Multi-boson production and searches for anomalous gauge couplings

(CMS Run I legacy)

Jing Li
Peking University, Beijing, China
IPHC, Strasbourg, France

On behalf of the CMS Collaboration

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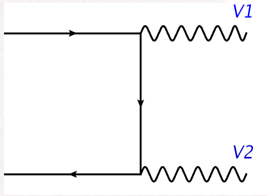
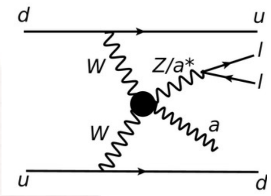
Introduction

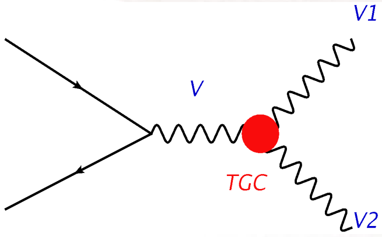
Rich results from Multi-boson measurement in Run1

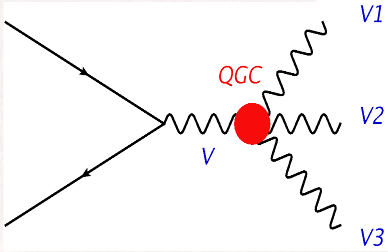
- Important backgrounds to Higgs and New Physics
- Crucial SM tests
  - deeper into VVV
  - vector boson scattering (VBS) and vector boson fusion (VBF): tests of SM unitarity at high energy
  - Many first measurements



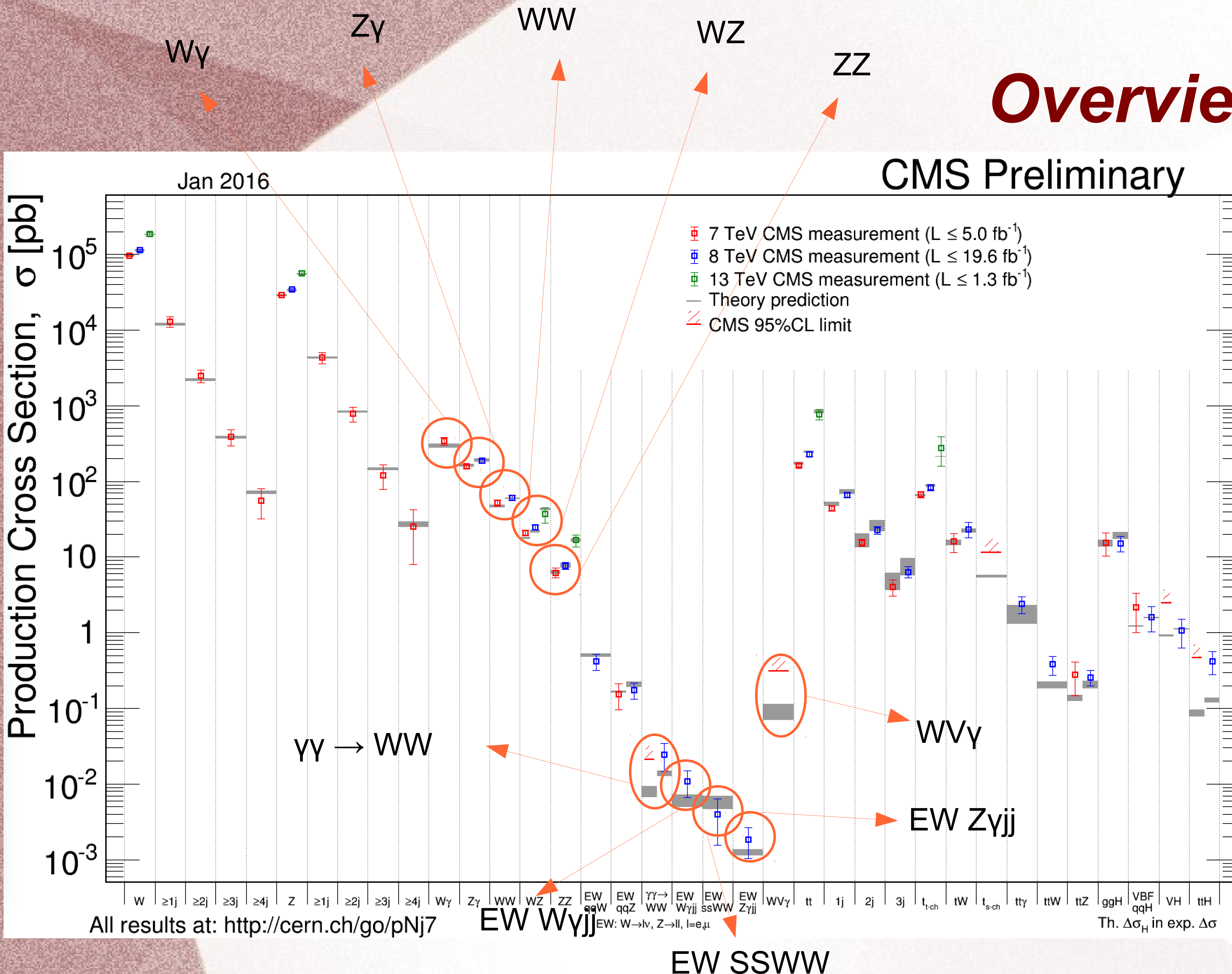


- High-tail enhancements: Sensitive to anomalous Triple (Quartic) Gauge Couplings





Overview



Wγ
Zγ
WW
WZ
ZZ
CMS Preliminary
Jan 2016
Production Cross Section, σ [pb]
7 TeV CMS measurement (L ≤ 5.0 fb-1)
8 TeV CMS measurement (L ≤ 19.6 fb-1)
13 TeV CMS measurement (L ≤ 1.3 fb-1)
Theory prediction
CMS 95%CL limit
γγ → WW
WVγ
EW Zγjj
EW Wγjj
EW SSWW
W ≥1j ≥2j ≥3j ≥4j Z ≥1j ≥2j ≥3j ≥4j Wγ Zγ WW WZ ZZ EW qqW EW qqZ γγ→WW EW Wγjj EW ssWW EW Zγjj WVγ tt 1j 2j 3j t t-ch tW t s-ch ttγ ttW ttZ ggH VBF qqH VH ttH
EW: W→lν, Z→ll, l=e,μ
All results at: http://cern.ch/go/pNj7
Th. ΔσH in exp. Δσ

Summary of CMS Run I results

	XS	Differential XS	aT(Q)GC
Wγ(lνγ)	7 TeV		7 TeV
EW Wγjj	8 TeV		8 TeV
Zγ(llγ)	7 TeV, 8 TeV	8 TeV	7 TeV, 8 TeV
Zγ(ννγ)	7 TeV, 8 TeV		7 TeV, 8 TeV
EW Zγjj	8 TeV		8 TeV
WW(lνlν)	7 TeV, 8 TeV	7 TeV, 8 TeV	7 TeV, 8 TeV
WW(lνjj)	8 TeV	8 TeV	8 TeV
ZZ(4l)	7 TeV, 8 TeV	8 TeV	7 TeV, 8 TeV
ZZ(2l2ν)	7 TeV, 8 TeV		7 TeV, 8 TeV
WZ(3lν)	7 TeV, 8 TeV		
WV	7 TeV		7 TeV
VZ(Vbb)	7 TeV		
γγ	7 TeV	7 TeV	
γγ → WW	7 TeV, 8 TeV		7 TeV, 8 TeV
WVγ(lνjjγ)	8 TeV		8 TeV
Vγγ	8 TeV		8 TeV

Red: new analysis that will introduced by this talk

8 TeV

SMP-14-016 submitted to EPJC | arXiv: 1507.03268

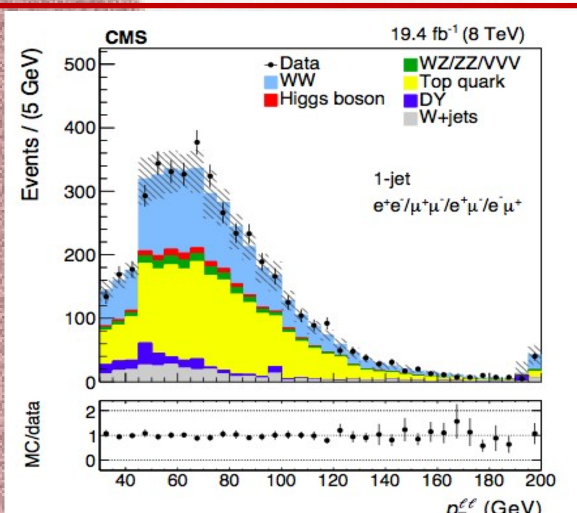
$W^+W^-(l\nu l\nu)$

Event selection:

- Two opposite-sign charged leptons
- Same-flavor final state: DY MVA, $|m_{ll}-m_z| > 15$ GeV to suppress DY bkg
- Large E_T^{miss}
- top-quark veto, 3rd lepton veto
- 0-jet and 1-jet category (first time the 1-jet category is used in the WW measurement at LHC)

Background: Top pair (dominant), V+jets, DY Z/γ^*, WZ/ZZ/VVV, $H \to W^+W^-$

Dominant Systematic Uncertainty: jet veto, lepton efficiency uncertainties



WWγ and WWZ aTGC measured with m_{ll}

Total cross section (zero/one jet)

$$\sigma_{W^+W^-} = 60.1 \pm 0.9\,(\text{stat.}) \pm 3.2\,(\text{exp.}) \pm 3.1\,(\text{th.}) \pm 1.6\,(\text{lum.})\ \text{pb}$$

Good agreement with theoretical prediction

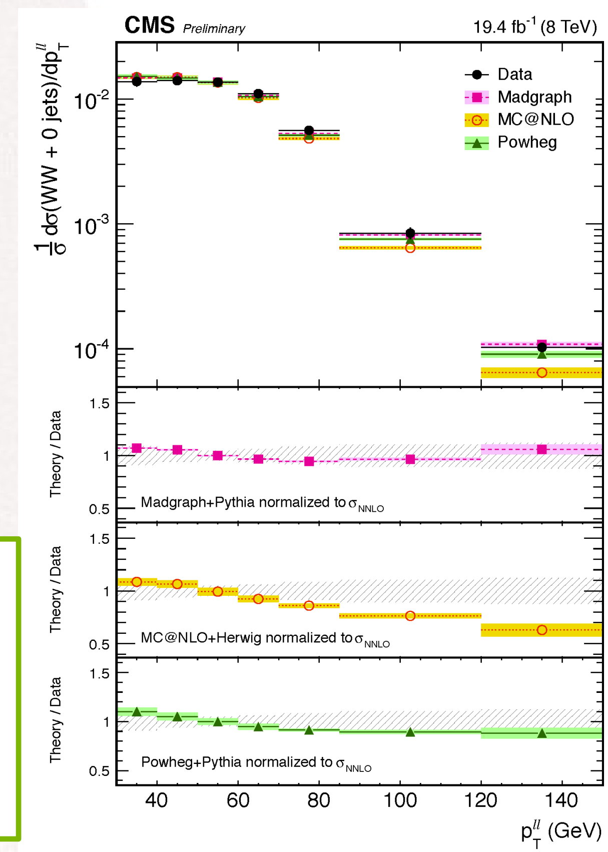
NEW

$$\sigma^{\text{NNLO}}(pp \to W^+W^-) = 59.8^{+1.3}_{-1.1}\ \text{pb}$$

arXiv:1408.5243

Analysis @ 7TeV has shown difference wrt SM prediction
Analysis @ 8 TeV applied reweighting to p_T^{WW} distribution to match NLO+NNLL calculation, thus increase jet veto accuracy

Normalized differential cross section measured as a function of kinematic variables (p_T^l, m_{ll}, p_T^{ll}, $\Delta\phi_{ll}$) and compared with theory predictions



7 TeV and8 TeV

SMP-12-016

EPJC 75 (2015) 511

ZZ(2l2ν)

Event selection:

- Two leptons with $|m_{ll}-m_{z}| < 7.5$ GeV
- Reduced $E_T^{miss} > 65$ GeV
- $0.4 < E_T^{miss}$ balance < 1.8
- b-tag veto, jet veto , 3rd lepton veto

$$7\,\text{TeV}: \quad \sigma(pp \to ZZ) = 5.1^{+1.5}_{-1.4}\,(\text{stat})\,^{+1.4}_{-1.1}\,(\text{syst}) \pm 0.1\,(\text{lumi})\,\text{pb},$$

$$8\,\text{TeV}: \quad \sigma(pp \to ZZ) = 7.2^{+0.8}_{-0.8}\,(\text{stat})\,^{+1.9}_{-1.5}\,(\text{syst}) \pm 0.2\,(\text{lumi})\,\text{pb}.$$

SM prediction: NLO QCD & NLO EW corrections,

$6.2^{+0.3}_{-0.2}$ pb ($7.6^{+0.4}_{-0.3}$ pb) at 7 (8) TeV

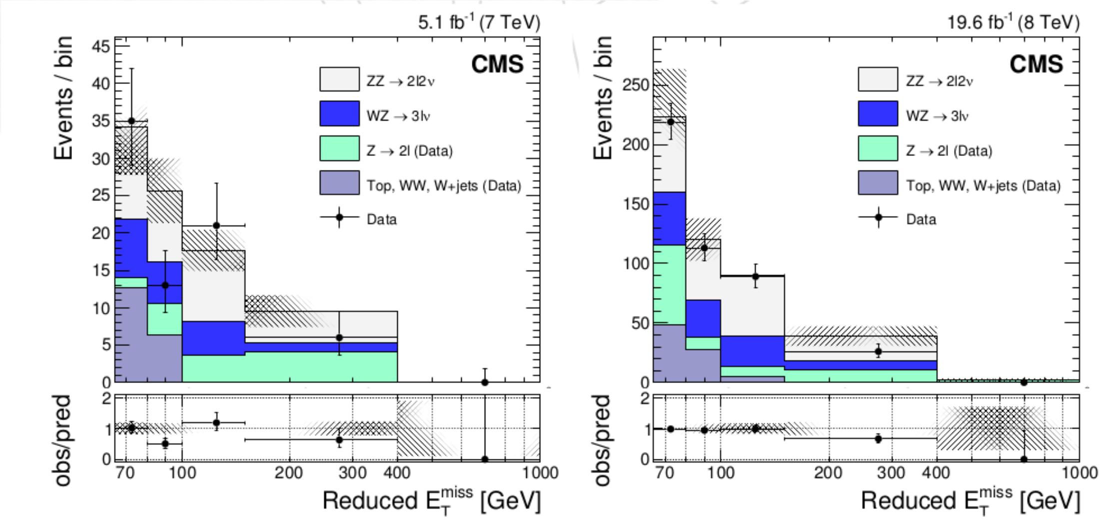
JHEP12(2013)071,PhysRevD.88.113005

- Background:

  DY Z+jets (dominant), WW/WZ, top

- Dominant Systematic:

  DY bkg normalization, jet energy scale



- First measurement at 8 TeV
- Less than 1 σ from the SM predictions
- ZZZ and γZZ aTGC measured with $p_{T,ll}$

8 TeV

SMP-14-019 submitted to PLB

arXiv: 1602.07152

$Z\gamma(\nu\nu\gamma)$

- Event selection:
  - $p_T^{\gamma} > 145$ GeV
  - $E_T^{miss} > 140$ GeV
  - Jet veto, lepton veto
- Background:
  - – $W\gamma \to l\nu\gamma$ (dominant) – estimated using simulation & checked in control region
  - – Large instrumental and non-collision backgrounds – estimated with data-driven methods

Measured cross section ($p_T^{\gamma} > 145$ GeV, $|\eta_{\gamma}|<1.4$):

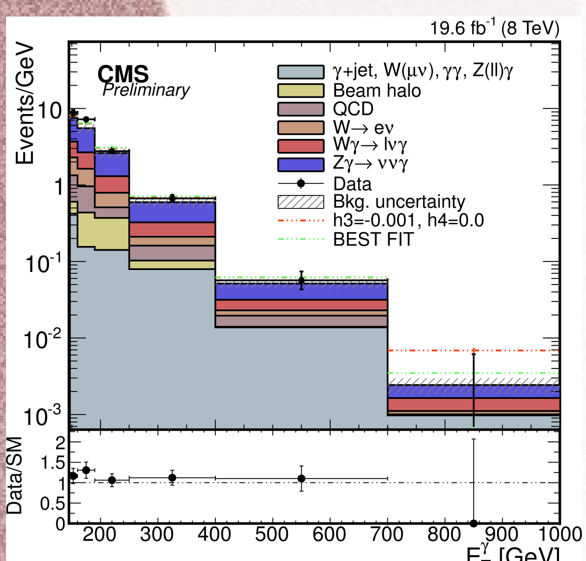
52.7 ± 2.1 (stat) ± 6.4 (syst) ± 1.4 (lumi) fb

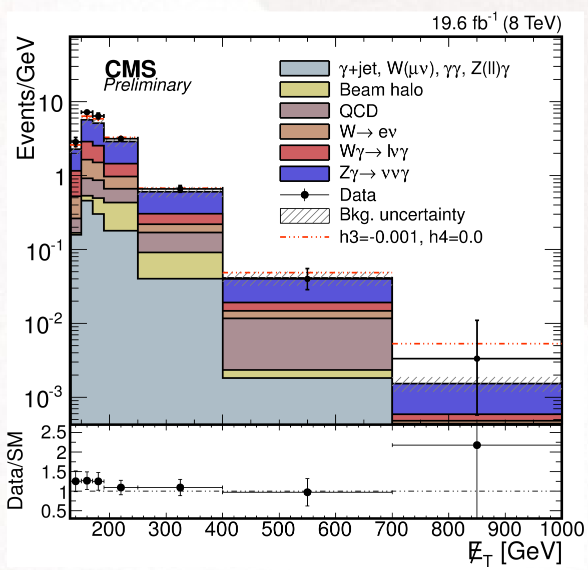
SM: $\sigma_{Z\gamma}$ (NNLO) $50.0^{+2.4}_{-2.2}$ **fb**

NEW

ZZγ and Zγγ aTGC measured with $E_{T,\gamma}$

Process	Estimate
$W(\to \ell\nu) + \gamma$	103 ± 21
$W \to e\nu$	60 ± 6
jet $\to \gamma$ MisID	45 ± 14
Beam halo	25 ± 6
Others	36 ± 3
Total background	269 ± 26
$Z(\to \nu\bar{\nu}) + \gamma$	345 ± 43
Data	630
Signal Events	361 ± 36





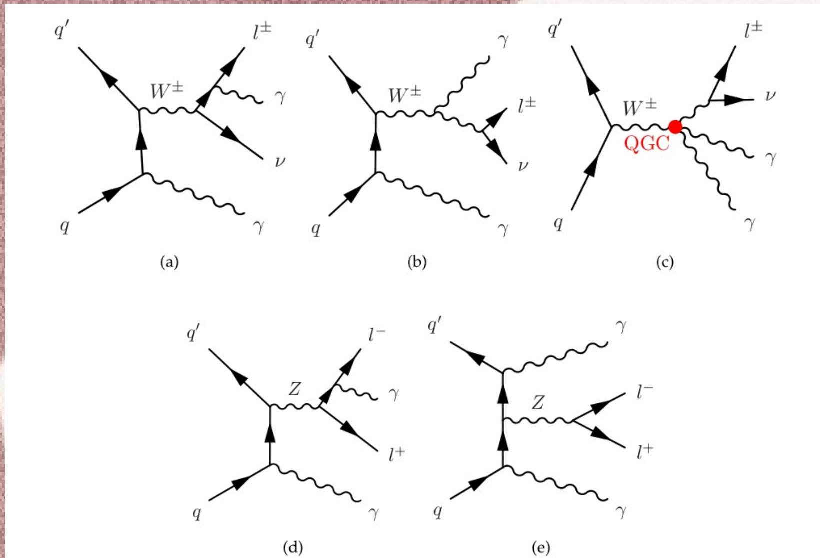
8 TeV

SMP-15-008

NEW

Disvovery!

Wγγ(lνγγ)/Zγγ(llγγ)



Background:
– Jets from fragmentation misidentified as photons: estimated using data-driven method (two-dimensional template normalization)
– Zγγ as an irreducible background for Wγγ: estimated from MC prediction and validated by the Zγγ cross-section measurement

Dominate Systematic:
– Wγγ: Misidentified jets, Zγγ theoretical cross section
– Zγγ: Misidentified jets

Event selection:

Wγγ
- One muon
- 2nd lepton (e/μ) veto with p_T > 10 GeV

Zγγ
- Two opposite sign electrons or muons

- Exactly two isolated photons

$$\sigma^{\mathrm{fid}}_{\mathrm{W}^{\pm}\gamma\gamma} \cdot \mathrm{BR}\,(\mathrm{W} \to \ell\nu) = 6.0 \pm 1.8\,(\mathrm{stat}) \pm 2.3\,(\mathrm{syst}) \pm 0.2\,(\mathrm{lumi})\,\mathrm{fb}\,.$$

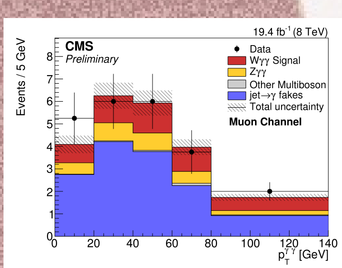
$$\sigma^{\mathrm{fid}}_{\mathrm{Z}\gamma\gamma} \cdot \mathrm{BR}\,(\mathrm{Z} \to \ell\ell) = 12.7 \pm 1.4\,(\mathrm{stat}) \pm 1.8\,(\mathrm{syst}) \pm 0.3\,(\mathrm{lumi})\,\mathrm{fb}$$

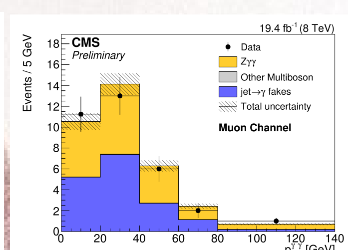
Definition of $\mathrm{W}^{\pm}\gamma\gamma$ Fiducial Region
$p_{\mathrm{T}}^{\gamma} > 25\,\mathrm{GeV}$, $\lvert\eta^{\gamma}\rvert < 2.5$
$p_{\mathrm{T}}^{\ell} > 25\,\mathrm{GeV}$, $\lvert\eta^{\ell}\rvert < 2.5$
Exactly one candidate muon and two candidate photons
$m_{\mathrm{T}}(\ell, \nu_{(\mathrm{s})}) > 40\,\mathrm{GeV}$
$\Delta R(\gamma,\gamma) > 0.4$ and $\Delta R(\gamma,\ell) > 0.4$

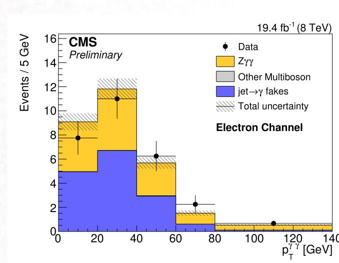
Significance of 2.4 σ for Wγγ and 5.9 σ for Zγγ (discovery !)

Definition of $\mathrm{Z}\gamma\gamma$ Fiducial Region
$p_{\mathrm{T}}^{\gamma} > 15\,\mathrm{GeV}$, $\lvert\eta^{\gamma}\rvert < 2.5$
$p_{\mathrm{T}}^{\ell} > 10\,\mathrm{GeV}$, $\lvert\eta^{\ell}\rvert < 2.5$
Exactly two candidate leptons and two candidate photons
lead $p_{\mathrm{T}}^{\gamma} > 20\,\mathrm{GeV}$
$M_{\ell\ell} > 40\,\mathrm{GeV}$
$\Delta R(\gamma,\gamma) > 0.4$, $\Delta R(\gamma,\ell) > 0.4$, and $\Delta R(\ell,\ell) > 0.4$

WWγγ aQGC measured with $p_T^{\gamma,\mathrm{lead}}$





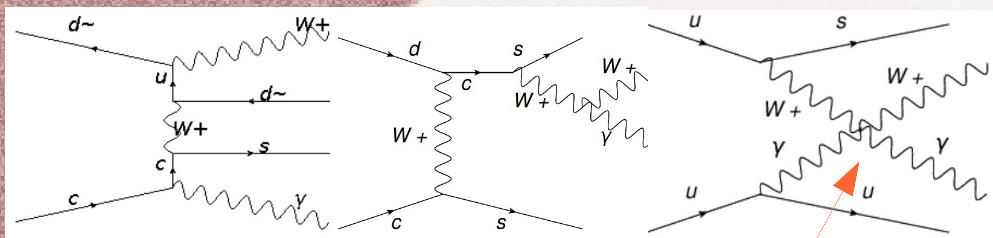


8 TeV

NEW

SMP-14-011

EW Wγjj(lνγjj)



VBS

Event selection:

- $p_T^{\gamma} > 22$ GeV
- $p_T^{l} > 25$ (30) GeV for e(μ)
- $E_T^{miss} > 35$GeV
- $p_T^{j1} > 40$ GeV, $p_T^{j2} > 30$ GeV,
- 2nd lepton veto, b-jet veto
- $W_{mT} > 30$ GeV
- $m_{jj} > 200$ GeV
- $|m_{e\gamma}-m_{z}| > 10$ GeV

Background:

– QCD Wγ+2 jets production: MC shape + data-driven normalization

– Jets & electrons misidentified as photons: estimated using data-driven method (ratio/template)

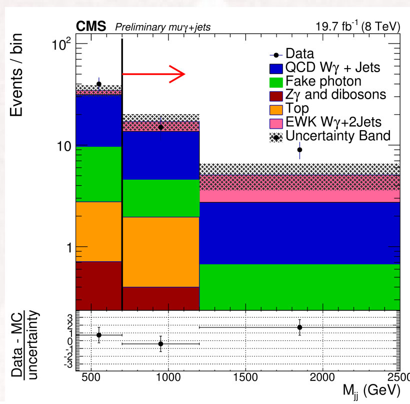
– Jets misidentified as electrons: estimated using data-driven method (template)

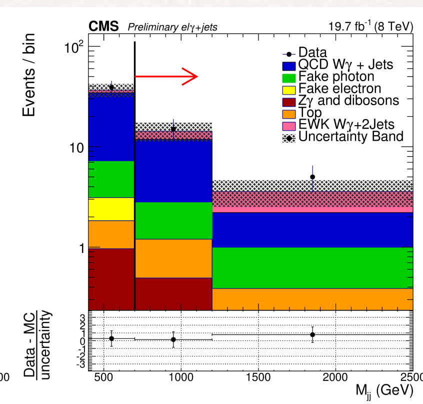
Dominate Systematic:

– QCD Wγ+2 jets prediction

– Jets & electrons misidentification

– Jet energy scale & resolution





Fiducial region:

- $p_T^{j1} > 30$ GeV, $|\eta^{j1}| < 4.7$,
- $p_T^{j2} > 30$ GeV, $|\eta^{j2}| < 4.7$,
- $M_{jj} > 700$ GeV, $|\Delta\eta(j,j)| > 2.4$,
- $p_T^{l} > 20$ GeV, $|\eta^{l}| < 2.4$,
- $p_T^{\gamma} > 20$ GeV, $|\eta^{\gamma}| < 1.4442$,
- $\not{E}_T > 20$ GeV,
- $\Delta R_{j,j}, \Delta R_{l,j}, \Delta R_{\gamma,j}, \Delta R_{l,\gamma} > 0.4$.

WWγγ aQGC measured with $p_{T,W}$

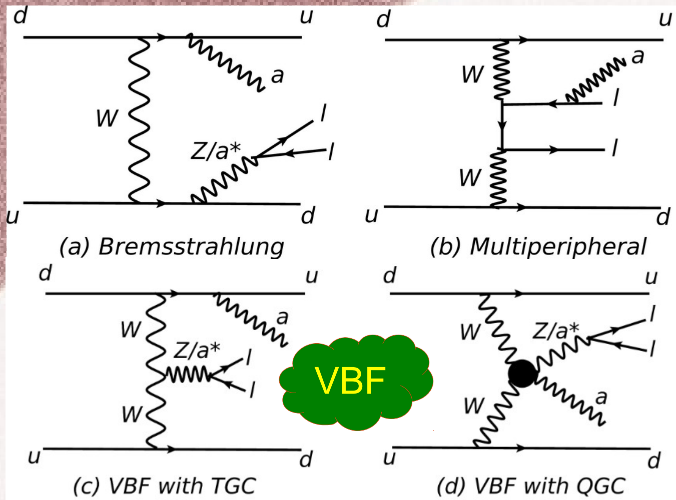
Items	EWK measurement	EWK+QCD measurement
$\hat{\mu}$	$1.78^{+0.99}_{-0.76}$	$0.99^{+0.21}_{-0.19}$
EWK fraction (search region)	100%	27.1%
EWK fraction (fiducial region)	100%	25.8%
Observed (Expected) significance	2.67(1.52) σ	7.69(7.49) σ
Theory cross section (fb) (NLO)	6.1 ± 1.2 (scale) ± 0.2 (PDF)	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.)

8 TeV

SMP-14-018

NEW

EW Zγjj(llγjj)



Background:
– QCD Zγ+2 jets production: MC shape + data-driven normalization
– Jets misidentified as photons: estimated using data-driven method (ratio/template)

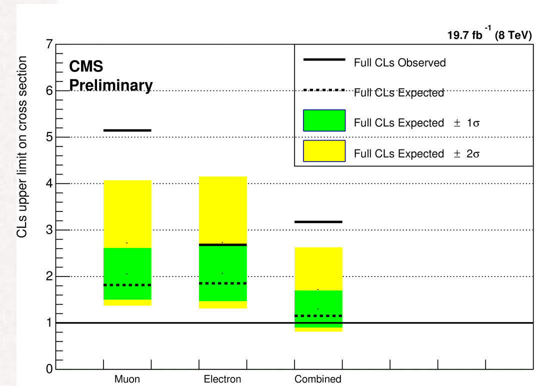
Dominate Systematic:
– QCD Zγ+2 jets prediction
– Jets misidentified as photons

Event selection:

- Two opposite sign leptons with $p_T > 20$ GeV
- Photon $p_T > 25$ GeV
- More than two jets with $p_T > 30$ GeV
- 70 GeV < m_{ll} < 110 GeV
- $|y_{Z\gamma} - (y_{j1} + y_{j2})/2| < 1.2$
- Control region: 150 GeV < m_{jj} < 400 GeV
- Signal region: $m_{jj} > 400$ GeV

Fiducial region:

- $p_T^{j1,j2} > 30$ GeV, $|\eta^{j1,j2}| < 4.7$,
- $M_{jj} > 400$ GeV, $\Delta\eta_{jj} > 2.5$,
- $p_T^{l1,l2} > 20$ GeV, $|\eta^{l1,l2}| < 2.4$,
- 70 GeV $< M_{ll} <$ 110 GeV,
- $p_T^{\gamma} > 20$ GeV, $|\eta^{\gamma}| < 1.4442$,
- $\Delta R_{jj}, \Delta R_{j\gamma}, \Delta R_{l\gamma}, \Delta R_{jl} > 0.4$,

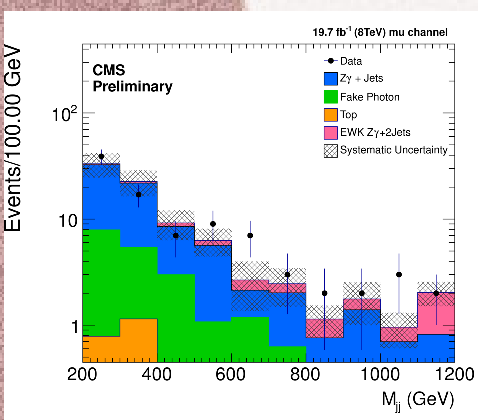


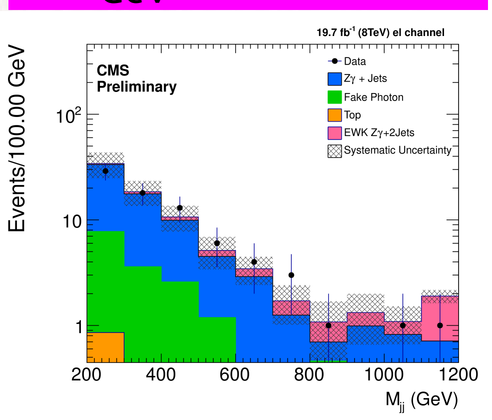
Measured cross section:

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

Good agreement with theoretical LO prediction

$$1.27 \pm 0.11(scale) \pm 0.05(PDF)\ \text{fb}$$





First evidence with an observed(expected) significance of 3.0(2.1)σ

WVγγ and ZVγγ aQGC measured with $m_{Z\gamma}$

anomalous Triple (Quartic) Gauge Couplings

- The self-interaction of electroweak vector bosons is less well measured
- The presence of the aT(Q)GC provides sensitivity to new physics that can cause alterations of the coupling strength
- At hard tail of phase space, they increase cross section significantly

anomalous Triple (Quartic) Gauge Couplings

aT(Q)GCs are modelled as effective Larangians depending on some parameters:

Charged aTGCs WWγ/WWZ

$$L/g_{WWV} = ig_1^V (W^*_{\mu\nu} W^\mu V^\nu - W_{\mu\nu} W^{*\mu} V^\nu) + i\kappa^V W^*_\mu W_\nu V^{\mu\nu} + \frac{\lambda^V}{M_W^2} W^*_{\rho\mu} W^\mu_\nu V^{\nu\rho}$$

5 parameters: $\Delta g_{1Z}(=g_{1Z}-1)$, $\Delta\kappa_Z(=\kappa_Z-1)$, $\Delta\kappa_\gamma(=\kappa_\gamma-1)$, λ_Z, λ_γ

LEP parametrization

$\lambda\gamma = \lambda z = \lambda$

$\Delta\kappa_z = \Delta g_{z1} - \Delta\kappa_\gamma . \tan^2\theta_w$

HISZ parametrization

$\Delta\kappa_Z = \Delta g_{1Z} (\cos^2\theta_W - \sin^2\theta_W)$,

$\Delta\kappa_\gamma = 2\Delta g_{1Z} \cos^2\theta_W$, $\lambda_Z = \lambda_\gamma$

NPB282 (1987) 253; PRD41 (1990) 2113

EFT parametrization

c_{WWW}/Λ^2, c_W/Λ^2 ,c_B/Λ^2

Annals Phys. (2013) 335

Neutral aTGCs
(Neutral TGCs not allowed in SM)

$$L = -\frac{e}{M_Z^2}[f_4^V(\partial_\mu V^{\mu\beta})Z_\alpha(\partial^\alpha Z_\beta) + f_5^V(\partial^\sigma V_{\sigma\mu})\tilde{Z}^{\mu\beta}Z_\beta]$$

Zγ channel: Zγγ/ZZγ

$h_3^{Z,\gamma}$, $h_4^{Z,\gamma}$

PRD47 (1993) 4889

ZZ channel: ZZγ/ZZZ

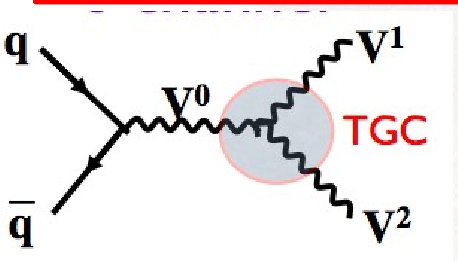
$f_4^{Z,\gamma}$, $f_5^{Z,\gamma}$

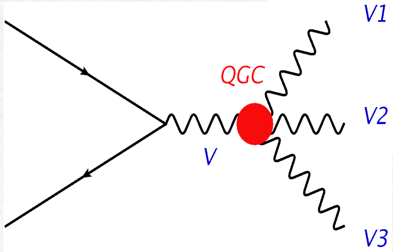
NPB282 (1987) 253

Neutral and charged aQGCs
WWγγ/WWZγ/ZZZγ/ZZγγ/Zγγγ

SM Lagrangian can be extended with dimension 8 operators

$L_{S0,S1}$, $L_{M0\sim7}$, $L_{T0\sim9}$



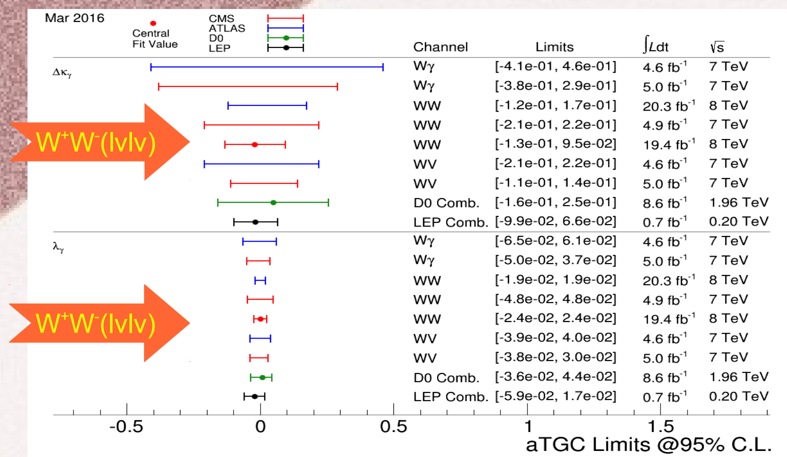


Summary of CMS Run I results

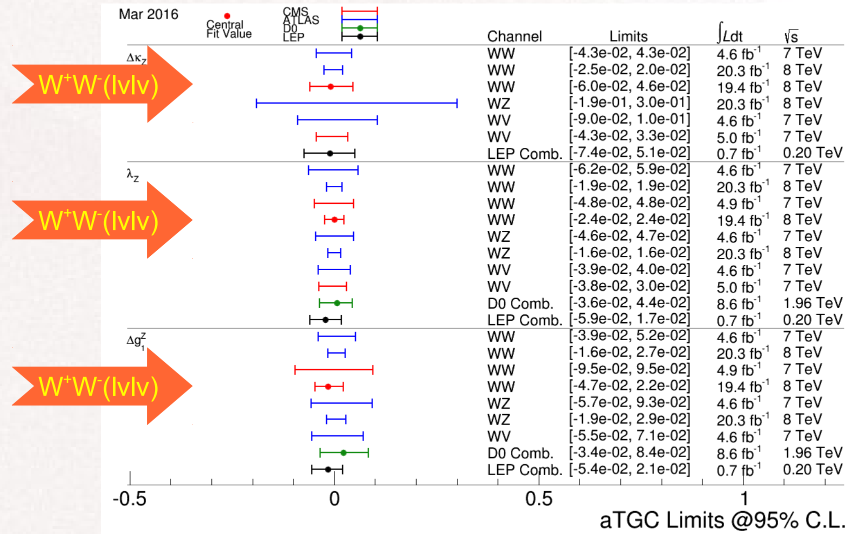
		aTGC/aQGC parameters	Limit Setting variable
$W\gamma$	$WW\gamma$	λ_γ, $\Delta\kappa_\gamma$	E_T^γ
EW $W\gamma jj$	$WW\gamma\gamma$	f_{T0-2}/Λ^4, f_{T5-7}/Λ^4, f_{M0-7}/Λ^4	p_T^w
$Z\gamma$	$ZZ\gamma$, $Z\gamma\gamma$	$h_3^{Z,\gamma}$, $h_4^{Z,\gamma}$	E_T^γ
EW $Z\gamma jj$	$WV\gamma\gamma$, $ZV\gamma\gamma$	f_{T0-2}/Λ^4, $f_{T8,9}/\Lambda^4$, f_{M0-3}/Λ^4	$m_{Z\gamma}$
WW(lvlv)	$WW\gamma$, WWZ	(EFF) c_{WWW}/Λ^2, c_W/Λ^2 ,c_B/Λ^2 (8 TeV) $\Lambda_{\gamma/Z}$, $\Delta\kappa_{\gamma/Z}$, Δg_{1Z} (7 TeV)	m_{ll} (8 TeV) $p_T^{l,lead}$ (7 TeV)
EW SSWW	WWWW	f_{S0}, f_{S1}	m_{ll}
ZZ(4l/2l2v)	ZZZ, $ZZ\gamma$	$f_4^{Z,\gamma}$, $f_5^{Z,\gamma}$	m_{4l} / $p_{T,ll}$
WZ	WWZ	λ_z, $\Delta\kappa_\gamma$	p_T^{dijet}
$\gamma\gamma \to WW$	$WW\gamma\gamma$	a_0^W/Λ^2, a_C^W/Λ^2, f_{M0-3}/Λ^4	$p_T^{dilepton}$
$WV\gamma$	$WW\gamma\gamma$, $WZ\gamma\gamma$	a_0^W/Λ^2, a_C^W/Λ^2, f_{T0}/Λ^4, κ_0^W/Λ^2, κ_C^W/Λ^2	E_T^γ
$V\gamma\gamma$	$WW\gamma\gamma$	f_{T0-2}/Λ^4, $f_{M2,3}/\Lambda^4$	$p_T^{\gamma,lead}$

aTGC

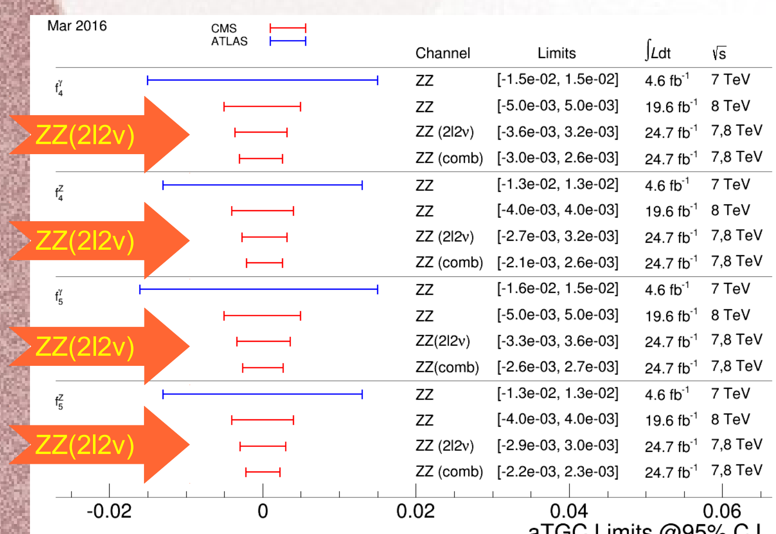
Charged aTGC:
WWγ



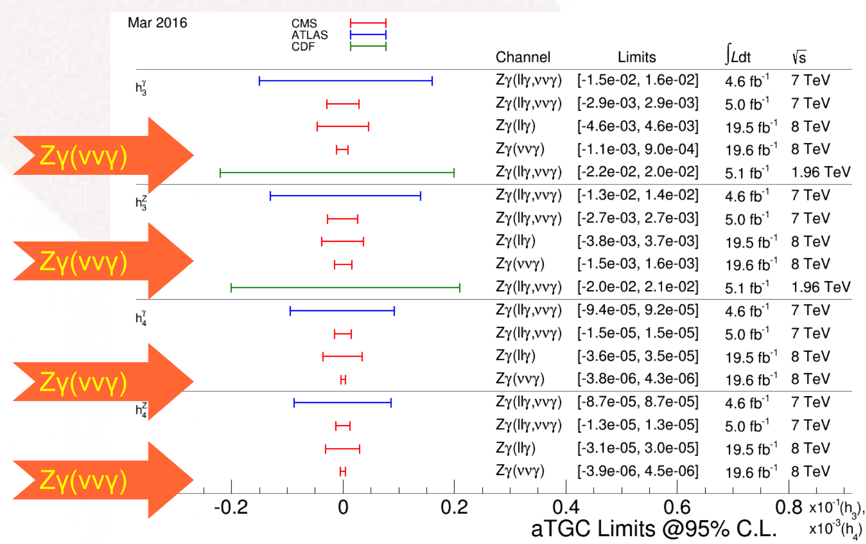
WWZ



Neutral aTGC:
ZZγ and ZZZ

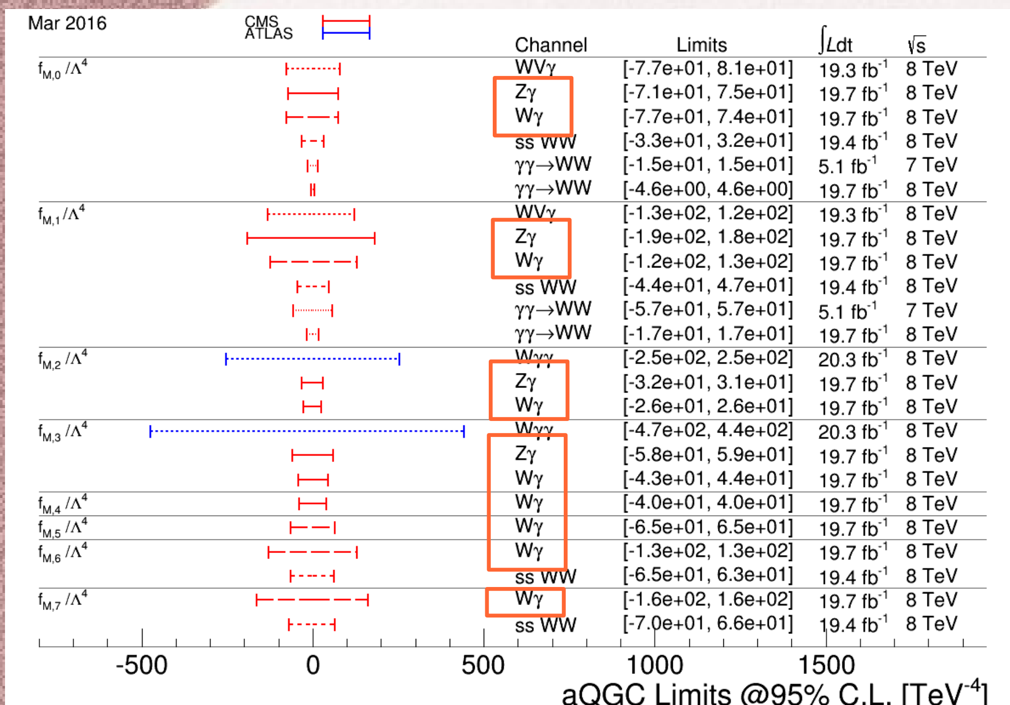


Zγγ and ZZγ

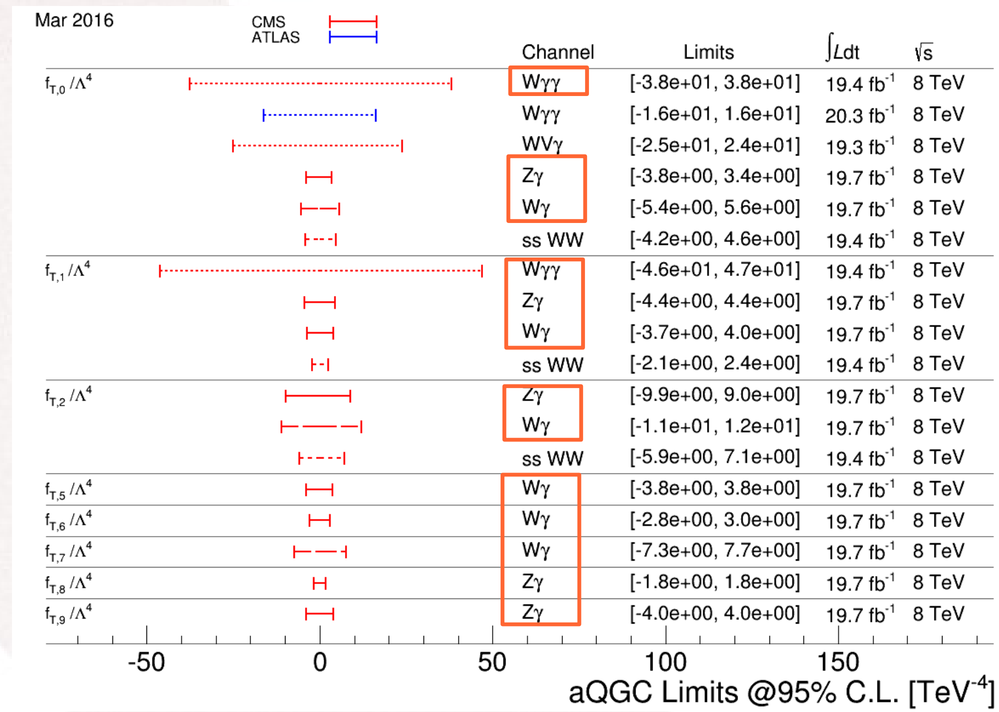


aQGC

Dimension 8 mixed transverse and longitudinal parameters



Dimension 8 transverse parameters

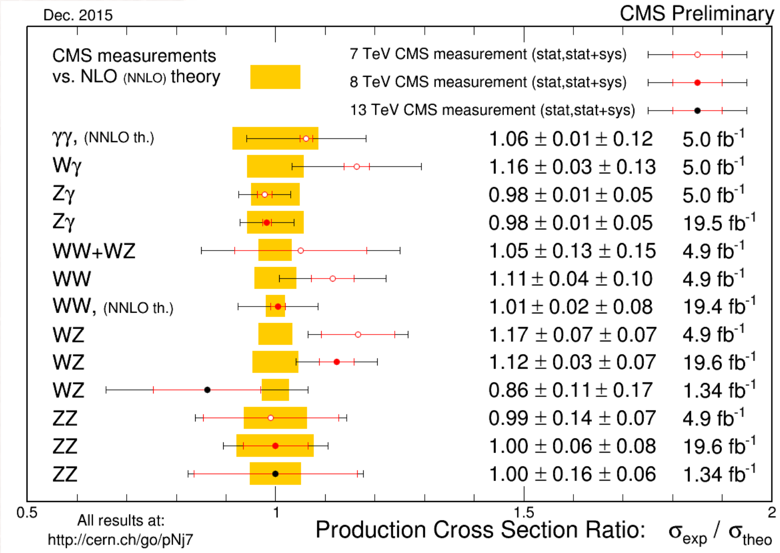


Summary

- Processes with multiple bosons in final state have been studied by CMS with Run I data at 7 and 8 TeV

- Production cross sections have been measured in agreement with SM prediction

- Search for anomalous triple and quartic gauge couplings showed no sign of new physics



- More results coming out with Run II data at 13 TeV (See talk from Xavier Coubez later)

Thank you

Thank you

Backup

8 TeV

Zγ(llγ)

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- Event selection:
  - Lepton: p_T > 20 GeV, |η|<2.5(2.4), l=e(μ)
  - Photon: E_T > 15 GeV, |η|<2.5
  - ΔR(l,γ)>0.7, m_{ll} > 50 GeV
- Background:
  - Dominated by DY + non-prompt photons
  - Two template observables (shower shape, isolation) used to measure the yield independently, then combined.
- Systematic:
  - dominated by template statistics and FSR contamination

Cross section phase space
$M_{\ell\ell} > 50\,\mathrm{GeV}$
$\Delta R(\ell,\gamma) > 0.7$
photon: $\lvert\eta\rvert < 2.5$, $I_{\mathrm{gen}} < 5\,\mathrm{GeV}$
leptons: $\lvert\eta\rvert < 2.5$, $p_{\mathrm{T}} > 20\,\mathrm{GeV}$

inclusive cross section:

σ = 2063 ± 19(stat) ± 98(syst) ± 54(lumi) fb

SM: $\sigma_{Z\gamma}$ (NNLO) = 2241 ± 22 fb

exclusive cross section (Jet veto on pT > 30 GeV and |η| < 2.4***):***

σ = 1770± 18(stat) ± 115(syst) ± 46(lumi) fb

SM: $\sigma_{Z\gamma}$ (NLO) = 1800 ± 120 fb

Differential cross section