

Evidence for the electroweak production of Zgamma with two jets and a search for anomalous quartic gauge couplings in pp collisions at $\sqrt{s} = 8\text{TeV}$

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On behalf of the CMS collaboration

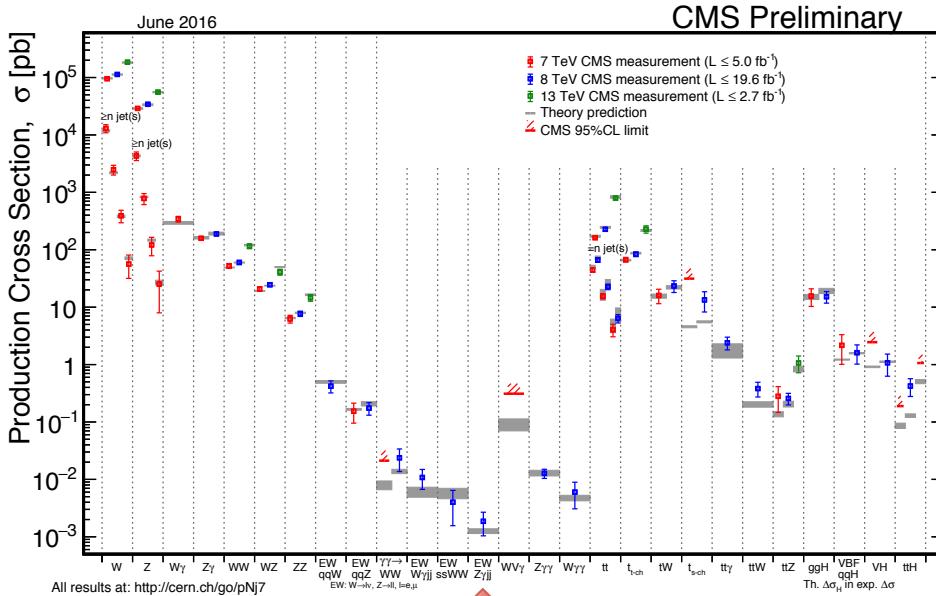
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Outline

- **Introduction**
- **Event selection and background modeling**
- **Systematic uncertainty**
- **Measurement of significance and cross section**
- **Parameterization and limit estimation for anomalous quartic gauge coupling**
- **Summary**

Introduction

CMS Standard Model Physics Summary of Cross section measurement for Run I



PAS (Physics Analysis Summaries) has been public:

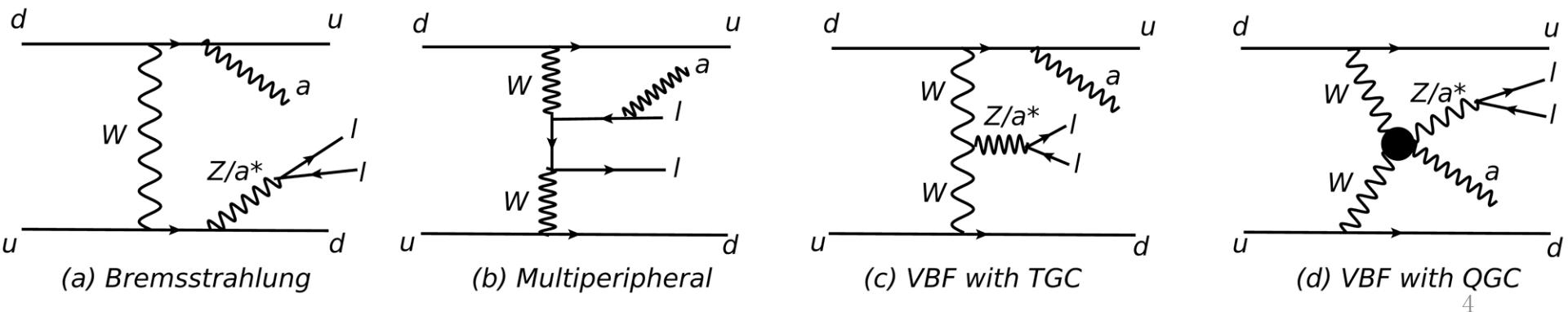
- <http://cds.cern.ch/record/2048148?ln=en>
- <https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMP14018>

Paper: Target to PLB

- Vector Boson Production (W/Z)
- Vector Boson + Jets Production (W/Z+Jets)
- **Multi-Boson Production (VV,VVV,EWK)**
- Jet Production

Introduction

- **Peculiar signature of EWK production and phase space:**
 - Presence of two high energetic hadronic (quark) jets with wide rapidity separation
 - Suppressed hadronic activity “between” the two jets (central region)
 - High $m(jj)$ region (> 400 GeV or more) enriched in EWK production
- **Understand more about the SM in unexplored phase spaces**
- **High-tail enhancements: new physics searches**
 - Sensitive to anomalous Triple (Quartic) Gauge Couplings
- **Vector Boson Scattering:** probing unitarization of cross section by Higgs boson
- **Important backgrounds to Higgs and new physics**



Data & MC Simulation

- **Data:** Full DoubleLepton 2012 8TeV data by CMS, 19.7fb^{-1}
- **Signal:** EWK $Z\gamma + 2\text{jets}$ ($Z \rightarrow \mu^+\mu^-,\text{e}^+\text{e}^-$)
- **Background:**
 - QCD $Z\gamma + 0\sim 3\text{jets}$ (MLM matching) (**Main**)
 - Jets $\rightarrow \gamma$ (estimated from data)
 - $t\bar{t}\gamma + \text{jets}$, Single Top
 - WZ , ZZ , WW

- Generated with MadGraph5 interfacing PYTHIA6
- Trigger and objects ID/ISO efficiencies are corrected (scale factor added)
- Pile up events added and reweighted to match in the data

Event Selection

$Z(\mu^+\mu^-, e^+e^-) + \gamma + 2\text{jets}$

Two leptons

- coming from primary vertex
- Standard lepton ID
- $pT > 20\text{GeV}$
- $|\eta| < 2.4/2.5$ for muons/electron
 $70\text{GeV} < M_{\parallel} < 110\text{GeV}$

One real photon

- Standard photon ID
- $pT > 25\text{GeV}$
- $|\eta| < 1.4442$

At least two jets

- Particle Flow ID
- $pT > 30\text{GeV}$
- $|\eta| < 4.7$
- the isolation radius of each jet is $\Delta R = 0.5$

The invariant mass of di-jet as $M_{jj} > 150\text{GeV}$

The isolations between different objects:

$$\Delta R_{j\gamma} > 0.5, \Delta R_{l\gamma} > 0.5, \Delta R_{jl} > 0.5$$

QCD Modeling (QCD Z γ +Jets)

- **QCD Z γ +Jets Normalization**
- MLM matching technique still suffers from large theoretical uncertainty.
- Control region: $150 \text{ GeV} < M_{jj} < 400 \text{ GeV}$
- Method: cut-count
correction factor = $(N_{\text{data}} - N_{\text{other_bkg}}) / N_{\text{QCD_Z}\gamma+\text{Jets}}$
- Uncertainties taken into account:
 - ◆ Statistic uncertainty: data, QCD Z γ +Jets, t $t\gamma$ +jets
 - ◆ Systematic uncertainty: fake photon background

● Data driven correction factors of QCD Z γ +Jets:
 $1.0 +/- 0.22$

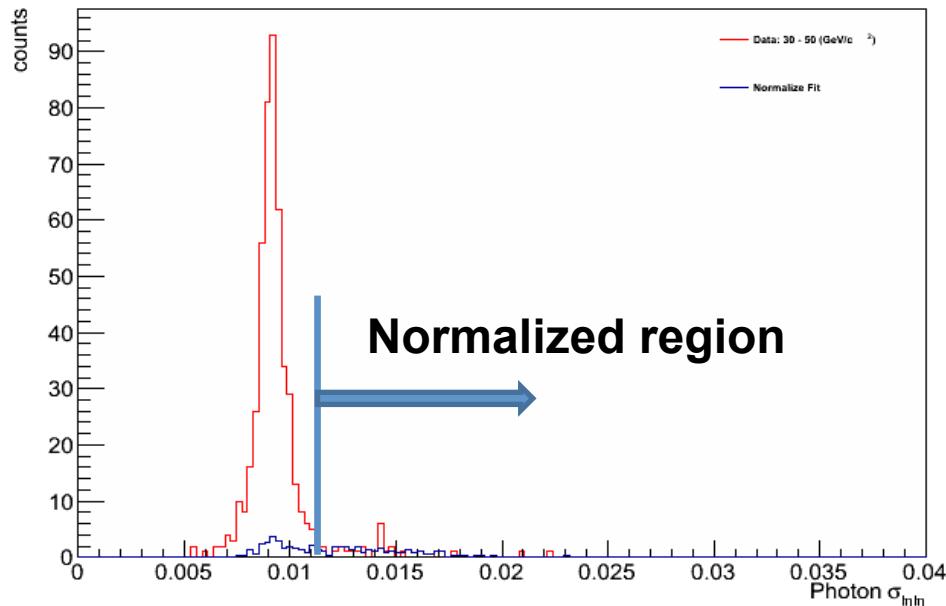
QCD Modeling (QCD Jets misidentified as photon)

- ◆ True Photon
- ◆ Electron misidentified photon (Z mass window suspend)
- ◆ **Jet misidentified photon**

data-driven method

Photon pT dependent estimation

- **Photon candidates :**
 - Standard photon ID on data
(removing the $\sigma_{inj\eta}$ selection)
- **Misidentified Photon candidates :**
 - fail the isolation requirement
(removing the $\sigma_{inj\eta}$ selection)

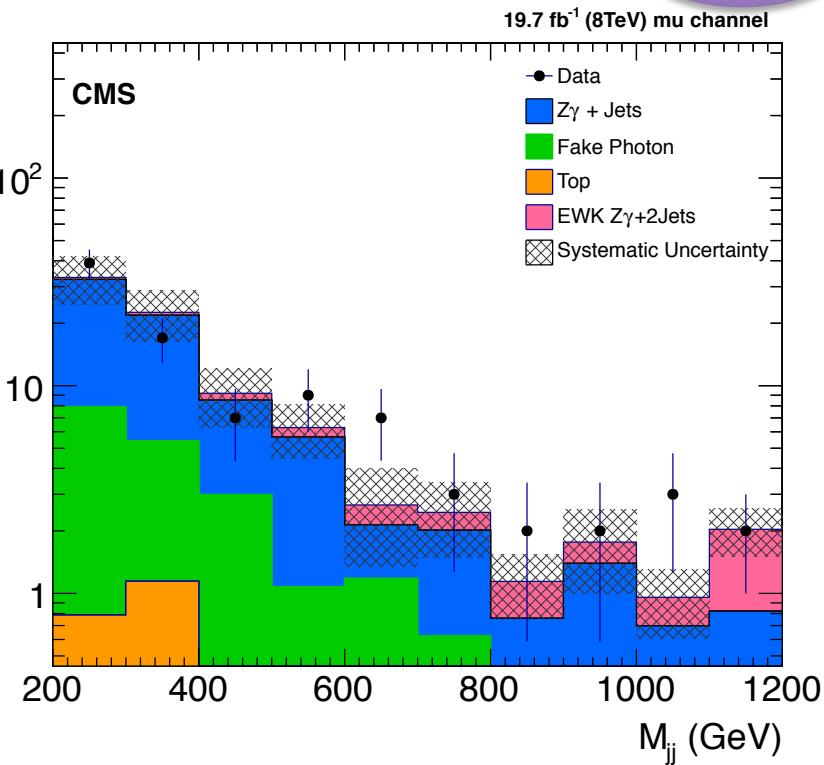


- ✓ Normalize misidentified photon candidates in the region of $\sigma_{inj\eta} > 0.011$
- ✓ A misidentified photon rate is defined as the ratio between the events of normalized distribution of misidentified photon candidates and real photon candidates in the region of $\sigma_{inj\eta} < 0.011$

Data & MC yields distribution

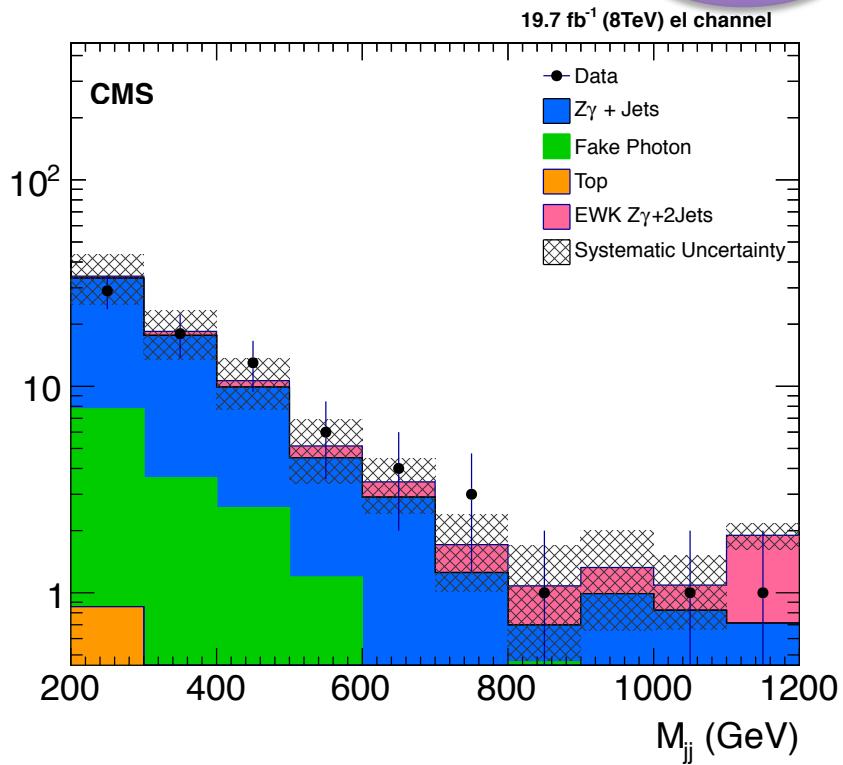
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Events/100.00 GeV



Muon Channel

Events/100.00 GeV



Electron Channel

Theoretical uncertainty

■ PDF uncertainty:

- Sample generated by MadGraph5
- Asymmetric Hessian method

■ Scale uncertainty:

- Varying $\mu(R)$ and $\mu(F)$ independently

$$(\mu_R, \mu_F) = (\kappa_R \mu_R, \kappa_F \mu_F)$$

- With $\kappa(R), \kappa(F) = (1,1), (0.5,0.5), (2,2)$

■ Interference uncertainty:

$$[\sigma(QCD + EWK) - \sigma(QCD) - \sigma(EWK)] / \sigma(EWK)$$

- Varying $\mu(R)=\mu(F)$ by a factor of 2(0.5)
- $\mu_R = \mu_F = (0.5, 1, 2) \times 2M_Z$

■ Cross section of $t\bar{t}y$ uncertainty:

20%

■ Generator Selection:

- $PTj > 30, |\eta_{aj}| < 4.7,$
- $PTl > 20, |\eta_{al}| < 2.5,$
- $Pta > 25, |\eta_a| < 1.5;$
- $DR(jj), DR(jl), DR(la), DR(ja) > 0.5$
- $M_{jj} > 400 \text{ GeV} / 800 \text{ GeV}$

■ $400 < M_{jj} < 800 \text{ GeV} :$

- Scale = **9%**
- PDF = **4.2%**
- Interference = **17.5%**

■ $M_{jj} > 800 \text{ GeV} :$

- Scale = **12%**
- PDF = **2.4%**
- Interference = **10.9%**

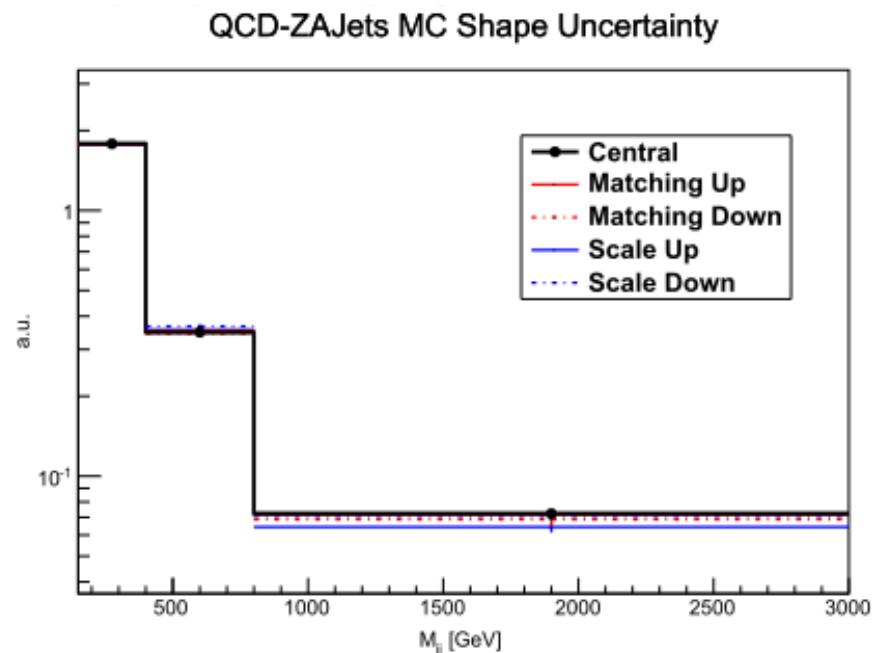
QCDZAJets Uncertainty

- Correction factor uncertainty in control region($150 \text{ GeV} < M_{jj} < 400 \text{ GeV}$):
 - ◆ statistic and systematic uncertainty
 - ◆ 22.0%

- Shape uncertainty in signal region($M_{jj} > 400 \text{ GeV}$):
 - ◆ varying factorization scales and matching scale by a factor of 2(0.5)
 - ◆ [400, 800] 4%
 - ◆ [800,inf] 10%

➤ Combine uncertainties:

- 400 GeV - 800 GeV
22.4%
- 800 GeV - infinite
24.2%



Jet misidentified photon uncertainty

◆ Normalization uncertainty

- The correlation between each PF isolation is not negligible, different choices of Isolation sideband can result in systematic uncertainty
- dividing the misidentified photon region into two regions based on isolation variables bounds in standard photon selection criteria and calculate the difference of the misidentified photon rate in each sub-region.

$$\sqrt{\sum_{iso.} (FR_{iso.}^{max} - FR_{iso.}^{min})^2} / 2$$

- Misidentified Photon candidates :
- Isolation variables: I_{ch} , I_{nh} , I_{pho}
- standard ID < **Isolation variables** < loose ID

◆ Shape of the templates

- the fake photon templates from MC Drell-Yan ($Z + \text{Jets}$) sample instead of those measured in data

$$(maxFR - min FR) / 2$$

Systematic Uncertainty

➤ Jet energy scale/resolution uncertainty

- Official recommended tools for calculation
- varying up and down the jet energy scale and resolution by 1σ and computing the effect on the acceptance.
- overall JES & JER: 14.1%

➤ HLT & lepton ID uncertainty (taken from official twiki page):

- HLT: 1.2% / 1.7% (mu/ele)
- ID: 1.9% / 1% (mu/ele)
- Official reference:
<https://twiki.cern.ch/twiki/bin/viewauth/CMS/MuonReferenceEffs>
<https://twiki.cern.ch/twiki/bin/viewauth/CMS/DileptonTriggerResults>

➤ Pileup uncertainty (propagated to final selection):

- Number of interactions variation: 5%
- Final uncertainty: 1%

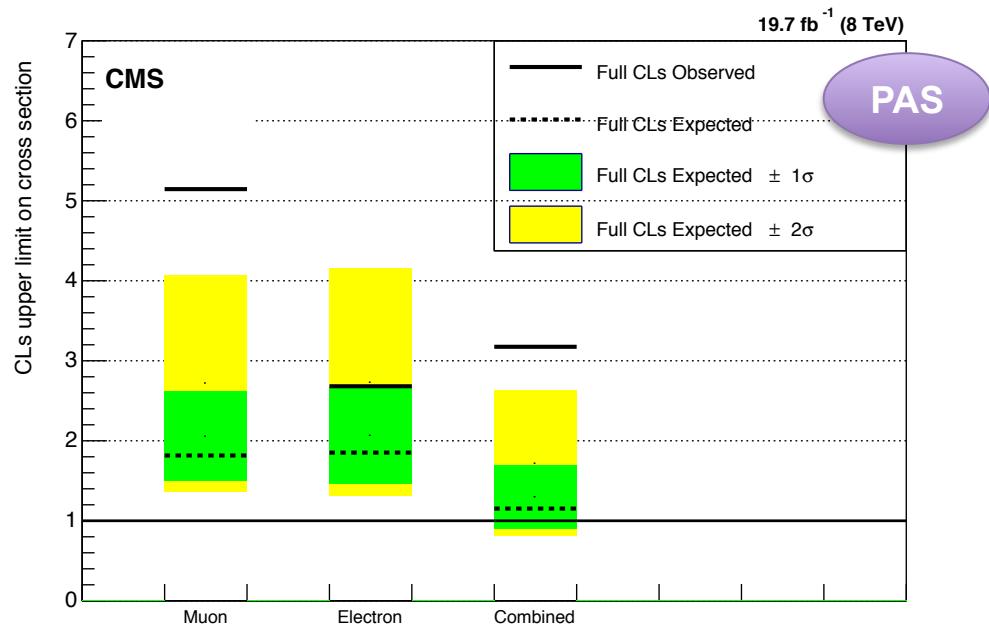
➤ Luminosity uncertainty (official recommend):

- 2.6%

Measurement of significance and fiducial cross section

➤ Final selection:

- $p_T^{j1} > 30 \text{ GeV}, |\eta^{j1}| < 4.7$
- $p_T^{j2} > 30 \text{ GeV}, |\eta^{j2}| < 4.7$
- $|\Delta\eta_{jj}| > 1.6$
- $M_{jj} > 400 \text{ GeV}$
- $p_T^{l1} > 20 \text{ GeV}, |\eta^{l1}| < 2.4 / 2.5 \text{ (muon/electron)}$
- $p_T^{l2} > 20 \text{ GeV}, |\eta^{l2}| < 2.4 / 2.5 \text{ (muon/electron)}$
- $70 \text{ GeV} < M_{ll} < 110 \text{ GeV}$
- $p_T^\gamma > 25 \text{ GeV}, |\eta^\gamma| < 1.4442$
- $\Delta R_{j\gamma}, \Delta R_{l\gamma} > 0.5$
- $\Delta\Phi_{Z\gamma,jj} > 2.0, \text{Zeppenfeld}_{Z\gamma,jj} < 1.2$



- ◆ Apply the CLs construction
- ◆ Use M_{jj} shape with two bins:
 $400 < M_{jj} < 800 \text{ GeV} \& M_{jj} > 800 \text{ GeV}$

Significance : 3.0σ (2.1σ) obs(exp)
Signal strength : $1.47 +0.87/-0.63$

Significance and Fiducial Cross Section

- $p_T^{j1} > 30 \text{ GeV}, |\eta^{j1}| < 4.7$
- $p_T^{j2} > 30 \text{ GeV}, |\eta^{j2}| < 4.7$
- $M_{jj} > 400 \text{ GeV}, |\Delta\eta_{jj}| > 2.4$
- $p_T^{l1} > 20 \text{ GeV}, |\eta^{l1}| < 2.4$
- $p_T^{l2} > 20 \text{ GeV}, |\eta^{l2}| < 2.4$
- $p_T^\gamma > 20 \text{ GeV}, |\eta^\gamma| < 1.4442$
- $\Delta R_{jj}, \Delta R_{j\gamma}, \Delta R_{l\gamma}, \Delta R_{jl} > 0.4$

EWK process ($M_{jj} > 400 \text{ GeV}$):

$$\sigma_{\text{fiducial}} = \sigma_{\text{generator}} \cdot \mu \cdot \alpha_{\text{acceptance of g to f}}$$

Fiducial cross section:

$$1.86^{+0.89}_{-0.75}(\text{stat.})^{+0.41}_{-0.27}(\text{sys.}) \pm 0.05(\text{lumi.}) \text{ fb}$$

LO theoretical prediction:

$$1.26 \pm 0.11(\text{scale}) \pm 0.05(\text{PDF}) \text{ fb}$$

EWK+QCD process ($M_{jj} > 800 \text{ GeV}$):

Significance: 4.5σ (4.3σ) obs(exp)

Cut-count method

Fiducial cross section:

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

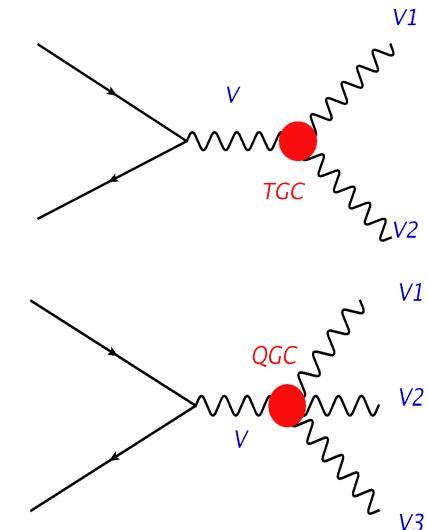
LO theoretical prediction:

$$0.78 \pm 0.09(\text{scale}) \pm 0.02(\text{PDF})$$

Anomalous Quartic Gauge Coupling

Theoretical Background

- New physics may appear as parameterized effective anomalous couplings with high energy degrees
- SM lagrangian can be extended with higher dimensional operators remaining $SU(2) \times U(1)$ gauge symmetry
- Implement gauge symmetry linearly, 8 dimensional phase space



	WWWW	WWZZ	ZZZZ	WWAZ	WWAA	ZZZA	ZZAA	ZAAA	AAAA
$\mathcal{L}_{S,0}, \mathcal{L}_{S,1}$	X	X	X	0	0	0	0	0	0
$\mathcal{L}_{M,0}, \mathcal{L}_{M,1}, \mathcal{L}_{M,6}, \mathcal{L}_{M,7}$	X	X	X	X	X	X	X	0	0
$\mathcal{L}_{M,2}, \mathcal{L}_{M,3}, \mathcal{L}_{M,4}, \mathcal{L}_{M,5}$	0	X	X	X	X	X	X	0	0
$\mathcal{L}_{T,0}, \mathcal{L}_{T,1}, \mathcal{L}_{T,2}$	X	X	X	X	X	X	X	X	X
$\mathcal{L}_{T,5}, \mathcal{L}_{T,6}, \mathcal{L}_{T,7}$	0	X	X	X	X	X	X	X	X
$\mathcal{L}_{T,8}, \mathcal{L}_{T,9}$	0	0	X	0	0	X	X	X	X

Parameters of AQGC

$$\begin{aligned}\mathcal{L}_{M,0} &= \frac{f_{M0}}{\Lambda^4} \text{Tr} [\mathbf{W}_{\mu\nu} \mathbf{W}^{\mu\nu}] \times \left[(D_\beta \Phi)^\dagger D^\beta \Phi \right], \\ \mathcal{L}_{M,1} &= \frac{f_{M1}}{\Lambda^4} \text{Tr} [\mathbf{W}_{\mu\nu} \mathbf{W}^{\nu\beta}] \times \left[(D_\beta \Phi)^\dagger D^\mu \Phi \right], \\ \mathcal{L}_{M,2} &= \frac{f_{M2}}{\Lambda^4} [B_{\mu\nu} B^{\mu\nu}] \times \left[(D_\beta \Phi)^\dagger D^\beta \Phi \right], \\ \mathcal{L}_{M,3} &= \frac{f_{M3}}{\Lambda^4} [B_{\mu\nu} B^{\nu\beta}] \times \left[(D_\beta \Phi)^\dagger D^\mu \Phi \right].\end{aligned}$$

- ◆ Sum of them is the Lagrangian of AQGCs
- ◆ Reference: arXiv:hep-ph/0606118

$$\begin{aligned}\mathcal{L}_{T,0} &= \frac{f_{T0}}{\Lambda^4} \text{Tr} [\hat{W}_{\mu\nu} \hat{W}^{\mu\nu}] \times \text{Tr} [\hat{W}_{\alpha\beta} \hat{W}^{\alpha\beta}], \\ \mathcal{L}_{T,1} &= \frac{f_{T1}}{\Lambda^4} \text{Tr} [\hat{W}_{\alpha\nu} \hat{W}^{\mu\beta}] \times \text{Tr} [\hat{W}_{\mu\beta} \hat{W}^{\alpha\nu}], \\ \mathcal{L}_{T,2} &= \frac{f_{T2}}{\Lambda^4} \text{Tr} [\hat{W}_{\alpha\mu} \hat{W}^{\mu\beta}] \times \text{Tr} [\hat{W}_{\beta\nu} \hat{W}^{\nu\alpha}], \\ \mathcal{L}_{T,8} &= \frac{f_{T8}}{\Lambda^4} B_{\mu\nu} B^{\mu\nu} B_{\alpha\beta} B^{\alpha\beta}, \\ \mathcal{L}_{T,9} &= \frac{f_{T9}}{\Lambda^4} B_{\alpha\mu} B^{\mu\beta} B_{\beta\nu} B^{\nu\alpha}.\end{aligned}$$

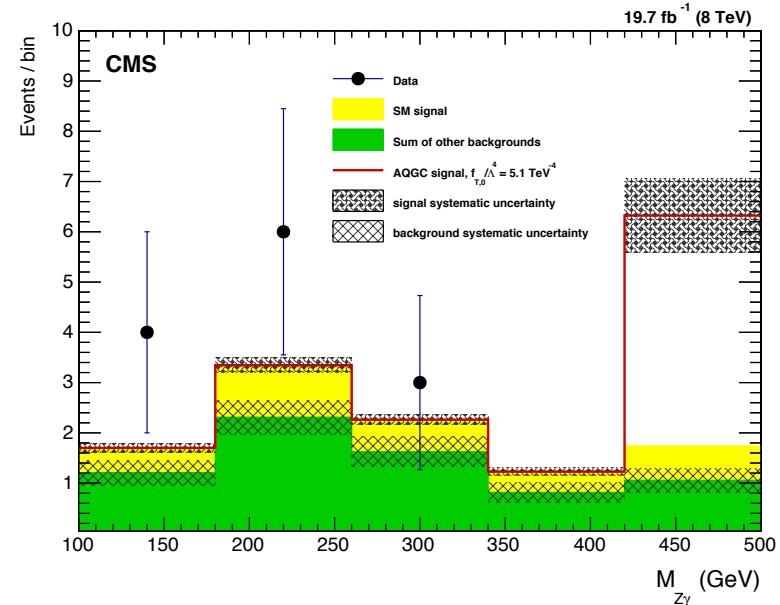
- Use Madgraph5 generator
- Generate multi-weight samples (13 points for each parameter)
- Measure 1-dim limit of LM0~3, LT0~LT2, LT8, LT9

Data & MC yields distribution

PAS

Kinematic selection for AQGC:

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



Distribution of $Z\gamma$ mass variable

- $Z\gamma$ mass variable to parameterize and estimate the AQGC signal limit
- We divide the region of $Z\gamma$ mass into five bins due to low statistics

DeltaNLL Limits

- parameter of interests = AQGC
- Signal shape = $R(M_{Z\gamma}, \text{aQGC}) * \text{SM shape}$
- Test statistics = $t_{\alpha_{\text{test}}}$
- assumed to follow a χ^2 distribution
- DeltaNLL = $t_{\alpha_{\text{test}}} / 2$
- 95% CL limit ----- DeltaNLL = 1.92

$$L(\boldsymbol{\alpha}, \boldsymbol{\theta}) = \prod_{i=1}^I \frac{[\psi^i(\boldsymbol{\alpha}, \boldsymbol{\theta})]^{N_{\text{pseudo}}} e^{-\psi^i(\boldsymbol{\alpha}, \boldsymbol{\theta})}}{N_{\text{pseudo}}^i!} \times \frac{1}{(2\pi)^J} e^{-\frac{1}{2}(\boldsymbol{\theta} - \boldsymbol{\theta}_0)^2}.$$

the maximum of the likelihood at the point α_{test}

$$t_{\alpha_{\text{test}}} = -2 \ln \frac{\mathcal{L}(\alpha_{\text{test}}, \hat{\boldsymbol{\theta}})}{\mathcal{L}(\bar{\boldsymbol{\alpha}}, \hat{\boldsymbol{\theta}})},$$

Global maximum of the likelihood

$\hat{\boldsymbol{\theta}}$ = nuisance parameters

$\bar{\boldsymbol{\alpha}}$ = anomalous coupling parameters

L = likelihood function

- **Reference:**

<https://twiki.cern.ch/twiki/bin/viewauth/CMS/SWGuideHiggsAnalysisCombinedLimit>

<https://twiki.cern.ch/twiki/bin/viewauth/CMS/ATGCRooStats>

<https://indico.cern.ch/event/335144/contribution/1/material/slides/0.pdf>

DeltaNLL limits

PAS

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

Summary

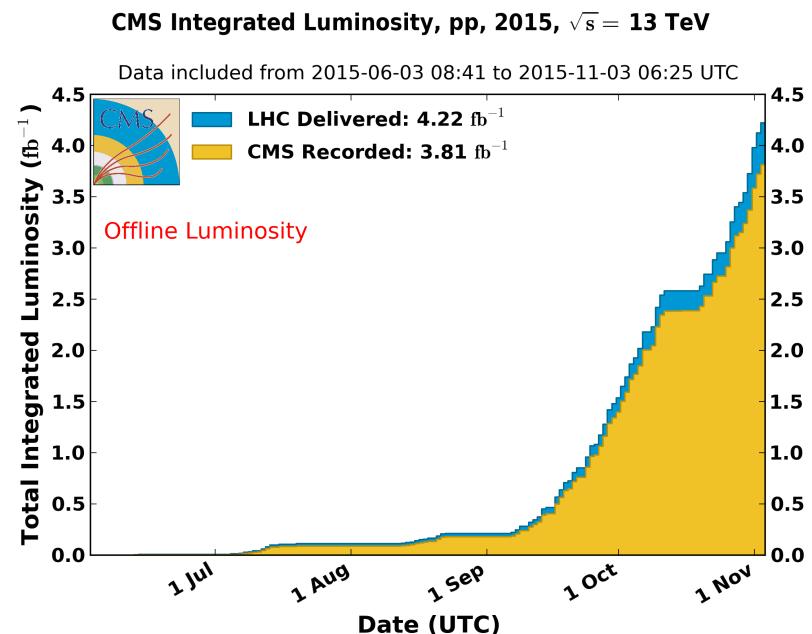
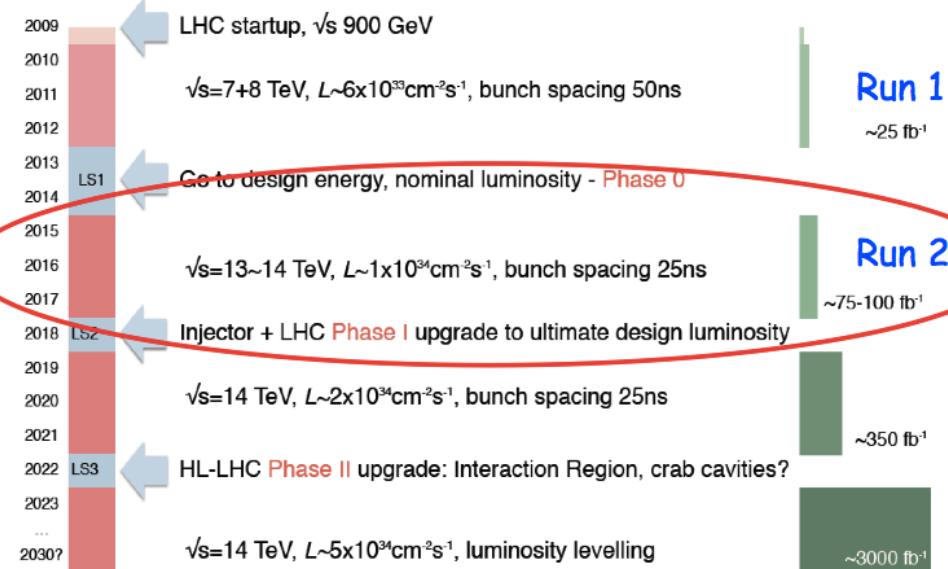
- The first evidence for electroweak production of $Z\gamma+2\text{jets}$
- Use the data collected in 2012 at 8 TeV, luminosity 19.7 fb^{-1}
- The expected and observed significances of signal process are respectively **2.1σ** and **3.0σ**
- The cross section of EWK $Z\gamma+2\text{jets}$ is
$$1.86^{+0.89}_{-0.75}(\text{stat.})^{+0.41}_{-0.27}(\text{sys.}) \pm 0.05(\text{lumi.}) \text{ fb}$$
which is consistent with the theoretical prediction.
- The fiducial cross section of EWK+QCD $Z\gamma+2\text{jets}$ is
$$1.00 \pm 0.43(\text{stat.}) \pm 0.26(\text{syst.}) \pm 0.03(\text{lumi.}) \text{ fb}$$
which is consistent with the theoretical prediction
- The limits on the parameters f_{M0-3}/Λ^4 and $f_{T0,1,2,8,9}/\Lambda^4$ of Anomalous Quartic Gauge Couplings have been set at 95% confidence level

Thank You!

Backup

Run II Prospect

Run2 Start on June/03, 2015



2σ expected sensitivity with 20 fb^{-1} at 8 TeV

Increase collider energy by X , increase luminosity by $X2$, reach goes up by a factor X .

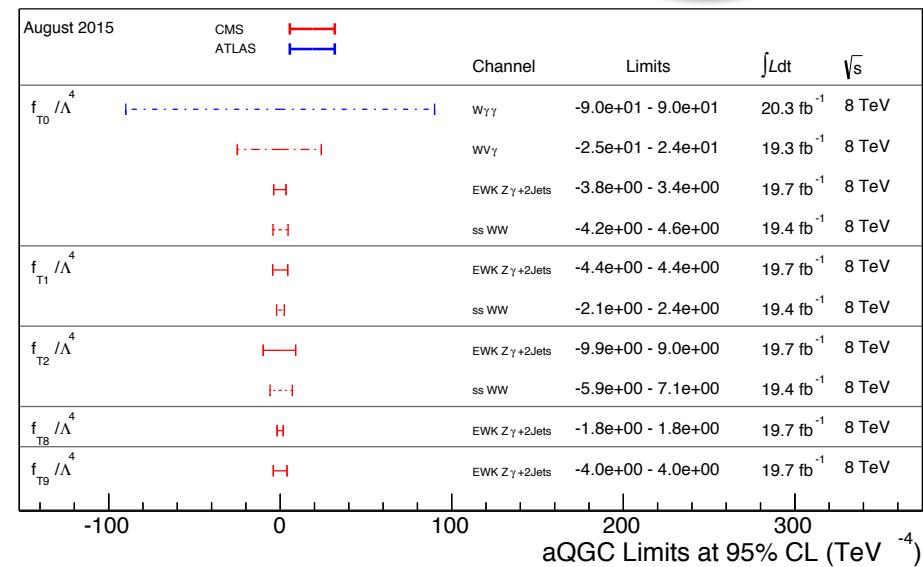
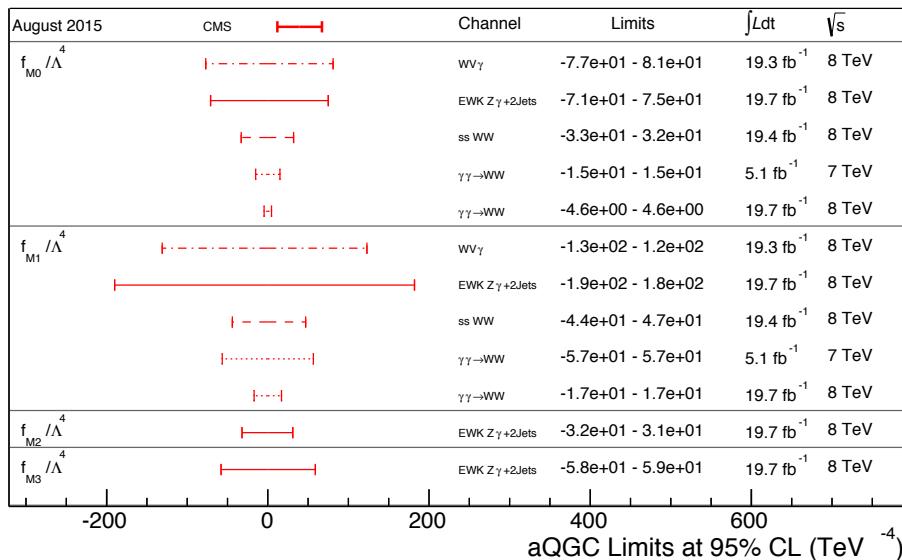
→ 5σ expected sensitivity with 50 fb^{-1} at 13 TeV

already during the Run2, the EWK VV scattering will be discovered

- sensitivity to partially-unitarized models will be reached
- sensitivity to anomalous quartic gauge couplings highly enhanced with respect to Run1

Comparison with existing limits

PAS



- **Exclusive $\gamma\gamma \rightarrow WW$ CMS arXiv:1305.5596** ($\Lambda_{ff} = 500$ GeV)
- **OPAL:** Phys.Rev. D70 (2004) 032005, arXiv:hep-ex/0402021
- **D0:** arXiv:1305.1258
- **WV γ CMS:** SMP-13-009
- **same sign WW:** CMS-PAS-SMP-13-015
- **W γ CMS:** SMP-14-011