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LHC Results on VBS Di-boson Production and aQGCs

James Faulkner On behalf of the CMS Collaboration



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T Additional Info on VBS and aQGCs

T CMS Run I Analyses

Overview:

- **T** CMS Run II Prospects
- TLimits on Anomalous Couplings

T Summary







Results on VBS Production and aQGCs



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
 - **T** Final state bosons and jets in pure electroweak process
 - **T** Two forward/backward jets at large $|\eta|$
 - The Large separation in rapidity between jets
 - T Large dijet invariant mass
 - **T** Vector bosons' daughters in central region







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Importance of VBS Measurements:







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

- T 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

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Importance of VBS Measurements:







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

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

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Results on VBS Production and aQGCs



Anomalous Quartic Gauge Couplings

Anomalous Quartic Gauge Couplings:



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

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



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

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

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Anomalous Quartic Gauge Couplings:



- **T** Assume $SU(2)_L \ge U(1)_Y$ gauge invariance, C&P conservation, $SU(2)_{C}$ custodial symmetry $\mathcal{L}_{\mathcal{EFT}} = \mathcal{L}_{SM} + \sum_{d>4} \sum_{i} \frac{c_i}{\Lambda^{d-4}} \mathcal{O}_i$
- T Linear realization (arXiv:hep-ph/0606118),

T Lowest order genuine quartic interaction: Dim. 8

T Following analyses assume no aTGC

T Exclude lepton flavor violating terms (such as d = 5, 7)

- **T** aGCs increase cross sections at high energies
 - **T** Sensitive observables: M^{VV} , p_T^V , etc.

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

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

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Results on VBS Production and aQGCs



CMS Run I Analyses





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 $(\mu^{\pm}\mu^{\pm}, e^{\pm}e^{\pm}, \mu^{\pm}e^{\pm}) + 2jets + E_{T}$

*Allow τ -lepton decays to μ ,e

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

```
\Delta R = 0.3, m_{11} > 50 \text{ GeV}
```

 $|m_{11} - m_{7}| > 15 \text{ GeV}$ (el. ch.), $E_{T} > 40 \text{ GeV}$

> 1 Anti-
$$k_{\rm T}$$
 jets (R = 0.5), $E_{\rm T}^{\rm jet}$ > 30 GeV

 $|\eta^{\text{jet}}| < 4.7, \, \text{m}_{\text{ii}} > 500 \, \text{GeV}, \, |\Delta \eta^{\text{jj}}| > 2.5$

Major Backgrounds:

```
Nonprompt leptons, WZ
```

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



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CMS

19.4 fb⁻¹ (8 TeV)

Data

12



	Nonprompt	WZ	VVV	Wrong sign	WW DPS	Total bkg.	W±W±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

- **T** Only statistical unc.'s listed above
- **T** EWK+QCD contributions included in signal
 - **T** EWK constitutes 85% 90% of total signal
- **T** Observed cross section x BR (fiducial) = $4.0^{+2.4}_{-2.0}$ (stat) $^{+1.1}_{-1.0}$ (syst) fb
- **T** Also measured $\sigma(WZjj) \times BR$ (fiducial) =10.8 ± 4.0 (stat) ± 1.3 (syst) fb

Image Source:

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



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



100

200

300

400

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500

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

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m_µ (GeV)

500

19.4 fb⁻¹ (8 TeV)

Expected 95% CL Observed 95% CL

SM

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

* Accepted for publication in JHEP

 $p^{(*)}\mu^{\pm}e^{\mp}p^{(*)} + E_T$

*Protons remain intact or dissociate into undetected system

Allow τ-lepton decays to μ,e

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

Major Background: Inclusive Diboson

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

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$\gamma\gamma \rightarrow$ WW: CMS-PAS-FSQ-13-008 arXiv 1604.04464



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

- **T** Only statistical unc.'s listed above
- **T** Vetoing additional tracks **drastically reduces backgrounds**
- **T** 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

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$\gamma\gamma \rightarrow$ WW: CMS-PAS-FSQ-13-008 arXiv 1604.04464



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



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

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



Dimension-6 AQGC parameter	$7 \text{TeV} (imes 10^{-4} \text{GeV}^{-2})$	$8 \text{TeV} (imes 10^{-4} \text{GeV}^{-2})$	7+8 TeV (× 10^{-4} GeV ⁻²)
$a_0^{\rm W} / \Lambda^2 (\Lambda_{\rm cutoff} = 500 {\rm GeV})$	$-1.5 < a_0^W / \Lambda^2 < 1.5$	$-1.1 < a_0^W / \Lambda^2 < 1.0$	$-0.9 < a_0^{\rm W} / \Lambda^2 < 0.9$
$a_{\rm C}^{\rm W}/\Lambda^2(\Lambda_{\rm cutoff}=500{\rm GeV})$	$-5 < a_C^W / \Lambda^2 < 5$	$-4.2 < a_C^W / \Lambda^2 < 3.4$	$-3.6 < a_C^W / \Lambda^2 < 3.0$
Dimension-8 AQGC parameter	$7 \text{TeV} (imes 10^{-10} \text{GeV}^{-4})$	$8 \text{TeV} (imes 10^{-10} \text{GeV}^{-4})$	7+8 TeV ($\times 10^{-10} \text{GeV}^{-4}$)
$f_{M,0}/\Lambda^4(\Lambda_{\rm cutoff}=500{\rm GeV})$	$-5.7 < f_{M,0} / \Lambda^4 < 5.7$	$-3.8 < f_{M,0} / \Lambda^4 < 4.2$	$-3.4 < f_{M,0} / \Lambda^4 < 3.4$
$f_{M,1} / \Lambda^4 (\Lambda_{\text{cutoff}} = 500 \text{GeV})$	$-19 < f_{M,1}/\Lambda^4 < 19$	$-16 < f_{M,1} / \Lambda^4 < 13$	$-14 < f_{M,1} / \Lambda^4 < 12$
$f_{M,2}/\Lambda^4(\Lambda_{\rm cutoff}=500{\rm GeV})$	$-2.8 < f_{M,2}/\Lambda^4 < 2.8$	$-1.9 < f_{M,2} / \Lambda^4 < 2.1$	$-1.9 < f_{M,2} / \Lambda^4 < 1.9$
$f_{M3}/\Lambda^4(\Lambda_{\rm cutoff}=500{\rm GeV})$	$-9.5 < f_{M,3} / \Lambda^4 < 9.5$	$-8.0 < f_{M,3} / \Lambda^4 < 6.5$	$-6.8 < f_{M,3} / \Lambda^4 < 5.7$
<i>y</i> 111,0, (Cuton)	y ,	• ·	
Dimension-6 AQGC parameter	$7 \text{ TeV} (\times 10^{-6} \text{ GeV}^{-2})$	$8 \text{ TeV} (\times 10^{-6} \text{ GeV}^{-2})$	7+8 TeV (×10 ⁻⁶ GeV ⁻²)
Dimension-6 AQGC parameter a_0^W / Λ^2 no form factor)	$\frac{7 \text{ TeV} (\times 10^{-6} \text{ GeV}^{-2})}{-4 < a_0^W / \Lambda^2 < 4}$	8 TeV (×10 ⁻⁶ GeV ⁻²) -1.2 < $a_0^W / \Lambda^2 < 1.2$	$\frac{7+8 \text{ TeV} (\times 10^{-6} \text{ GeV}^{-2})}{-1.1 < a_0^W / \Lambda^2 < 1.1}$
Dimension-6 AQGC parameter a_0^W / Λ^2 no form factor) a_C^W / Λ^2 no form factor)	$7 \text{ TeV} (\times 10^{-6} \text{ GeV}^{-2})$ $-4 < a_0^W / \Lambda^2 < 4$ $-15 < a_C^W / \Lambda^2 < 15$	$8 \text{ TeV} (\times 10^{-6} \text{ GeV}^{-2})$ -1.2 < $a_0^W / \Lambda^2 < 1.2$ -4.4 < $a_C^W / \Lambda^2 < 4.4$	$\begin{array}{c} \hline 7+8\text{TeV}~(\times 10^{-6}\text{GeV}^{-2})\\ \hline -1.1 < a_0^{\text{W}}/\Lambda^2 < 1.1\\ -4.1 < a_{\text{C}}^{\text{W}}/\Lambda^2 < 4.1 \end{array}$
Dimension-6 AQGC parameter a_0^W / Λ^2 no form factor) a_C^W / Λ^2 no form factor) Dimension-8 AQGC parameter	$\begin{array}{l} 7{\rm TeV}\;(\times 10^{-6}{\rm GeV}^{-2})\\ -4 < a_0^{\rm W}/\Lambda^2 < 4\\ -15 < a_C^{\rm W}/\Lambda^2 < 15\\ 7{\rm TeV}\;(\times 10^{-12}{\rm GeV}^{-4}) \end{array}$	$\begin{split} &8\text{TeV}\;(\times 10^{-6}\text{GeV}^{-2})\\ &-1.2 < a_0^{\text{W}}/\Lambda^2 < 1.2\\ &-4.4 < a_C^{\text{W}}/\Lambda^2 < 4.4\\ &8\text{TeV}\;(\times 10^{-12}\text{GeV}^{-4}) \end{split}$	$\begin{array}{l} \hline 7+8{\rm TeV}(\times10^{-6}{\rm GeV}^{-2})\\ -1.1 < a_0^{\rm W}/\Lambda^2 < 1.1\\ -4.1 < a_C^{\rm W}/\Lambda^2 < 4.1\\ \hline 7+8{\rm TeV}(\times10^{-12}{\rm CeV}^{-4}) \end{array}$
Dimension-6 AQGC parameter a_0^W / Λ^2 no form factor) a_C^W / Λ^2 no form factor) Dimension-8 AQGC parameter $f_{M,0} / \Lambda^4$ no form factor)	$\begin{array}{l} 7{\rm TeV}(\times 10^{-6}{\rm GeV}^{-2})\\ -4 < a_0^{\rm W}/\Lambda^2 < 4\\ -15 < a_C^{\rm W}/\Lambda^2 < 15\\ 7{\rm TeV}(\times 10^{-12}{\rm GeV}^{-4})\\ -15 < f_{M,0}/\Lambda^4 < 15 \end{array}$	$\begin{split} &8\text{TeV}~(\times 10^{-6}\text{GeV}^{-2})\\ &-1.2 < a_0^W/\Lambda^2 < 1.2\\ &-4.4 < a_C^W/\Lambda^2 < 4.4\\ &8\text{TeV}~(\times 10^{-12}\text{GeV}^{-4})\\ &-4.6 < f_{M,0}/\Lambda^4 < 4.6 \end{split}$	$\begin{array}{l} \hline 7+8 {\rm TeV}(\times 10^{-6} {\rm GeV}^{-2})\\ \hline -1.1 < a_0^W/\Lambda^2 < 1.1\\ -4.1 < a_C^W/\Lambda^2 < 4.1\\ \hline 7+8 {\rm TeV}(\times 10^{-12} {\rm CeV}^{-4})\\ \hline -4.2 < f_{M,0}/\Lambda^4 < 4.2 \end{array}$
Dimension-6 AQGC parameter a_0^W / Λ^2 no form factor) a_C^W / Λ^2 no form factor) Dimension-8 AQGC parameter $f_{M,0} / \Lambda^4$ no form factor) $f_{M,1} / \Lambda^4$ no form factor)	$\begin{array}{l} 7{\rm TeV}(\times 10^{-6}{\rm GeV}^{-2})\\ -4 < a_0^{\rm W}/\Lambda^2 < 4\\ -15 < a_C^{\rm W}/\Lambda^2 < 15\\ 7{\rm TeV}(\times 10^{-12}{\rm GeV}^{-4})\\ -15 < f_{M,0}/\Lambda^4 < 15\\ -57 < f_{M,1}/\Lambda^4 < 57 \end{array}$	$\begin{split} &8\text{TeV}(\times 10^{-6}\text{GeV}^{-2})\\ &-1.2 < a_0^{\text{W}}/\Lambda^2 < 1.2\\ &-4.4 < a_C^{\text{W}}/\Lambda^2 < 4.4\\ &8\text{TeV}(\times 10^{-12}\text{GeV}^{-4})\\ &-4.6 < f_{M,0}/\Lambda^4 < 4.6\\ &-17 < f_{M,1}/\Lambda^4 < 1\end{split}$	$\begin{array}{l} \hline 7+8{\rm TeV}(\times10^{-6}{\rm GeV}^{-2})\\ \hline -1.1 < a_0^{\rm W}/\Lambda^2 < 1.1\\ -4.1 < a_C^{\rm W}/\Lambda^2 < 4.1\\ \hline 7+8{\rm TeV}(\times10^{-12}{\rm CeV}^{-4})\\ \hline -4.2 < f_{M,0}/\Lambda^4 < 4.2\\ -16 < f_{M,1}/\Lambda^4 < 16 \end{array}$
Dimension-6 AQGC parameter a_0^W / Λ^2 no form factor) a_C^W / Λ^2 no form factor) Dimension-8 AQGC parameter $f_{M,0} / \Lambda^4$ no form factor) $f_{M,1} / \Lambda^4$ no form factor) $f_{M,2} / \Lambda^4$ no form factor)	$\begin{array}{l} 7{\rm TeV}(\times 10^{-6}{\rm GeV}^{-2})\\ -4 < a_0^{\rm W}/\Lambda^2 < 4\\ -15 < a_C^{\rm W}/\Lambda^2 < 15\\ 7{\rm TeV}(\times 10^{-12}{\rm GeV}^{-4})\\ -15 < f_{M,0}/\Lambda^4 < 15\\ -57 < f_{M,1}/\Lambda^4 < 57\\ -7.6 < f_{M,2}/\Lambda^4 < 7.6 \end{array}$	$\begin{split} &8\text{TeV}(\times 10^{-6}\text{GeV}^{-2})\\ &-1.2 < a_0^{\text{W}}/\Lambda^2 < 1.2\\ &-4.4 < a_C^{\text{W}}/\Lambda^2 < 4.4\\ &8\text{TeV}(\times 10^{-12}\text{GeV}^{-4})\\ &-4.6 < f_{M,0}/\Lambda^4 < 4.6\\ &-17 < f_{M,1}/\Lambda^4 < 17\\ &-2.3 < f_{M,2}/\Lambda^4 < 2.3 \end{split}$	$\begin{array}{l} \hline 7+8 {\rm TeV} (\times 10^{-6} {\rm GeV}^{-2}) \\ \hline -1.1 < a_0^W / \Lambda^2 < 1.1 \\ -4.1 < a_C^W / \Lambda^2 < 4.1 \\ \hline 7+8 {\rm TeV} (\times 10^{-12} {\rm CeV}^{-4}) \\ \hline -4.2 < f_{M,0} / \Lambda^4 < 4.2 \\ -16 < f_{M,1} / \Lambda^4 < 16 \\ -2.1 < f_{M,2} / \Lambda^4 < 2.1 \end{array}$

Most stringent limits to date

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

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W γjj: CMS-PAS-SMP-14-011

 $\mu(e) + \gamma + \not E_{T} + 2 jets$

Allow τ -lepton decays to μ ,e

$$\begin{split} |y_{W\gamma} - (y_{j1} + y_{j2})/2.0| &< 0.6, \\ |\Delta \phi_{W\gamma, dijet}| &> 2.6, \\ p_T^{j1} &> 30 \text{ GeV}, |\eta^{j1}| &< 4.7, \\ p_T^{j2} &> 30 \text{ GeV}, |\eta^{j2}| &< 4.7, \\ M_{jj} &> 700 \text{ GeV}, |\Delta \eta(j, j)| &> 2.4, \\ p_T^{l} &> 20 \text{ GeV}, |\eta^{l}| &< 2.4, \\ p_T^{\gamma} &> 20 \text{ GeV}, |\eta^{\gamma}| &< 1.4442, \\ E_T &> 20 \text{ GeV}, \\ \Delta R_{j,j}, \Delta R_{l,j}, \Delta R_{\gamma,j}, \Delta R_{l,\gamma} &> 0.4 \end{split}$$

Major Backgrounds:

QCD Wy+jets, Fake Photons

Image Source:

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

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W yjj: CMS-PAS-SMP-14-011

				CMS preliminary $\int L dt = 19.7 \text{ fb}^{-1}$ $\sqrt{s} = 8 \text{ T}$
			28.6 GeV	6 Data Sum of backgrounds 5 Signal, AQGC=0 (SM)
Process	Muon channel	Electron channel		$\sum_{m_{0}} \frac{1}{100} \frac{1}$
EWK-induced W γ +2jets	5.8 ± 1.8	3.8 ± 1.2	Its	4 Background uncertainty
QCD-induced W γ +jets	11.2 ± 3.2	10.3 ± 3.2	en	
W + jets, 1 jet $ ightarrow \gamma$	3.1 ± 0.8	2.2 ± 0.6	>	3
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 WV γ , V \rightarrow two jets	0.3 ± 0.2	0.3 ± 0.2		
MC $Z\gamma$ + 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
ĥ	$1.78^{+0.99}_{-0.76}$	$0.99^{+0.21}_{-0.19}$
EWK fraction (search region)	100%	27.1%
EWK fraction (fiducial region)	100%	25.8%
Observed (Expected) significance	2.67(1.52) <i>σ</i>	$7.69(7.49) \sigma$
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.)

60

80

Image Source:

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

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100 120 140 160 180 200 220 240 p^W_T [GeV]

s

W γjj: CMS-PAS-SMP-14-011



No Form Factor (etc.) applied

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

Most stringent limits to date

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

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Zγjj: CMS-PAS-SMP-14-018

 $\mu\mu(ee) + \gamma + 2$ jets

Allow τ -lepton decays to μ ,e

Major Backgrounds:

QCD $Z\gamma$ + Jets, Fake Photons

 $\begin{array}{l} \Delta \eta_{jj} > 1.6, \\ \Delta \phi_{Z\gamma, jj} > 2.0, \\ |y_{Z\gamma} - (y_{j1} + y_{j2})/2.0| < 1.2, \\ p_T^{j1, j2} > 30 \text{ GeV}, |\eta^{j1, j2}| < 4.7, \\ M_{jj} > 400 \text{ GeV}, \\ \end{array}$ $\begin{array}{l} p_T^{l1, l2} > 20 \text{ GeV}, |\eta^{l1, l2}| < 2.4, \\ 70 \text{ GeV} < M_{ll} < 110 \text{ GeV}, \\ p_T^{\gamma} > 20 \text{ GeV}, |\eta^{\gamma}| < 1.4442, \\ \Delta R_{jj}, \Delta R_{j\gamma}, \Delta R_{l\gamma}, \Delta R_{jl} > 0.4, \end{array}$

Image Source:

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

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W

Events/1<u>00.00</u>

Events/100.00 GeV

Data CMS Zγ + Jets Preliminary Fake Photon 10² Тор EWK Zγ+2Jets Systematic Uncertainty 10 400 600 200 800 1000 1200 M_{ii} (GeV) 19.7 fb⁻¹ (8TeV) el channel Data CMS Zγ + Jets Preliminary Fake Photon 10² Top EWK Zγ+2Jets Systematic Uncertainty 10

400

200

600

800

1000

19.7 fb⁻¹ (8TeV) mu channel

22

1200

M_{ii} (GeV)

Zyjj: CMS-PAS-SMP-14-018





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/publicresults/preliminary-results/SMP-14-018/index.html

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Zγjj: CMS-PAS-SMP-14-018

- Higher photon p_T
 threshold applied
 to aQGC MC to
 enhance statistics
 generated
 - $$\begin{split} p_T^{j1,j2} &> 30 \text{ GeV}, \, |\eta^{j1,j2}| < 4.7 \\ M_{jj} &> 400 \text{ GeV}, \, \Delta \eta_{jj} > 2.5 \\ p_T^{l1,2} &> 20 \text{ GeV}, \, |\eta^{l1,l2}| < 2.4 \\ 70 \text{ GeV} &< M_{ll} < 110 \text{ GeV} \\ p_T^{\gamma} &> 60 \text{ GeV}, \, |\eta^{\gamma}| < 1.4442 \end{split}$$





results/preliminary-results/SMP-14-018/index.html

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Zγjj: CMS-PAS-SMP-14-018



No Form Factor (etc.) applied

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

Most stringent limits to date

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

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Results on VBS Production and aQGCs



CMS Run II Prospects

CMS Run II Prospects:

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





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

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/day)

qd)

ntegi

Results on VBS Production and aQGCs



Compilation of aQGC Limits

Limits on Anomalous Couplings:



April 2016	CMS			ſ	
		Cha	nnel Limits	∫ <i>L</i> dt	√s
f _{M,0} /Λ ⁴		WV	([-7.7e+01, 8	.1e+01] 19.3 fb ⁻¹	8 TeV
	⊢-I	Zγ	[-7.1e+01, 7	.5e+01] 19.7 fb ⁻¹	8 TeV
	⊢-(Wγ	[-7.7e+01, 7	.4e+01] 19.7 fb ⁻¹	8 TeV
	F-I	ss V	/W [-3.3e+01, 3	.2e+01] 19.4 fb ⁻¹	8 TeV
	I. I.	γγ—	WW [-4.2e+00, 4	.2e+00] 24.7 fb ⁻¹	7,8 TeV
$f_{M,1}/\Lambda^4$	+I	WV	([-1.3e+02, 1	.2e+02] 19.3 fb ⁻¹	8 TeV
	F	Zγ	[-1.9e+02, 1	.8e+02] 19.7 fb ⁻¹	8 TeV
	⊢ −1	Wγ	[-1.2e+02, 1	.3e+02] 19.7 fb ⁻¹	8 TeV
	F-I	ss V	/W [-4.4e+01, 4	.7e+01] 19.4 fb ⁻¹	8 TeV
	Н	γγ—	WW [-1.6e+01, 1	.6e+01] 24.7 fb ⁻¹	7,8 TeV
$f_{M,2} / \Lambda^4$	H	Ζγγ	[-5.1e+02, 5	.1e+02] 20.3 fb ⁻¹	8 TeV
	łł	Wγγ	[-2.5e+02, 2	.5e+02] 20.3 fb ⁻¹	8 TeV
	н	Zγ	[-3.2e+01, 3	.1e+01] 19.7 fb ⁻¹	8 TeV
	Н	Wγ	[-2.6e+01, 2	.6e+01] 19.7 fb ⁻¹	8 TeV
$f_{M,3} / \Lambda^4$		🗕 Ζγγ	[-9.2e+02, 8	.5e+02] 20.3 fb ⁻¹	8 TeV
	ŀI	Wγγ	[-4.7e+02, 4	.4e+02] 20.3 fb ⁻¹	8 TeV
	н	Zγ	[-5.8e+01, 5	.9e+01] 19.7 fb ⁻¹	8 TeV
	н	Wγ	[-4.3e+01, 4	.4e+01] 19.7 fb ⁻¹	8 TeV
$f_{M,4} / \Lambda^4$	Н	Wγ	[-4.0e+01, 4	.0e+01] 19.7 fb ⁻¹	8 TeV
$f_{M,5} / \Lambda^4$	FH	Wγ	[-6.5e+01, 6	.5e+01] 19.7 fb ⁻¹	8 TeV
$f_{M,6} / \Lambda^4$	⊢−− 1	Wγ	[-1.3e+02, 1	.3e+02] 19.7 fb ⁻¹	8 TeV
	F - 1	ss V	/W [-6.5e+01, 6	.3e+01] 19.4 fb ⁻¹	8 TeV
$f_{M,7} / \Lambda^4$	⊢	Wγ	[-1.6e+02, 1	.6e+02] 19.7 fb ⁻¹	8 TeV
		ss V	/W [-7.0e+01, 6	.6e+01] 19.4 fb ⁻¹	8 TeV
-10	00 0	1000	2000	3000	ı
			aQGC Limits	@95% C.L.	[TeV ⁻⁴]

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

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Limits on Anomalous Couplings:



April 2016	CMS H			c	
	ATLAS	Channel	Limits	J <i>L</i> dt	٧s
$f_{T,0} / \Lambda^4$	·····	Wγγ	[-3.8e+01, 3.8e+01]	19.4 fb ⁻¹	8 TeV
	HH	Ζγγ	[-1.6e+01, 1.9e+01]	20.3 fb ⁻¹	8 TeV
	l	Wγγ	[-1.6e+01, 1.6e+01]	20.3 fb ⁻¹	8 TeV
	I	WVγ	[-2.5e+01, 2.4e+01]	19.3 fb ⁻¹	8 TeV
	H	Ζγ	[-3.8e+00, 3.4e+00]	19.7 fb ⁻¹	8 TeV
	⊢−−− I	Wγ	[-5.4e+00, 5.6e+00]	19.7 fb ⁻¹	8 TeV
	F1	ss WW	[-4.2e+00, 4.6e+00]	19.4 fb ⁻¹	8 TeV
$f_{T,1}/\Lambda^4$	<u>+</u>	ι Wγγ	[-4.6e+01, 4.7e+01]	19.4 fb ⁻¹	8 TeV
	⊢	Ζγ	[-4.4e+00, 4.4e+00]	19.7 fb ⁻¹	8 TeV
	H	Wγ	[-3.7e+00, 4.0e+00]	19.7 fb ⁻¹	8 TeV
	F-I	ss WW	[-2.1e+00, 2.4e+00]	19.4 fb ⁻¹	8 TeV
$f_{T,2}/\Lambda^4$	⊢−−−−	Ζγ	[-9.9e+00, 9.0e+00]	19.7 fb ⁻¹	8 TeV
	⊢ — — I	Wγ	[-1.1e+01, 1.2e+01]	19.7 fb ⁻¹	8 TeV
	FI	ss WW	[-5.9e+00, 7.1e+00]	19.4 fb ⁻¹	8 TeV
$f_{T,5}/\Lambda^4$	⊢ −−−1	Ζγγ	[-9.3e+00, 9.1e+00]	20.3 fb ⁻¹	8 TeV
	H	Wγ	[-3.8e+00, 3.8e+00]	19.7 fb ⁻¹	8 TeV
$f_{T,6} / \Lambda^4$	н	Wγ	[-2.8e+00, 3.0e+00]	19.7 fb ⁻¹	8 TeV
$f_{T,7}/\Lambda^4$	⊢1	Wγ	[-7.3e+00, 7.7e+00]	19.7 fb ⁻¹	8 TeV
$f_{T,8}/\Lambda^4$	Н	Ζγ	[-1.8e+00, 1.8e+00]	19.7 fb ⁻¹	8 TeV
$f_{T,9} / \Lambda^4$	⊢	Ζγγ	[-7.4e+00, 7.4e+00]	20.3 fb ⁻¹	8 TeV
		Ζγ	[-4.0e+00, 4.0e+00]	19.7 fb ⁻¹	8 TeV
	-50 0	50	100	150	
	-50 0		CC Limite @05		[T\/-4]
		aQ		70 U.L.	

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

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- **T** Vector Boson Scattering excellent candidate for probing:
 - **T** Electroweak Symmetry Breaking in Standard Model
 - **T** Higgs properties
 - **T** Gauge structure of electroweak physics
 - Anomalous triple or quartic gauge couplings (aTGC/aQGC)
- **T** LHC Run I analyses show evidence for VBS in various channels
 - **T** $\gamma\gamma \rightarrow WW$, Same-sign WW+jets, W γ +jets, Z γ +jets
- **T** Results still consistent with SM predictions
- LHC Run II analyses well underway and with great potential
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 $(\mu^{\pm}\mu^{\pm}, e^{\pm}e^{\pm}, \mu^{\pm}e^{\pm}) + 2jets + \mu_{T}$

*Allow τ -lepton decays to μ ,e

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

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

 $|m_{11} - m_{Z}| > 15 \text{ GeV} (el. ch.), \not E_{T} > 40 \text{ GeV}$

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

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

Major Backgrounds:

Top quark, Drell-Yan, WZ



 0.4 ± 0.1

 1.0 ± 0.1 0.3 ± 0.1

 0.1 ± 0.1

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

Image Source:

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

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W±W3

 4.2 ± 0.8

12

 1.8 ± 0.1

 8.9 ± 0.1

 2.6 ± 0.5

 5.7 ± 0.8

 0.1 ± 0.1

$\gamma\gamma \rightarrow$ WW: CMS-PAS-FSQ-13-008 arXiv 1604.04464

*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%

Selectionstep	Data	Exclusive	Total	Indusive	Drell-Yan	$\gamma \gamma \rightarrow \tau \tau$	Other
-		$\gamma\gamma \rightarrow WW$	background	diboson			backgrounds
Trigger and Preselection	19406	26.9 ± 0.2	22180±1890	1546 ± 1.5	7093 ± 75	18.1 ± 0.8	13520 ± 1890
$m(\mu^{\pm}e^{\mp}) > 20 \text{ GeV}$	18466	26.6 ± 0.2	21590 ± 1850	1507 ± 1.5	7065 ± 75	18.1 ± 0.8	13000 ± 1850
Muon and electron identification	6541	22.5 ± 0.2	6640 ± 93	1306 ± 1.1	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
$p_{\rm T}(\mu^{\pm}e^{\mp}) > 30 {\rm GeV}$	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

W

W

n(*)

Image Source:

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

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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

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