Multi-boson Measurements, and Triple and Quartic Gauge Couplings with the CMS

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on behalf of
The CMS collaboration

DIS 2015
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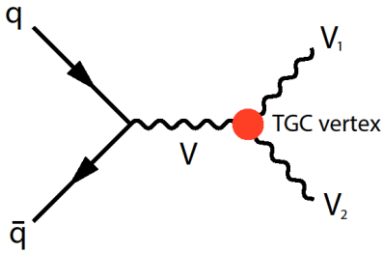
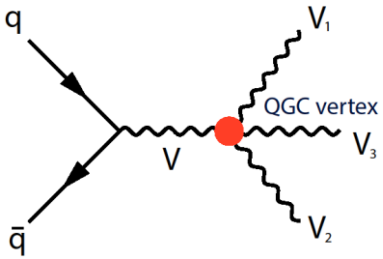
Overview

- Test of the standard model - **cross section measurements**
  - Wγ, Zγ production
  - WW/WZ production
  - ZZ production
  - exclusive γγ -> WW
  - WVγ production (limits)
- Irreducible background to new physics searches and Higgs boson analyses

- Probe boson self-interactions, search for **anomalous couplings**
  - **Triple gauge couplings**
    - ✓ Di-boson production
    - ✓ EW production of single vector boson (not covered by this talk)
  - **Quartic gauge couplings**
    - ✓ Tri-boson production
    - ✓ EW di-boson production





Summary of Run I results from CMS

Recent updates

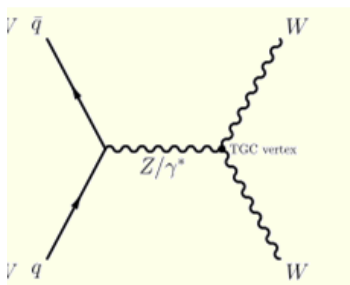
Channel(final state)	7 TeV	8 TeV
Wγ (lνγ)	XS,AC	
Zγ (llγ)	XS,AC	XS,AC
Zγ (ννγ)	XS,AC	
WW(lνlν)	XS,AC	XS,dX,AC
WZ(3lν)	XS	XS
ZZ(4l)	XS,AC	XS,dX,AC
ZZ(2l2ν)	XS,AC	XS,AC
WV(lνjj)	XS,AC	
VZ(Vbb)		XS
γγ->WW(ll)	XS,AC	
WVγ(lνjjγ)		XS,AC

XS: cross section ; AC: limits on aTGC or aQGC; dX differential cross section

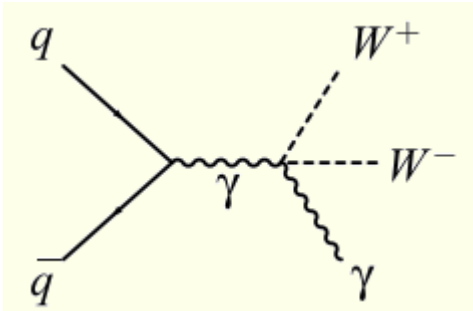
Typical signature – multi bosons

Signature for combination of γ,W,Z:

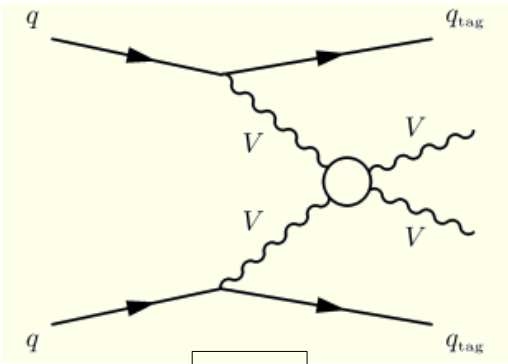
- Leptons/photon
  - High p_T, isolated muons/electrons and/or photons
- Z bosons
  - Reconstructed invariant mass – window cut
- W bosons
  - Large Missing E_T from undetected neutrino
  - Transverse mass selection cut (typically)



Di-boson



Tri-boson

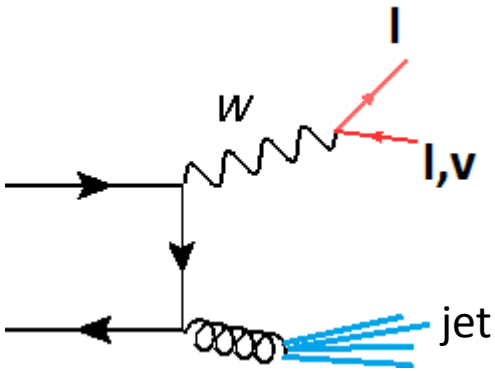


VBS

Typical backgrounds

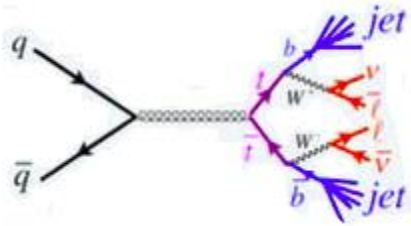
- V + jets
  - High p_T leptons
  - Jets misidentification as lepton/photon
  - Lepton/jet outside of the acceptance leads to missing E_T

V+jets



- TTbar and single top
  - Prompt isolated lepton from W bosons
  - Large missing E_T

ttbar



- Other multi-boson processes
  - Appear as background to each other

8 TeV

Recent update

Zγ->llγ

SMP-13-014

*Signature **Zγ->llν**:*

two leptons + γ

Event selection:

$p_T^l > 20$ GeV, $|\eta^l|<2.5(2.4)$, l=e(μ)

$E_T^\gamma > 15$ GeV, $|\eta^\gamma|<2.5$

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.*

Uncertainties dominated by template statistics and FSR contamination

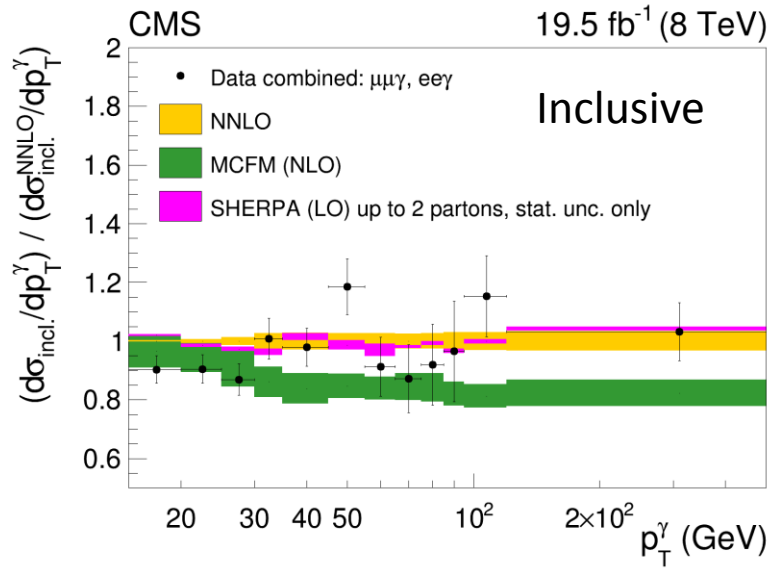
Total inclusive cross section:

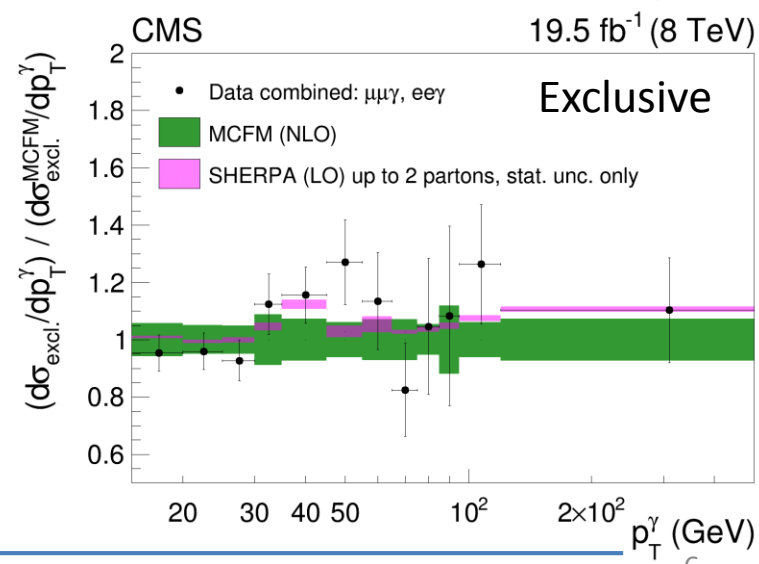
σ = 2063 ± 19(stat) ± 98(syst) ± 54(lumi) fb

SM: $\sigma_{Z\gamma}$ (NLO) = 2100 ± 120 fb

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

Differential cross section





7 TeV

Zγ->llγ / Wγ->lνγ

Phys. Rev. D 89, 092005

*Signature **Zγ->llγ**:*

two leptons + γ

Event selection:

$p_T^l > 20$ GeV, $|\eta^l|<2.5(2.4)$, l=e(μ)

$p_T^\gamma > 15$ GeV, $|\eta^\gamma|<2.5$

$\Delta R(l,\gamma)>0.7$, $m_{ll} > 50$ GeV

*Signature **Wγ->lνγ** :*

Single lepton + E_T^{miss} + γ

Event selection:

$p_T^l > 35$ GeV, $|\eta^l|<2.5(2,1)$, l=e(μ)

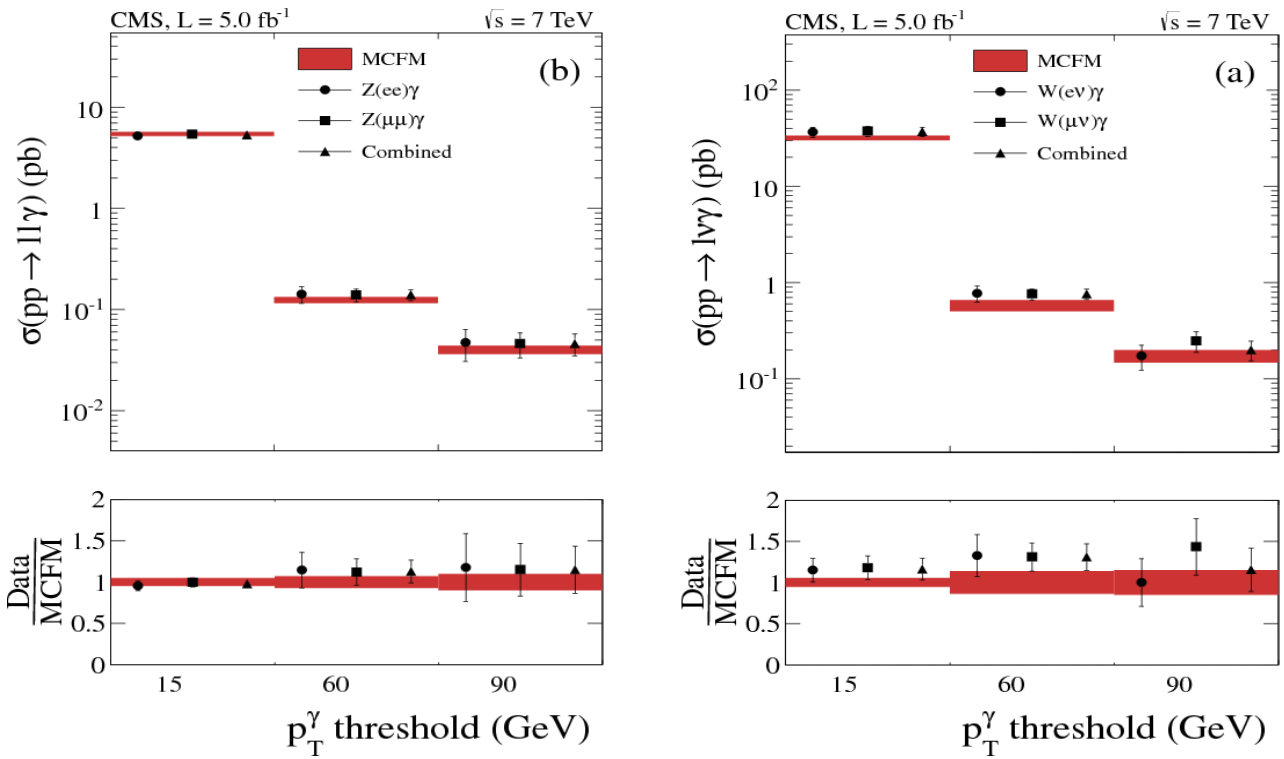
$p_T^\gamma > 15$ GeV, $|\eta^\gamma|<2.5$

$\Delta R(l,\gamma)>0.7$, $M_T^W>70$ GeV

only one lepton

Background:

Jets mimicking photons is the dominant background. Using data-driven methods to estimate most of them.



7 TeV

Zγ->ννγ

J. High Energy Phys. 10 (2013) 164

Signature:

$E_T^{miss} + \gamma$

Event selection:

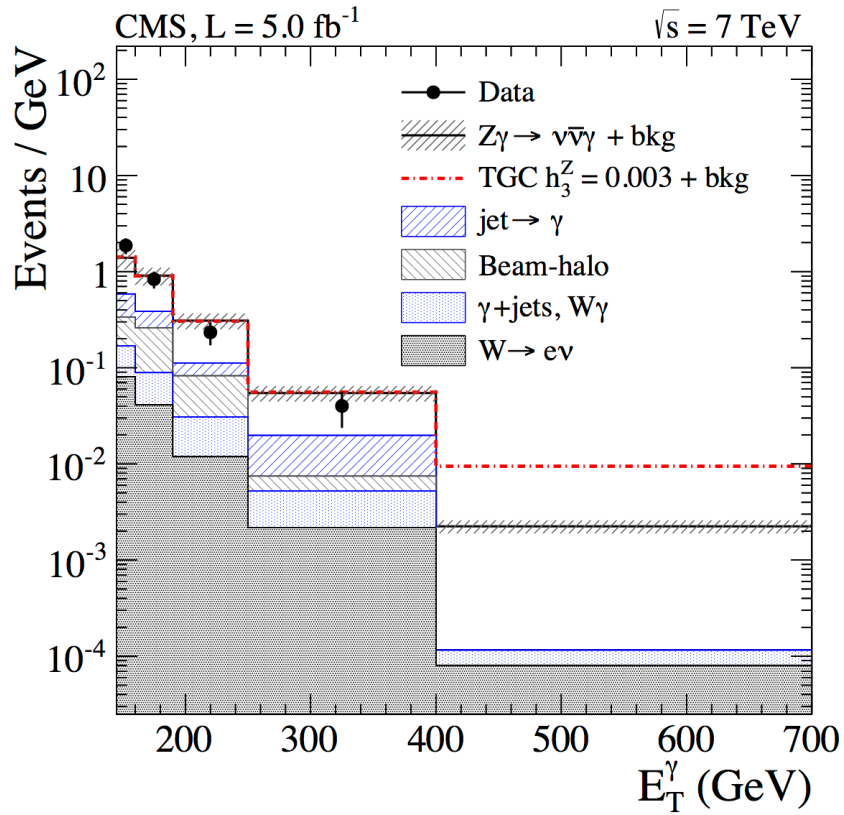
$p_T^{\gamma} > 145$ GeV, $|\eta^{\gamma}| < 1.4$

$E_T^{miss} > 130$ GeV,

$p_T^{jets} < 40$ GeV, $p_T^{tracks} < 20$ GeV

✓Large instrumental and non-collision backgrounds – estimated with data-driven methods

Source	Estimate
Misidentified jets	11.2 ± 2.8
Beam-gas processes	11.1 ± 5.6
Misidentified electrons	3.5 ± 1.5
$W\gamma$	3.3 ± 1.0
$\gamma\gamma$	0.6 ± 0.3
γ+jet	0.5 ± 0.2
Total	30.2 ± 6.5
$Z\gamma \to \nu\nu\gamma$ (NLO)	45.3 ± 6.9
data	73



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

21.3 ± 4.2 (stat.) ± 4.3 (syst.) ± 0.5 (lumi.) fb

SM: $\sigma_{Z\gamma}$ (NLO,BAUR) 21.9 ± 1.1 fb

8 TeV

Recent update

WW->2l2v

SMP-14-016

Signature:

Two opposite charge leptons + E_T^{miss}

Event selection:

p_T^l > 20 GeV, 3rd l veto >10 GeV

Less than 2 jets with p_T > 30 GeV, b-tag veto

Projected E_T^{miss} > 20 GeV

$|m_{ll}-m_Z|$ > 15 GeV (ee, μμ)

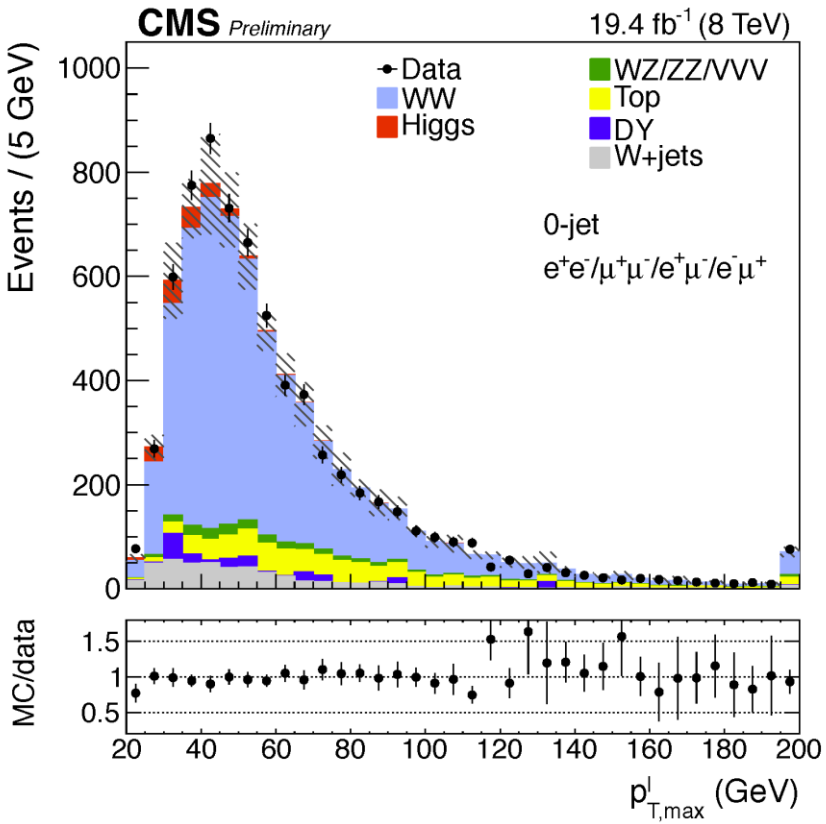
di-lepton p_T > 45(30) GeV for ee, μμ(eμ)

Background:

Top, V+jets, VV

Multiple control regions to estimate the yields

Systematics dominated by jet veto and lepton efficiency uncertainties



Total measured cross section at 8 TeV:

60.1 ± 0.9(stat) ± 3.2(exp) ± 3.1(th) ± 1.6(lum) pb.

SM: σ_{WW}(NNLO) = $59.8^{+1.3}_{-1.1}$pb

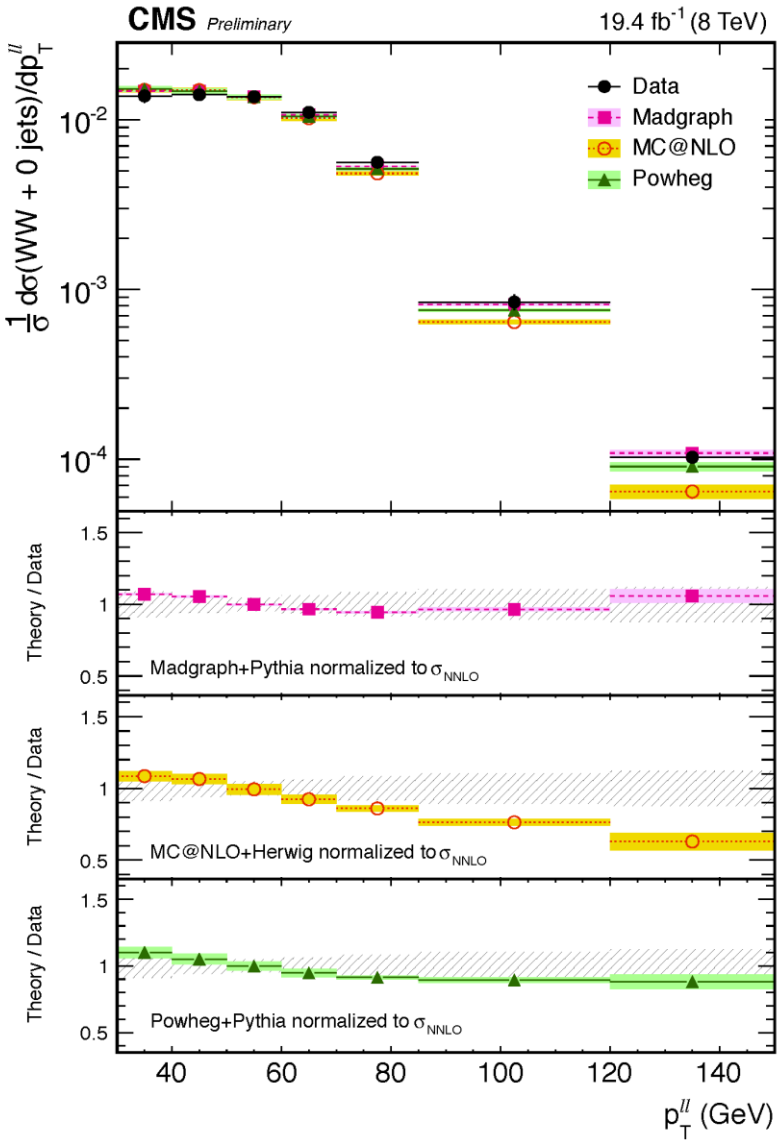
8 TeV

Recent update

WW->2l2ν

SMP-14-016

- W^+W^- unfolded (normalized) differential cross section measured as a function of kinematic variables (**$p_{T,l}$, m_{ll}, $p_{T,ll}$, $\Delta\varphi_{ll}$**) and compared with theory predictions
  - ✓ Comparison with Madgraph, MC@NLO and Powheg
  - ➢ Some shape trends both at low and high p_T



7 TeV 8 TeV

ZZ->lll'l'

Phys. Lett. B 740 (2015) 250

Signature:

Four leptons $l^-l^+l^{-\prime}l^{+\prime}$, l=e,μ, l'= l=e,μ,τ

Include Z->ττ for the second candidate

Event selection:

p_T^l > 20(10) GeV, leading(other) lepton(s)

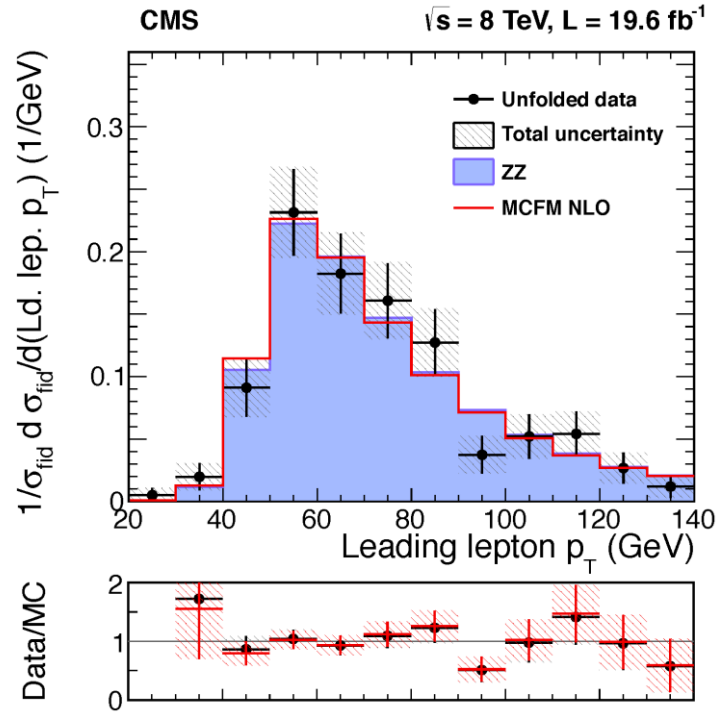
$|\eta^l|$<2.5(2.4), l=e(μ)

60< m_{ll} < 120 GeV (each pair)

20/30 < $m_{\tau\tau}$<90 GeV (eμ/other)

Background:

Jet is misidentified as lepton in WZ/Z+jets and tt. Data driven estimate – control region with relaxed isolation.



Differential fiducial cross section

Measured cross section pp->ZZ (**60 < M_Z < 120 GeV**) :

$6.24 \pm {}^{+0.86}_{-0.80}$ (stat.) ${}^{+0.41}_{-0.32}$(syst .) ± 0.14 (lumi.) pb @ 7 TeV

7.7 ± 0.5 (stat.) ${}^{+0.5}_{-0.4}$(syst .) ± 0.4 (theo.) ± 0.3 (lumi.) pb @ 8 TeV

SM: σ_{ZZ}(MCFM,qq(NLO),gg(LO)) = 6.3 ± 0.4 pb @ 7 TeV

SM: σ_{ZZ}(MCFM,qq(NLO),gg(LO)) = 7.7 ± 0.6 pb @ 8 TeV

- Leading lepton p_T
- Z p_T
- ZZ p_T
- m_{ZZ}
- Angular distributions

All decay modes combined.

7 TeV 8 TeV

ZZ->2l2ν

arXiv.1503.05467

Submitted to EPJC

Signature:

Two opposite charge leptons + E_t^{miss}

Event selection:

$p_T^l > 20$ GeV, l=e,μ

$(m_{ll} - 91) < 7.5$ GeV

di-lepton $p_T > 45$ GeV

b-tag veto for jet with $p_T > 20$ GeV

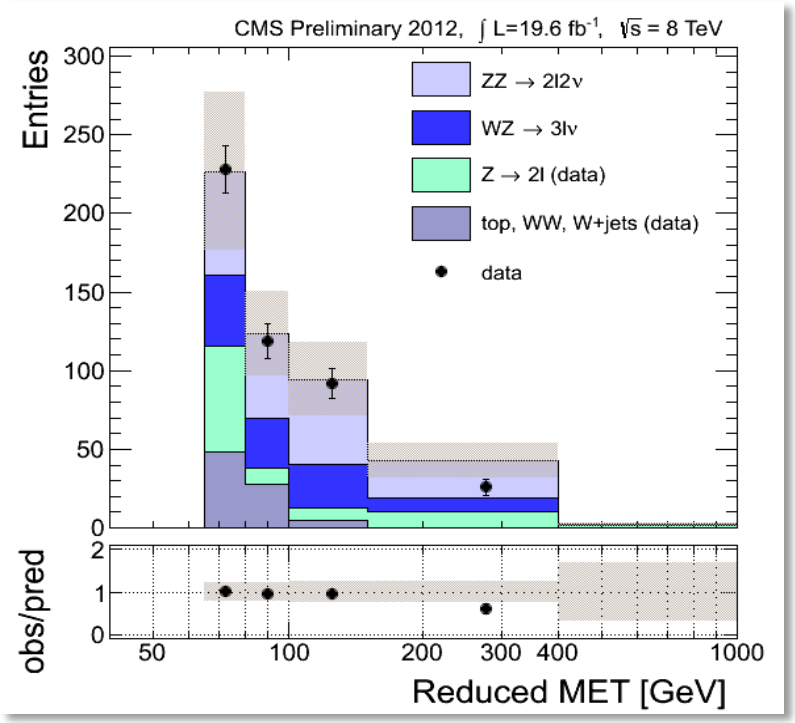
no jets with $p_T > 30$ GeV, lepton veto

reduced – $E_T^{miss} > 65$ GeV

$\Delta\varphi(E_t^{miss}, l) > 0.2$, $\Delta\varphi(E_t^{miss}, jet) > 0.5$

Background:

WZ, Z+jets, WW, top. Data-driven estimates with γ-jet and m_Z side bands.



Measured pp->ZZ cross section:

$5.2 \pm {}^{+1.5}_{-1.4}$ (stat.) $\pm {}^{+1.4}_{-1.1}$(syst .) ± 0.2 (lumi.) pb @ 7 TeV

6.9 ± 0.8 (stat.) $\pm {}^{+1.8}_{-1.4}$(syst .) ± 0.3 (lumi.) pb @ 8 TeV

SM: σ_{ZZ}(MCFM,qq(NLO),gg(LO)) = 6.3 ± 0.4 pb @ 7 TeV

SM: σ_{ZZ}(MCFM,qq(NLO),gg(LO)) = 7.7 ± 0.6 pb @ 8 TeV

7 TeV 8 TeV

WZ->3lν

SMP-12-006

Signature:

Two opposite charge leptons + 3rd lepton+ E_T^{miss}

Event selection:

Z reconstruction:

$p_T^l > 20$ (10) GeV

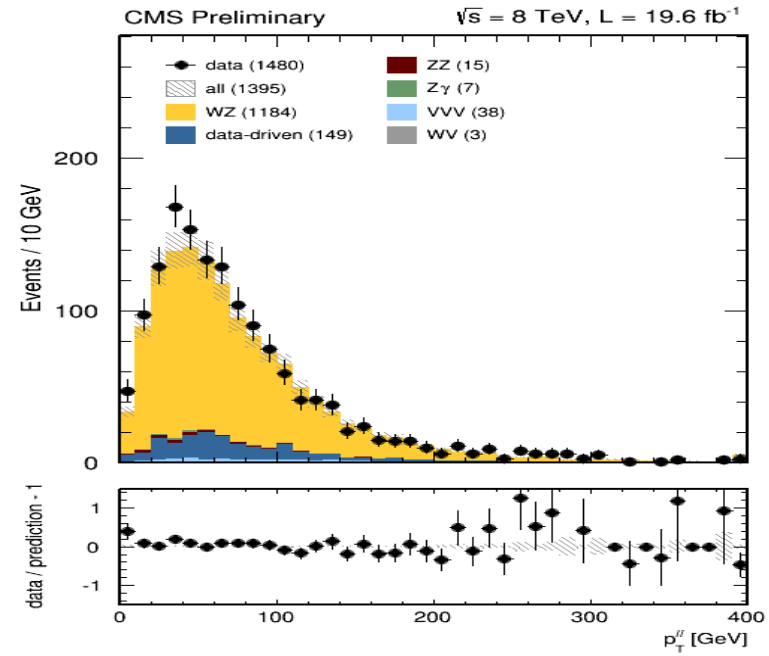
$71<m_{ll}<111$ GeV (and closest to m_Z)

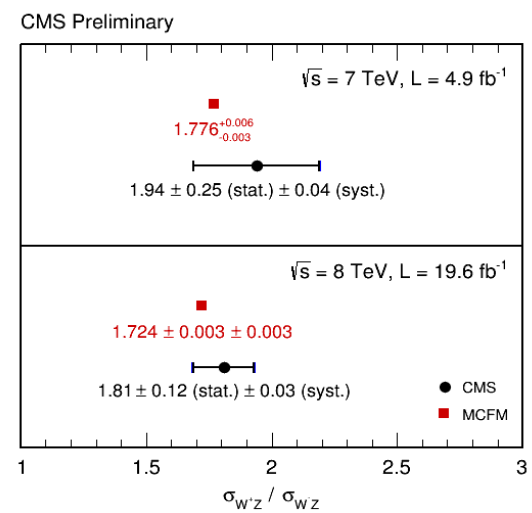
W reconstruction:

$p_T^l > 20$ GeV, $E_T^{miss} > 30$ GeV

Background:

- Fake lepton - real Z plus a jet faking a lepton – the *dominant background*
  - Non Peaking - no Z boson (e.g. tt)
  - Prompt Lepton - real Z and an isolated lepton(-like) object (e.g. ZZ, Z).





Measured pp->WZ cross section:

20.8 ± 1.3(stat.) ± 1.1 (syst.) ± 0.5(lumi.) pb @ 7 TeV

24.6 ± 0.8(stat.) ± 1.1 (syst.) ± 1.1(lumi.) pb @ 8 TeV

SM: σ_{WZ}(MCFM, NLO) = 17.8 $^{+0.7}_{-0.5}$ pb @ 7 TeV

SM: σ_{WZ}(MCFM, NLO) = 21.91 $^{+1.17}_{-0.88}$ pb @ 8 TeV

7 TeV

WV->lvjj

Eur.Phys.J. C73 (2013) 2283

Signature:

lepton + E_T^{miss} + jets

one W boson decays leptonically (l = e,m)

the other boson **V(W or Z)** decays hadronically (jj)

Event selection:

p_T^l > 35(25) GeV, l=e(μ)

$|\eta^l|$<2.5(2.1), l=e(μ)

M_T^W> 50(30) GeV, l=e(μ)

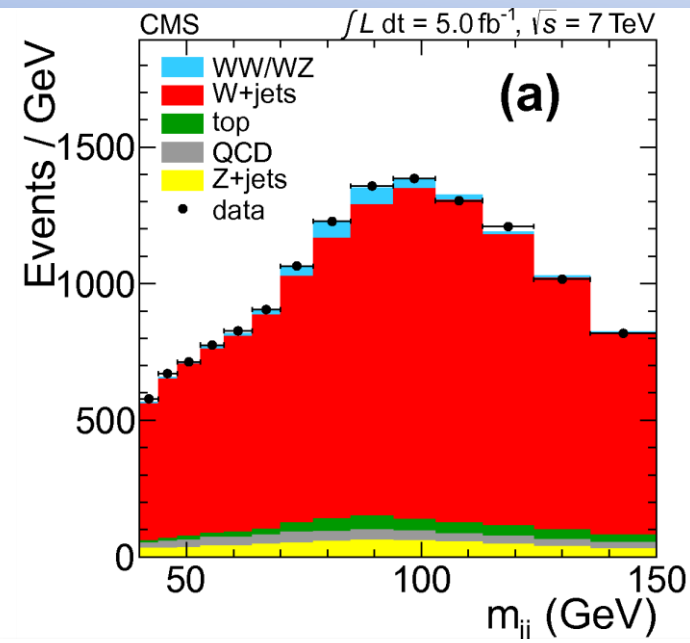
E_T^{miss} > 30(25) GeV, l=e(μ)

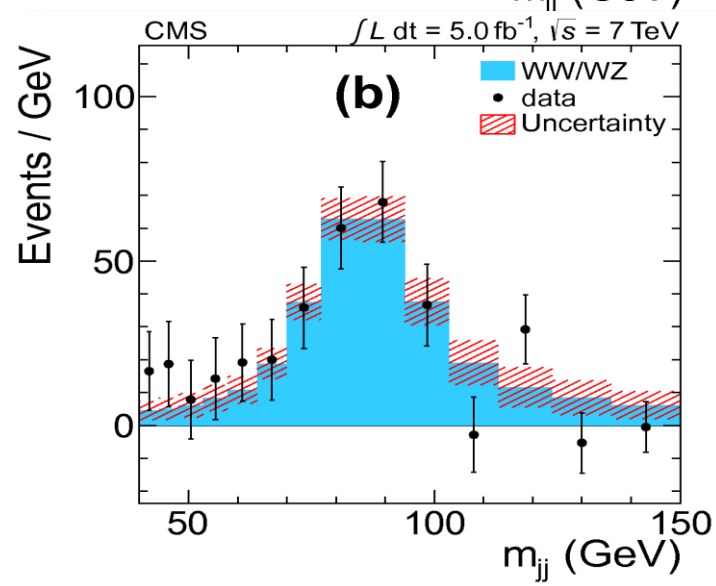
p_T^{jet} > 35 GeV, $|\eta^{jet}|$<2.4, jet b-tag veto

Background:

W+jets(dominant), top, Z+jets,

jet -> l misidentification.





Measured cross section pp -> WW and pp-> WZ

68.9 ± 8.7 (stat.) ± 9.7 (syst.) ± 1.5 (lum.) pb

SM: $\sigma_{WW}+\sigma_{WZ}$(MCFM, NLO) = 65.6 ± 2.2 pb

8 TeV

VZ->Vbb

EPJC 74 (2014) 2973

Signature:

Two b-jets+ E_T^{miss} + 0,1,2 leptons

V = W, Z

Event selection:

2 b-jets (|η|<2.5), m_{jj}<250 GeV

0l(Z →νν): E_T^{miss} > 100 GeV

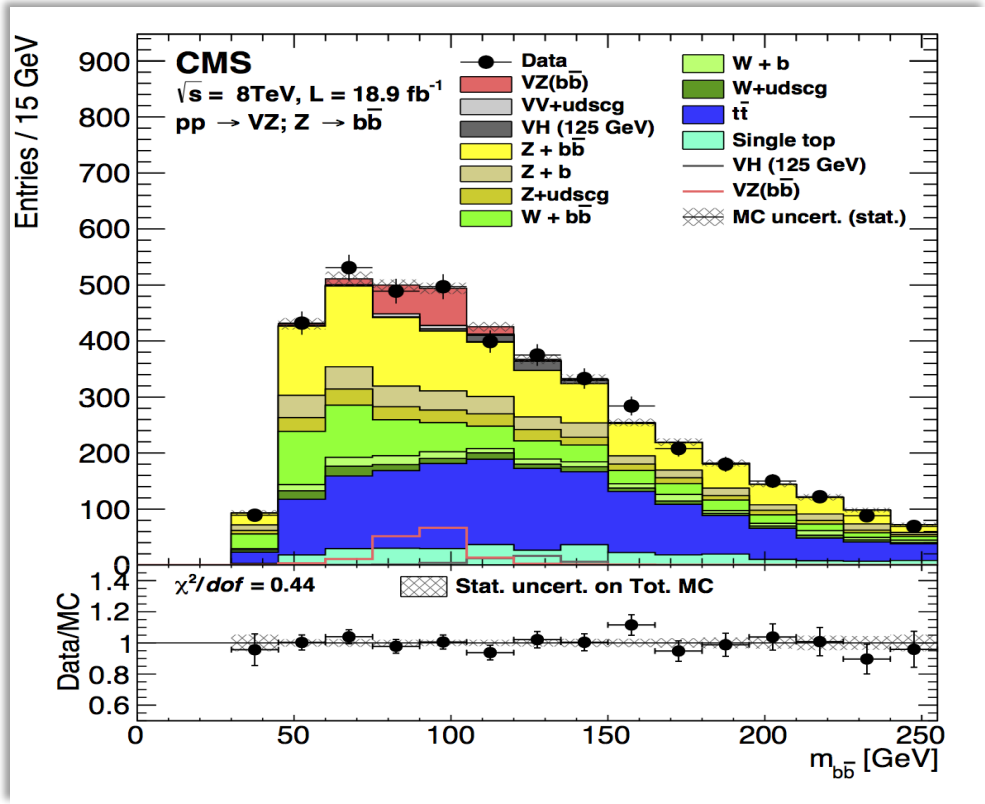
1l(W →lν): E_T^{miss} > 45 GeV

2l(Z →ll): 75GeV < m_{ll}< 105 GeV

Fit of multivariate discriminant/ m_{jj}

Background:

V+jets, top, VH



Measured cross section **pp → WZ** (60 <m_Z< 120 GeV)

30.7 ± 9.3(stat.) ± 7.1(syst.) ± 4.1(theo.) ± 1.0(lumi.) pb

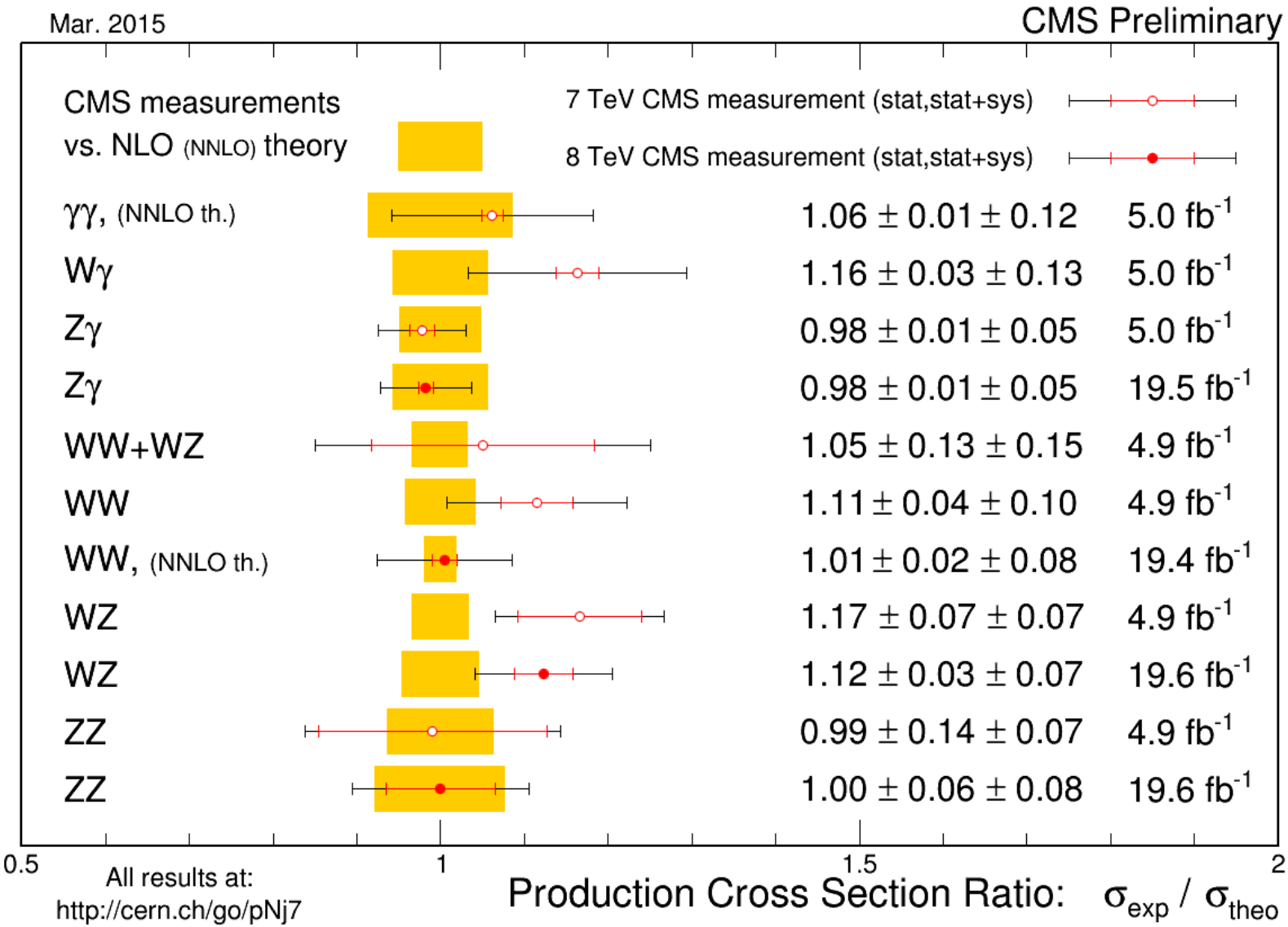
SM: σ_{WZ}(MCFM, NLO) = 22.3 ±1.1 pb

Measured cross section **pp → ZZ** (60 <m_Z< 120 GeV)

6.5 ± 1.7(stat.) ± 1.0(syst.) ± 0.9(theo.) ± 0.2(lumi.) pb

SM: σ_{ZZ}(MCFM, NLO) = 7.7 ±0.4 pb

Summary – cross sections measurements

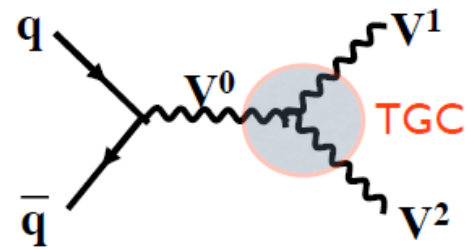


Triple Gauge Couplings

❖ Predicted by the gauge structure of the SM

❖ Neutral TGC (ZZZ, ZZγ, Zγγ) are forbidden at tree level by the SM

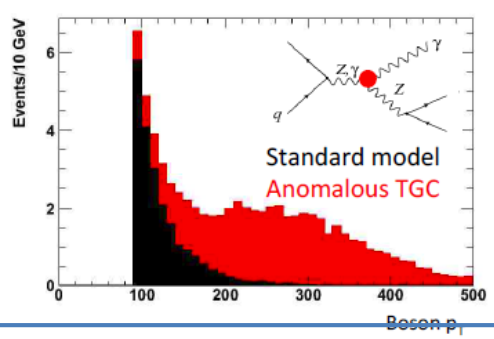
❖ SM predictions: $\lambda_\gamma=\lambda_Z=0$, $g_1^Z=\kappa_\gamma=\kappa_Z=1$



❖ aTGC modeled using an effective Lagrangian depending on few parameters

❖ aTGC modify ***total cross sections*** and ***kinematics***

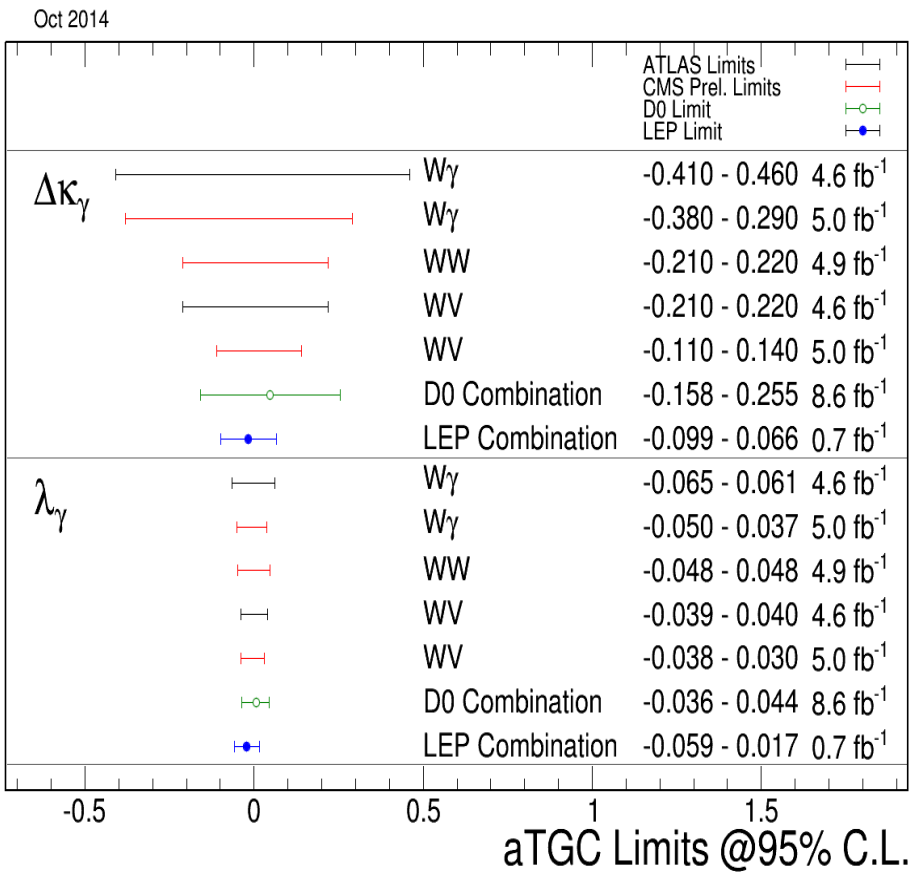
❖ aTGC sensitivity to $M^{VV'}$, p_T^V, etc...

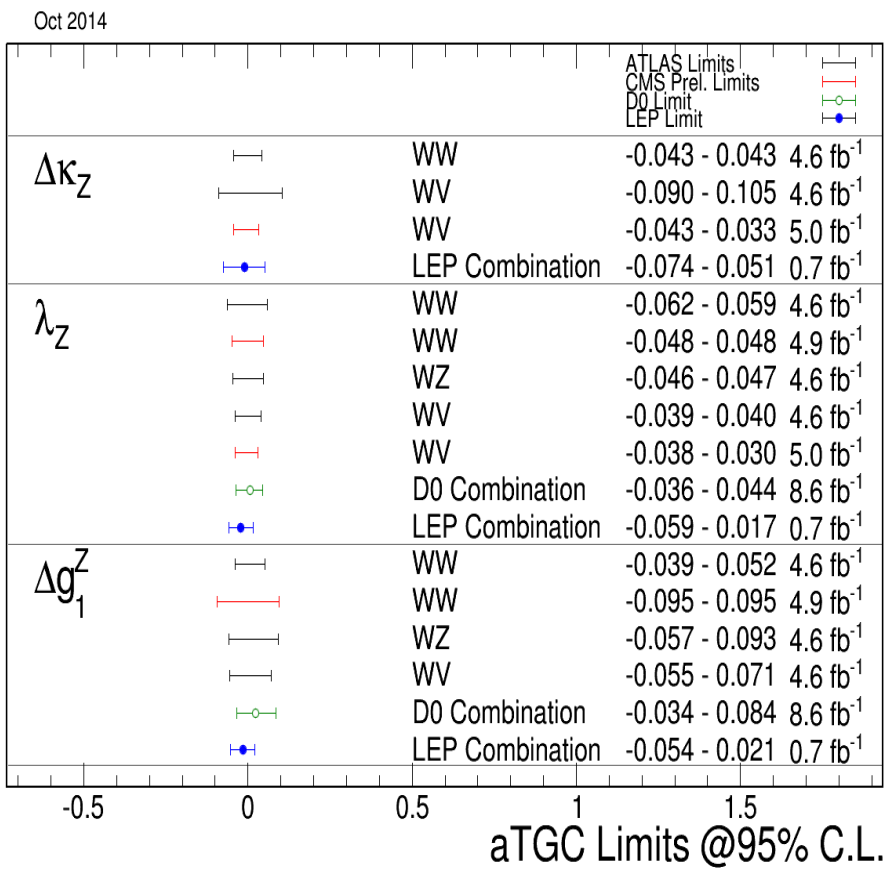


Coupling	Parameters	Channel
WWγ	$\Delta\kappa_\gamma$, λ_γ	WW, Wγ
WWZ	Δg_1^Z, $\Delta\kappa_Z$, λ_Z	WW, WZ
ZZγ	h_3^Z, h_4^Z	Zγ
Zγγ	h_3^γ, h_4^γ	Zγ
ZZZ	f_4^Z, f_5^Z	ZZ
ZγZ	f_4^γ, f_5^γ	ZZ

Charged aTGC limits

- ✓ Comparison with other measurements from LHC, LEP and Tevatron
  - ➢ Sensitivity reaching LEP sensitivity

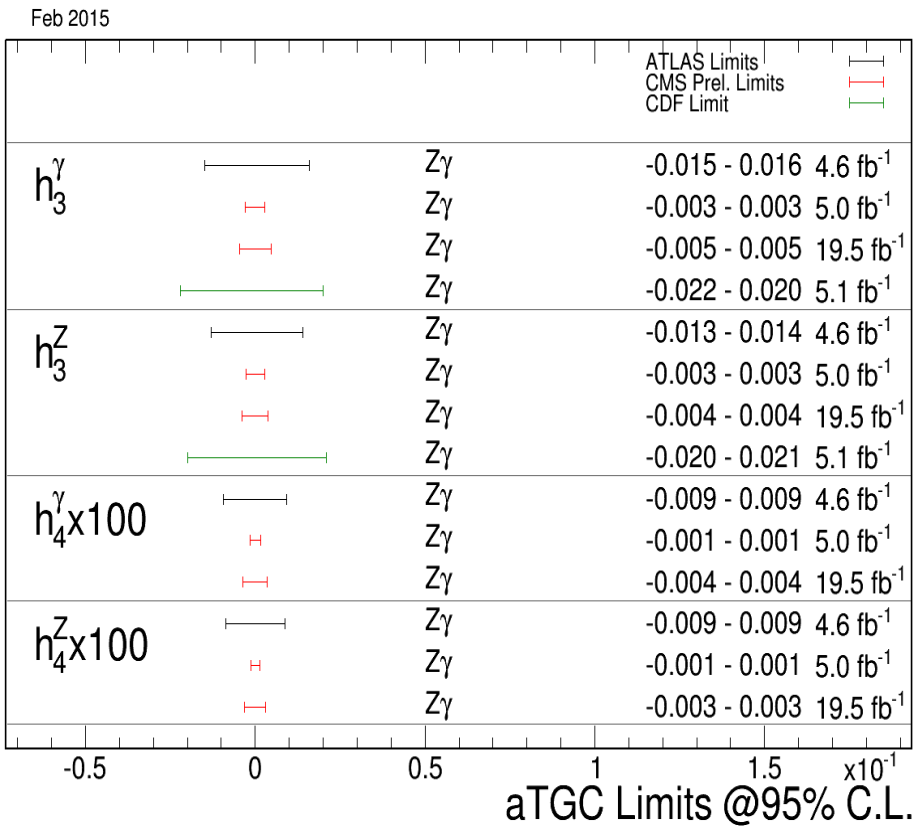


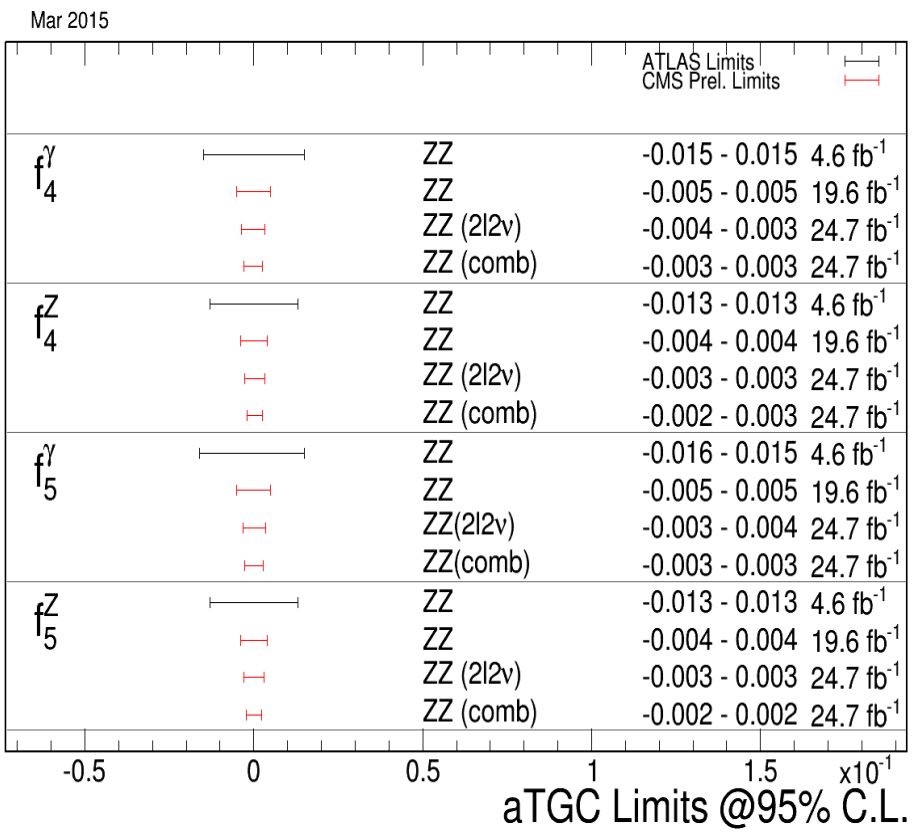


https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMPaTGC

Neutral aTGC limits

✓ Comparison with other measurements from LHC and Tevatron





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

7 TeV

γγ->WW

JHEP 1307 (2013) 116

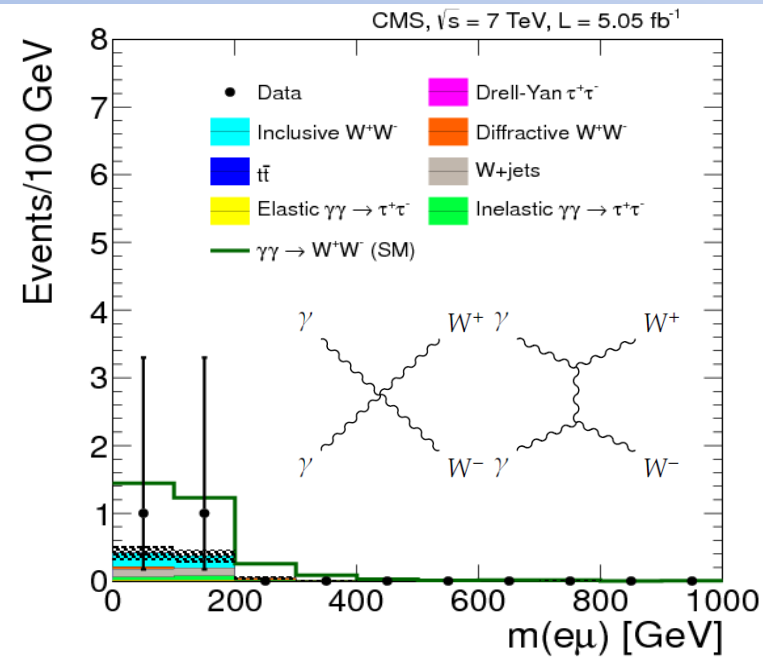
- ✓ pp→ γγ(→ WW)p*p* with forward scattered protons escaping detection. Protons stay intact, or dissociate into an undetected low-mass system
- ✓ Reconstruct a vertex with
  WW→μ^+e^- or μ^-e^+(opposite flavor)
- ✓ lepton p_T>20GeV, |η|<2.4,
- ✓ m_{ll}>20GeV, p_T^{ll}>30GeV
- ✓ no extra tracks from the μe vertex.

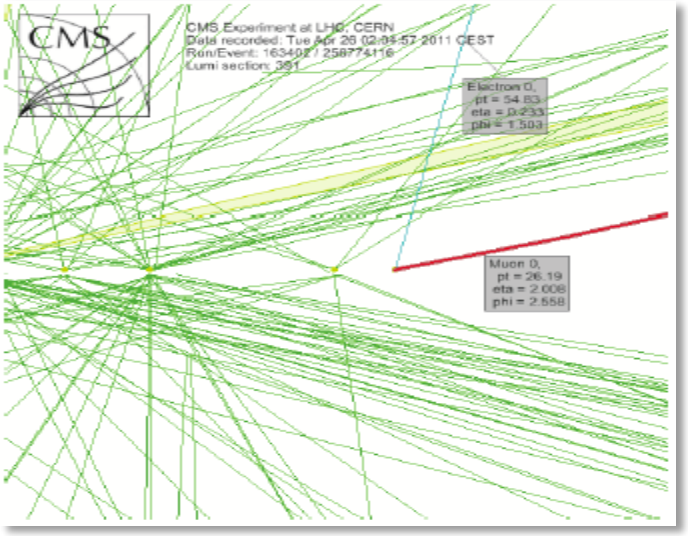
Backgrounds:

Inclusive W^+W^-, Drell-Yan to ττ, γγ → ττ.

The SM expectation is **2.2 ± 0.4 signal** and **0.84 ± 0.15 background** events.
Two signal events are observed

Measured cross section: $\mathbf{2.2^{+3.3}_{-2.0}}$ **fb**
SM: **3.8 ± 0.9 fb**





8 TeV

WVγ -> lνjjγ

Phys. Rev. D 90, 032008 (2014)

Signature:

lepton + E_T^{miss} + jets + γ

One W boson decays leptonically (l = e,m)

The other boson V (W or Z) decays hadronically (jj)

Event selection:

$p_T^{\gamma} > 30$ GeV, $|\eta^{\gamma}|<1.44$

$p_T^{l} > 30(25)$ GeV, l=e(μ)

$|\eta^{l}|<2.5(2.1)$, l=e(μ)

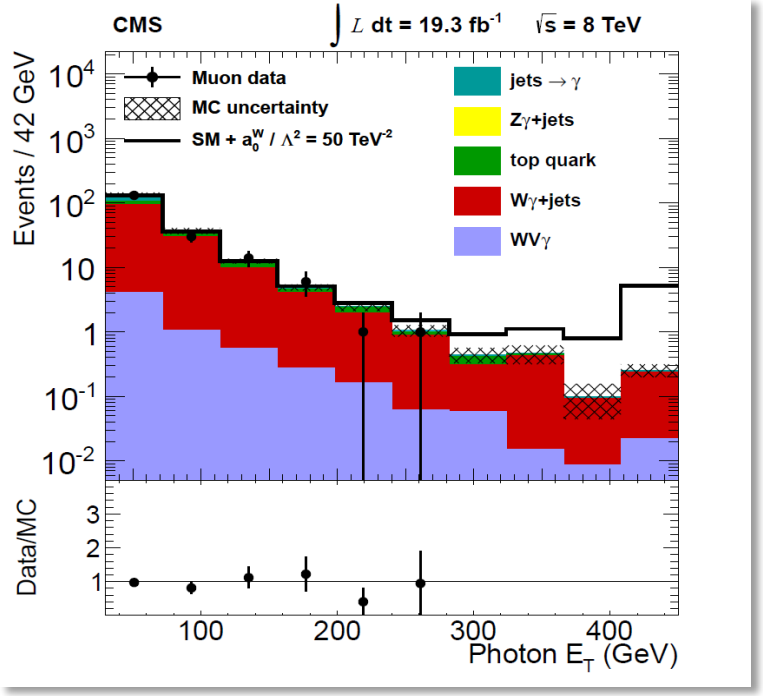
$M_T^{W} > 30$ GeV, $E_T^{miss} > 35$ GeV, $70<m_{jj}<120$ GeV

$p_T^{jets} > 30$ GeV, $|\eta^{jet}|<2.4$, jet b-tag veto

Background:

Wγ +jets(dominant), top, Zγ +jets,

jet->γ misidentification.



Process	Muon channel number of events	Electron channel number of events
SM WWγ	6.6 ± 1.5	5.0 ± 1.1
SM WZγ	0.6 ± 0.1	0.5 ± 0.1
Wγ + jets	136.9 ± 10.5	101.6 ± 8.5
WV + jet, jet → γ	33.1 ± 4.8	21.3 ± 3.3
MC $t\bar{t}\gamma$	12.5 ± 3.0	9.1 ± 2.2
MC single top quark	2.8 ± 0.8	1.7 ± 0.6
MC Zγ + jets	1.7 ± 0.1	1.5 ± 0.1
Multijets	—	7.2 ± 5.1
Total prediction	194.2 ± 11.5	147.9 ± 10.7
Data	183	139

Limit on SM cross section at 95% CL ($p_T^{\gamma} > 30$ GeV, $|\eta^{\gamma}|<1.44$): **311 fb**

SM (NLO): **91.6 ± 21.7 fb**

Anomalous Quartic Gauge Couplings

- Effective lagrangian parameterizes low energy effects of BSM physics

- Different realizations for quartic interactions
  - ❖ nonlinear realization of $SU(2)_L xU(1)$ - lowest order genuine quartic interaction: dimension 6 (arXiv:hep-ph/0310141)
  - ❖linear realization - lowest order genuine quartic interaction: dimension 8 (arXiv:hep-ph/0606118)
- Parameters conversion from the nonlinear realization to the linear realization. The linear realization has parameters with no analog in the nonlinear realization

Variety of parameters available that modify quartic couplings.

	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

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

aQGC limits

❖ The ***γγ → WW*** analysis interprets the results in terms of LEP-like "dimension-6" γγWW aQGC's.

$$-4.0 \times 10^{-6} < a_0^W/\Lambda^2 < 4.0 \times 10^{-6}\,\mathrm{GeV}^{-2}\ (a_C^W/\Lambda^2 = 0, \text{no form factor}),$$
$$-1.5 \times 10^{-5} < a_C^W/\Lambda^2 < 1.5 \times 10^{-5}\,\mathrm{GeV}^{-2}\ (a_0^W/\Lambda^2 = 0, \text{no form factor}).$$

❖ The ***WVγ*** results are Interpreted in terms of both dimension-6 and dimension-8 (linear) anomalous *WWγγ and WWZγ couplings*

Observed limits	Expected limits
$-21 < a_0^W/\Lambda^2 < 20\,\mathrm{TeV}^{-2}$	$-24 < a_0^W/\Lambda^2 < 23\,\mathrm{TeV}^{-2}$
$-34 < a_C^W/\Lambda^2 < 32\,\mathrm{TeV}^{-2}$	$-37 < a_C^W/\Lambda^2 < 34\,\mathrm{TeV}^{-2}$
$-25 < f_{T,0}/\Lambda^4 < 24\,\mathrm{TeV}^{-4}$	$-27 < f_{T,0}/\Lambda^4 < 27\,\mathrm{TeV}^{-4}$
$-12 < \kappa_0^W/\Lambda^2 < 10\,\mathrm{TeV}^{-2}$	$-12 < \kappa_0^W/\Lambda^2 < 12\,\mathrm{TeV}^{-2}$
$-18 < \kappa_C^W/\Lambda^2 < 17\,\mathrm{TeV}^{-2}$	$-19 < \kappa_C^W/\Lambda^2 < 18\,\mathrm{TeV}^{-2}$

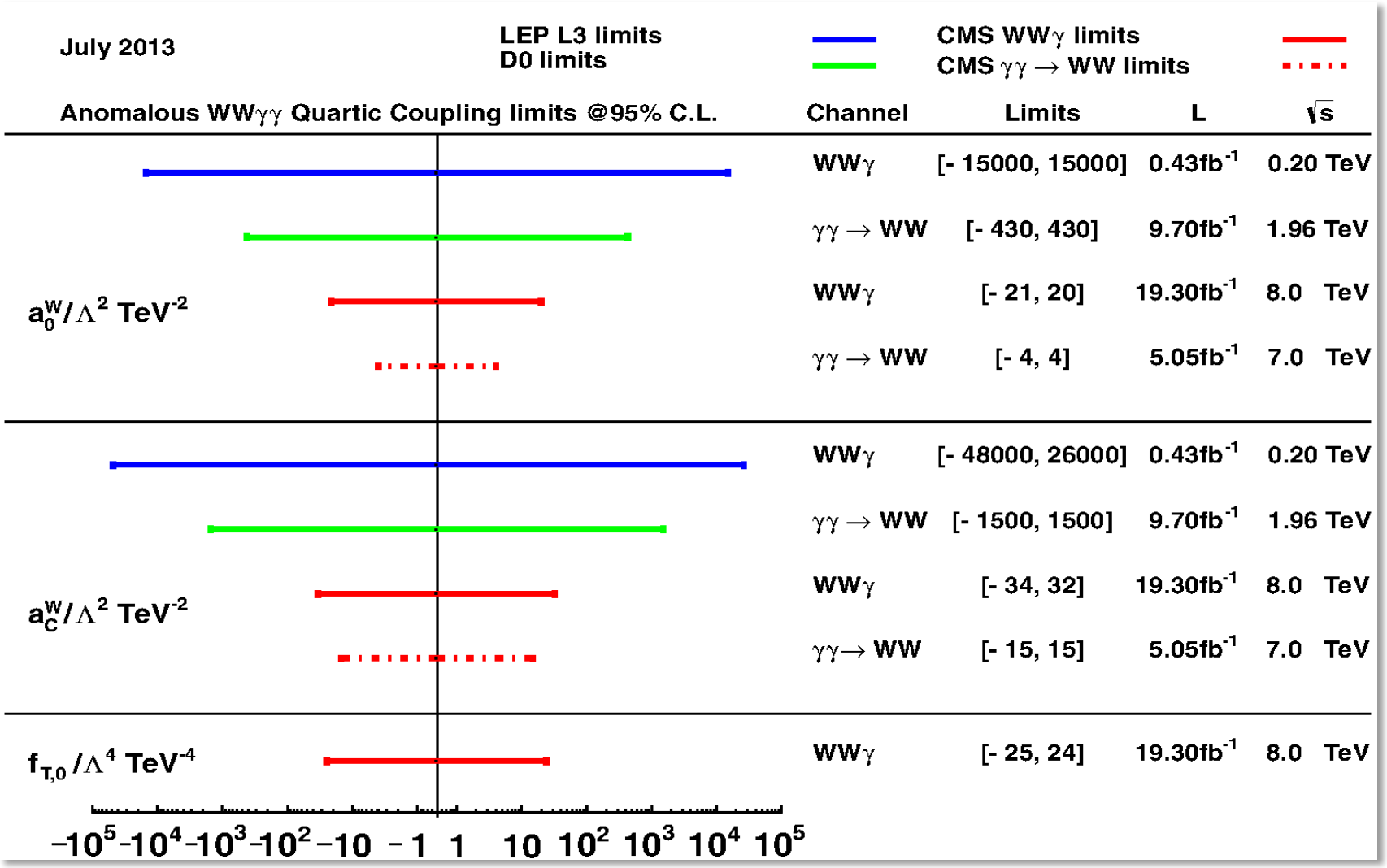
Observed limits (TeV^{-4})	Expected limits (TeV^{-4})
$-77 < f_{M,0}/\Lambda^4 < 81$	$-89 < f_{M,0}/\Lambda^4 < 93$
$-131 < f_{M,1}/\Lambda^4 < 123$	$-143 < f_{M,1}/\Lambda^4 < 131$
$-39 < f_{M,2}/\Lambda^4 < 40$	$-44 < f_{M,2}/\Lambda^4 < 46$
$-66 < f_{M,3}/\Lambda^4 < 62$	$-71 < f_{M,3}/\Lambda^4 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

First limits on CP-conserving *WWZγ* couplings k_c^W, k_0^W

Translation of the limits on WWγγ a_0^W and a_C^W (dimension-6) to limits on $f_{M,I}$ (dimension-8).

aQGC – WWγγ limits comparison

Orders of magnitude better than LEP and Tevatron limits on WWγγ.



Summary

- Processes with *multiple bosons* in final state has been studied with Run1 data at 7 and 8 TeV

  - ✓ *Production cross* section have been measured and is found to be in agreement with the SM prediction (NLO).

  - ✓ Contribution from anomalous triple and quartic gauge coupling is not observed
    - – limits are set , many of them are world leading

- Many opportunities and challenges ahead as the start of LHC Run II is approaching