Production of Multiple Electroweak Bosons at CMS

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on behalf of the CMS Collaboration

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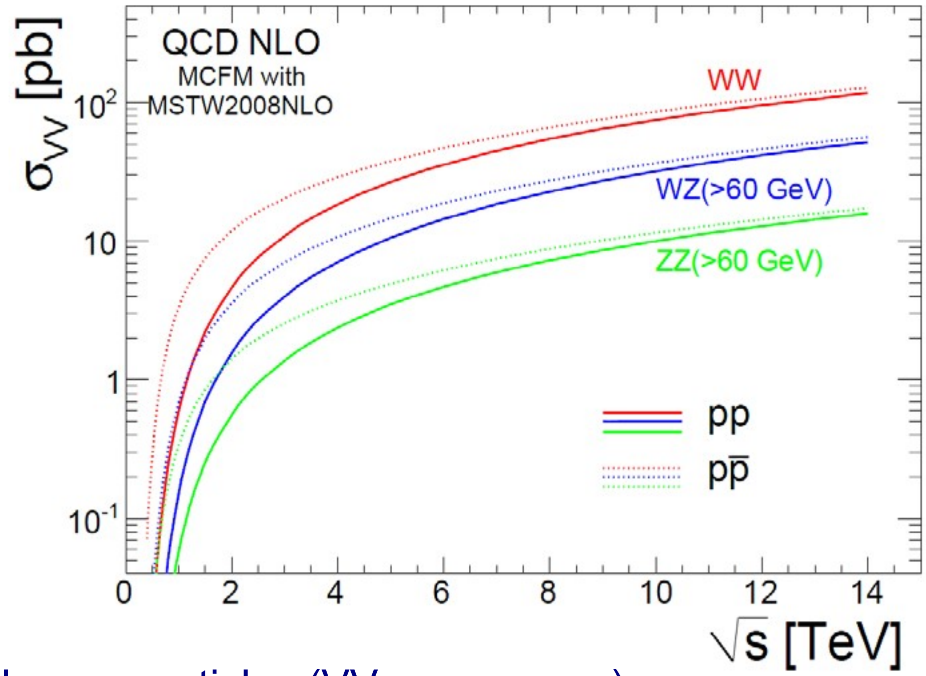
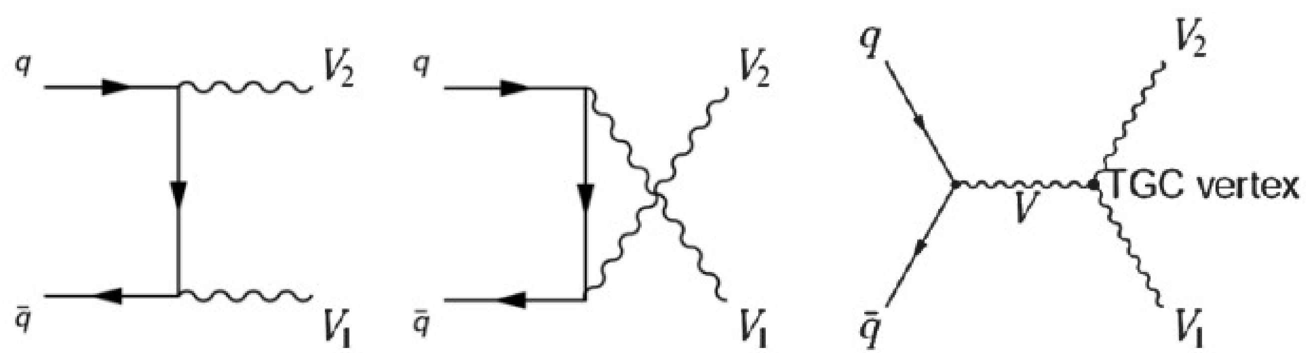
Diboson Physics

- Fundamental test of the Standard Model
  - Vector boson self-interactions probe the non-abelian gauge structure of the SM
- Importance for Higgs searches
  - Despite the relatively small cross section $\mathcal{O}$(1-100 pb), diboson processes are irreducible background to many Higgs searches: $H \rightarrow WW, ZZ, Z\gamma$



- Probe for New Physics
  - Diboson cross sections are sensitive to possible new particles (VV resonances)
  - Anomalous triple and quadruple gauge couplings (aTGC, aQGC) modify diboson cross sections and kinematics

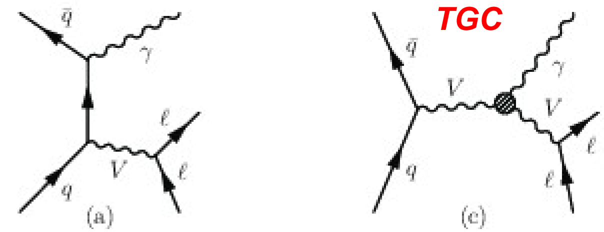


Overview of Diboson Physics at CMS

- Most diboson processes studied with full 2011 CMS data set at 7 TeV
- First results at 8 TeV for WW and ZZ

Process	Int. luminosity at 7 TeV	Int. luminosity at 8 TeV	Limits on TGC, QGC
$W\gamma \to \ell\nu\gamma$	5.0 fb^{-1}	-	$WW\gamma$
$Z\gamma \to \ell\ell\gamma$	5.0 fb^{-1}	-	$ZZ\gamma$, $Z\gamma\gamma$
$Z\gamma \to \nu\nu\gamma$	5.0 fb^{-1}	-	$ZZ\gamma$, $Z\gamma\gamma$
$WW + WZ \to \ell\nu jj$	5.0 fb^{-1}	-	$WW\gamma$, WWZ
$WZ \to 3\ell\nu$	1.0 fb^{-1}	-	WWZ
$WW \to 2\ell 2\nu$	4.9 fb^{-1}	3.5 fb^{-1}	$W\gamma W$, WZW
$ZZ \to 4\ell$	5.0 fb^{-1}	5.3 fb^{-1}	ZZZ, $Z\gamma Z$
$ZZ \to 2\ell 2\nu$	1.1 fb^{-1}	-	ZZZ, $Z\gamma Z$
Exclusive $\gamma\gamma \to WW \to e\mu 2\nu$	5.0 fb^{-1}	-	$\gamma\gamma WW$

$W\gamma \rightarrow \ell\nu\gamma$ ($\ell = e, \mu$)

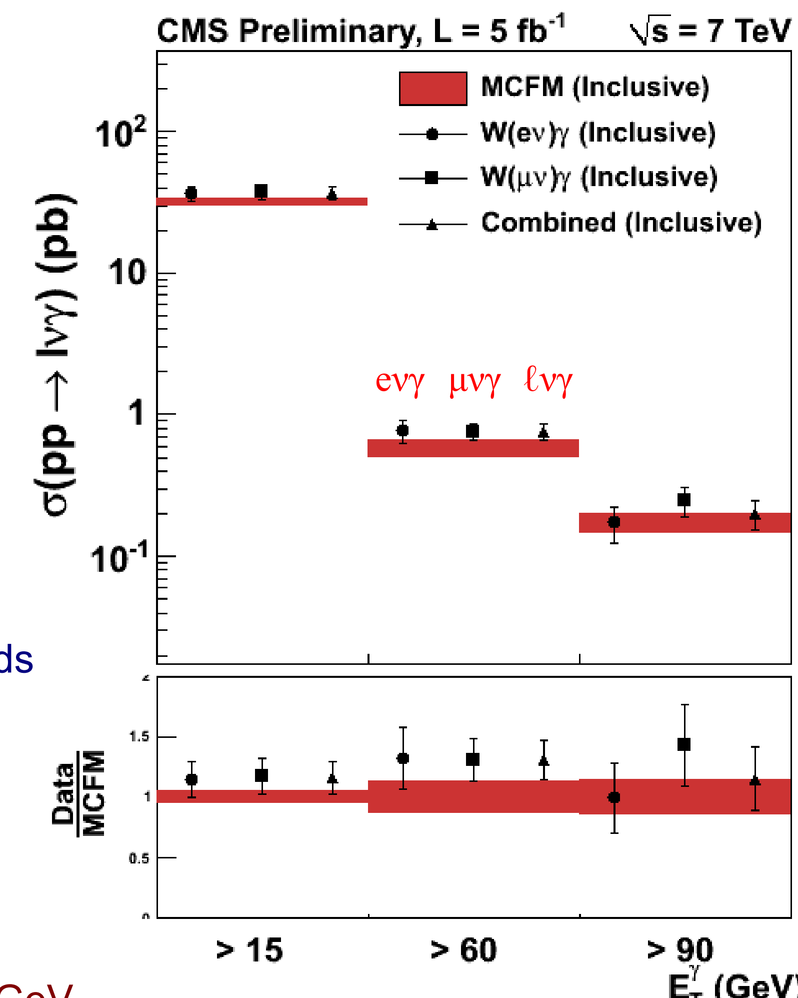


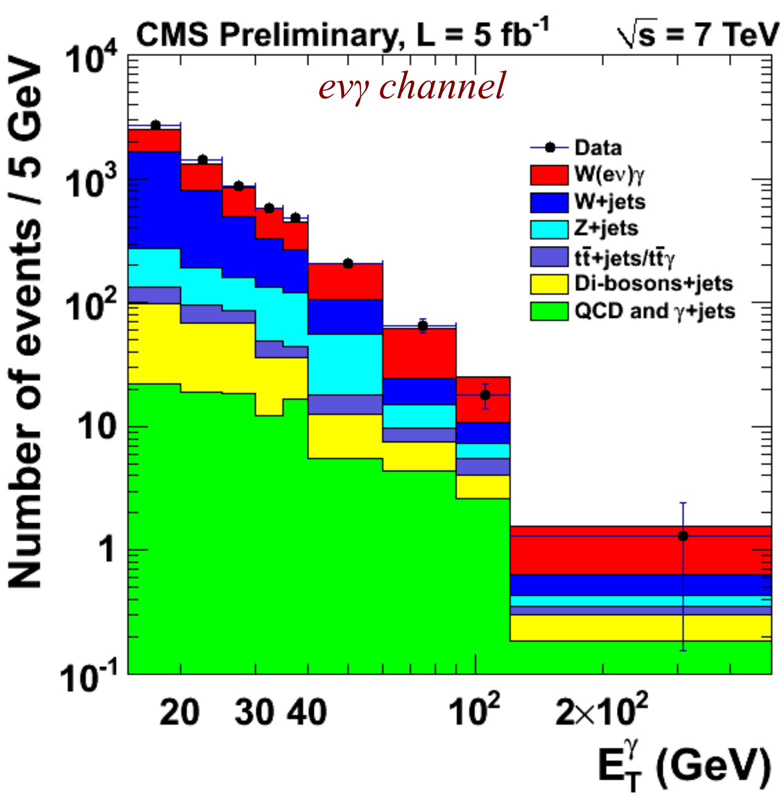
Signature and selection

- Exactly 1 isolated lepton: $p_T > 35$ GeV/c + trigger
- 1 isolated photon: $p_T > 15$ GeV/c, $\Delta R(\gamma, \ell) > 0.7$
- Large W transverse mass: $M_T(\ell, E_t^{miss}) > 70$ GeV/c^2

Main backgrounds

- W + jets, tt + jets: mis-identified jet
- DY, diboson: mis-identified electron





- Cross sections for different $E_T(\gamma)$ thresholds
- Dominant systematic: $\rightarrow$ data-driven W+jets

@ 7 TeV, $E_T(\gamma) > 15$ GeV

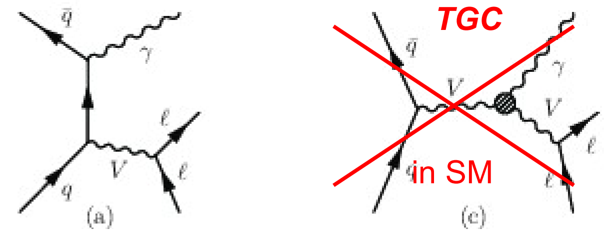
$$\sigma_{CMS}(pp \rightarrow \ell\nu\gamma) = (37.0 \pm 0.8_{stat} \pm 4.0_{syst} \pm 0.8_{lumi}) \text{ pb}$$

$$\sigma_{NLO}(pp \rightarrow \ell\nu\gamma) = (31.8 \pm 1.8) \text{ pb} \quad \text{(from MCFM)}$$

1σ

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEWK11009

$Z\gamma \rightarrow \ell\ell\gamma$ (ℓ = e, μ)

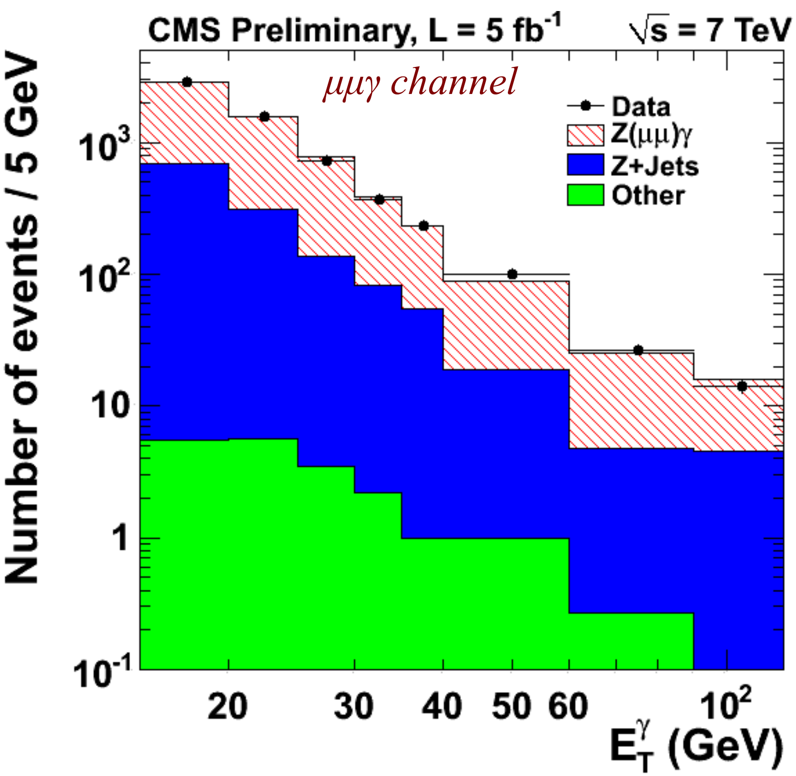


Signature and selection

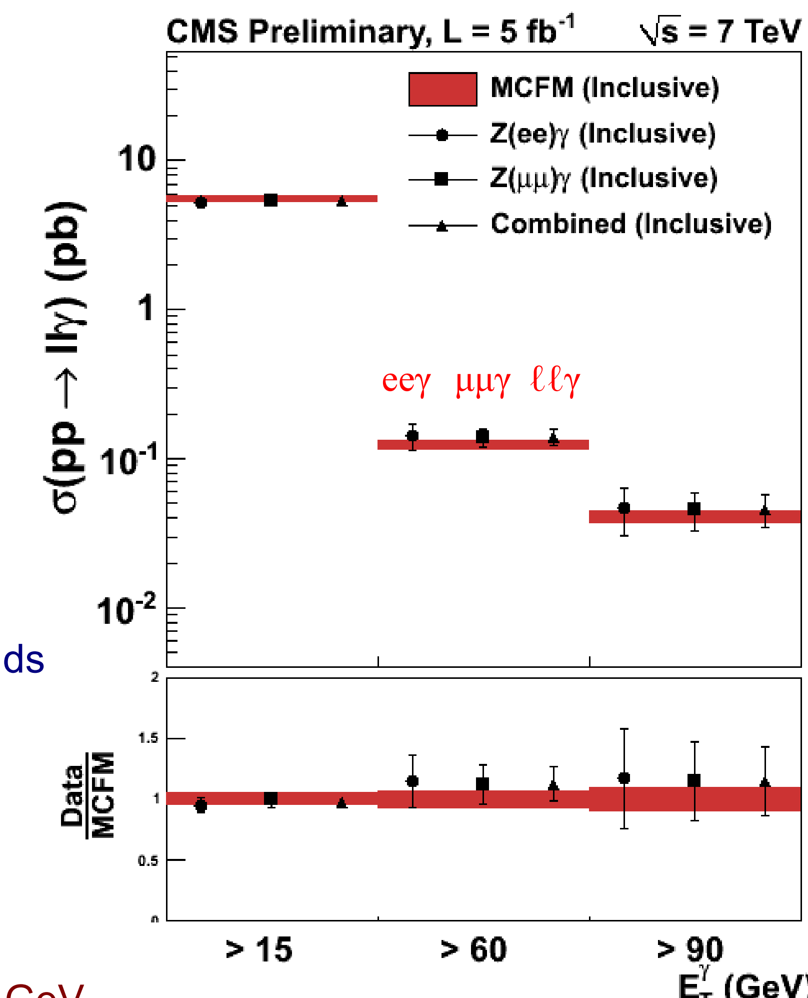
- 2 isolated leptons: p_T > 20 GeV/c + trigger
- 1 isolated photon: p_T > 15 GeV/c, $\Delta R(\gamma, \ell)$ > 0.7
- Z invariant mass: $M(\ell\ell)$ > 50 GeV/c^2

Main backgrounds

- Z + jets: mis-identified jet
- Diboson: mis-identified electron



- Cross sections for different $E_T(\gamma)$ thresholds
- Fair agreement with SM NLO predictions from MCFM



@ 7 TeV, $E_T(\gamma)$ > 15 GeV

$$\sigma_{CMS}(pp \rightarrow \ell\ell\gamma) = (5.33 \pm 0.08_{stat} \pm 0.25_{syst} \pm 0.12_{lumi})\ \text{pb}$$

$$\sigma_{NLO}(pp \rightarrow \ell\ell\gamma) = (5.4 \pm 0.2)\ \text{pb} \quad \text{(from MCFM)}$$

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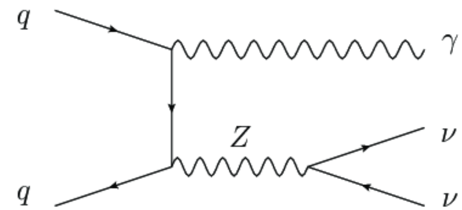
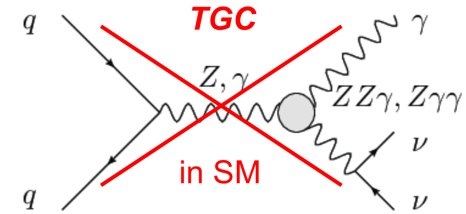
$Z\gamma \rightarrow \nu\nu\gamma$



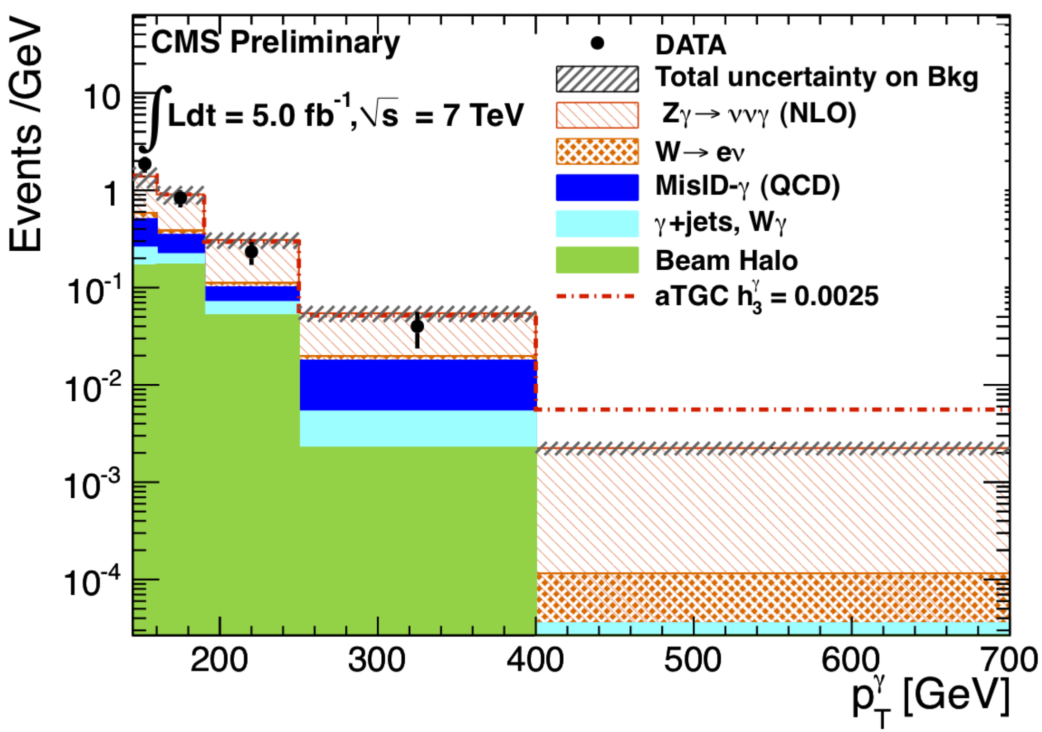


Signature and selection

- 1 high-p_T, isolated photon: p_T > 145 GeV/c + trigger
- Large missing E_T: E_T^{miss} > 130 GeV

Main backgrounds

- bremsstrahlung from cosmic and beam-halo muons
  → photon in time with beam crossing
  → veto on cosmic and beam-halo muons
- multijets → isolation, shower shape consistent with a γ
- $W \rightarrow e\nu$ → no tracker activity matched to the γ candidate



- Large systematic uncertainty
- Main systematics from background measurement
  - non-collision: beam halo, cosmics
  - collision: jet and track veto efficiency
- Very good agreement with SM NLO predictions

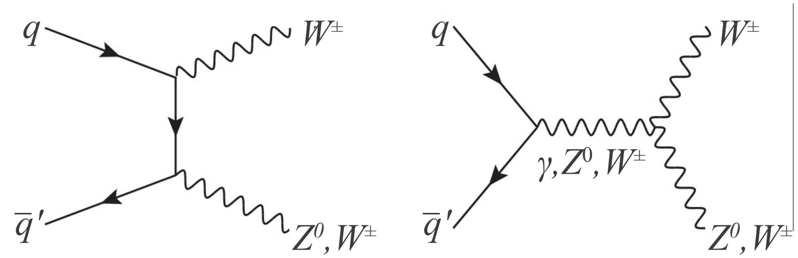
@ 7 TeV, $E_T(\gamma)$ > 145 GeV, $|\eta(\gamma)|$ < 1.4

$\sigma_{CMS}(pp \rightarrow \nu\nu\gamma) = (21.3 \pm 4.2_{stat} \pm 4.3_{syst} \pm 0.5_{lumi})$ fb

$\sigma_{NLO}(pp \rightarrow \nu\nu\gamma) = (21.9 \pm 1.1)$ fb (from BAUR)

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMP12020

WW + WZ → ℓνjj (ℓ = e, μ)

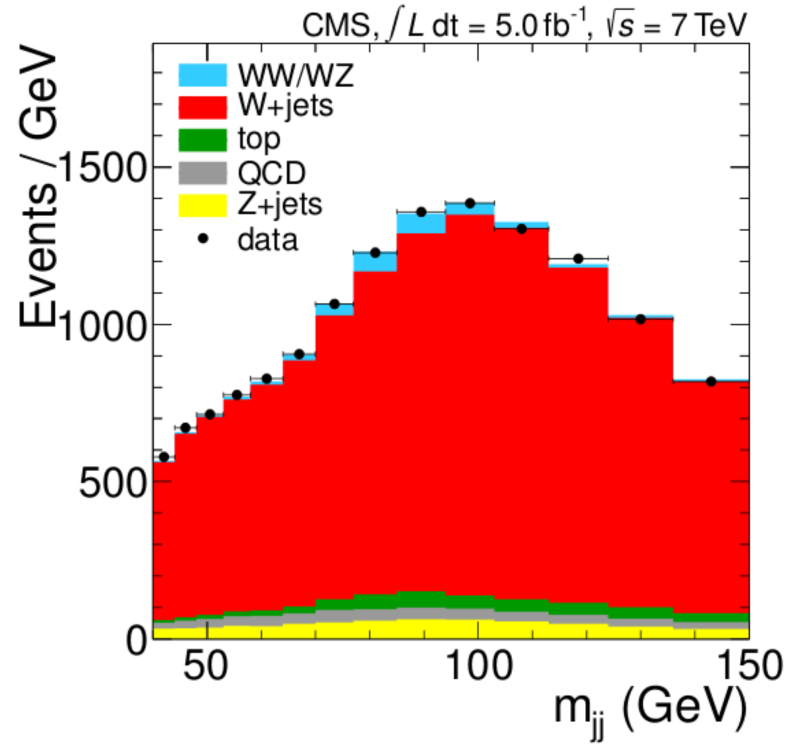


Signature and selection

- Exactly 1 isolated lepton: p_T > 25/30 GeV/c (μ/e) + trigger
- Exactly 2 jets: p_T > 35 GeV/c
- Large missing E_T: E_T^{miss} > 25/30 GeV (μ/e)
- W transverse mass: $M_T(\ell, E_t^{miss})$ > 30/35 GeV/c^2 (μ/e)

Main backgrounds

- W(ℓν) + jets, top (tt, tW), DY + jets. multijets



- ×6 branching ratio of fully leptonic decay
  - ➔ larger statistics at high p_T
- Access to boson mass

  … but

- Jet resolution does not allow to separate W and Z mass
  - ➔ inclusive measurement of WW and WZ
- Large background
  - ➔ signal and background yields determined with an unbinned likelihood fit to the dijet mass spectrum

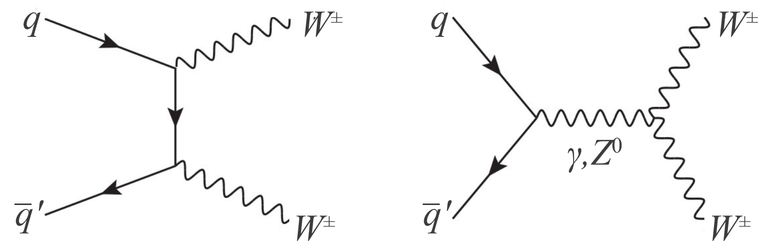
Inclusive WW + WZ cross section @ 7 TeV

σ_{CMS} = (68.9 ± 8.7$_{stat}$ ± 9.7$_{syst}$ ± 1.5$_{lumi}$) pb

σ_{NLO} = (65.6 ± 2.2) fb (from MCFM)

CERN-PH-EP-2012-311, arXiv:1210.7544

$WW \to \ell\nu\ell\nu$ (ℓ = e, μ)

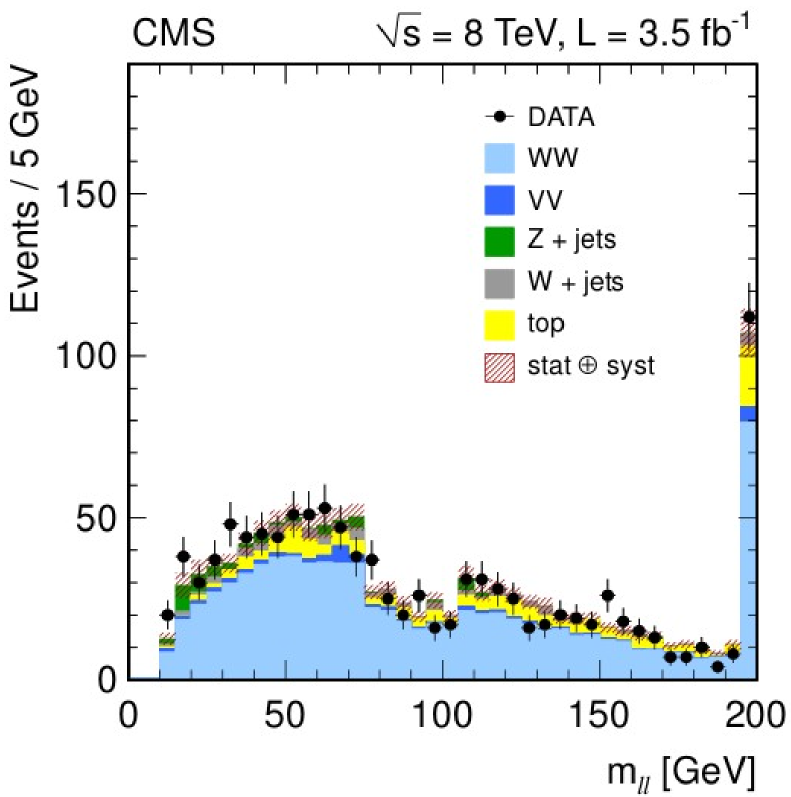


Signature and selection

- 2 isolated leptons: p_T > 20 GeV/c + trigger
- Large missing E_T: E_T^{miss} > 20/45 GeV (eμ/ee,μμ)

Main backgrounds

- $Z^{(*)}$ + jets → veto $\ell^+\ell^-$ compatible with Z mass
- top ($t\bar{t}$, tW) → veto high-p_T jets, top-tagged jets
- WZ, ZZ → veto events with a third lepton



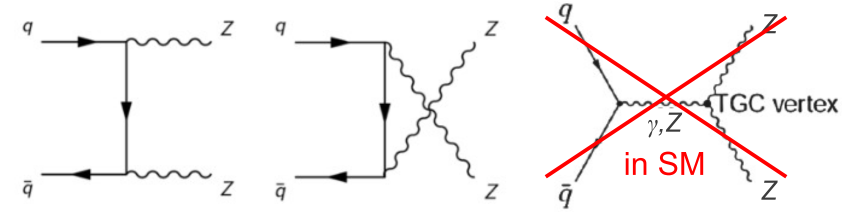
- Measured cross sections slightly above NLO predictions
- Contribution from Higgs to WW production around 4% (not included in theoretical prediction)

Inclusive WW cross section:

	σ_{CMS} [pb]	σ_{NLO} [pb] (MCFM)
7 TeV	$52.4 \pm 2.0_{stat} \pm 4.5_{syst} \pm 1.2_{lumi}$	47.0 ± 2.0
8 TeV	$69.9 \pm 2.8_{stat} \pm 5.6_{syst} \pm 3.1_{lumi}$	$57.3^{+2.4}_{+1.6}$

CERN-PH-EP-2012-376, Phys. Lett. B 721 (2013) 190-211

$ZZ \to 2\ell 2\ell'$ (ℓ=e,μ/ ℓ'=e,μ,τ)



Signature and selection

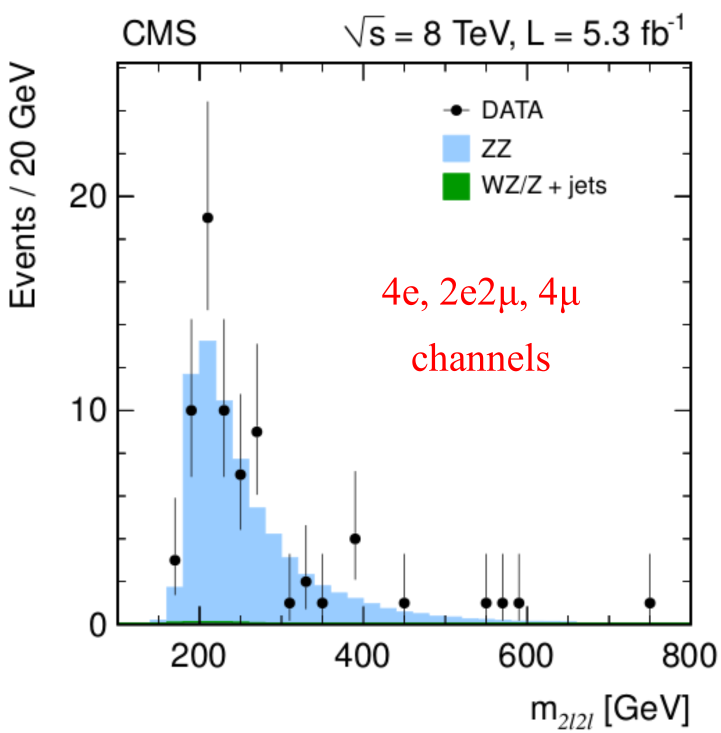
- 4 isolated leptons: p_T > 20/10/7/5 GeV/c + trigger
- Two on-shell Z candidates: 60 < $M_{\ell\ell}$ < 120 GeV/c^2

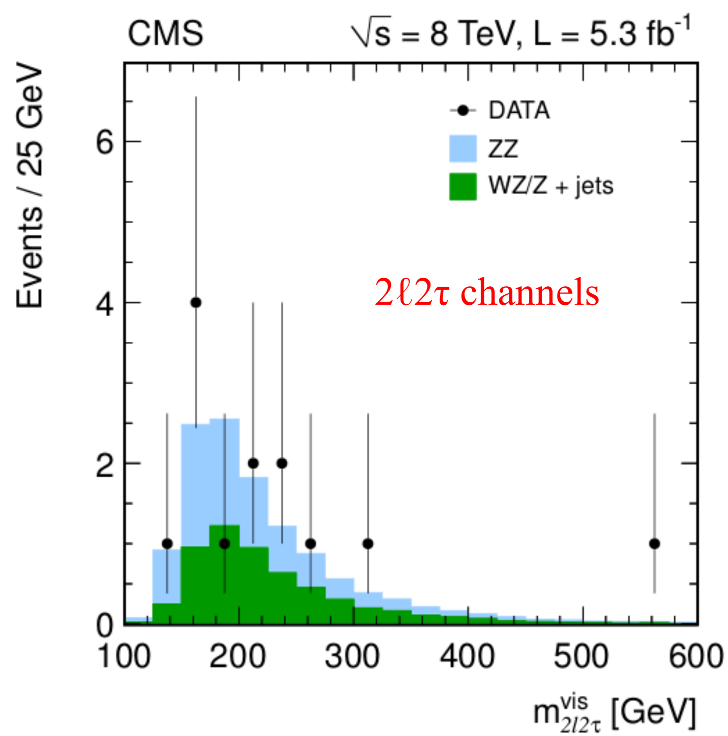
Main backgrounds

- Very clean signature, small background
- WZ + jets, Z + jets, tt, Z + bb

Inclusive ZZ cross section, 60 < M_Z < 120 GeV/c^2

	σ_{CMS} [pb]	σ_{NLO} [pb]
7 TeV	$6.24^{+0.86}_{-0.80}\,_{stat}\;^{+0.41}_{-0.32}\,_{syst} \pm 0.14_{lumi}$	6.3 ± 0.4
8 TeV	$8.4 \pm 1.0_{stat} \pm 0.7_{syst} \pm 0.4_{lumi}$	7.7 ± 0.4

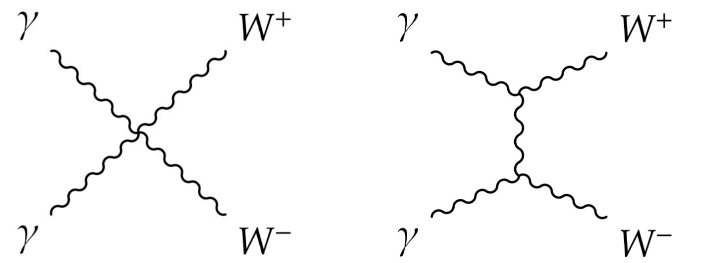




- Good agreement with NLO predictions in all channels
- Results dominated by statistical uncertainties

CERN-PH-EP-2012-376,
Phys. Lett. B 721 (2013) 190-211

Exclusive $\gamma\gamma \rightarrow WW \rightarrow e\nu\mu\nu$



- Process $pp \rightarrow p^{(*)}\gamma\gamma p^{(*)} \rightarrow p^{(*)} W^+W^- p^{(*)}$
- Both exclusive ("elastic") and quasi-exclusive (single/double dissociation) production considered
- Only opposite-flavour ($e\mu$) final states analyzed ~ 10 times more background in ee/μμ channels
  - $\gamma\gamma \rightarrow \mu\mu$ used for efficiency measurements

Signature and selection

- 2 isolated leptons $e^{\pm}\mu^{\mp}$: p_T > 20 GeV/c + trigger
- Dilepton p_T: $p_T(e\mu)$ > 30 GeV/c
- Dilepton mass: $M(e\mu)$ > 20 GeV/c^2
- $e\mu$ vertex with no extra tracks

Main backgrounds

- Inclusive WW, W + jets, $\tau\tau$ + jets, DY + jets

- 2 events observed, with an expectation of

  (2.2 ± 0.5) signal + (0.84 ± 0.23) background events
- This is translated into a cross section measurement and upper limit:

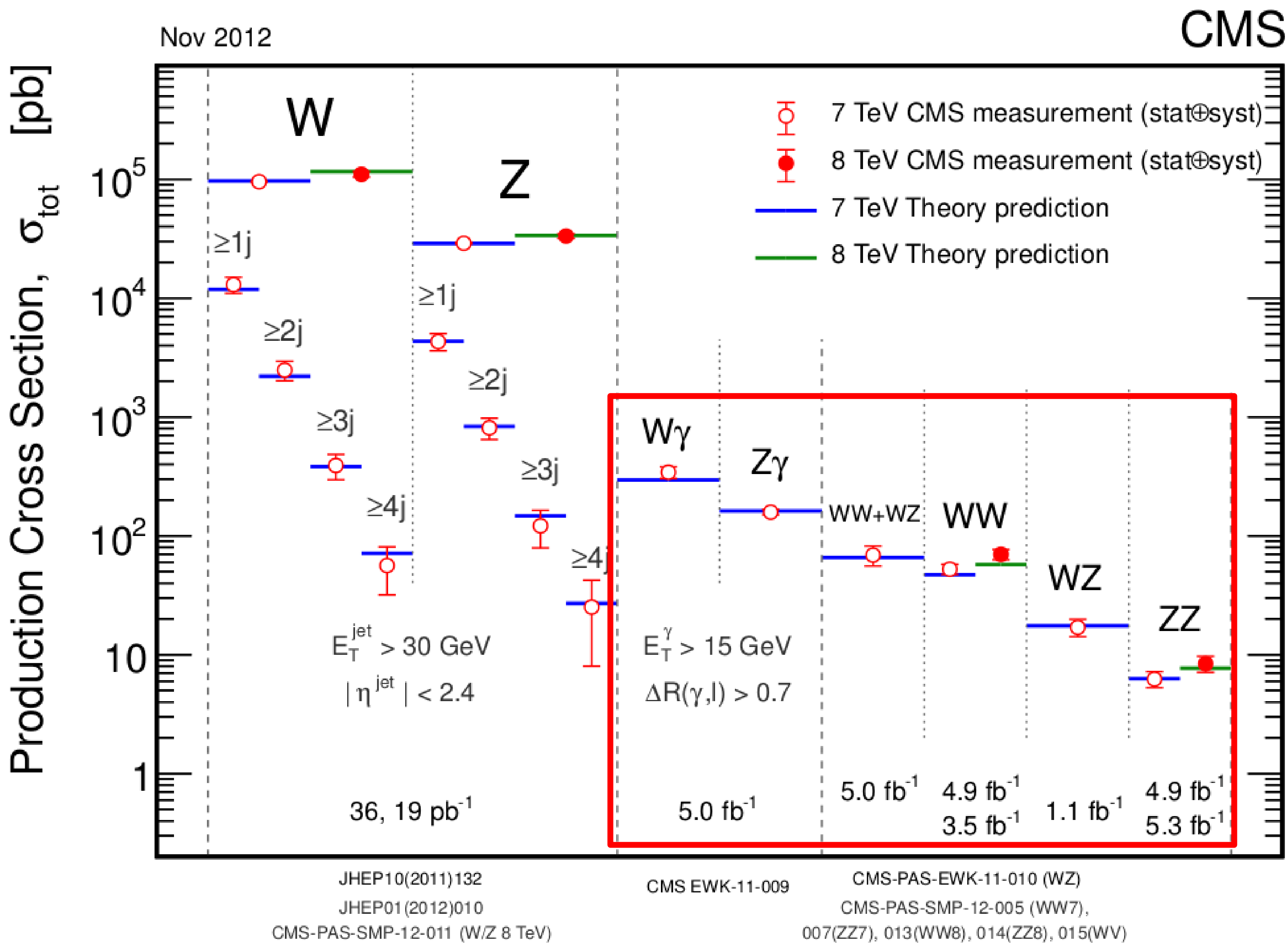
Exclusive $pp \rightarrow p^{(*)}WWp^{(*)} \rightarrow p^{(*)}e\mu p^{(*)}$ @ 7 TeV

$\sigma_{CMS} = 2.1^{+3.1}_{-1.9}$ (stat+syst) fb, < 8.4 fb at 95% CL

$\sigma_{SM} = (3.8 \pm 0.9)$ fb (from CalcHEP)

http://cms-physics.web.cern.ch/cms-physics/public/FSQ-12-010-pas.pdf

Summary of Diboson Cross Sections



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

Triple and Quartic Gauge Couplings

- The SM predicts exact values for vector boson couplings
- Non-SM couplings are signatures of New Physics
- aTGC and aQGC can be modelled with an effective Lagrangian e.g.

$$\mathcal{L}/g_{WWV} = ig_1^V\left[W^\dagger_{\mu\nu}W^\mu V^\nu - W^\dagger_\mu V_\nu W^{\mu\nu}\right] + i\kappa^V W^\dagger_\mu W_\nu V^{\mu\nu} + \frac{i\lambda^V}{M_W^2}W^\dagger_{\lambda\mu}W^\mu{}_\nu V^{\nu\lambda}$$

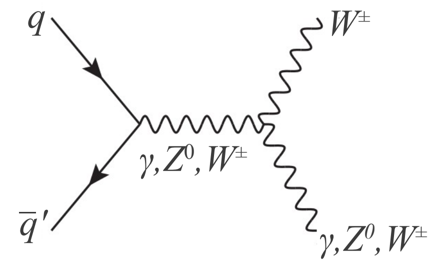
coupling	parameters	channels
WWγ	λ_γ $\Delta\kappa_\gamma$	WW, Wγ
WWZ	λ_Z $\Delta\kappa_Z$ $\Delta g_1{}^Z$	WW, WZ
Zγγ	$h_3{}^\gamma$ $h_4{}^\gamma$	Zγ
ZZγ	$h_3{}^Z$ $h_4{}^Z$	Zγ
ZγZ	f_4^Z $h_5{}^Z$	ZZ
ZZZ	f_4^Z f_5^Z	ZZ
γγWW	$a_0{}^W/\Lambda$ $a_C{}^W/\Lambda$	$\gamma\gamma \to WW$

all 0 in SM

form factors can be used to prevent unitarity violation at high energies

- Anomalous couplings modify the diboson kinematic spectra
  - diboson invariant mass M^{VV}, boson transverse momentum $p_T{}^V$, etc.
- In absence of deviations from the SM expectations, upper limits on aTGC/aQGC parameters can be set using the profile-likelihood formalism and CL_s method
  - systematics are included as nuisance parameters

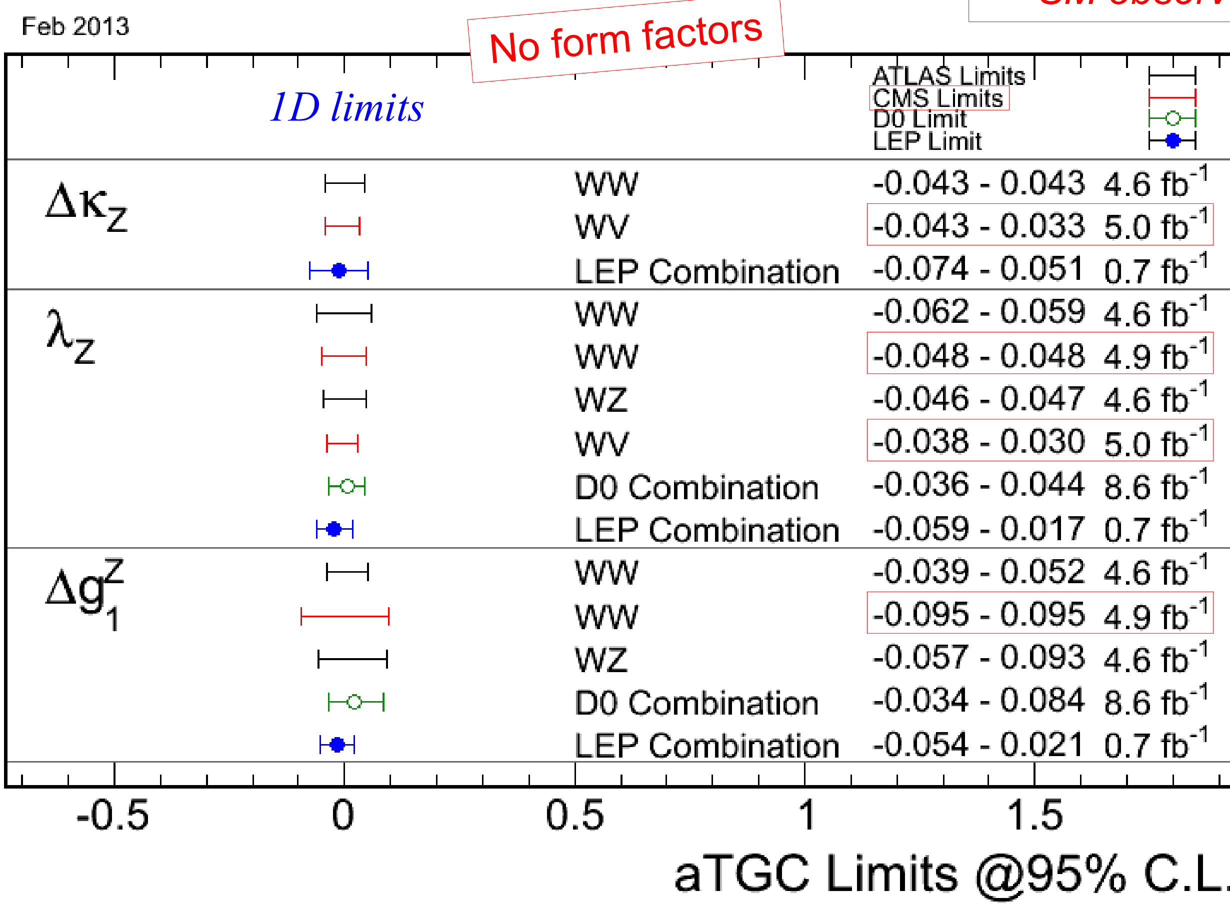
Charged aTGCs

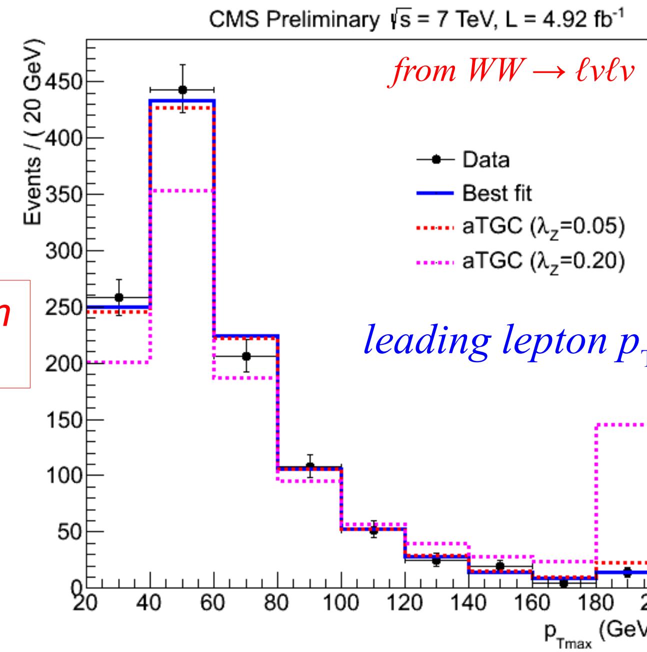


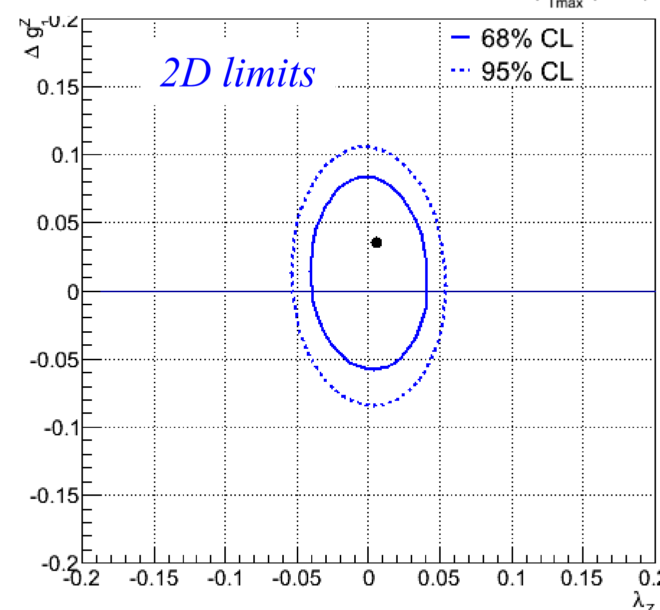
- Vertex WWV (V = γ, Z) probed via WW, WZ, Wγ production
- Limits on parameters

  (1) $\Delta g_1^{\,Z}$, (2) $\Delta\kappa_Z = \Delta g_1^{\,Z} - \Delta\kappa_\gamma \cdot \tan^2\theta_W$, (3) $\lambda = \lambda_Z = \lambda_\gamma$
- 95% CL limits set by using variables such as leading-lepton p_T or boson p_T

No deviations from SM observed

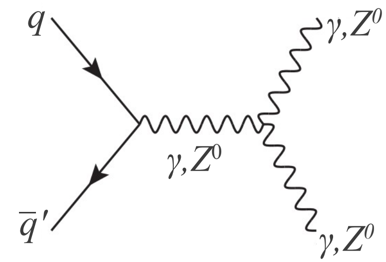




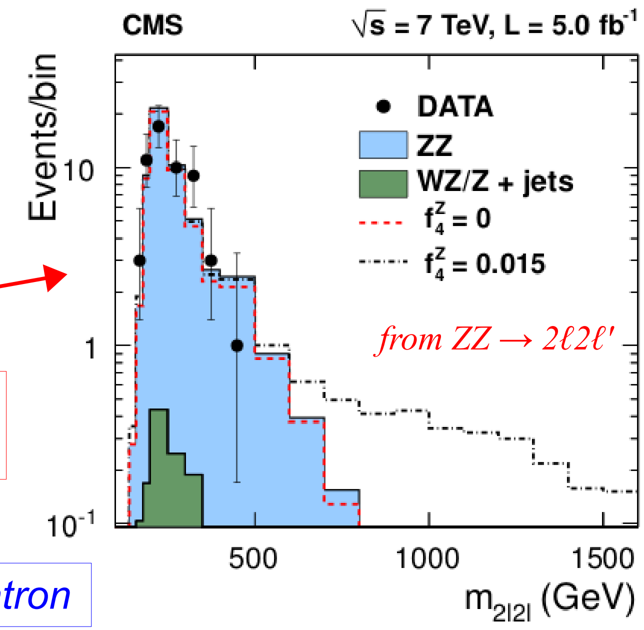


https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMPaTGC

Neutral aTGCs



- Vertices: ZVγ and ZVZ
  - Channels: $Z\gamma \to ee\gamma$ / $\mu\mu\gamma$ / $\nu\nu\gamma$ and $ZZ \to 2\ell 2\ell'$
- Parameters: h_3^V and h_4^V, and f_4^V and f_5^V
- 95% CL limits set by using photon p_T and 4ℓ invariant mass

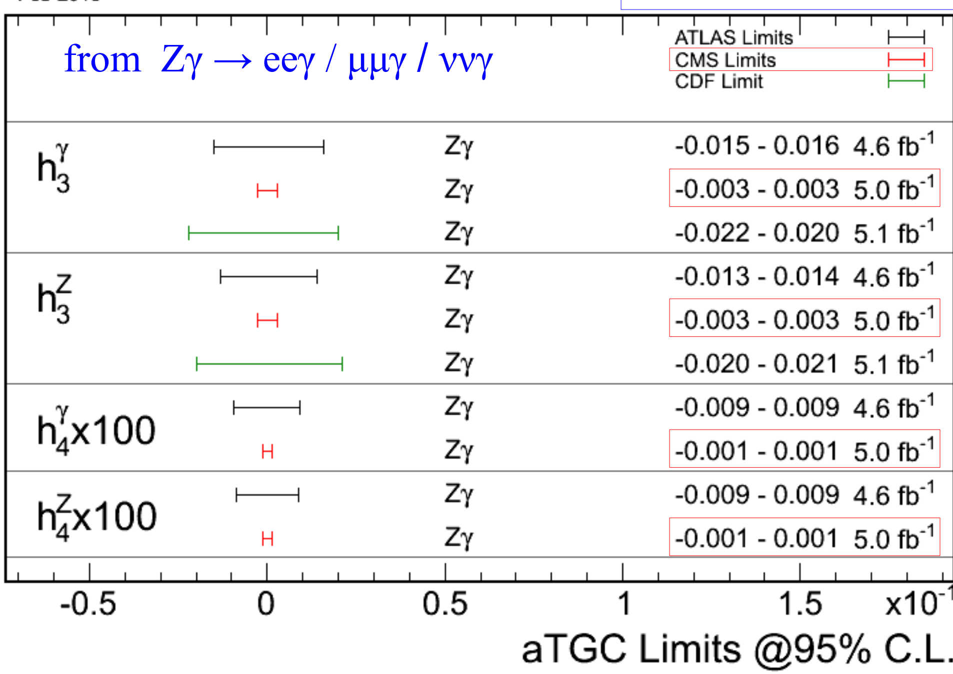


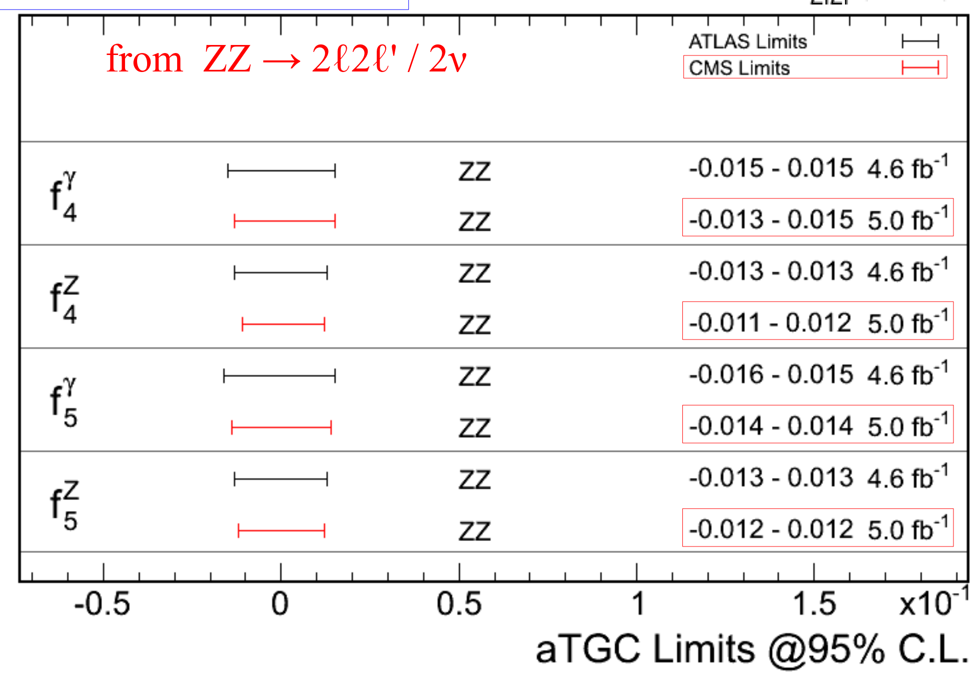
No deviations from SM observed

No form factors

Improve previous limits from LEP, Tevatron

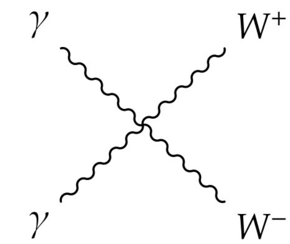
Feb 2013



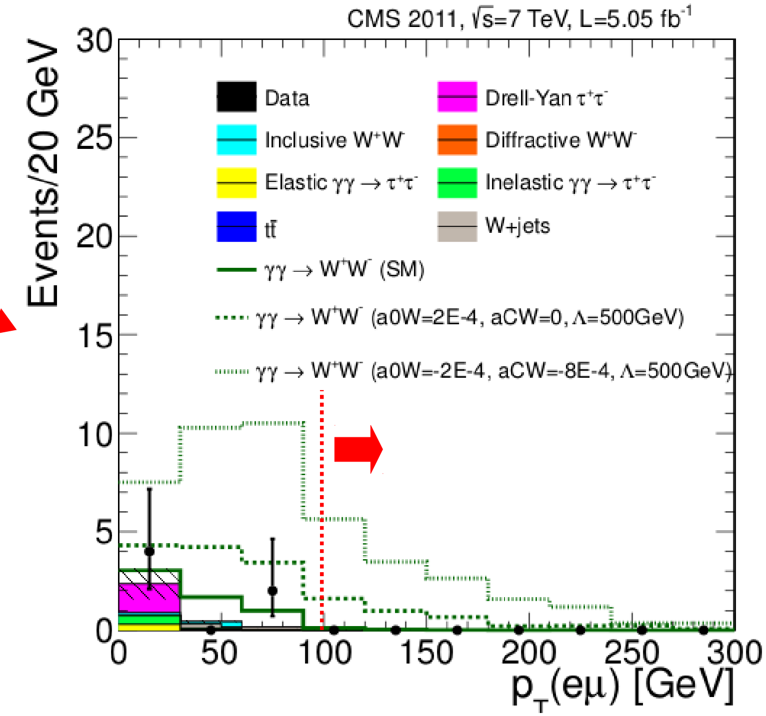


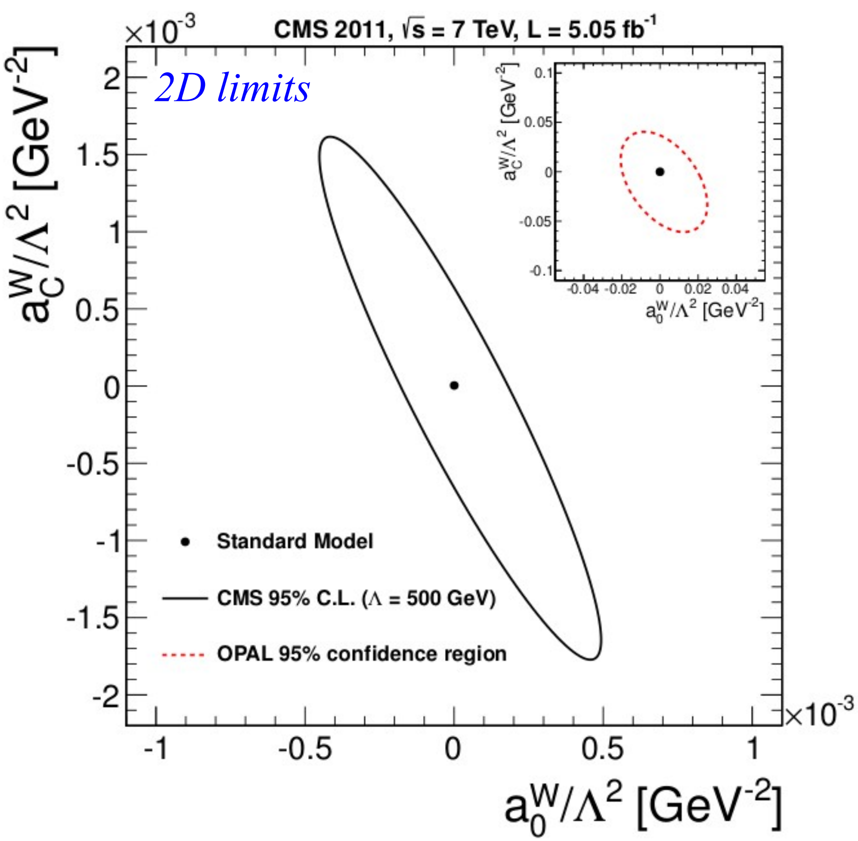
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMPaTGC

aQGCs



- Vertex $\gamma\gamma WW$ probed via exclusive $\gamma\gamma \rightarrow WW$ production
- Limits on parameters a_0^W/Λ and a_C^W/Λ
- 95% CL limits set by using the dilepton p_T tail
  - $p_T(e\mu) > 100$ GeV/c
- No events observed → set upper limits on aQGCs





1D limits	a_0^W/Λ	a_C^W/Λ
Form factor ($\Lambda = 500$ GeV)	[–1.7; 1.7] ×10^{-4} LEP: [–0.020; 0.020]	[–6.0; 6.0] ×10^{-4} LEP: [–0.053; 0.037]
No form factor	[–2.8; 2.8] ×10^{-6}	[–10.2; 10.2] ×10^{-6}

Improve previous limits from LEP by orders of magnitude

http://cms-physics.web.cern.ch/cms-physics/public/FSQ-12-010-pas.pdf

Summary

- Most important diboson processes were measured at CMS with full 2011 dataset at 7 TeV (5 fb^{-1}); WW and ZZ also at 8 TeV with first 5 fb^{-1} of 2012 dataset
  - Measured cross sections are in good agreement with NLO SM predictions
- Anomalous TGC searches showed no apparent deviation from SM
  - Upper limits set on aTGC parameters
    - Charged aTGC limits are in the same ballpark as previous measurements (LEP, Tevatron)
    - Neutral aTGC limits improve results from previous experiments
- First measurement of QGCs at a hadron collider
  - Measured in exclusive $\gamma\gamma \rightarrow WW$ production
  - Upper limits on aQGC parameters are set, greatly improving previous results from LEP