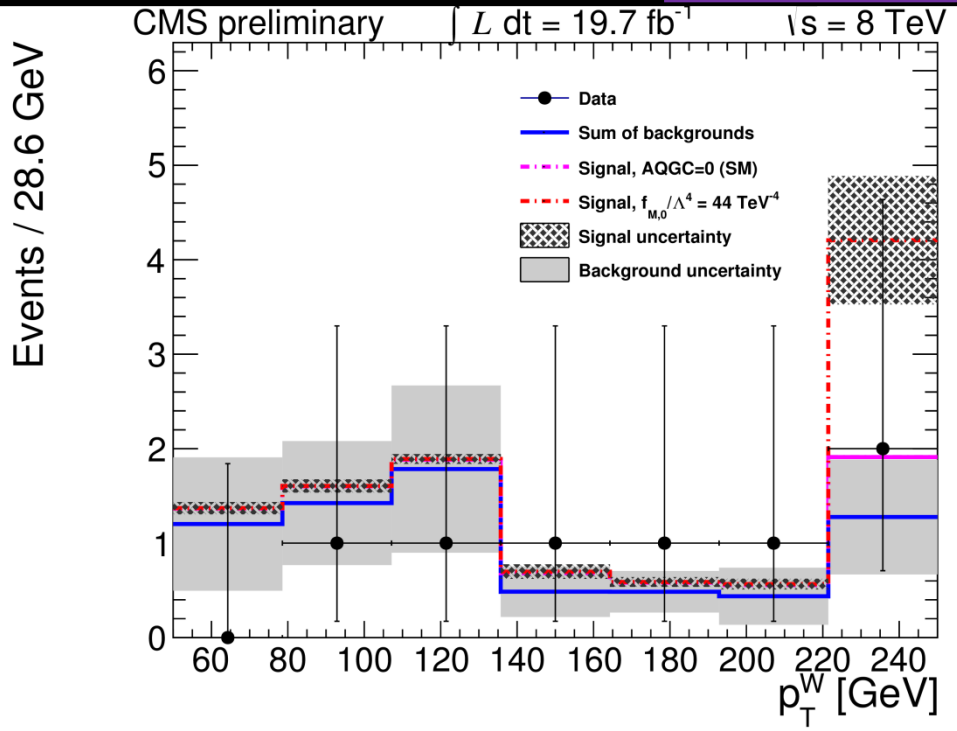


Image Source:
http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/SMP-14-011/index.html

W γjj: CMS-PAS-SMP-14-011



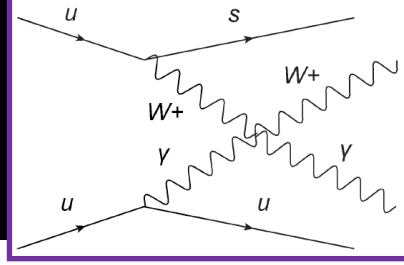
Process	Muon channel	Electron channel
EWK-induced Wγ+2jets	5.8 ± 1.8	3.8 ± 1.2
QCD-induced Wγ+jets	11.2 ± 3.2	10.3 ± 3.2
W + jets, 1 jet $\rightarrow \gamma$	3.1 ± 0.8	2.2 ± 0.6
MC $t\bar{t}\gamma$	1.2 ± 0.6	0.4 ± 0.2
MC single top quark	0.5 ± 0.5	0.6 ± 0.4
MC WVγ, V$\rightarrow$ two jets	0.3 ± 0.2	0.3 ± 0.2
MC Zγ + jets	0.2 ± 0.2	0.3 ± 0.2
Total prediction	22.1 ± 3.8	17.9 ± 3.5
Data	24	20



Items	EWK measurement	EWK+QCD measurement
$\hat{\mu}$	$1.78^{+0.99}_{-0.76}$	$0.99^{+0.21}_{-0.19}$
EWK fraction (search region)	100%	27.1%
EWK fraction (fiducial region)	100%	25.8%
Observed (Expected) significance	2.67(1.52) σ	7.69(7.49) σ
Theory cross section (fb)	6.1 ± 1.2 (scale) ± 0.2 (PDF)	23.5 ± 6.6 (scale) ± 0.8 (PDF)
Measured cross section (fb)	10.8 ± 4.1 (stat.) ± 3.4 (syst.) ± 0.3 (lumi.)	23.2 ± 4.3 (stat.) ± 1.7 (syst.) ± 0.6 (lumi.)

Image Source:
http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/SMP-14-011/index.html

W γjj: CMS-PAS-SMP-14-011



No Form Factor (etc.) applied

Observed Limits	Expected Limits
$-77\,(\mathrm{TeV}^{-4}) < f_{M0}/\Lambda^4 < 74\,(\mathrm{TeV}^{-4})$	$-47\,(\mathrm{TeV}^{-4}) < f_{M0}/\Lambda^4 < 44\,(\mathrm{TeV}^{-4})$
$-125\,(\mathrm{TeV}^{-4}) < f_{M1}/\Lambda^4 < 129\,(\mathrm{TeV}^{-4})$	$-72\,(\mathrm{TeV}^{-4}) < f_{M1}/\Lambda^4 < 79\,(\mathrm{TeV}^{-4})$
$-26\,(\mathrm{TeV}^{-4}) < f_{M2}/\Lambda^4 < 26\,(\mathrm{TeV}^{-4})$	$-16\,(\mathrm{TeV}^{-4}) < f_{M2}/\Lambda^4 < 15\,(\mathrm{TeV}^{-4})$
$-43\,(\mathrm{TeV}^{-4}) < f_{M3}/\Lambda^4 < 44\,(\mathrm{TeV}^{-4})$	$-25\,(\mathrm{TeV}^{-4}) < f_{M3}/\Lambda^4 < 27\,(\mathrm{TeV}^{-4})$
$-40\,(\mathrm{TeV}^{-4}) < f_{M4}/\Lambda^4 < 40\,(\mathrm{TeV}^{-4})$	$-23\,(\mathrm{TeV}^{-4}) < f_{M4}/\Lambda^4 < 24\,(\mathrm{TeV}^{-4})$
$-65\,(\mathrm{TeV}^{-4}) < f_{M5}/\Lambda^4 < 65\,(\mathrm{TeV}^{-4})$	$-39\,(\mathrm{TeV}^{-4}) < f_{M5}/\Lambda^4 < 39\,(\mathrm{TeV}^{-4})$
$-129\,(\mathrm{TeV}^{-4}) < f_{M6}/\Lambda^4 < 129\,(\mathrm{TeV}^{-4})$	$-77\,(\mathrm{TeV}^{-4}) < f_{M6}/\Lambda^4 < 77\,(\mathrm{TeV}^{-4})$
$-164\,(\mathrm{TeV}^{-4}) < f_{M7}/\Lambda^4 < 162\,(\mathrm{TeV}^{-4})$	$-99\,(\mathrm{TeV}^{-4}) < f_{M7}/\Lambda^4 < 97\,(\mathrm{TeV}^{-4})$
$-5.4\,(\mathrm{TeV}^{-4}) < f_{T0}/\Lambda^4 < 5.6\,(\mathrm{TeV}^{-4})$	$-3.2\,(\mathrm{TeV}^{-4}) < f_{T0}/\Lambda^4 < 3.4\,(\mathrm{TeV}^{-4})$
$-3.7\,(\mathrm{TeV}^{-4}) < f_{T1}/\Lambda^4 < 4.0\,(\mathrm{TeV}^{-4})$	$-2.2\,(\mathrm{TeV}^{-4}) < f_{T1}/\Lambda^4 < 2.5\,(\mathrm{TeV}^{-4})$
$-11\,(\mathrm{TeV}^{-4}) < f_{T2}/\Lambda^4 < 12\,(\mathrm{TeV}^{-4})$	$-6.3\,(\mathrm{TeV}^{-4}) < f_{T2}/\Lambda^4 < 7.9\,(\mathrm{TeV}^{-4})$
$-3.8\,(\mathrm{TeV}^{-4}) < f_{T5}/\Lambda^4 < 3.8\,(\mathrm{TeV}^{-4})$	$-2.3\,(\mathrm{TeV}^{-4}) < f_{T5}/\Lambda^4 < 2.4\,(\mathrm{TeV}^{-4})$
$-2.8\,(\mathrm{TeV}^{-4}) < f_{T6}/\Lambda^4 < 3.0\,(\mathrm{TeV}^{-4})$	$-1.7\,(\mathrm{TeV}^{-4}) < f_{T6}/\Lambda^4 < 1.9\,(\mathrm{TeV}^{-4})$
$-7.3\,(\mathrm{TeV}^{-4}) < f_{T7}/\Lambda^4 < 7.7\,(\mathrm{TeV}^{-4})$	$-4.4\,(\mathrm{TeV}^{-4}) < f_{T7}/\Lambda^4 < 4.7\,(\mathrm{TeV}^{-4})$

Most stringent limits to date

Image Source:
http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/SMP-14-011/index.html

Zγjj: CMS-PAS-SMP-14-018

μμ(ee) + γ + 2 jets

Allow τ-lepton decays to μ,e

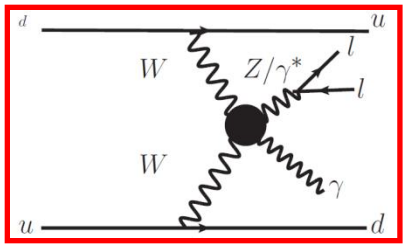
Major Backgrounds:

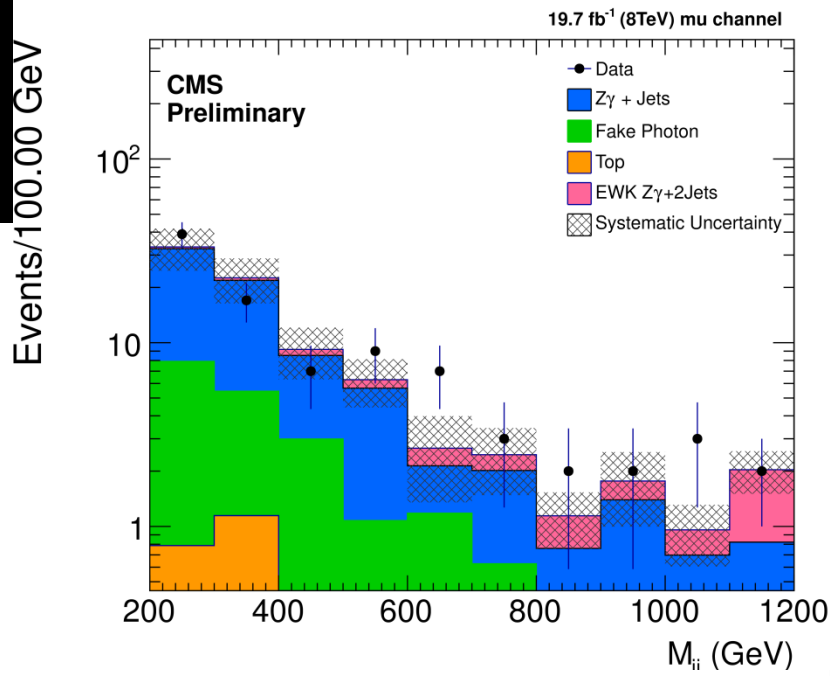
QCD Zγ + Jets, Fake Photons

$\Delta\eta_{jj} > 1.6,$
$\Delta\phi_{Z\gamma,jj} > 2.0,$
$|y_{Z\gamma} - (y_{j1} + y_{j2})/2.0| < 1.2,$

$p_T^{j1,j2} > 30\ \text{GeV}, |\eta^{j1,j2}| < 4.7,$
$M_{jj} > 400\ \text{GeV},$

$p_T^{l1,l2} > 20\ \text{GeV}, |\eta^{l1,l2}| < 2.4,$
$70\ \text{GeV} < M_{ll} < 110\ \text{GeV},$
$p_T^{\gamma} > 20\ \text{GeV}, |\eta^{\gamma}| < 1.4442,$
$\Delta R_{jj}, \Delta R_{j\gamma}, \Delta R_{l\gamma}, \Delta R_{jl} > 0.4,$





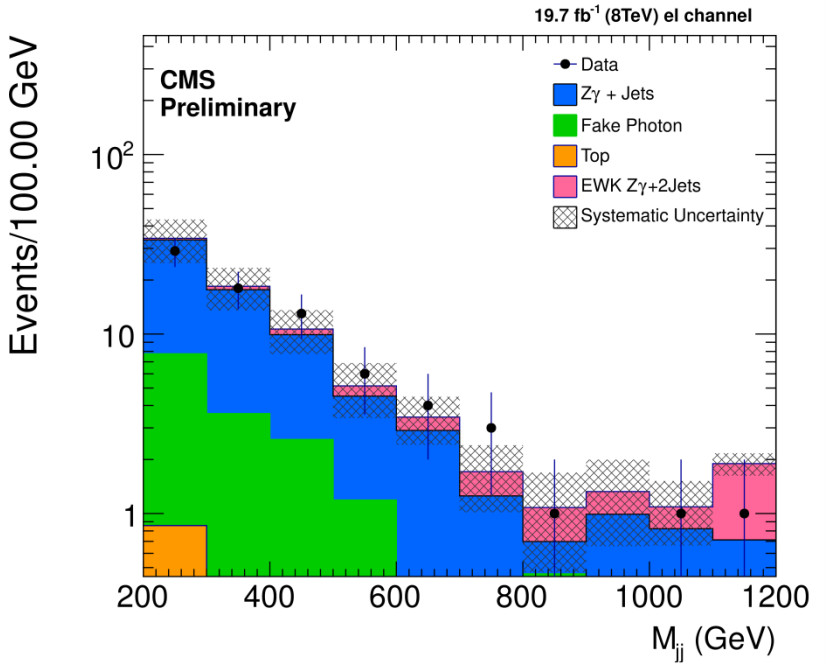
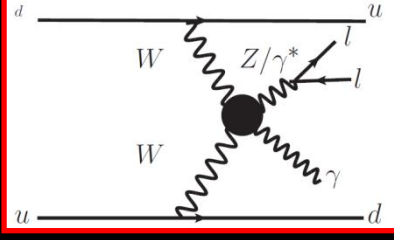


Image Source:
http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/SMP-14-018/index.html

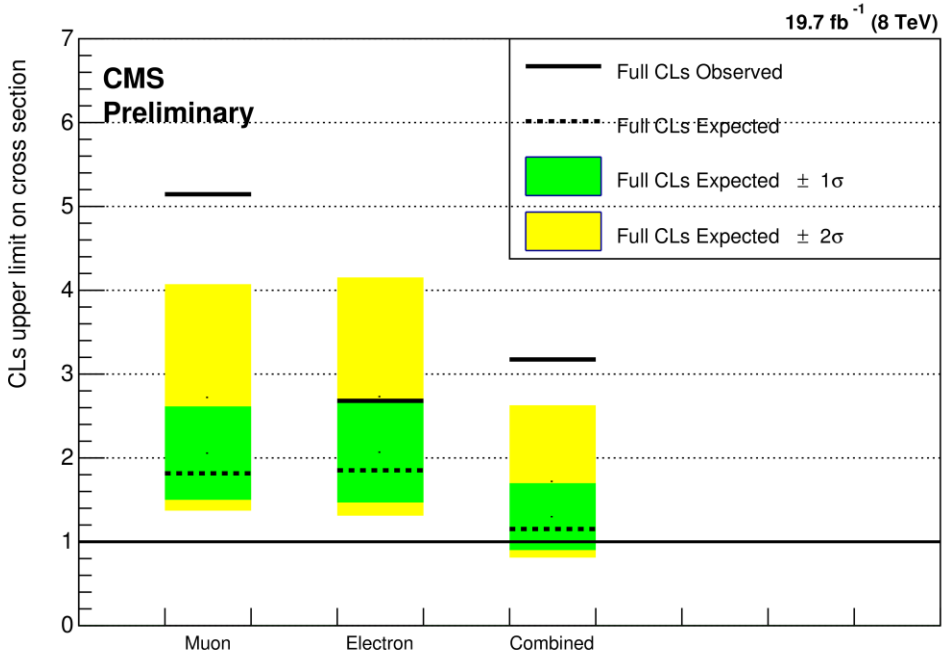
Zγjj: CMS-PAS-SMP-14-018



Total Cross Section x BR (fiducial):

$1.86^{+0.90}_{-0.75}\,(\text{stat})^{+0.34}_{-0.26}\,(\text{sys}) \pm 0.05\,(\text{lumi})$ fb

EWK

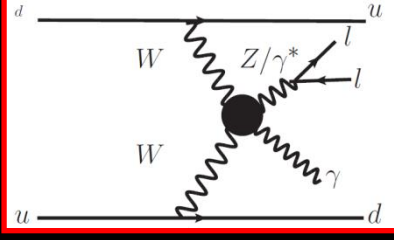


Also measured EWK+QCD cross section in tigher fiducial region: M_{jj} > 800 GeV

$1.00 \pm 0.43(stat.) \pm 0.26(syst.) \pm 0.03(lumi.)$ fb

Image Source:
http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/SMP-14-018/index.html

Zγjj: CMS-PAS-SMP-14-018



- Higher photon p_T threshold applied to aQGC MC to enhance statistics generated

$p_T^{j1,j2} > 30$ GeV, $|\eta^{j1,j2}| < 4.7$
$M_{jj} > 400$ GeV, $\Delta\eta_{jj} > 2.5$
$p_T^{l1,2} > 20$ GeV, $|\eta^{l1,l2}| < 2.4$
70 GeV $< M_{ll} < 110$ GeV
$p_T^{\gamma} > 60$ GeV, $|\eta^{\gamma}| < 1.4442$

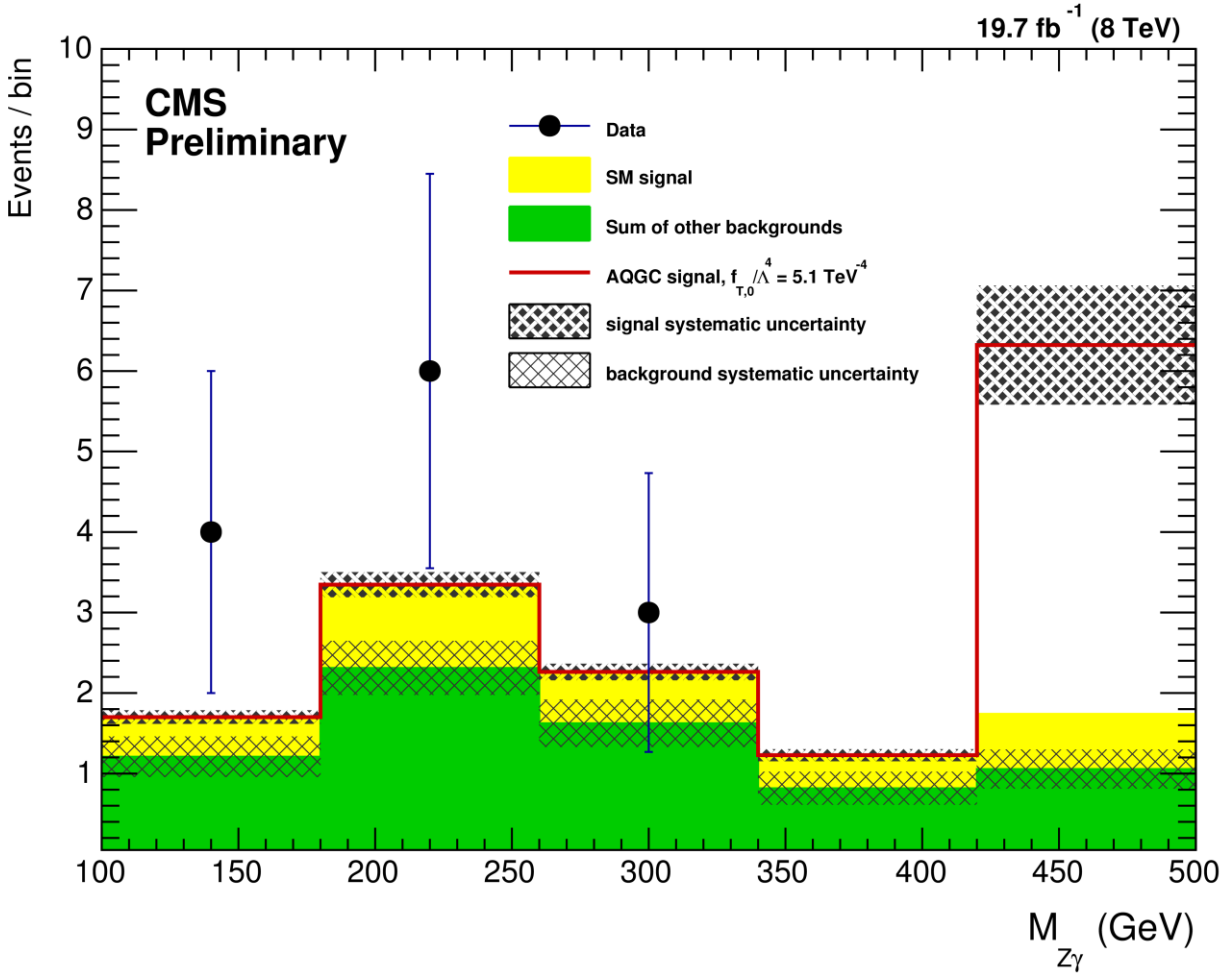
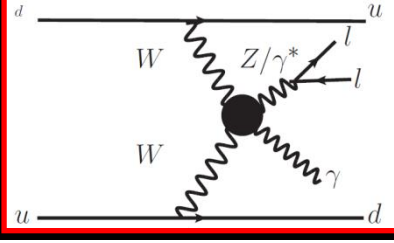


Image Source:
http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/SMP-14-018/index.html

Zγjj: CMS-PAS-SMP-14-018



No Form Factor (etc.) applied

Observed Limits	Expected Limits
$-71\ (\text{TeV}^{-4}) < f_{M0}/\Lambda^4 < 75\ (\text{TeV}^{-4})$	$-109\ (\text{TeV}^{-4}) < f_{M0}/\Lambda^4 < 111\ (\text{TeV}^{-4})$
$-190\ (\text{TeV}^{-4}) < f_{M1}/\Lambda^4 < 182\ (\text{TeV}^{-4})$	$-281\ (\text{TeV}^{-4}) < f_{M1}/\Lambda^4 < 280\ (\text{TeV}^{-4})$
$-32\ (\text{TeV}^{-4}) < f_{M2}/\Lambda^4 < 31\ (\text{TeV}^{-4})$	$-47\ (\text{TeV}^{-4}) < f_{M2}/\Lambda^4 < 47\ (\text{TeV}^{-4})$
$-58\ (\text{TeV}^{-4}) < f_{M3}/\Lambda^4 < 59\ (\text{TeV}^{-4})$	$-87\ (\text{TeV}^{-4}) < f_{M3}/\Lambda^4 < 87\ (\text{TeV}^{-4})$
$-3.8\ (\text{TeV}^{-4}) < f_{T0}/\Lambda^4 < 3.4\ (\text{TeV}^{-4})$	$-5.1\ (\text{TeV}^{-4}) < f_{T0}/\Lambda^4 < 5.1\ (\text{TeV}^{-4})$
$-4.4\ (\text{TeV}^{-4}) < f_{T1}/\Lambda^4 < 4.4\ (\text{TeV}^{-4})$	$-6.5\ (\text{TeV}^{-4}) < f_{T1}/\Lambda^4 < 6.5\ (\text{TeV}^{-4})$
$-9.9\ (\text{TeV}^{-4}) < f_{T2}/\Lambda^4 < 9.0\ (\text{TeV}^{-4})$	$-14.0\ (\text{TeV}^{-4}) < f_{T2}/\Lambda^4 < 14.5\ (\text{TeV}^{-4})$
$-1.8\ (\text{TeV}^{-4}) < f_{T8}/\Lambda^4 < 1.8\ (\text{TeV}^{-4})$	$-2.7\ (\text{TeV}^{-4}) < f_{T8}/\Lambda^4 < 2.7\ (\text{TeV}^{-4})$
$-4.0\ (\text{TeV}^{-4}) < f_{T9}/\Lambda^4 < 4.0\ (\text{TeV}^{-4})$	$-6.0\ (\text{TeV}^{-4}) < f_{T9}/\Lambda^4 < 6.0\ (\text{TeV}^{-4})$

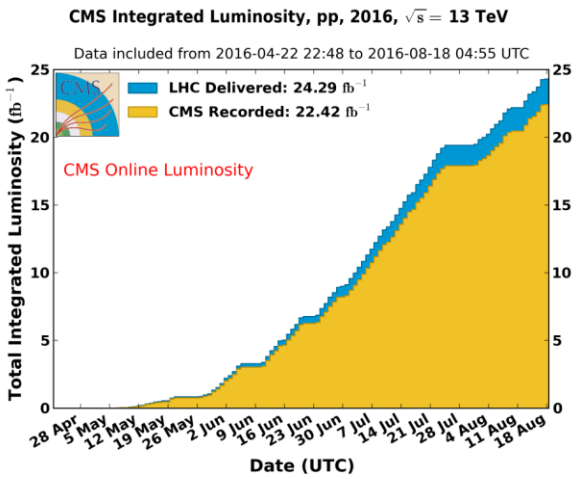
Most stringent limits to date

Image Source:
http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/SMP-14-018/index.html

CMS Run II Prospects

CMS Run II Prospects:

- Data collected this year (so far) approximately the integrated luminosity of 2012
  - More physics events still being recorded and added to current dataset!
  - More precise measurements on VBS processes
  - Slated to greatly improve on existing aGC limits
- All mentioned analyses from Run I are in gear for high luminosity datasets



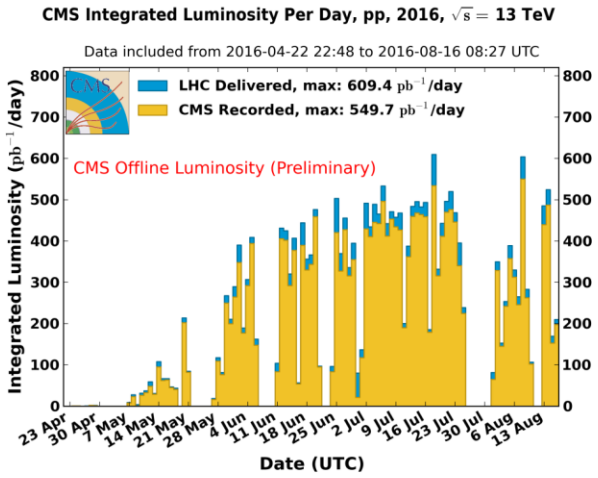


Image Source: https://twiki.cern.ch/twiki/bin/view/CMSPublic/LumiPublicResults#2016_Proton_Proton_13_TeV_Collis

Compilation of aQGC Limits

Limits on Anomalous Couplings:

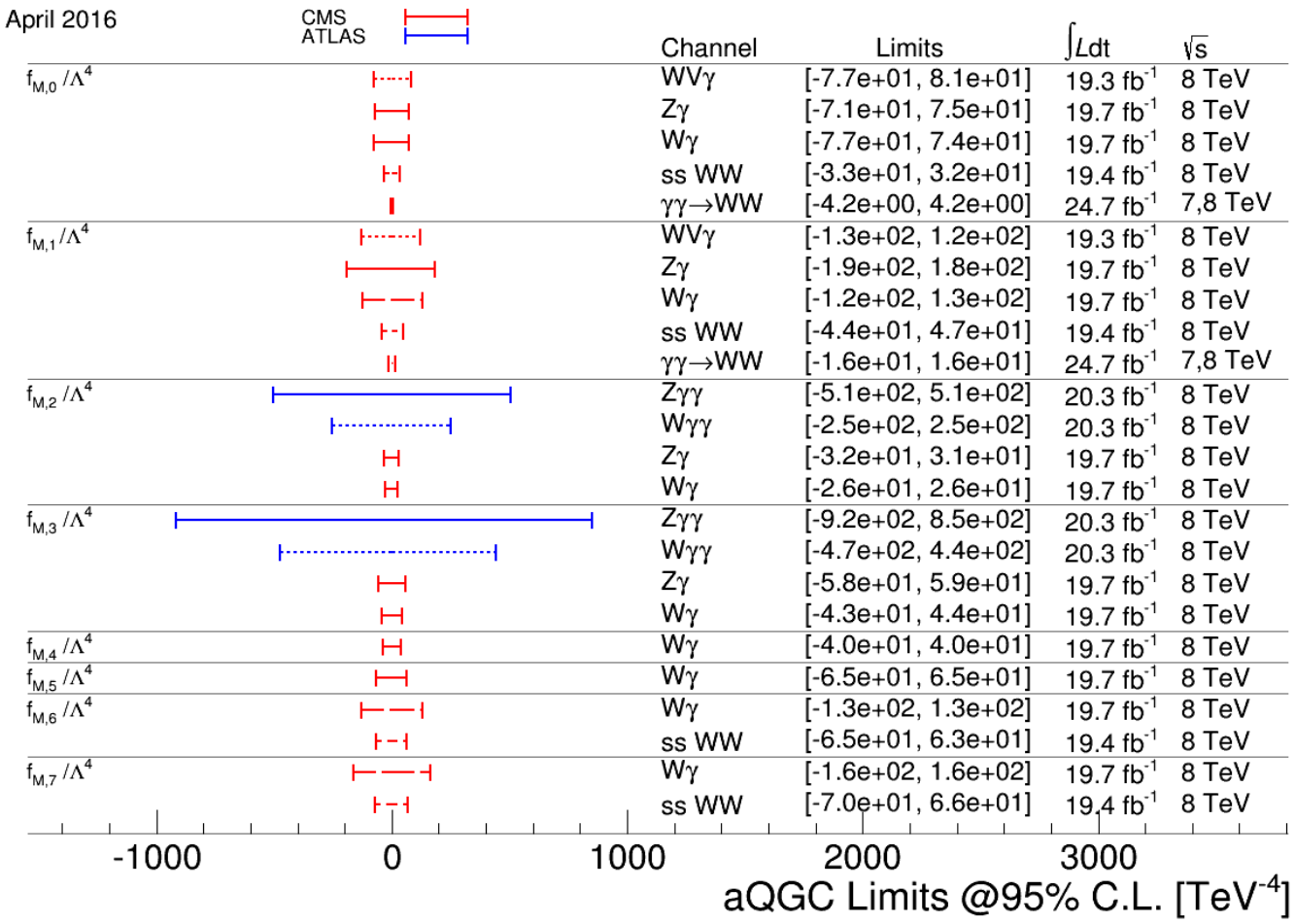


Image Source: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMPaTGC#aQGC_Results

Limits on Anomalous Couplings:

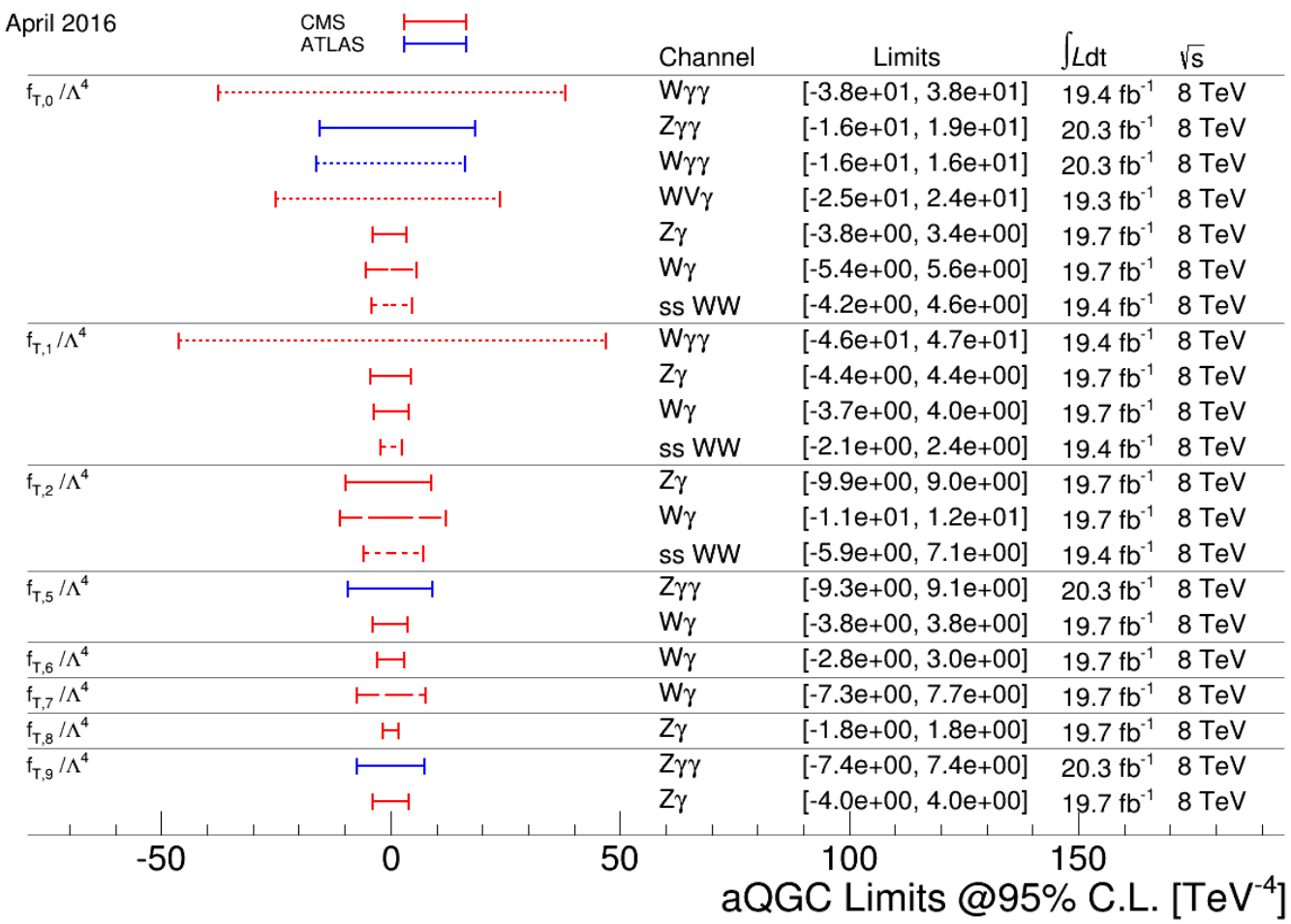


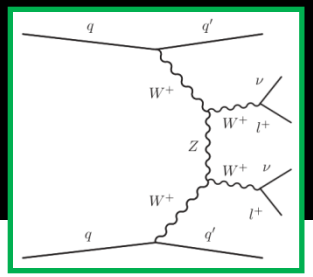
Image Source: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMPaTGC#aQGC_Results

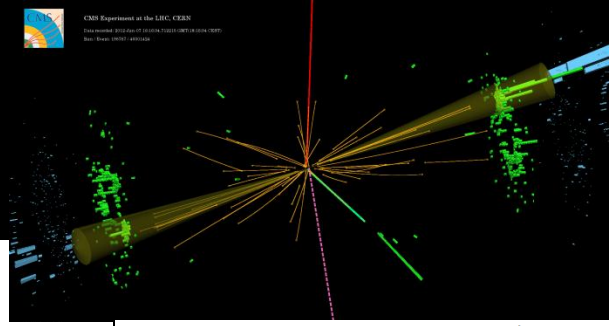
Summary:

- Vector Boson Scattering excellent candidate for probing:
  - Electroweak Symmetry Breaking in Standard Model
  - Higgs properties
  - Gauge structure of electroweak physics
  - Anomalous triple or quartic gauge couplings (aTGC/aQGC)
- LHC Run I analyses show evidence for VBS in various channels
  - $\gamma\gamma \rightarrow WW$, Same-sign WW+jets, $W\gamma$+jets, $Z\gamma$+jets
- Results still consistent with SM predictions
- LHC Run II analyses well underway and with great potential

TEXAS TECH UNIVERSITY™

Same-sign WW plus 2 Jets: P.R.L. 114, 051801 (2015)





$(\mu^{\pm}\mu^{\pm}, e^{\pm}e^{\pm}, \mu^{\pm}e^{\pm})$ + 2jets + $\not{E}_T$

*Allow τ-lepton decays to μ,e

$p_T^{lepton} > 20$ GeV, $|\eta^{lepton}| < 2.4(2.5)$

$\Delta R = 0.3$, $m_{ll} > 50$ GeV

$|m_{ll} - m_Z| > 15$ GeV (el. ch.), $\not{E}_T > 40$ GeV

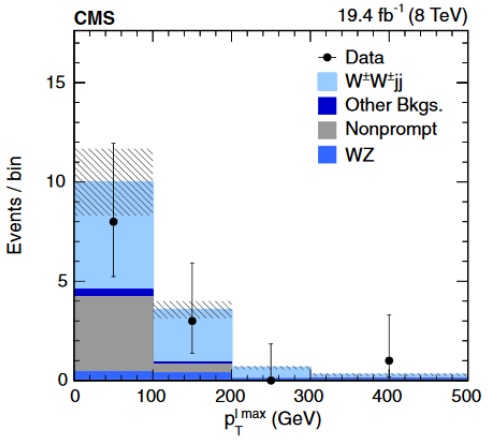
> 1 Anti-k_T jets ($R = 0.5$), $E_T^{jet} > 30$ GeV

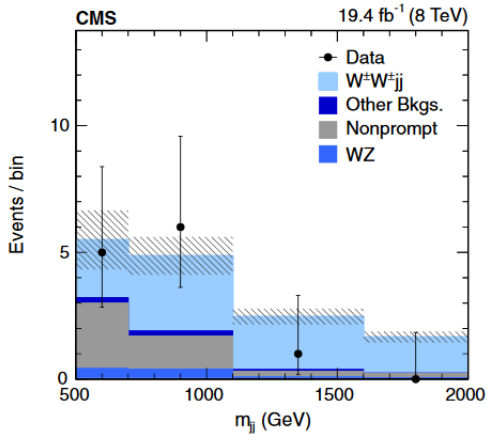
$|\eta^{jet}| < 4.7$, $m_{jj} > 500$ GeV, $|\Delta\eta^{jj}| > 2.5$

Major Backgrounds:

Top quark, Drell-Yan, WZ

Observed (Expected) Significance: 2.0σ (3.1σ)



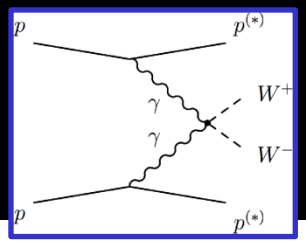


Source	Signal	WW DPS	WZ	Wrong sign	VVV	Non-prompt
Luminosity	2.6	2.6	-	2.6	2.6	-
Lepton efficiency	3.6	3.6	3.6	3.6	3.6	-
Momentum resolution	0.2	0.2	0.2	0.2	0.2	-
b-tagging	2.0	2.0	-	2.0	2.0	-
E_T^{miss}	1.0	1.0	1.0	1.0	1.0	-
JES	3.0	3.0	3.0	3.0	3.0	-
PDF	7.7	7.0	7.1	-	-	-
QCD scales EWK	5.0	-	-	-	-	-
QCD scales VVV	-	-	-	-	50.0	-
WZ normalization	-	-	37.0	-	-	-
Wrong sign normalization	-	-	-	10.0	-	-
Nom-prompt normalization	-	-	-	-	-	36.0
Statistical uncertainty	2.0	57.0	15.0	55.0	18.0	19.0

	Nonprompt	WZ	VVV	Wrong sign	WW DPS	Total bkg.	$W^{\pm}W^{\pm}jj$	Data
$\mu^{\pm}\mu^{\pm}$	2.1 ± 0.6	0.2 ± 0.1	0.1 ± 0.1	—	—	2.4 ± 0.6	3.0 ± 0.1	2
$e^{\pm}e^{\pm}$	0.6 ± 0.2	0.3 ± 0.1	0.1 ± 0.1	—	—	1.0 ± 0.2	1.4 ± 0.1	3
$e^{\pm}\mu^{\pm}$	1.5 ± 0.4	0.5 ± 0.1	0.1 ± 0.1	0.1 ± 0.1	0.1 ± 0.1	2.3 ± 0.5	4.5 ± 0.1	7
W^+W^+	2.1 ± 0.6	0.6 ± 0.1	0.2 ± 0.1	0.1 ± 0.1	0.1 ± 0.1	3.1 ± 0.6	7.1 ± 0.1	10
W^-W^-	2.1 ± 0.5	0.4 ± 0.1	0.1 ± 0.1	—	—	2.6 ± 0.5	1.8 ± 0.1	2
$W^{\pm}W^{\pm}$	4.2 ± 0.8	1.0 ± 0.1	0.3 ± 0.1	0.1 ± 0.1	0.1 ± 0.1	5.7 ± 0.8	8.9 ± 0.1	12

Image Source:
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMP13015

γγ→WW: CMS-PAS-FSQ-13-008 arXiv 1604.04464



$p^{(*)}\mu^{\pm}e^{\mp}p^{(*)} + \not{E}_T$

*Protons remain intact or dissociate into undetected system

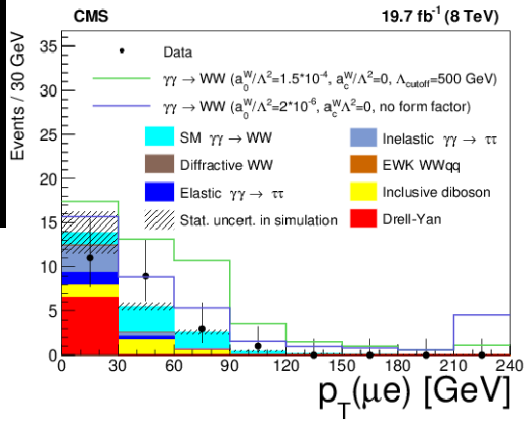
Allow τ-lepton decays to μ,e

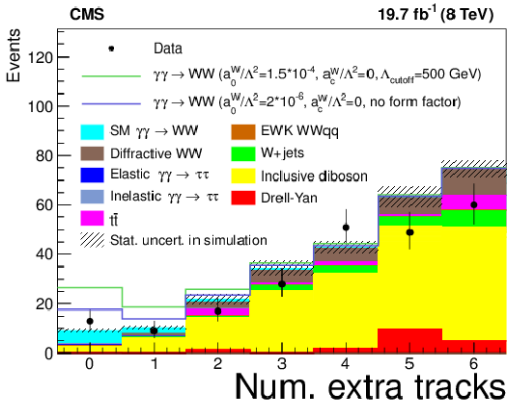
$p_T^{lepton} > 20$ GeV, $p_T^{ll} > 30$ GeV, no additional tracks
$|\eta^{lepton}| < 2.4$

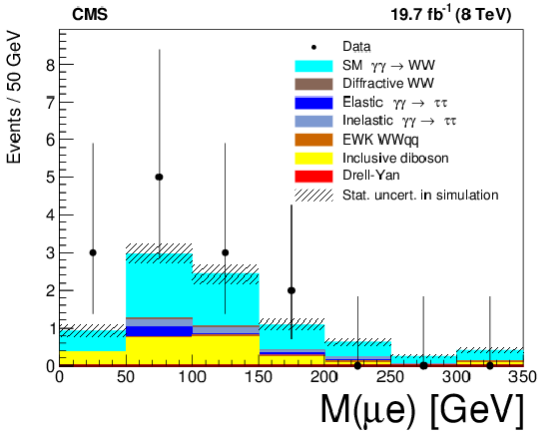
Major Background:
Inclusive Diboson

Observed (Expected) Significance

3.4σ (2.8σ)





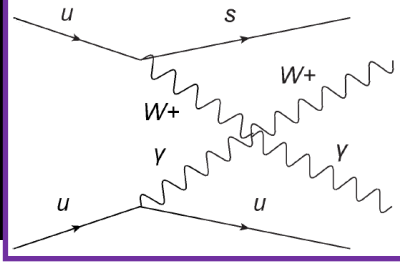


	Uncertainty
Proton dissociation factor	10.5%
Efficiency correction for no add. tracks	5.0%
Trigger and lepton identification	2.4%
Integrated luminosity	2.6%
Total	12.2%

Selection step	Data	Exclusive $\gamma\gamma \to WW$	Total background	Inclusive diboson	Drell-Yan	$\gamma\gamma \to \tau\tau$	Other backgrounds
Trigger and Preselection	19406	26.9±0.2	22180±1890	1546±15	2096±75	18.1±0.8	13520±1890
$m(\mu^{\pm}e^{\mp}) > 20$ GeV	18466	26.6±0.2	21590±1850	1507±15	2065±75	18.1±0.8	13000±1850
Muon and electron identification	6541	22.5±0.2	6640±93	1306±11	4219±58	12.6±0.7	1102±72
$\mu^{\pm}e^{\mp}$ vertex with no add. tracks	24	6.7±0.2	15.2±2.5	3.7±0.7	6.5±2.3	4.3±0.5	0.7±0.1
$p_T(\mu^{\pm}e^{\mp}) > 30$ GeV	13	5.3±0.1	3.9±0.5	2.3±0.4	0.1±0.1	0.9±0.2	0.6±0.1

Image Source:
http://cms-results.web.cern.ch/cms-results/public-results/publications/FSQ-13-008/index.html

W γjj:
CMS-PAS-SMP-14-011



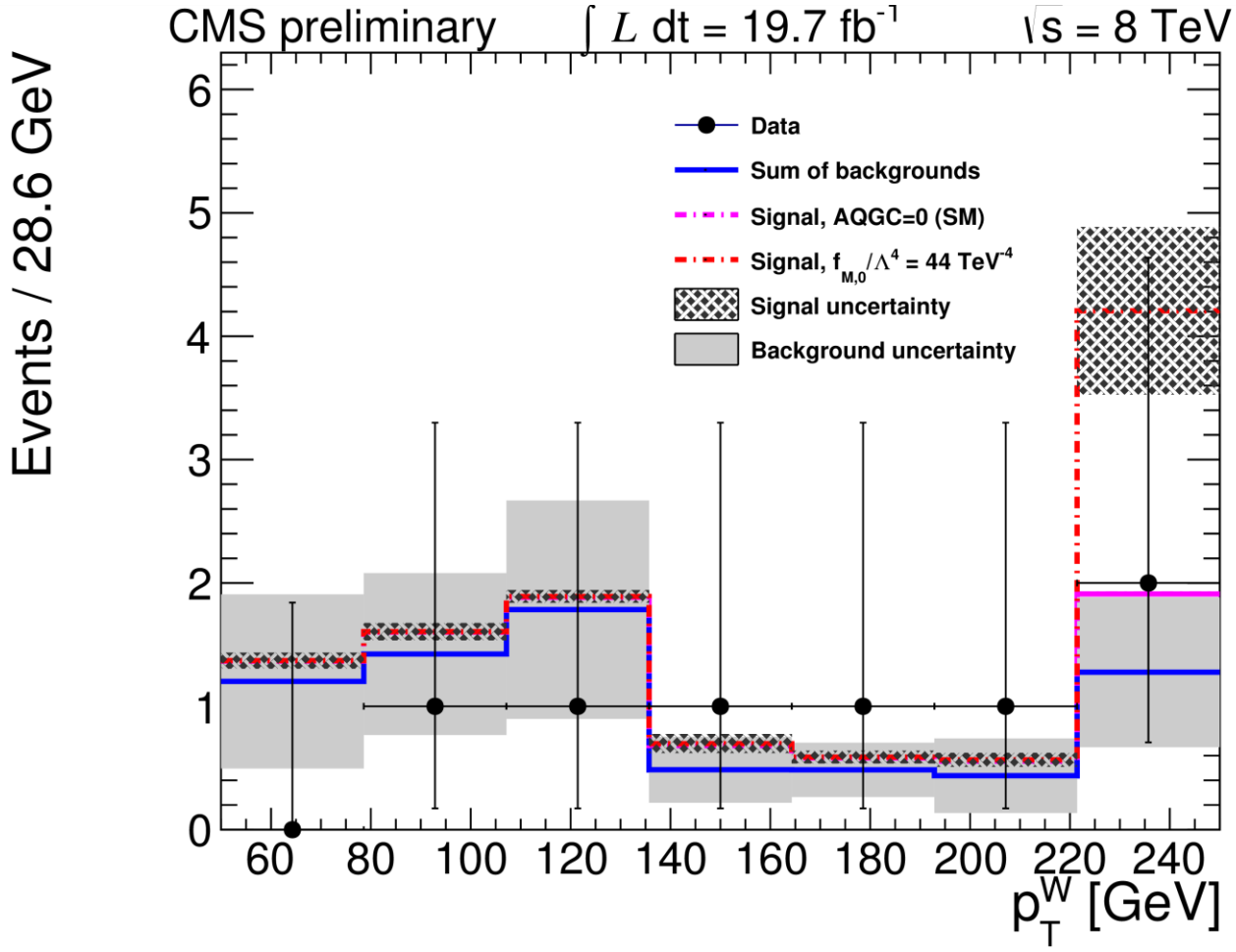


Image Source:
http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/SMP-14-011/index.html