Multi-boson production and searches for anomalous gauge couplings at the LHC
(run1 and run2 prospective)

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On behalf of the CMS and ATLAS Collaboration

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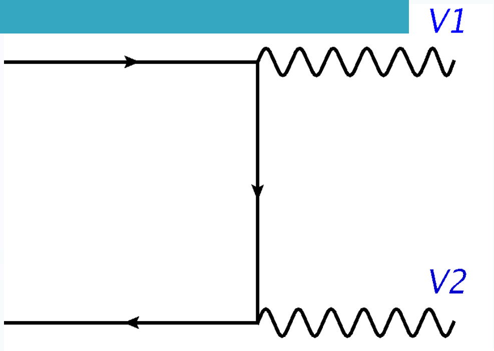
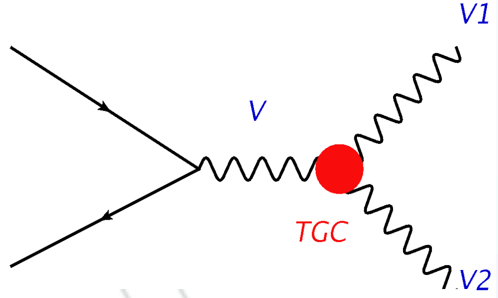
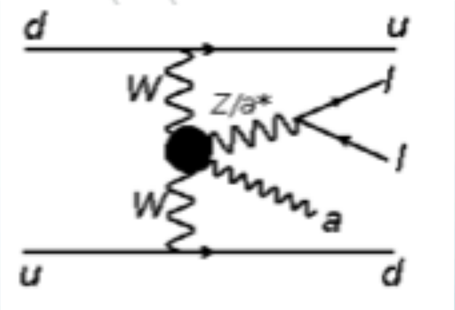
Introduction

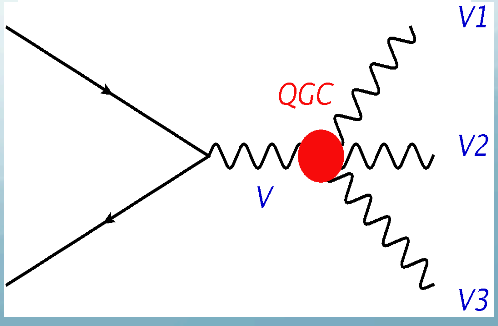
Most of Multi-boson processes have been measured in CMS and ATLAS.

- Multi-boson measurements important test of EWK sector of SM.
- 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







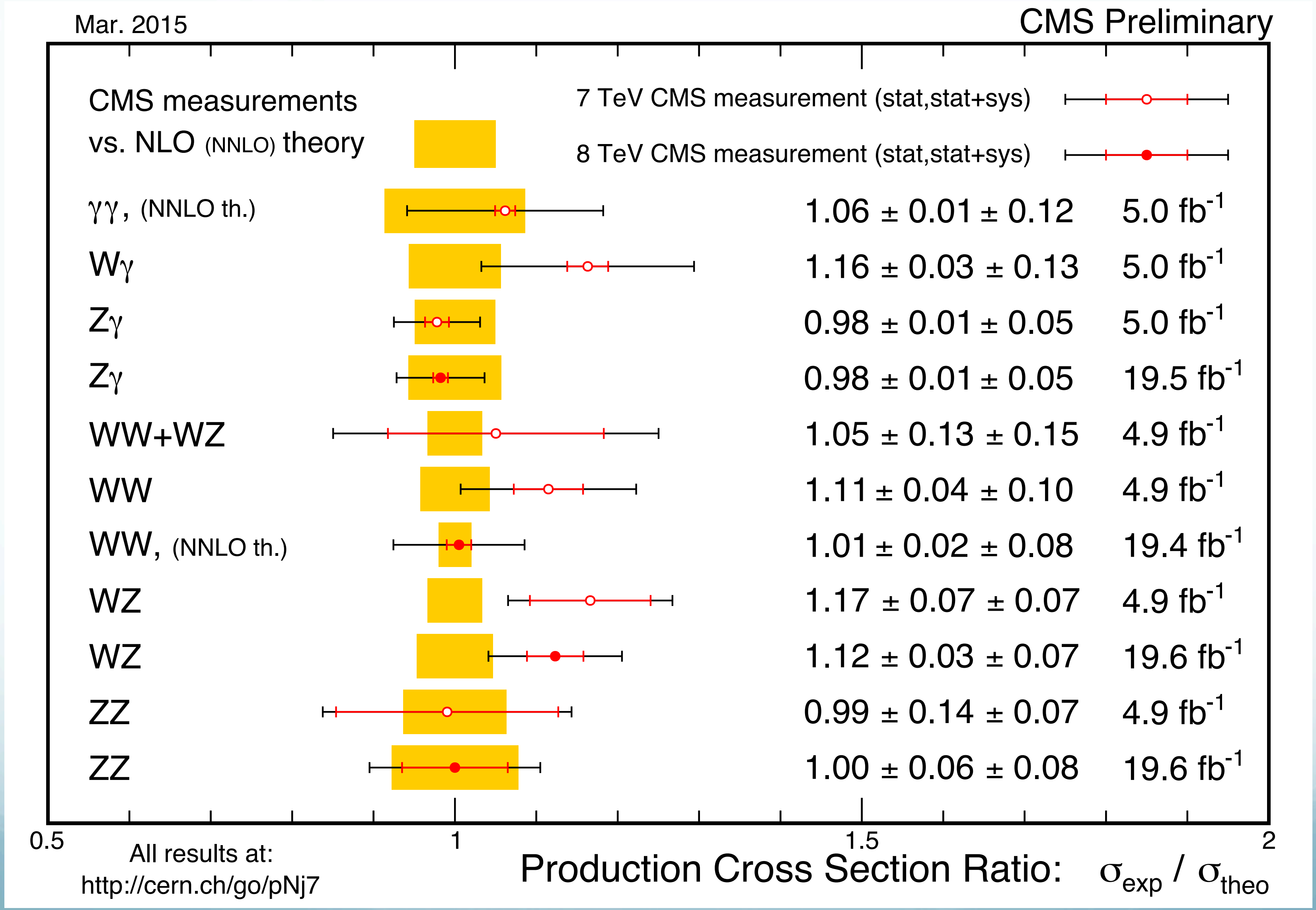


Summary of LHC Run I Results

	CMS		ATLAS	
	7 TeV	8 TeV	7 TeV	8 TeV
Wγ(lνγ)	xs, ac		xs, dx, ac	
Zγ(llγ)	xs, ac	xs, dx, ac	xs, dx, ac	
Zγ($\nu\nu$γ)	xs, ac		xs, dx, ac	
WW(lνlν)	xs, dx, ac	xs, dx, ac	xs, dx, ac	xs
WW(lνjj)		xs, dx		xs, ac
ZZ(4l)	xs, ac	xs, dx, ac	xs, ac	xs
ZZ(2l2ν)	xs, ac	xs, ac	xs, dx,ac	
WZ(3lν)	xs	xs	xs, dx, ac	xs
WV(lνjj)	xs, ac		xs, ac	
VZ(Vbb)	xs			
WVγ		xs limit, ac		
Wγγ				xs, ac

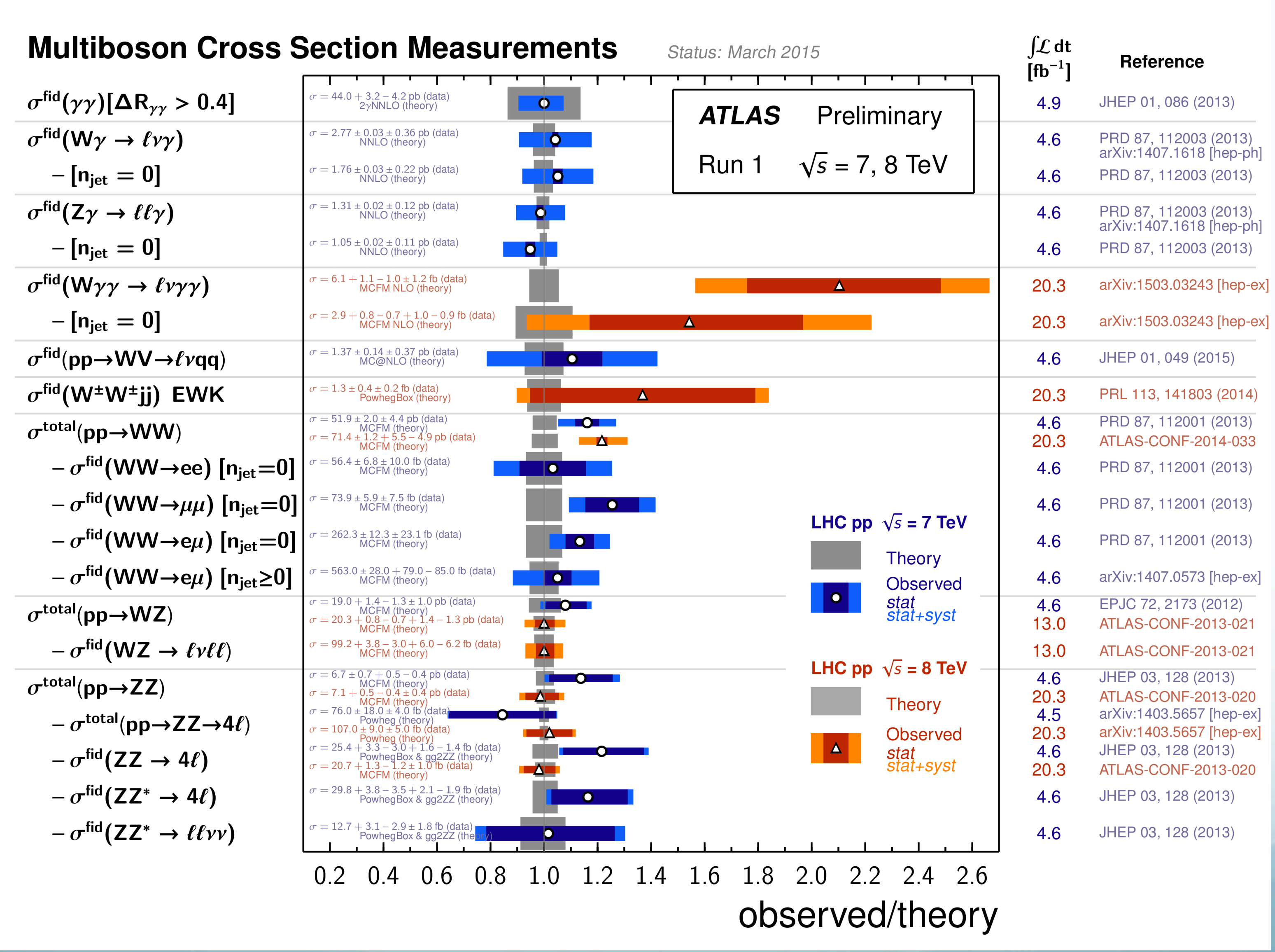
XS: cross section AC: limits on aT(Q)GC dX: differential cross section
Red: the analysis that will introduced by this talk

Overview



Mar. 2015
CMS Preliminary
CMS measurements
vs. NLO (NNLO) theory
7 TeV CMS measurement (stat,stat+sys)
8 TeV CMS measurement (stat,stat+sys)
γγ, (NNLO th.)
Wγ
Zγ
Zγ
WW+WZ
WW
WW, (NNLO th.)
WZ
WZ
ZZ
ZZ
1.06 ± 0.01 ± 0.12 5.0 fb-1
1.16 ± 0.03 ± 0.13 5.0 fb-1
0.98 ± 0.01 ± 0.05 5.0 fb-1
0.98 ± 0.01 ± 0.05 19.5 fb-1
1.05 ± 0.13 ± 0.15 4.9 fb-1
1.11 ± 0.04 ± 0.10 4.9 fb-1
1.01 ± 0.02 ± 0.08 19.4 fb-1
1.17 ± 0.07 ± 0.07 4.9 fb-1
1.12 ± 0.03 ± 0.07 19.6 fb-1
0.99 ± 0.14 ± 0.07 4.9 fb-1
1.00 ± 0.06 ± 0.08 19.6 fb-1
0.5
1
1.5
2
All results at:
http://cern.ch/go/pNj7
Production Cross Section Ratio: σexp / σtheo

Overview


Multiboson Cross Section Measurements
Status: March 2015
ATLAS Preliminary
Run 1 √s = 7, 8 TeV
∫ℒ dt [fb⁻¹]
Reference
LHC pp √s = 7 TeV
Theory
Observed
stat
stat+syst
LHC pp √s = 8 TeV
Theory
Observed
stat
stat+syst
observed/theory
0.2 0.4 0.6 0.8 1.0 1.2 1.4 1.6 1.8 2.0 2.2 2.4 2.6
σfid(γγ)[ΔRγγ > 0.4] 4.9 JHEP 01, 086 (2013)
σfid(Wγ → ℓνγ) 4.6 PRD 87, 112003 (2013) arXiv:1407.1618 [hep-ph]
– [njet = 0] 4.6 PRD 87, 112003 (2013)
σfid(Zγ → ℓℓγ) 4.6 PRD 87, 112003 (2013) arXiv:1407.1618 [hep-ph]
– [njet = 0] 4.6 PRD 87, 112003 (2013)
σfid(Wγγ → ℓνγγ) 20.3 arXiv:1503.03243 [hep-ex]
– [njet = 0] 20.3 arXiv:1503.03243 [hep-ex]
σfid(pp→WV→ℓνqq) 4.6 JHEP 01, 049 (2015)
σfid(W±W±jj) EWK 20.3 PRL 113, 141803 (2014)
σtotal(pp→WW) 4.6 PRD 87, 112001 (2013) 20.3 ATLAS-CONF-2014-033
– σfid(WW→ee) [njet=0] 4.6 PRD 87, 112001 (2013)
– σfid(WW→μμ) [njet=0] 4.6 PRD 87, 112001 (2013)
– σfid(WW→eμ) [njet=0] 4.6 PRD 87, 112001 (2013)
– σfid(WW→eμ) [njet≥0] 4.6 arXiv:1407.0573 [hep-ex]
σtotal(pp→WZ) 4.6 EPJC 72, 2173 (2012) 13.0 ATLAS-CONF-2013-021
– σfid(WZ → ℓνℓℓ) 13.0 ATLAS-CONF-2013-021
σtotal(pp→ZZ) 4.6 JHEP 03, 128 (2013) 20.3 ATLAS-CONF-2013-020
– σtotal(pp→ZZ→4ℓ) 4.5 arXiv:1403.5657 [hep-ex] 20.3 arXiv:1403.5657 [hep-ex]
– σfid(ZZ → 4ℓ) 4.6 JHEP 03, 128 (2013) 20.3 ATLAS-CONF-2013-020
– σfid(ZZ* → 4ℓ) 4.6 JHEP 03, 128 (2013)
– σfid(ZZ* → ℓℓνν) 4.6 JHEP 03, 128 (2013)

ATLAS — 7 TeV — Wγ(lνγ) /Zγ(l+l-γ)/Zγ(ννγ)

Phys. Rev. D 87, 112003 (2013)

Wγ

- Event selection:

1 lepton $p_T^l > 25$ GeV
1 photon $E_T^\gamma > 15$ GeV
$E_T^{miss} > 35$ GeV.
$m_T > 40$ GeV.
$|m_{e\gamma}-m_Z| > 15$ GeV

- Background:

Jets from W+jets misidentified as photon
heavy quark from γ+jets decays as lepton

Zγ

- Event selection:

l+l-, $p_T^l > 25$ GeV
Mll > 40 GeV
One photon $E_T^\gamma > 15$ GeV

- Background:

Jets from Z+jets misidentified as photon

Zγ

- Event selection:

$E_T^{miss} > 90$ GeV.
1 photon $E_T^\gamma > 100$ GeV
Δφ(Emiss,γ) > 2.6 Δφ(Emiss, jet)> 0.4 (if jet are found)
Lepton veto

- Background:

τνγ and lνγ events from Wγ
W(lν) e -> photon
Z+jets jets -> photon
γ+jets $E_{jets} \to E_t^{miss}$

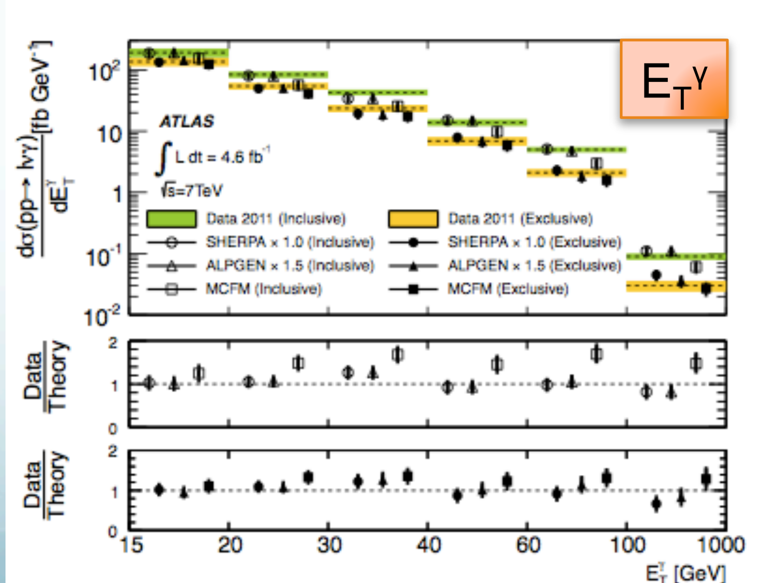
- Systematic:

photon identification and isolation efficiency.

$4.6 fb^{-1}$

	$\sigma^{ext-fid}$[pb] Measurement	$\sigma^{ext-fid}$[pb] MCFM Prediction
	$N_{jet} \geq 0$	
$\ell\nu\gamma$	2.77 ± 0.03 (stat) ± 0.33 (syst) ± 0.14 (lumi)	1.96 ± 0.17
$\ell^+\ell^-\gamma$	1.31 ± 0.02 (stat) ± 0.11 (syst) ± 0.05 (lumi)	1.18 ± 0.05
$\nu\bar{\nu}\gamma$	0.133 ± 0.013 (stat) ± 0.020 (syst) ± 0.005 (lumi)	0.156 ± 0.012
	$N_{jet} = 0$	
$\ell\nu\gamma$	1.76 ± 0.03 (stat) ± 0.21 (syst) ± 0.08 (lumi)	1.39 ± 0.13
$\ell^+\ell^-\gamma$	1.05 ± 0.02 (stat) ± 0.10 (syst) ± 0.04 (lumi)	1.06 ± 0.05
$\nu\bar{\nu}\gamma$	0.116 ± 0.010 (stat) ± 0.013 (syst) ± 0.004 (lumi)	0.115 ± 0.009

MCFM (NLO)



CMS

7 TeV

Wγ(lνγ) /Zγ(llγ)

Phys. Rev. D 89, 092005 (2014)

- Event Selection:

Selection	$W\gamma \to e\nu\gamma$	$W\gamma \to \mu\nu\gamma$	$Z\gamma \to ee\gamma$	$Z\gamma \to \mu\mu\gamma$
Trigger	single electron	single muon	dielectron	dimuon
p_T^{ℓ} (GeV)	>35	>35	>20	>20
$\lvert\eta^{\ell}\rvert$	EB or EE	<2.1	EB or EE	<2.4
p_T^{γ} (GeV)	>15	>15	>15	>15
$\lvert\eta^{\gamma}\rvert$	EB or EE	EB or EE	EB or EE	EB or EE
$\Delta R(\ell,\gamma)$	>0.7	>0.7	>0.7	>0.7
M_T^W (GeV)	>70	> 70		
$m_{\ell\ell}$ (GeV)			>50	>50
Other criterion	only one lepton	only one lepton		

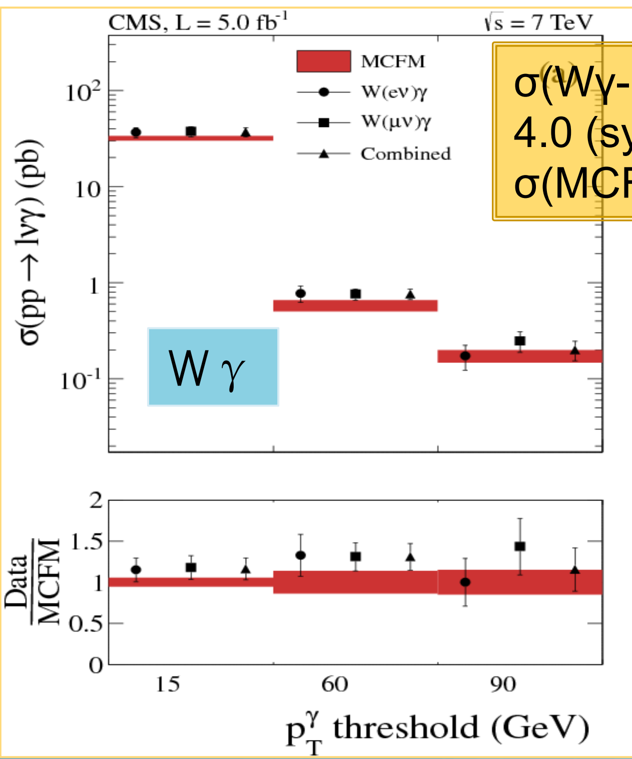
- Background:

Jets from W/Z+jets, misidentified as photons. Estimated using data-driven method (template/ ratio)

- Dominate Systematic:

Wγ: Jets misidentified as photons

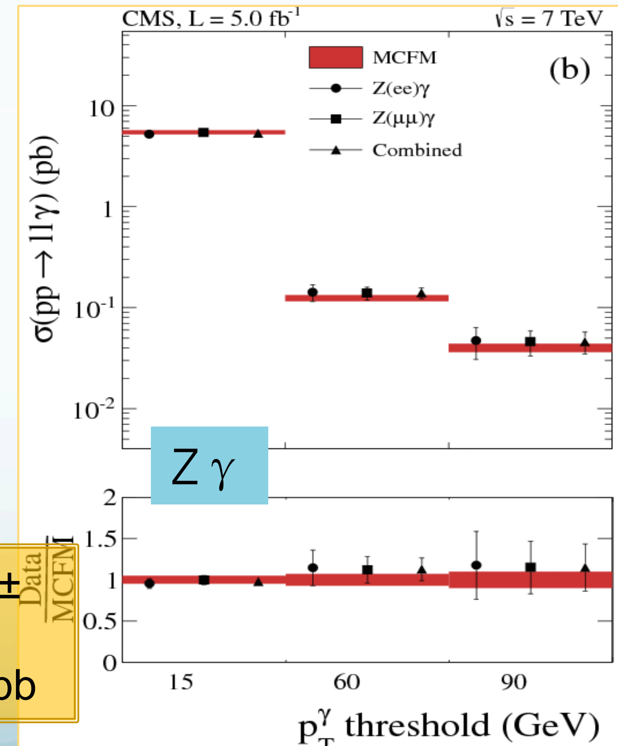
Zγ: lepton ID/ISO



σ(Wγ->lν) = 37.0 ± 0.8 (stat.) ± 4.0 (syst.) ± 0.8 (lum.) pb
σ(MCFM-NLO) = 31.8 ± 1.8 pb

Fiducial region:
p_T^{γ} > 15 GeV
ΔR(l, γ) > 0.7
m_{ll} > 50 GeV, for Zγ

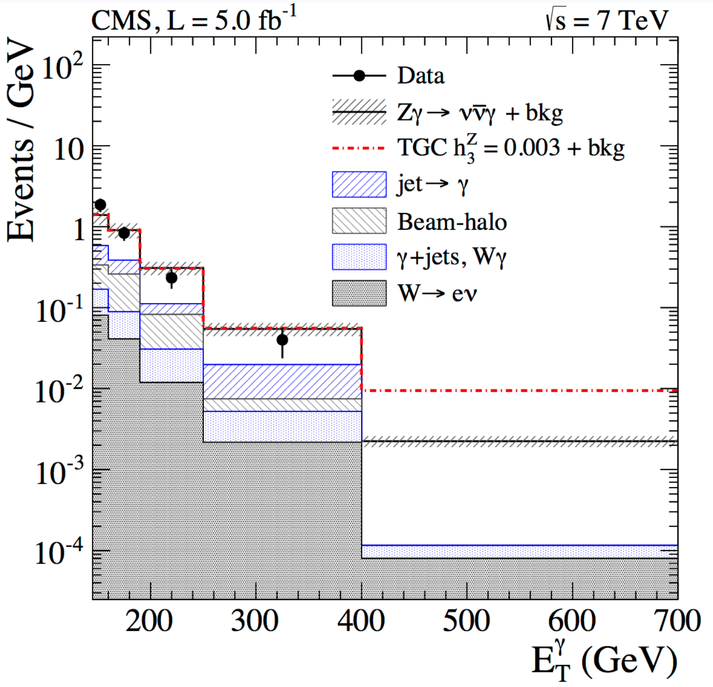
σ(Zγ->lν) = 5.33 ± 0.08 (stat.) ± 0.25 (syst.) ± 0.12 (lum.) pb
σ(MCFM-NLO) = 5.45 ± 0.27 pb



CMS 7 TeV Zγ (ννγ)

JHEP 10 (2013) 164

- Event selection:
  - p_T^{γ} > 145 GeV, $|\eta^{\gamma}|$<1.4
  - E_T^{miss} > 130 GeV,
  - Veto: p_T^{jets}<40 GeV,
  - p_T^{tracks}<20 GeV, ΔR(track, γ) > 0.04
- Background:
  - Large instrumental and non-collision backgrounds – estimated with data-driven methods



Source	Number of selected events
Misidentified jets	11.2 ± 2.8
Beam-halo muon 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 background	30.2 ± 6.5
$Z\gamma \to \nu\bar{\nu}\gamma$ (NLO)	45.3 ± 6.9
Data	73

Measured cross section
(E_T^{miss} > 130 GeV, p_T^{γ} > 145 GeV, $|\eta^{\gamma}|$<1.4):
21.3 ± 4.2 (stat.) ± 4.3 (syst.) ± 0.5 (lumi.) fb

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

CMS

8 TeV

Zγ(llγ)

JHEP 04 (2015) 164

- Event selection:
  - p_T^l > 20 GeV, $|\eta^l|$<2.5(2.4), l=e(μ)
  - E_T^γ > 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.
- 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: $|\eta| < 2.5$, $I_{gen} < 5\,\mathrm{GeV}$
leptons: $|\eta| < 2.5$, $p_T > 20\,\mathrm{GeV}$

inclusive cross section:

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

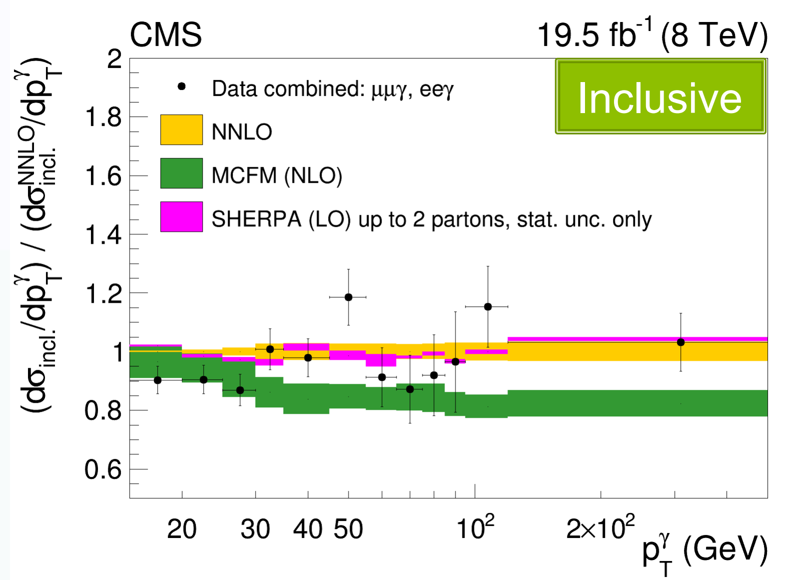
SM: $\sigma_{Z\gamma}$ (NNLO) = 2241 ± 22 fb

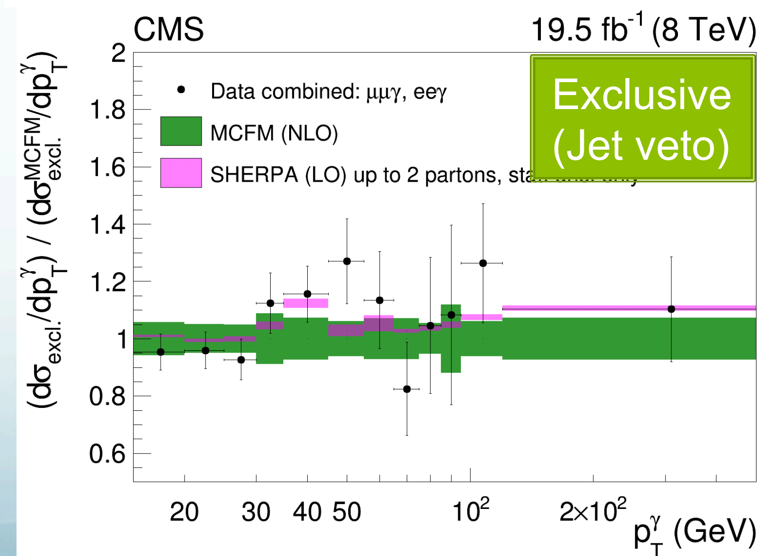
exclusive cross section (Jet veto on** p_T > 30 GeV and |η| < 2.4**):

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

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

Differential cross section





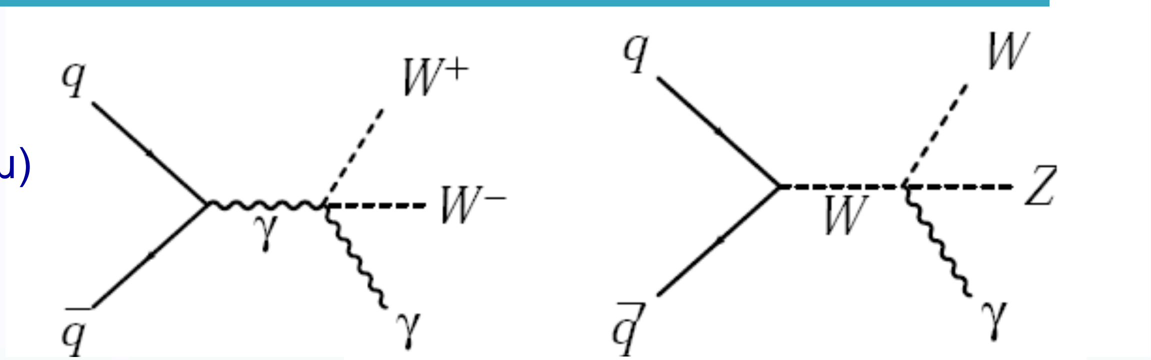
CMS

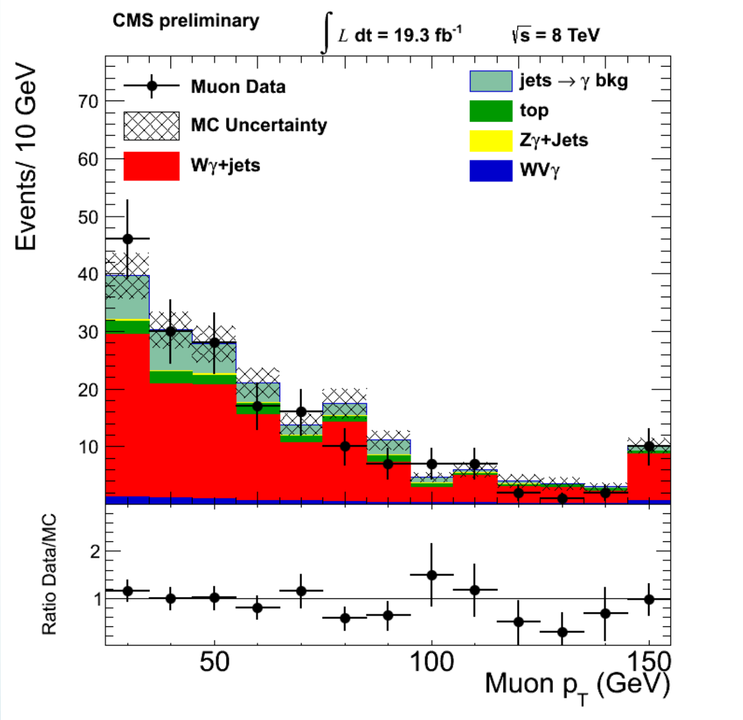
8 TeV

WVγ(lνjjγ)

Phys. Rev. D 90, 032008 (2014)

- Events selections:
  - Exactly one isolated lepton:
  - (p_T^l>35(25)GeV & |ηl|<2.5) (l = e, μ)
  - Two PF AK5 Jets with b veto:
  - p_T >30GeV & $|\eta_j|$<2.4
  - E_T^{miss}>35 GeV
  - $\Delta\varphi(E_T^{miss},J_1)$>0.4, $\Delta R_{j\gamma}$>0.5, $\Delta R_{l\gamma}$>0.5
  - M_T^W>30 GeV
  - $|M_{\gamma e}-M_Z|$>10GeV
  - $|\Delta\eta_{jj}|$<1.4, 70GeV<M_{jj}<110GeV
- Background:
  - W + jets: sideband
  - Fake Photon: ratio method
  - (data-driven)





σ(WVγ)< 311fb, 3.4 times SM (91.6±21.7fb) with E_T^γ >30GeV

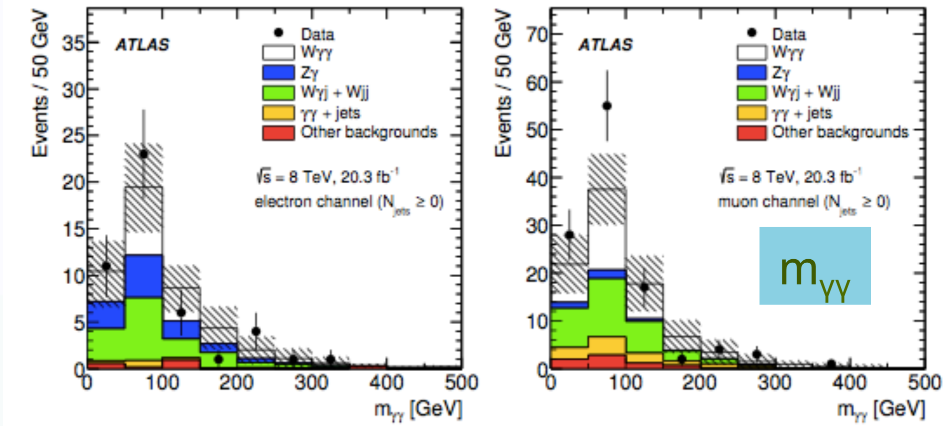
ATLAS

8 TeV

$W\gamma\gamma(l\nu\gamma\gamma)$

arXiv:1503.03243

- Events selections:
  - p_T^l>20GeV (l = e, μ, γ)
  - p_T^j >30GeV & $|\eta_j|$<4.4 (Excusive: Jet veto)
  - $\Delta R_{j\gamma}$>0.3, ΔR_{jl}>0.3
  - E_t^{miss}>25 GeV
  - $\Delta R_{l\gamma}$>0.7, $\Delta R_{\gamma\gamma}$ > 0.4
  - M_T^W>40 GeV
  - $|M_{\gamma e}-M_Z|$>13GeV



Definition of the fiducial region
$p_T^{\ell} > 20$ GeV, $p_T^{\nu} > 25$ GeV, $\lvert\eta_\ell\rvert < 2.5$
$m_T > 40$ GeV
$E_T^{\gamma} > 20$ GeV, $\lvert\eta^{\gamma}\rvert < 2.37$, iso. fraction $\epsilon_h^p < 0.5$
$\Delta R(\ell,\gamma) > 0.7$, $\Delta R(\gamma,\gamma) > 0.4$, $\Delta R(\ell/\gamma,\text{jet}) > 0.3$
Exclusive: no anti-k_t jets with $p_T^{\text{jet}} > 30$ GeV, $\lvert\eta^{\text{jet}}\rvert < 4.4$

- Background:
  - The fake-photon background from Wγj + Wjj
  - Jet fake electron, muon from heavy-flavor decays by γγ + jets (data-driven)
- Systematic:
  - data-driven background

	σ^{fid} [fb]	σ^{MCFM} [fb]
Inclusive ($N_{\text{jet}} \geq 0$)		
$\mu\nu\gamma\gamma$	$7.1\ ^{+1.3}_{-1.2}$ (stat.) ±1.5 (syst.) ±0.2 (lumi.)	2.90 ± 0.16
$e\nu\gamma\gamma$	$4.3\ ^{+1.8}_{-1.6}$ (stat.) $^{+1.9}_{-1.8}$ (syst.) ±0.2 (lumi.)	
$\ell\nu\gamma\gamma$	$6.1\ ^{+1.1}_{-1.0}$ (stat.) ±1.2 (syst.) ±0.2 (lumi.)	
Exclusive ($N_{\text{jet}} = 0$)		
$\mu\nu\gamma\gamma$	3.5 ± 0.9 (stat.) $^{+1.1}_{-1.0}$ (syst.) ±0.1 (lumi.)	1.88 ± 0.20
$e\nu\gamma\gamma$	$1.9\ ^{+1.4}_{-1.1}$ (stat.) $^{+1.1}_{-1.2}$ (syst.) ±0.1 (lumi.)	
$\ell\nu\gamma\gamma$	$2.9\ ^{+0.8}_{-0.7}$ (stat.) $^{+1.0}_{-0.9}$ (syst.) ±0.1 (lumi.)	

CMS

8 TeV

$W^+W^- \rightarrow 2l2\nu$

SMP-14-016

Event selection:

- 2 isolated leptons with $p_T^l > 20$ GeV
  3rd lepton veto with $pT^l > 10$ GeV
  (WW,WZ reduction)
- Less than 2 jets with pT > 30 GeV,
  Anti b-tagging *(tt reduction)*
- Projected $E_T^{miss} > 20$ GeV
- $|m_{ll}-m_Z| > 15$ GeV (ee, μμ)
- $p_T^{di\text{-}lep} > 45(30)$ GeV for SF(OF)
  (DY, fake leptons reduction)

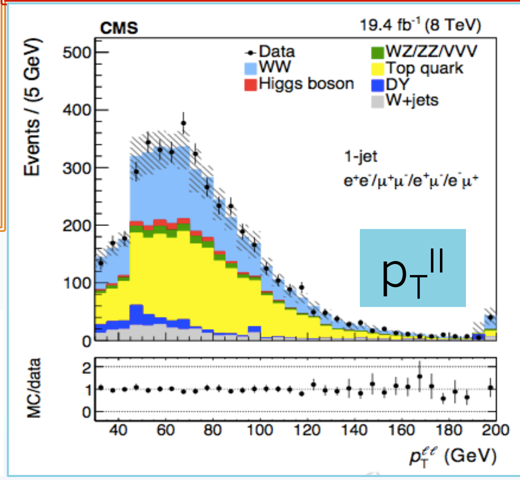
Background:

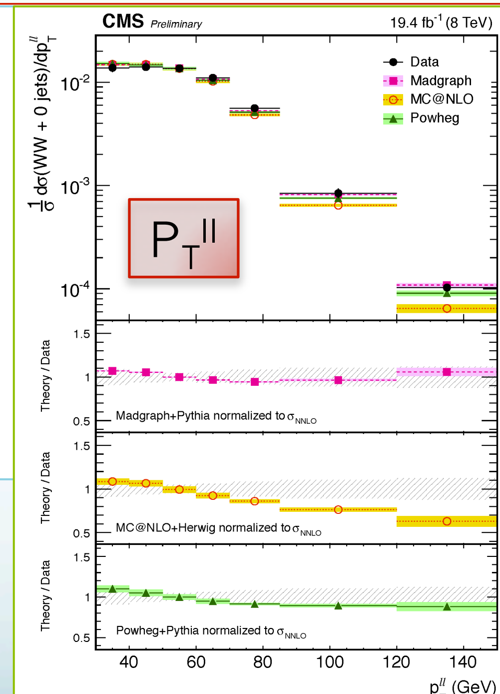
- Top pair (dominant), V+jets, DY Z/γ∗, diboson,
  H->W+W- (CMS only)

Systematic Uncertainty

jet veto

lepton efficiency uncertainties





Total cross section (zero/one jet)

Event category		W^+W^- production cross section (pb.)
zero-jet category	Different-flavor	$59.7 \pm 1.1\,(\text{stat.}) \pm 3.3\,(\text{exp.}) \pm 3.5\,(\text{th.}) \pm 1.6\,(\text{lum.})$
	Same-flavor	$64.3 \pm 2.1\,(\text{stat.}) \pm 4.6\,(\text{exp.}) \pm 4.3\,(\text{th.}) \pm 1.7\,(\text{lum.})$
one-jet category	Different-flavor	$59.1 \pm 2.8\,(\text{stat.}) \pm 6.0\,(\text{exp.}) \pm 6.2\,(\text{th.}) \pm 1.6\,(\text{lum.})$
	Same-flavor	$65.1 \pm 5.5\,(\text{stat.}) \pm 8.3\,(\text{exp.}) \pm 8.0\,(\text{th.}) \pm 1.7\,(\text{lum.})$

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

Good agreement with theoretical prediction

$59.8^{+1.3}_{-1.1}$ (NNLO)

Analysis @ 7TeV has shown difference wrt SM prediction

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

ATLAS

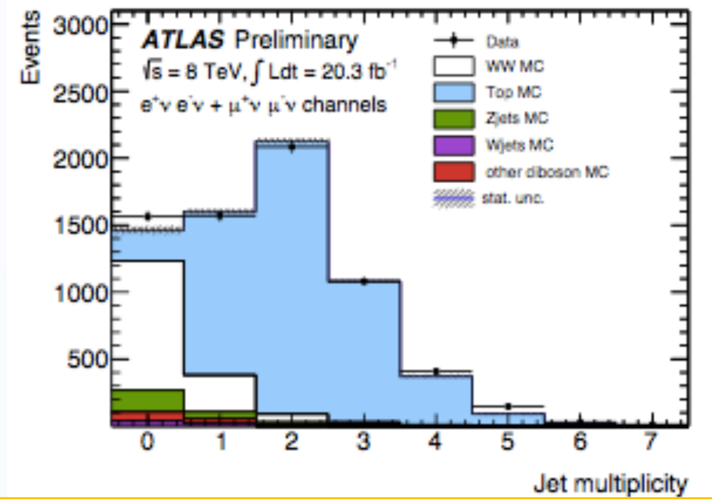
8 TeV

$W^+W^- \rightarrow 2l2\nu$

ATLAS-CONF-2014-033,
Phys.Rev.D87 (2013) 112001

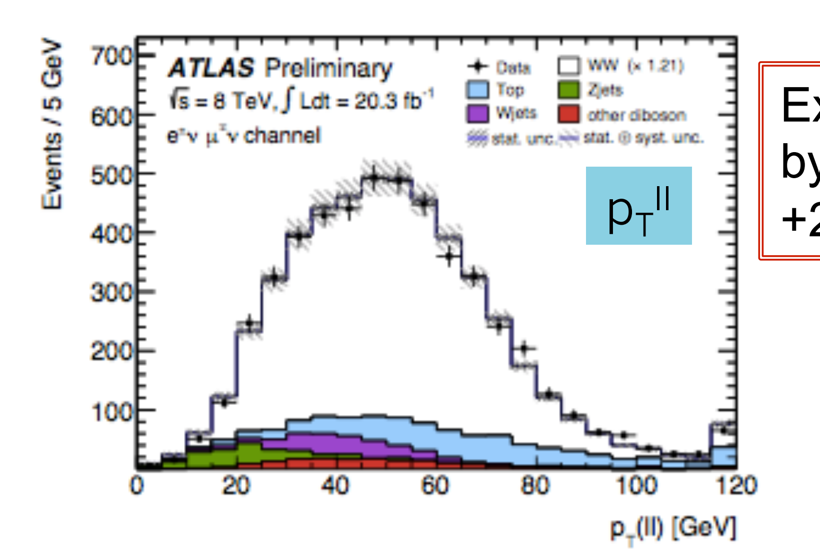
Event selection:

- H->WW as signal
- 3rd lepton veto with $p_T^l > 7$ GeV
  (WW;WZ reduction)
- **0 jets** with pT > 25 GeV
  (tt reduction)
- $E_T^{miss}{}_{Rel} > 15(45)$ GeV for OF(SF)
- $P_t^{miss} > 20/45$ GeV, $\Delta\Phi(E_t^{miss}, P_T^{miss}) < 0.6/0.3$
  (DY reduction)

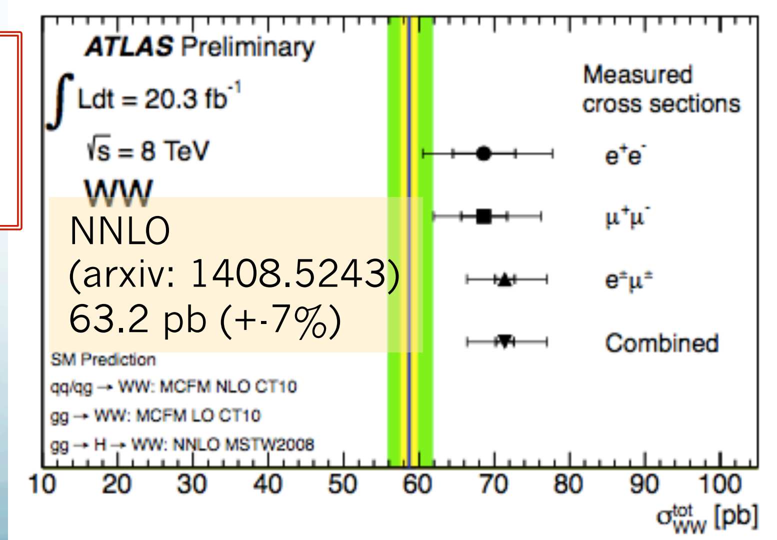


Total cross section

$$71.4^{+1.2}_{-1.2}\ (\text{stat})\ ^{+5.0}_{-4.4}\ (\text{syst})\ ^{+2.2}_{-2.1}\ (\text{lumi})\ \text{pb}$$



Excess by +2.1σ



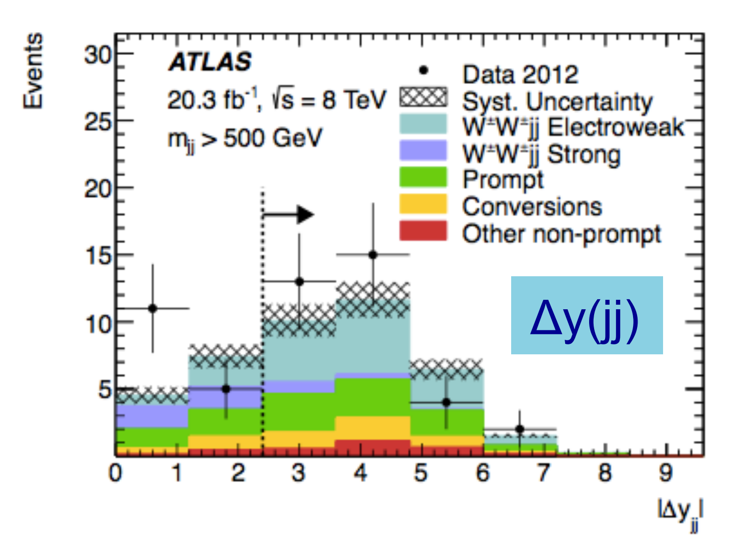
ATLAS

8 TeV

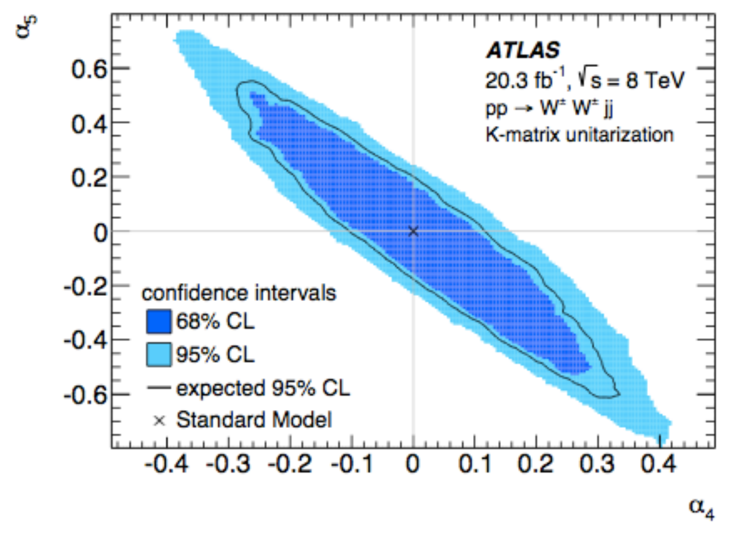
$W^{\pm}W^{\pm}$ jj

PRL 113 (2014) 141803

- Event Selection:
  - Two fiducial region:
  - inclusive region (EWK+QCD) and VBS region (EWK)
  - Two same-sign lepton with p_T>25 GeV
  - mjj>500 GeV, $|\Delta y(jj)|$>2.4 (VBS region only)
  - Veto third lepton pT>10 GeV *(diboson reduction)*
  - m_{ll}>50 GeV *(W+jets,top reduction)*
  - $|m_{ll}-m_Z|$> 15 GeV, E_T^{miss} > 40 GeV *(DY)*
- Background:
  - Dominated by WZ->lνll, g conversions (Wg+jets), and non-EWK W+W+jj



- Measured significance and cross section:
  - 4.5(3.4) σ evidence for EWK+QCD
  - 3.6(2.8) σ evidence for EWK ("VBS")
  - **first evidence ever!**
  - EWK+QCD σ^{fid} = 2.1 ± 0.5(stat) ± 0.3(syst) fb.
  - σ (fid,theory) = 1.52 ± 0.11fb
  - EWK σ^{fid} = 1.3 ± 0.4(stat) ± 0.2(syst) fb.
  - σ (fid,theory) = 0.95 ± 0.06 fb.



Place limits on aQGCs (WWWW vertex)

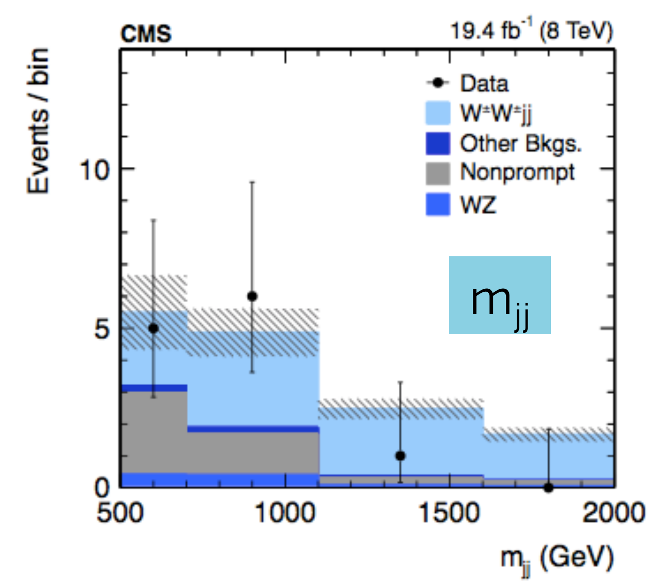
CMS

8 TeV

$W^{\pm}W^{\pm}$ jj

PRL 114 (2015) 051801

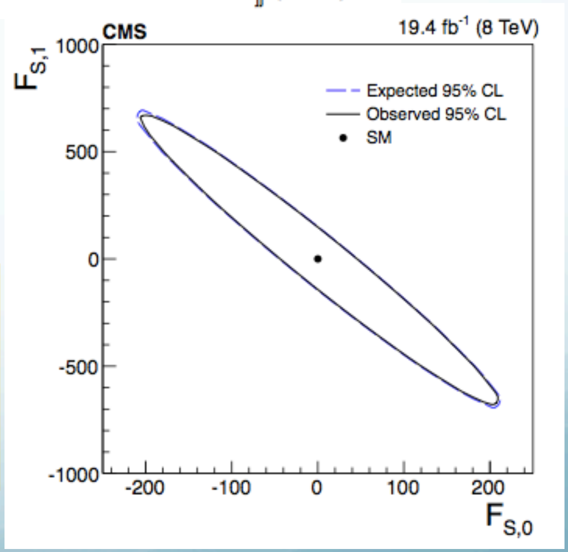
- Event selection:
  - Two same-sign lepton with P_T>20 GeV
  - mjj>500 GeV, |Dy(jj)|>2.5 (VBS topology)
  - Veto third lepton pT>7 GeV *(diboson reduction)*
  - M_{ll}>20 GeV, $|m_{ll}-m_Z|$> 10 GeV, E_T^{miss} > 40 GeV
- Background:
  - Largest background from non- prompt leptons (data-driven) (75%)



- Measured significance and cross section:
  - 2.0(3.1) σ evidence for EWK+QCD
  - 1.9(2.9) σ evidence for EWK ("VBS")
  - s(fid,obs) = $4.0^{+2.4}_{-2.0}\,(\text{stat})^{+1.1}_{-1.0}\,(\text{syst})$ fb.
  - s(fid,theory) = 5.8 +/- 1.2 fb

Fiducial region:
p_T^l>10 GeV and $|\eta^l|$ < 2.5,
p_T^j>20 GeV and $|\eta^j|$ < 5.0,
m_{jj} > 300 GeV, and $|\Delta\eta_{jj}|$ > 2.5

- Use Mjj to set limits on aQGCs



CMS ATLAS 8 TeV

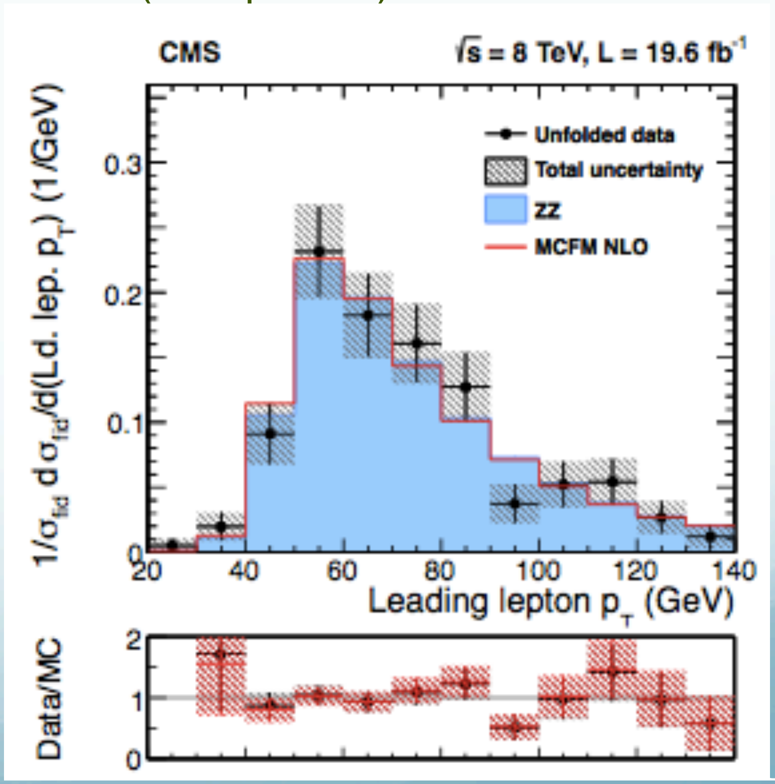
ZZ(lll'l')

PLB 740 (2015) 250
CONF-2013-020

- 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)
  FSR photons with $|m_{ll\gamma} - m_Z| < |m_{ll} - m_Z|$ and $m_{ll\gamma}$ < 100 GeV

- Background:
  Jet is misidentified as lepton in WZ/Z +jets and tt. Data driven estimate – control region with relaxed isolation.
- Systematic:
  misidentification rates and the limited statistics of the control regions in the data (fake photon)



CMS

Measured cross section

$$7.7 \pm 0.5\,(\mathrm{stat})\,^{+0.5}_{-0.4}\,(\mathrm{syst}) \pm 0.4\,(\mathrm{theo}) \pm 0.2\,(\mathrm{lumi})$$

SM:
σ_{WW}(MCFM,qq(NLO),gg(LO)) = 7.7 ± 0.6 pb

ATLAS

Measured cross section

$$\sigma_{ZZ}^{tot} = 7.1^{+0.5}_{-0.4}(\mathrm{stat.}) \pm 0.3(\mathrm{syst.}) \pm 0.2(\mathrm{lumi.})\ \mathrm{pb}.$$

SM:
σ_{WW}(MCFM,NLO) = $7.2^{+0.3}_{-0.2}$ pb.

CMS

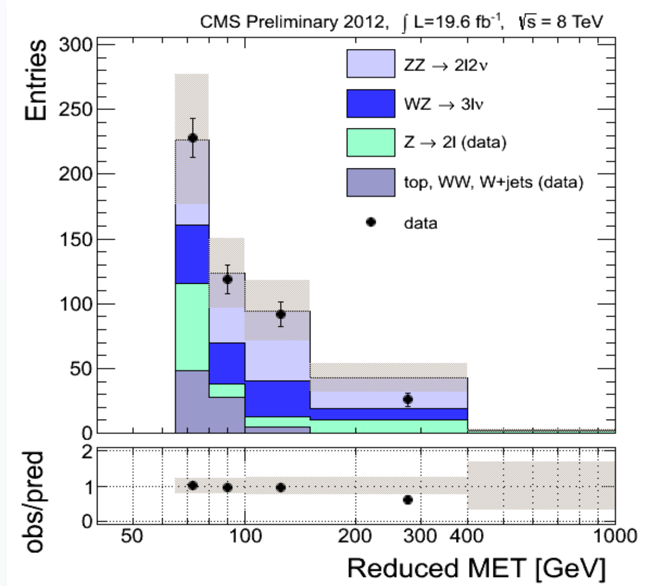
7, 8 TeV

ZZ(2l2ν)

SMP-12-016

- Event selection:

Variable	Value
Dilepton invariant mass	$\|m(\ell\ell) - 91\| < 7.5\,\mathrm{GeV}$
Dilepton p_T	$p_T^{\ell\ell} > 45\,\mathrm{GeV}$
b-tagged jets	based on vertex info (for jet with $p_T > 20\,\mathrm{GeV}$)
Jet veto	no jets with $p_T > 30\,\mathrm{GeV}$
Reduced E_T^{miss}	>65 GeV
E_T^{miss} balance	$0.4 < E_T^{miss} / p_T^{\ell\ell} < 1.8$
$\Delta\phi(p_T^{miss}, \mathrm{jet})$	>0.5 rad
$\Delta\phi(p_T^{miss}, \mathrm{lepton})$	>0.2 rad
Lepton veto	no additional leptons (e/μ) with $p_T > 10/3\,\mathrm{GeV}$



- Background:

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

- Systematic:

  DY bkg normalization, JES

Measured cross section:

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

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

SM: σ_{WW}(MCFM,qq(NLO),gg(LO))

6.3 ± 0.4 pb @ 7 TeV

7.7 ± 0.6 pb @ 8 TeV

- Most precise measurements
- First measurement at 8 TeV
- Less than 1 σ from the SM predictions

CMS ATLAS 7, 8 TeV

WZ(lll'ν)

SMP-12-006
CONF-2013-021

Event selection:

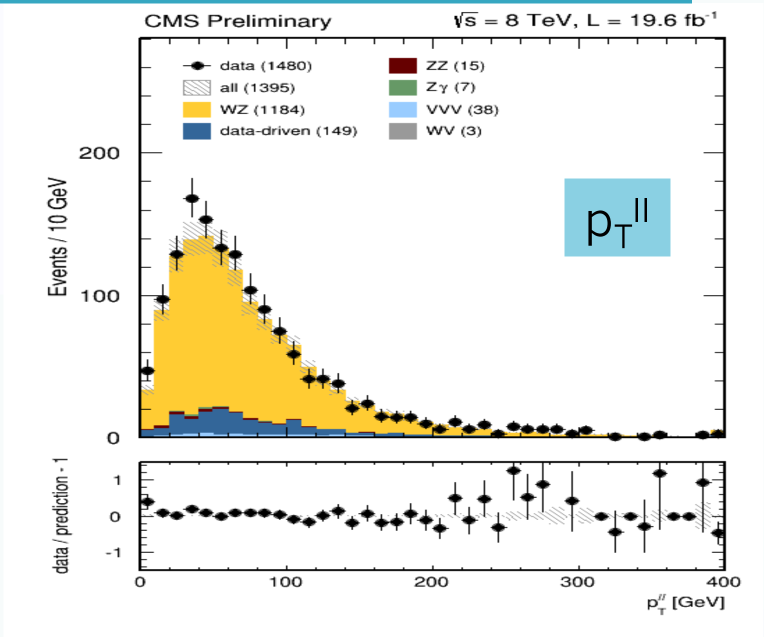
Two opposite charge leptons + 3rd lepton+ E_T^{miss}
Z reconstruction:
$p_T^l > 20$ (10) GeV
$|mll - m_Z| < 20$ GeV (and closest to m_Z)
W reconstruction:
$p_T^l > 20$ GeV, $E_T^{miss} > 30$ GeV

Background:

- Fake lepton - real Z plus a jet faking a lepton – the dominant background
- Non Peaking - no Z boson (e.g. tt)
- Prompt Lepton –ZZ -> 4l (lost 1 lepton).

Systematic:

Dominated by data-driven (Z+jets,tt)



CMS

Measured pp->WZ cross section ($71<m_{ll}<111$ GeV):

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

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

ATLAS

Measured pp->WZ total cross section ($66<m_{ll}<116$ GeV):

$20.3^{+0.8}_{-0.7}$(stat.) $^{+1.2}_{-1.1}$(syst.) $^{+0.7}_{-0.6}$(lumi.)

SM: σ_{WZ}(MCFM, NLO) = 20.3 ± 0.8 pb

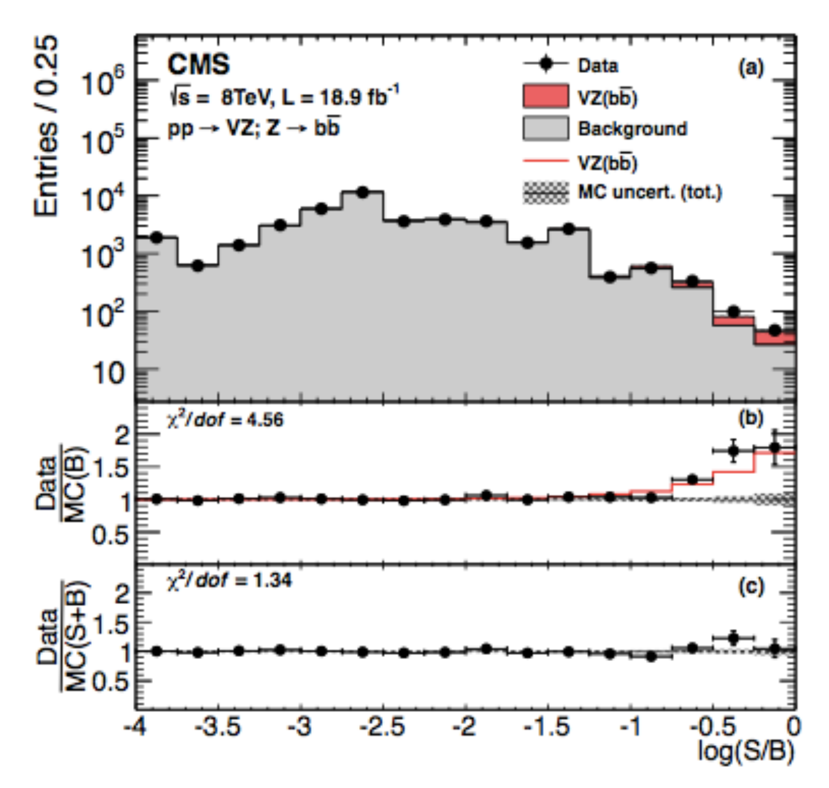
CMS

8 TeV

VZ(Vbb)

EPJC 74 (2014) 2973

- Signature:
  - Two b-jets+ E_t^{miss} + 0,1,2 leptons
- Event selection:
  - 2 b-jets ($|\eta|<2.5$), $m_{jj}<250$ GeV
  - 0l($Z \rightarrow \nu\nu$): $E_T^{miss} > 100$ GeV
  - 1l($W \rightarrow l\nu$): $E_T^{miss} > 45$ GeV
  - 2l($Z \rightarrow ll$): 75GeV < m_{ll}< 105 GeV
  - Fit of multivariate discriminant/ m_{jj}
- Background:
  - QCD V+jets, top, VH



the VZ process is observed with a statistical significance of 6.3 σ (5.9 σ expected).

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_{WZ}(MCFM, NLO) = 7.7 ±0.4 pb

Anomalous Triple (Quartic) Gauge Couplings

- **AT(Q)GC are less well measured in EWK**
- **They are signature of New Physics**
- **At hard tail of phase space, they increase Xsec significantly**

Charged aTGCs WWγ/WWZ

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

5 parameters: $\Delta g_{1Z}(=g_{1Z}-1)$, $\Delta K_Z(=K_Z-1)$, $\Delta K_\gamma(=K_\gamma-1)$, λZ, $\lambda\gamma$

LEP parametrization

$\lambda_\gamma = \lambda_z = \lambda$

$\Delta K_Z = \Delta g^Z_1 - \Delta K_\gamma . \tan^2\theta_W$

HISZ parametrization

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

$\Delta K_\gamma = 2\Delta g_{1Z} \cos^2\theta_W$, $\lambda Z = \lambda\gamma$

EFT parametrization

c_{WWW}/Λ^2, c_W/Λ^2, c_B/Λ^2

NPB282 (1987) 253; PRD41 (1990) 2113

j.aop.2013.04.016

Neutral aTGCs

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

Zγ channel: Zγγ/ZZγ

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

PRD47 (1993) 4889

ZZ channel: ZZγ/ZZZ

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

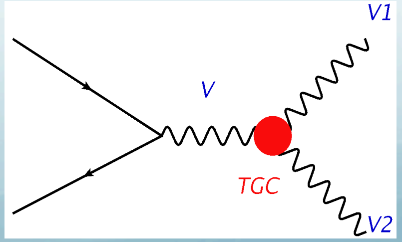
NPB282 (1987) 253

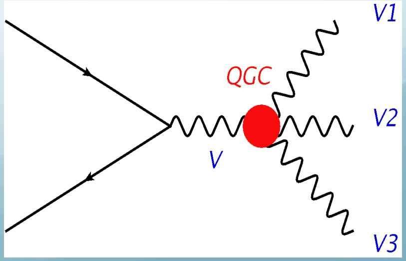
Neutral TGCs not allowed in SM

aQGCs WWγγ/WWZγ

SM lagrangian can be extended with 8 dimensional operators

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



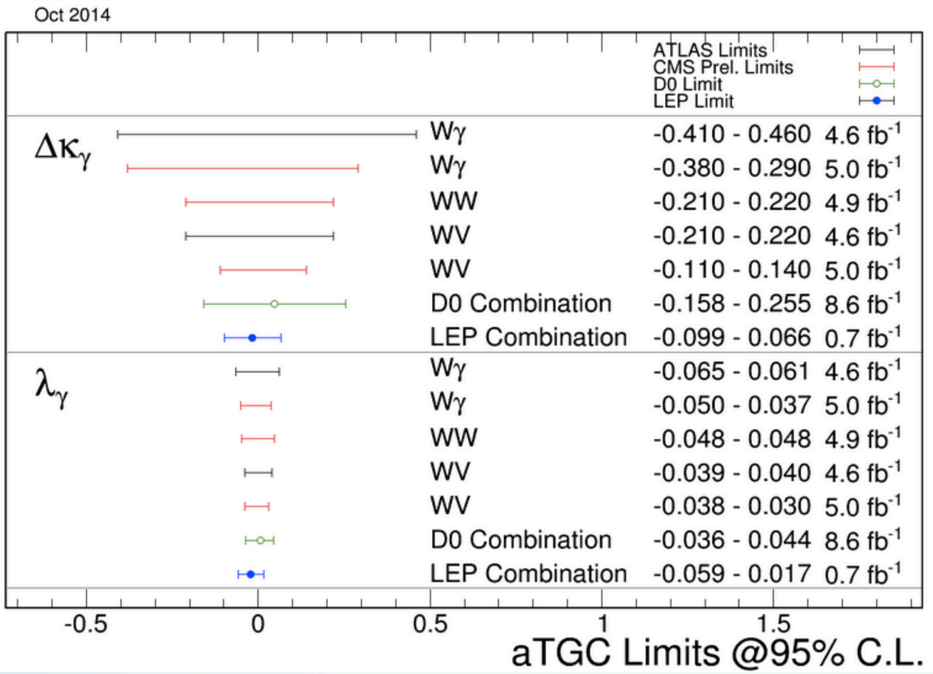


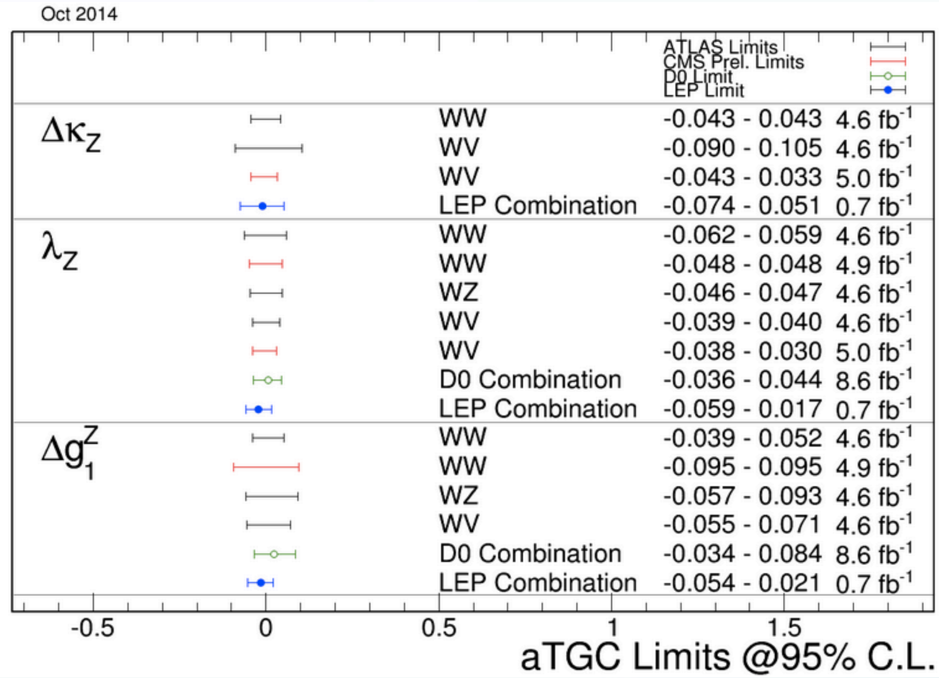
Triple and Quartic Anomalous Gauge Couplings

Process (l=e,μ)	aTGC/QGC Parameters		Limit Setting variable
Wγ	WWγ	$\lambda_{\gamma,}$ ΔK_{γ} (charged)	E_T
Zγ	ZZγ, Zγγ	$h_3^{Z,\gamma}$, $h_4^{Z,\gamma}$ (neutral)	E_T
Zγ	ZZγ, Zγγ	$h_3^{Z,\gamma}$, $h_4^{Z,\gamma}$ (neutral)	E_T
WW(lνlν)	WWγ, WWZ	(EFT) c_{WWW}/Λ^2, c_W/Λ^2 ,c_B/Λ^2 (CMS 8 TeV) $\lambda_{z/\gamma,}$ $\Delta K_{z/\gamma,}\Delta g^Z_1$ (ATLAS,CMS 7 TeV)	M_{ll} (CMS 8 TeV) Max P_T^l
ZZ(4l, 2l2ν)	ZZZ, ZZγ	$f_4^{Z,\gamma}$, $f_5^{Z,\gamma}$ (neutral)	M_{4l}
WZ->lνjj	WWγ, WWZ	$\lambda_{z,}$ $\Delta K_{\gamma,}$	$P_t^{di\text{-}jet}$
WVγ	WWγγ, WZγγ	a_0^w, a^w_c ,f_{T0}, K_0^w, K_c^w	E_t
WW(lνjj)	WWWW	α_4, α_5 (ATLAS), $f_{S0,}$ f_{S1} (CMS)	m_{ll}
Wγγ	WWγγ	f_{T0}/Λ^4, f_{M2}/Λ^4, and f_{M3}/Λ^4	$m_{\gamma\gamma}$

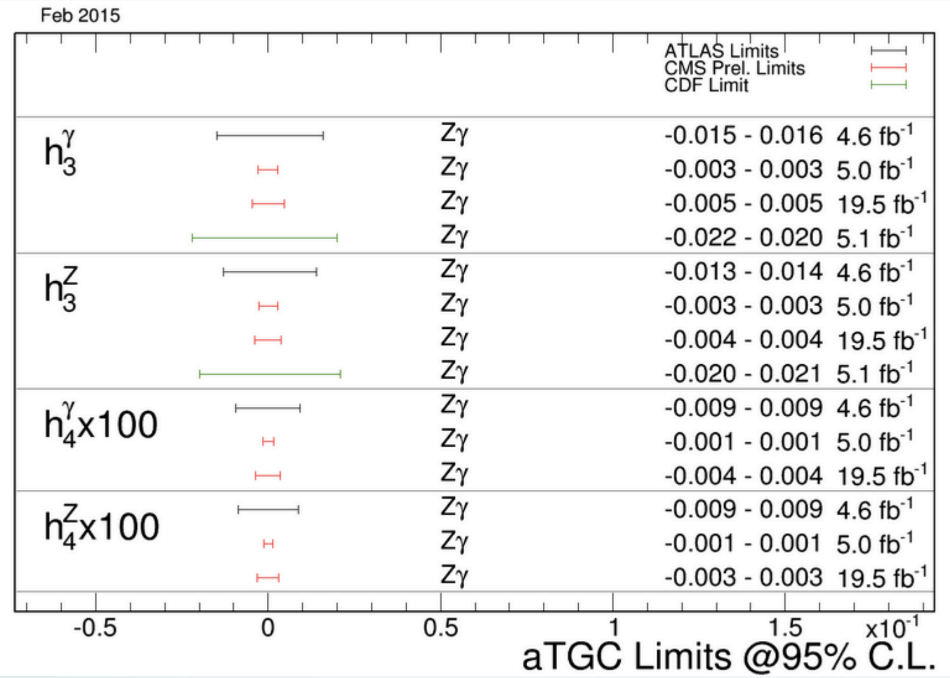
- With or without form factor, K Matrix for unitarization
- deltaNLL, CLs or profile likelihood methods used to set the upper limit

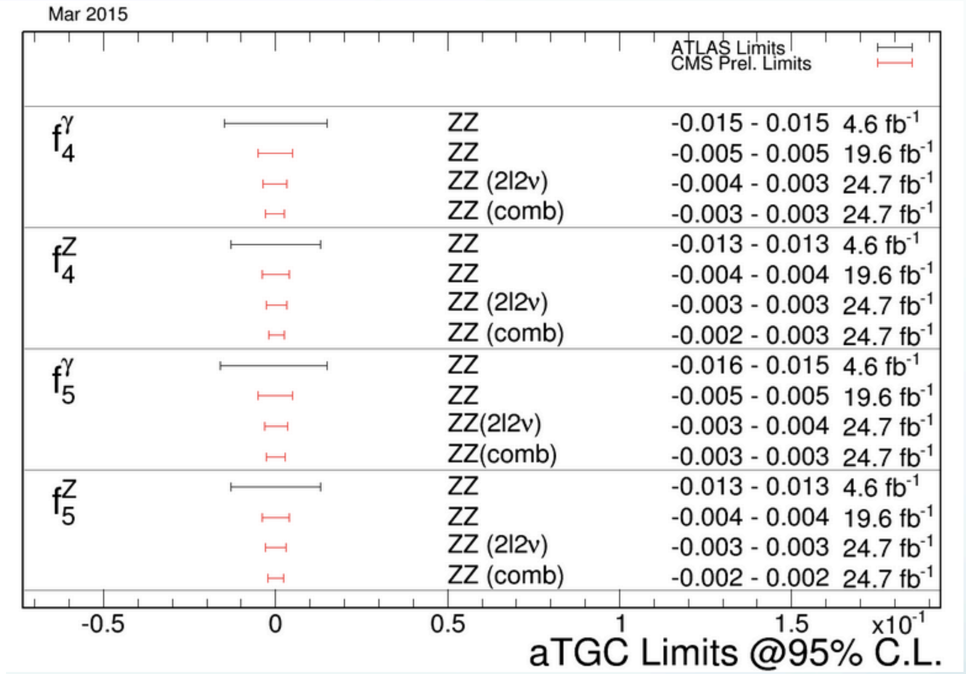
Charged aTGC





Neutral aTGC

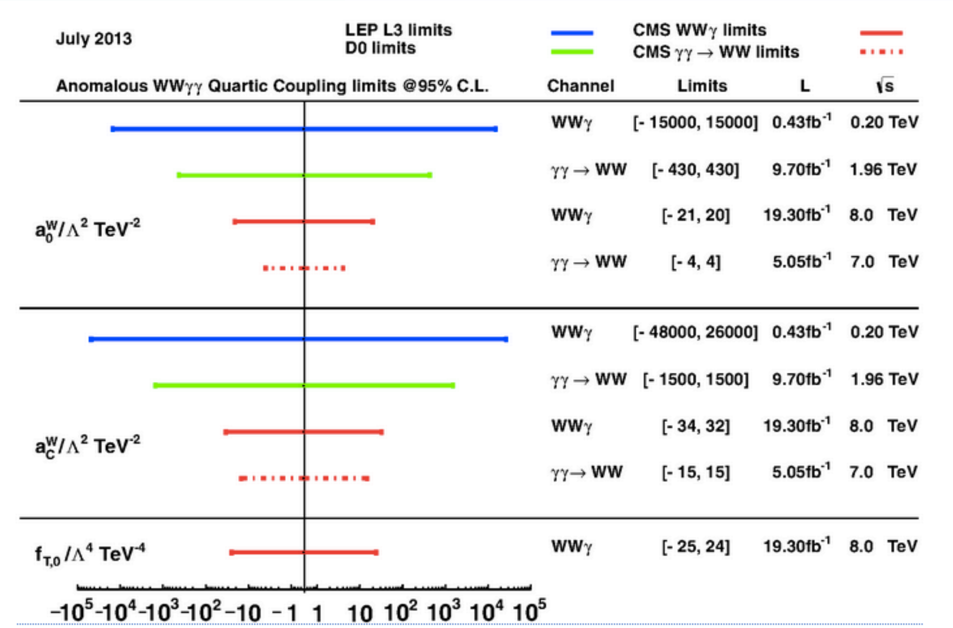




aQGC

limits on γγWW

Limits are set in on dimension 6 and dimension 8 effective field theory operators.

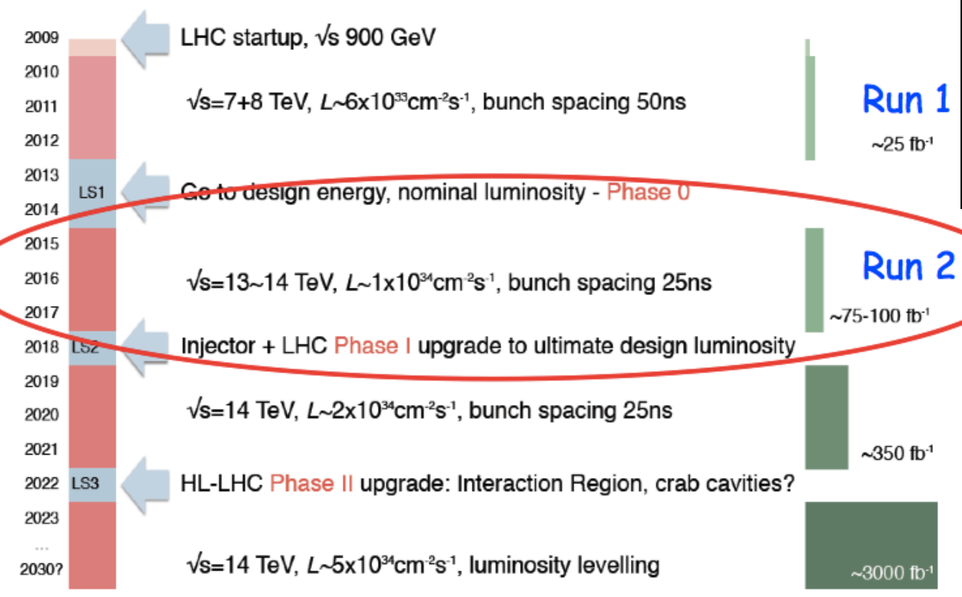


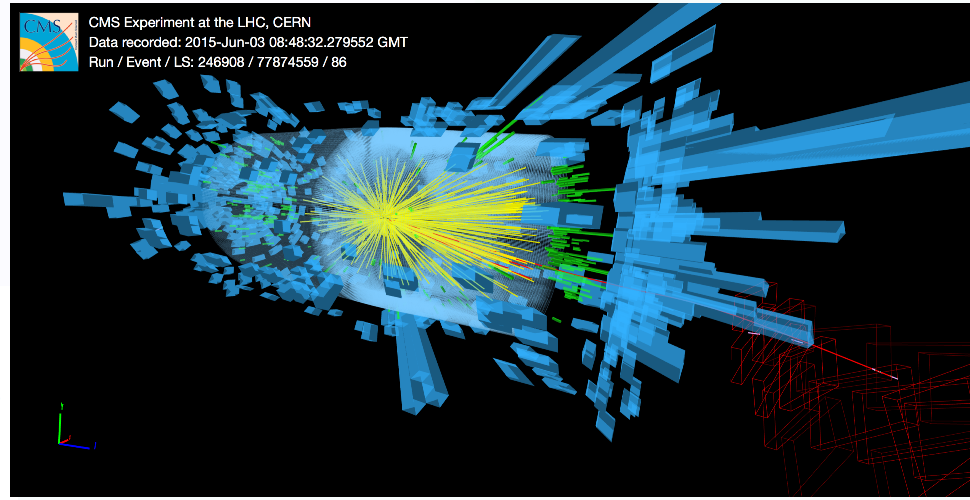
WW+WZljj

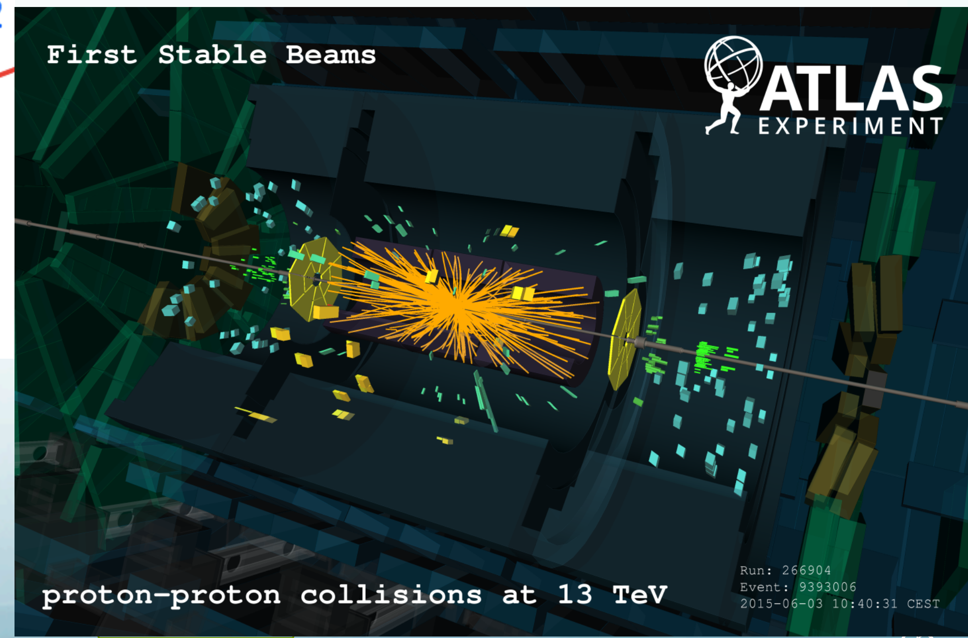
Observed Limits	Expected Limits
$-21\ (\text{TeV}^{-2}) < a_0^W/\Lambda^2 < 20\ (\text{TeV}^{-2})$	$-24\ (\text{TeV}^{-2}) < a_0^W/\Lambda^2 < 23\ (\text{TeV}^{-2})$
$-34\ (\text{TeV}^{-2}) < a_C^W/\Lambda^2 < 32\ (\text{TeV}^{-2})$	$-37\ (\text{TeV}^{-2}) < a_C^W/\Lambda^2 < 34\ (\text{TeV}^{-2})$
$-25\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

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

RUN II Prospective





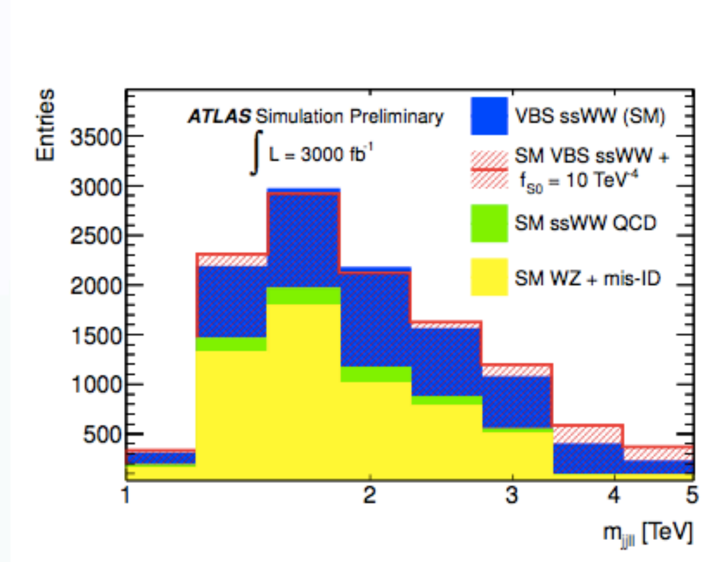


RUN II Prospective

ATLAS-PHYS-PUB-2013-006
arXiv:1309.7452
arXiv:1408.5243

Expected Cross-Sections (WW)

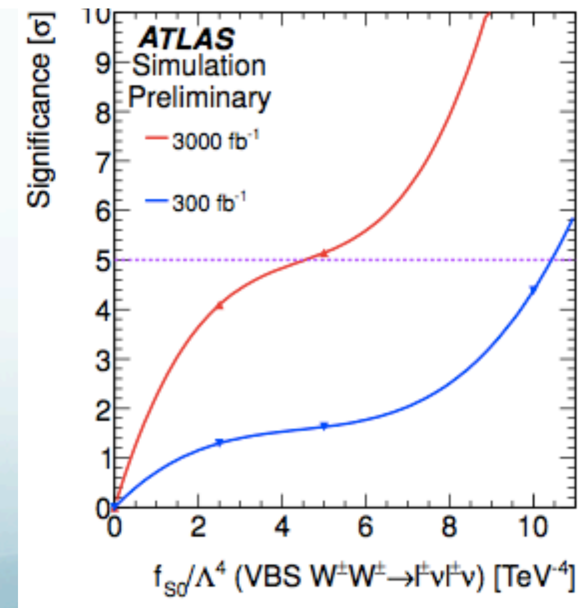
$\frac{\sqrt{s}}{\text{TeV}}$	σ_{LO}	σ_{NLO}	σ_{NNLO}	$\sigma_{gg\to H\to WW^*}$
7	$29.52^{+1.6\%}_{-2.5\%}$	$45.16^{+3.7\%}_{-2.9\%}$	$49.04^{+2.1\%}_{-1.8\%}$	$3.25^{+7.1\%}_{-7.8\%}$
8	$35.50^{+2.4\%}_{-3.5\%}$	$54.77^{+3.7\%}_{-2.9\%}$	$59.84^{+2.2\%}_{-1.9\%}$	$4.14^{+7.2\%}_{-7.8\%}$
13	$67.16^{+5.5\%}_{-6.7\%}$	$106.0^{+4.1\%}_{-3.2\%}$	$118.7^{+2.5\%}_{-2.2\%}$	$9.44^{+7.4\%}_{-7.9\%}$
14	$73.74^{+5.9\%}_{-7.2\%}$	$116.7^{+4.1\%}_{-3.3\%}$	$131.3^{+2.6\%}_{-2.2\%}$	$10.64^{+7.5\%}_{-8.0\%}$



WZ + jj processes, 5 significance discovery values and 95% CL limits (with/without unitarity violation bound)

Parameter	Luminosity [fb^{-1}]	14 TeV		33 TeV	
		5σ	95% CL	5σ	95% CL
$c_{\phi d}/\Lambda^2$ [TeV^{-2}]	3000	15.2 (15.2)	9.1 (9.1)	12.6 (12.7)	7.7 (7.7)
	300	28.5 (28.7)	17.1 (17.1)	23.1 (23.3)	14.1 (14.2)
f_{T1}/Λ^4 [TeV^{-4}]	3000	0.6 (0.9)	0.4 (0.5)	0.3 (0.6)	0.2 (0.3)
	300	1.1 (1.6)	0.7 (1.0)	0.6 (0.9)	0.3 (0.6)

Channel	Parameter	(95% CL limits) 14TeV, 300 fb-1	(95% CL limits) 14TeV, 3000 fb-1
W±W±jj	$f_{S,0}/\Lambda^4$(TeV^{-4})	[−6.8, 6.8]	[−0.8, 0.8]
WZ jj	$f_{T,1}/\Lambda^4$(TeV^{-4})	[−0.7, 0.7]	[−0.3, 0.3]
Zγγ	$f_{T,9}/\Lambda^4$(TeV^{-4})	[−0.9, 0.9]	[−0.3, 0.3]



Summary

- Processes with **multiple bosons** in final state has been studied by both CMS and ATLAS with Run1 data at 7 and 8 TeV
- Production cross section have been measured in agreement with the SM prediction (NLO or NNLO)
- Search for anomalous triple and quartic gauge coupling show no sign of new physics
  – tightest limits are set for several coupling
- Many opportunities and challenges ahead as the start of LHC Run II is approaching

Backup

7 TeV

Wγ(lνγ) /Zγ(l+l-γ)/Zγ(ννγ)

Phys. Rev. D 87, 112003 (2013)

Fiducial region (ATLAS)

Cuts	$pp \to \ell\nu\gamma$	$pp \to \ell^+\ell^-\gamma$	$pp \to \nu\bar{\nu}\gamma$
Lepton	$p_T^\ell > 25$ GeV	$p_T^\ell > 25$ GeV	—
	$\|\eta_\ell\| < 2.47$	$\|\eta_\ell\| < 2.47$	—
	$N_\ell = 1$	$N_{\ell^+} = 1, N_{\ell^-} = 1$	$N_\ell = 0$
	$p_T^\nu > 35$ GeV	—	—
Boson	—	$m_{\ell^+\ell^-} > 40$ GeV	$p_T^{\nu\nu} > 90$ GeV
Photon	$E_T^\gamma > 15$ GeV	$E_T^\gamma > 15$ GeV	$E_T^\gamma > 100$ GeV
	$\|\eta^\gamma\| < 2.37, \Delta R(\ell,\gamma) > 0.7$		
	$\epsilon_h^p < 0.5$		
Jet	$E_T^{jet} > 30$ GeV, $\|\eta^{jet}\| < 4.4$		
	$\Delta R(e/\mu/\gamma, jet) > 0.3$		
	Inclusive : $N_{jet} \geq 0$, Exclusive : $N_{jet} = 0$		

Fiducial region (CMS)

$p_T^\gamma > 15$ GeV
$\Delta R(l, \gamma) > 0.7$
$m_{ll} > 50$ GeV, for $Z\gamma$

ATLAS 8 TeV

$W^+W^- \rightarrow 2l2\nu$

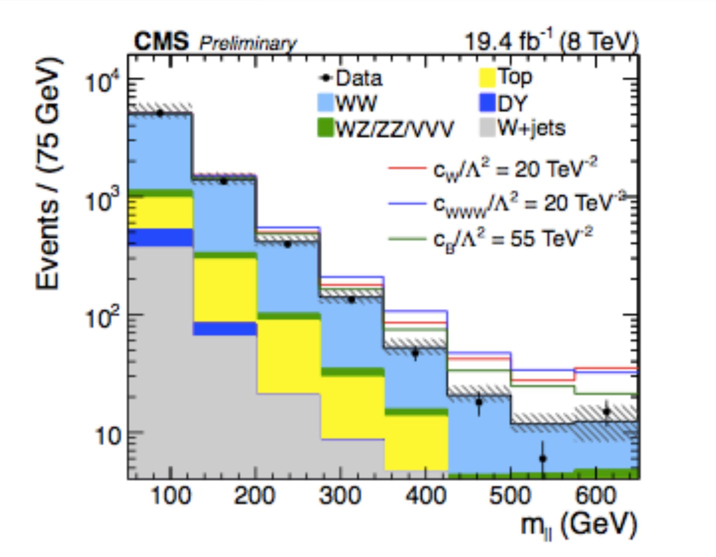
ATLAS-CONF-2014-033,
Phys.Rev.D87 (2013) 112001

the relative missing transverse momentum ($E_T^{miss}{}_{Rel}$) is introduced. It is calculated as E_t^{miss} * sin|ΔΦ|, where ΔΦ is the azimuthal angular difference between the E_t^{miss} vector and the closest selected jet or lepton in the event. However, if ΔΦ > p/2, then $E_T^{miss}{}_{Rel}$ is defined to be equal to E_t^{miss} .

E_T^{miss} includes information within the full calorimeter coverage (|h| < 4.9).
In addition, a track-based missing transverse momentum (P_T^{miss}) is used, which only includes information limited to the ID coverage (|h| < 2.5).

$W^+W^- \rightarrow 2l2\nu$

Limits on charge aTGC in the EFT framework (CMS).



$$\mathcal{O}_{WWW} = \frac{c_{WWW}}{\Lambda^2} \mathrm{Tr}[W_{\mu\nu} W^{\nu\rho} W_{\rho}^{\mu}],$$
$$\mathcal{O}_{W} = \frac{c_{W}}{\Lambda^2} (D^\mu \Phi)^\dagger W_{\mu\nu} (D^\nu \Phi),$$
$$\mathcal{O}_{B} = \frac{c_{B}}{\Lambda^2} (D^\mu \Phi)^\dagger B_{\mu\nu} (D^\nu \Phi).$$

Dim 6 EFT operators

Coupling constant	This result (TeV^{-2})	This result 95% interval (TeV^{-2})	World average (TeV^{-2})
c_{WWW}/Λ^2	$0.1^{+3.2}_{-3.2}$	$[-5.7, 5.9]$	-5.5 ± 4.8 (from λ_γ)
c_W/Λ^2	$-3.6^{+5.0}_{-4.5}$	$[-11.4, 5.4]$	$-3.9^{+3.9}_{-4.8}$ (from g_1^Z)
c_B/Λ^2	$-3.2^{+15.0}_{-14.5}$	$[-29.2, 23.9]$	$-1.7^{+13.6}_{-13.9}$ (from κ_γ and g_1^Z)

CMS ATLAS 8 TeV

ZZ(lll'l')

PLB 740 (2015) 250
CONF-2013-020

- Event selection:
  - **ZZ->lll'l'**
    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)
    FSR photons with $|m_{ll\gamma} - m_Z| < |m_{ll} - m_Z|$ and $m_{ll\gamma}$ < 100 GeV
  - **ZZ->llττ (τ_l, τ_h)**
    20/30 < $m_{\tau\tau}$<90 GeV ($\tau_e\tau_\mu$/other)

Measured cross section

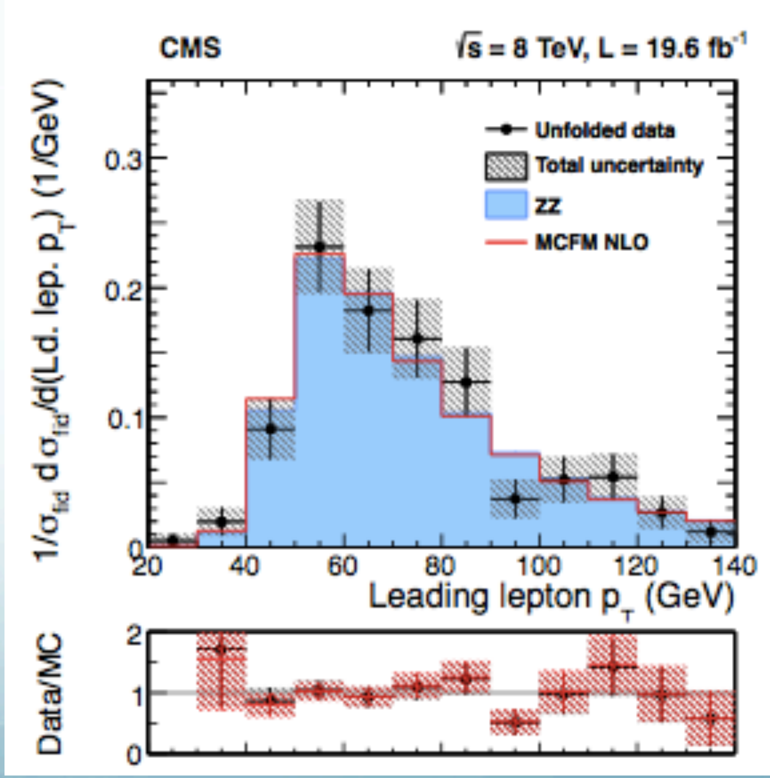
$$7.7 \pm 0.5\,(\text{stat}) {}^{+0.5}_{-0.4}\,(\text{syst}) \pm 0.4\,(\text{theo}) \pm 0.2\,(\text{lumi})$$

SM:
σ_{WW}(MCFM,qq(NLO),gg(LO)) = 7.7 ± 0.6 pb

Differential fiducial cross section
- Leading lepton p_T, p_T^Z, p_T^{ZZ}, m_{ZZ}
- Angular distributions

All decay modes combined.

- Background:
  Jet is misidentified as lepton in WZ/Z +jets and tt. Data driven estimate – control region with relaxed isolation.
- Systematic:
  misidentification rates and the limited statistics of the control regions in the data (fake photon)



ATLAS

8 TeV

ZZ(lll'l')

CONF-2013-020

- Event selection:
  - only ZZ->lll'l'

  p_T^l > 25(10) GeV, leading(other) lepton(s)

  $|\eta^l|$<2.5(2.4), l=e(μ)

  66< m_{ll} < 116 GeV (each pair)

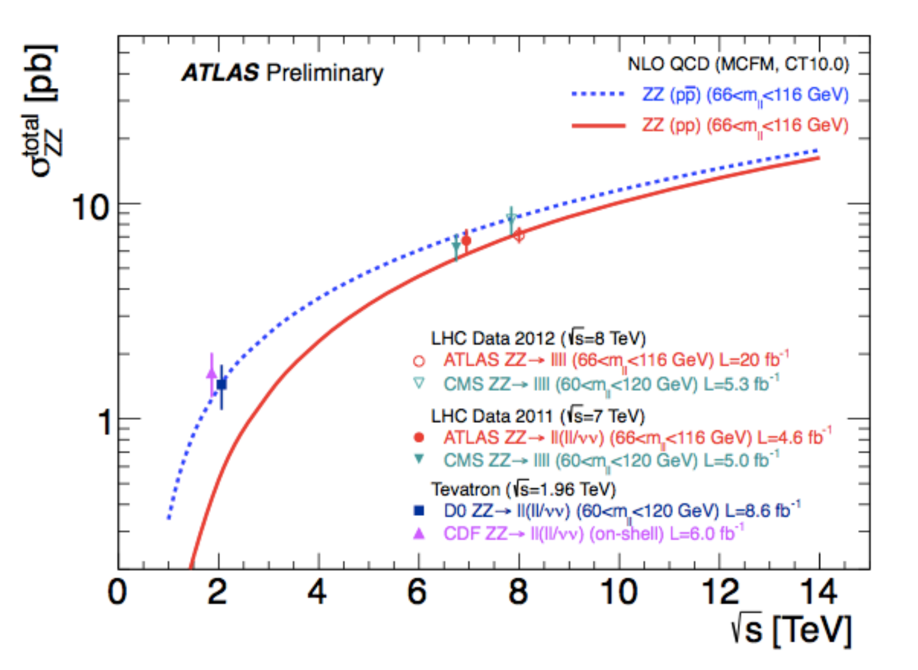
- Background:

  Jet or photon misidentified as lepton in W/Z+jets/γ

  Data driven estimate – control region with relaxed isolation.

- Systematic:

  Dominated by lepton ID/ISO efficiency



Measured cross section

$$\sigma_{ZZ}^{tot} = 7.1^{+0.5}_{-0.4}(\text{stat.}) \pm 0.3(\text{syst.}) \pm 0.2(\text{lumi.})\ \text{pb}.$$

SM:

σ_{WW}(MCFM,NLO) = $7.2^{+0.3}_{-0.2}$ pb,

CMS

7, 8 TeV

ZZ(2l2ν)

SMP-12-016

A good $E_{\mathrm{T}}^{\mathrm{miss}}$ measurement is critical for the extraction of the ZZ $\rightarrow 2\ell2\nu$ signal given that the [无标题] $E_{\mathrm{T}}^{\mathrm{miss}}$ distinguishes this process from the DY background. Since the average $E_{\mathrm{T}}^{\mathrm{miss}}$ of the signal is moderate ($\sim$50 GeV), we cannot simply require a high-$E_{\mathrm{T}}^{\mathrm{miss}}$. We follow the approach of constructing a "reduced $E_{\mathrm{T}}^{\mathrm{miss}}$" variable, as done in the D0 [23, 24] and OPAL [25] experiments. The concept behind a reduced $E_{\mathrm{T}}^{\mathrm{miss}}$ is to reduce the instrumental contribution to mismeasured $E_{\mathrm{T}}^{\mathrm{miss}}$ by considering possible contributions to fake $E_{\mathrm{T}}^{\mathrm{miss}}$. In each event, $p_{\mathrm{T}}^{\mathrm{miss}}$ and jet momenta are decomposed along an orthogonal set of axes in the transverse plane of the detector. One of the axes is defined by the p_{T} of the charged dilepton system, the other perpendicular to it. We define the recoil of the $\ell^+\ell^-$ system in two different ways: (i) the clustered recoil ($\vec{R}_{\mathrm{c}}$) is the vectorial sum of the momenta of the PF jets reconstructed in the event, and (ii) the unclustered recoil ($\vec{R}_{\mathrm{u}}$) is the vectorial sum of the transverse momenta of all PF candidates in the event, with the exception of the two leptons. On each axis (i = parallel/orthogonal to the dilepton system p_{T}), the reduced $E_{\mathrm{T}}^{\mathrm{miss}}$ projection is defined as

$$\text{reduced } E_{\mathrm{T}}^{\mathrm{miss}\,i} = -p_{\mathrm{T}}^{\ell\ell,i} - R_{\mathrm{c/u}}^{i},$$

where $R_{\mathrm{c/u}}$ represents the choice of R_{c} or R_{u} that minimizes the absolute value of that reduced $E_{\mathrm{T}}^{\mathrm{miss}}$ component, and $p_{\mathrm{T}}^{\ell\ell}$ is the transverse momentum of the Z boson. The presence of genuine $E_{\mathrm{T}}^{\mathrm{miss}}$ in the recoil of the charged dilepton system is expected to be evident in the parallel projection, while the component perpendicular to the $\ell^+\ell^-$ system is mostly dominated by jet and $E_{\mathrm{T}}^{\mathrm{miss}}$ resolution. The absolute reduced $E_{\mathrm{T}}^{\mathrm{miss}}$ variable is the sum in quadrature of the two components. The reduced $E_{\mathrm{T}}^{\mathrm{miss}}$ shows better DY background suppression than the standard PF $E_{\mathrm{T}}^{\mathrm{miss}}$ at the same signal efficiency. It is also found to be more stable than the PF $E_{\mathrm{T}}^{\mathrm{miss}}$ under variations in pileup conditions and JES.

CMS 7 TeV

WV($l\nu jj$)

Eur.Phys.J. C73 (2013) 2283

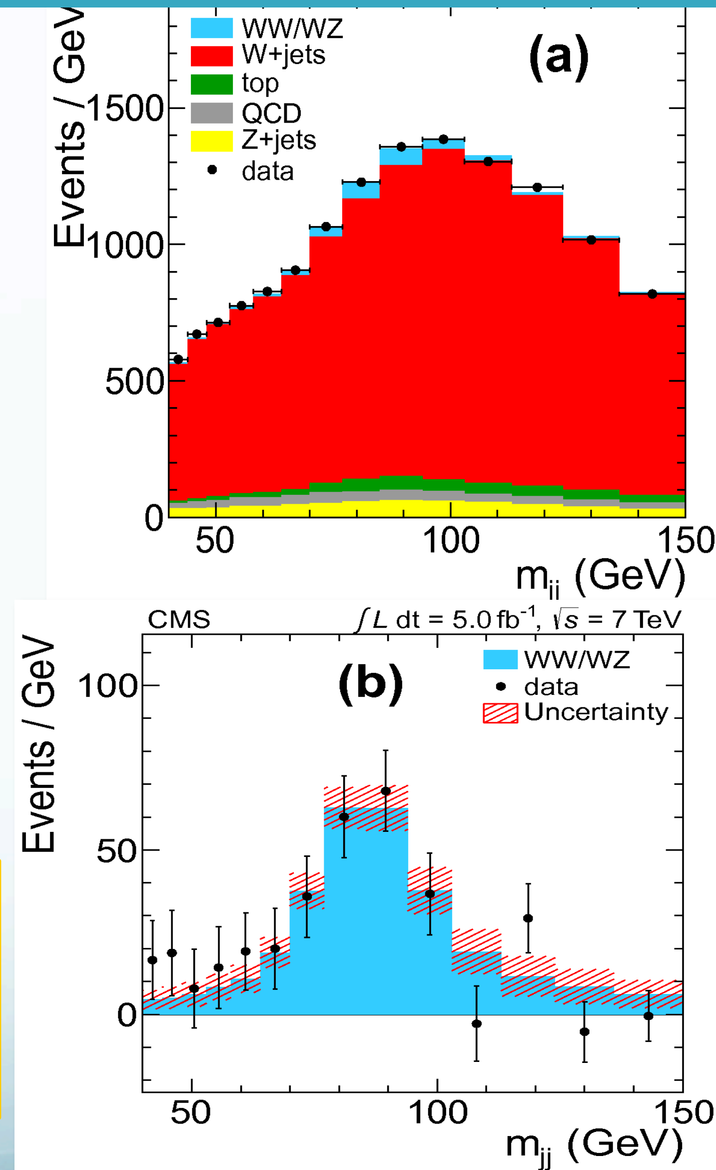
one W boson decays leptonically (l = e,m)

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
  - 40 < Mjj <150 GeV
- 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



ATLAS

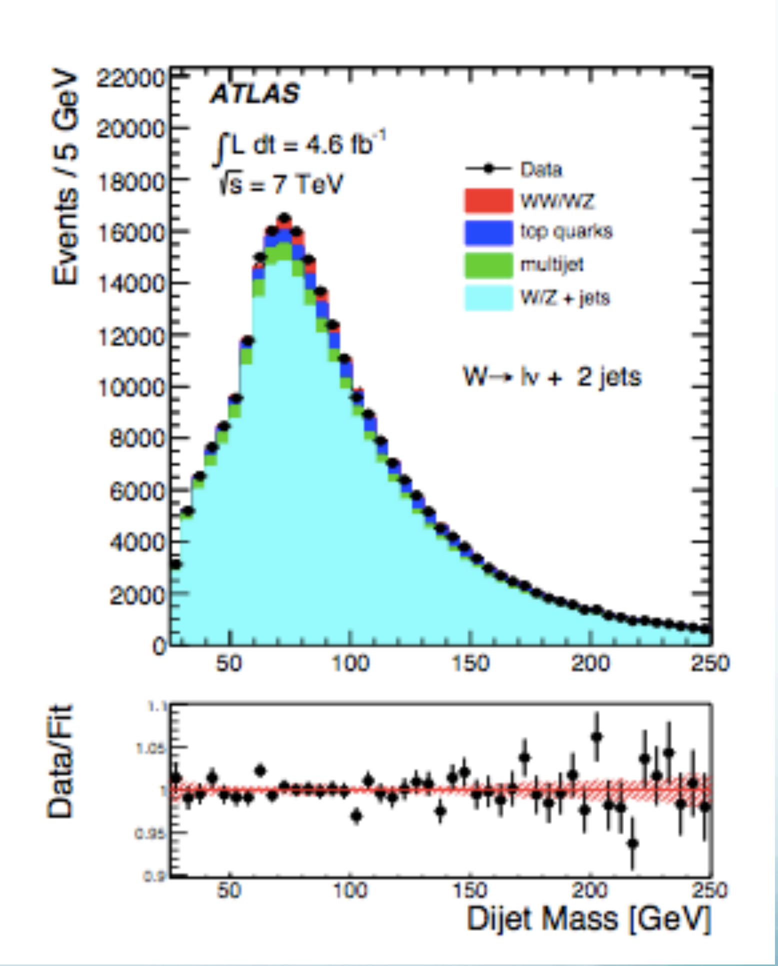
7 TeV

WV(lνjj)

JHEP01(2015)049

one W boson decays leptonically (l = e,m)
the other boson **V(W or Z)** decays hadronically (jj)

- Event selection:
  - p_T^l > 25 GeV$|\eta^l|$<2.5
  - M_T^W> 40 GeV,
  - E_T^{miss} > 30 GeV
  - p_T^{jet} > 30(25) GeV, $|\eta^{jet}|$<2.0, jet b-tag veto
  - $|\Delta\varphi$(E miss , j1)| > 0.8
  - $|\Delta\eta$(j1,j2)| < 1.5
  - 25 < mjj < 250 GeV
- Background:
  - W+jets(dominant), top, Z+jets,
  - jet -> l misidentification.
- Systematic:
  - W/Z + jets rate and shape modelling



Measured cross section pp -> WW and pp-> WZ
68 ± 7 (stat.) ± 19 (syst.) pb ,

SM: $\sigma_{WW}+\sigma_{WZ}$(MCFM, NLO) = 61.1 ± 2.2 pb.

CMS

7, 8 TeV

WZ(lll'ν)

SMP-12-006

Event selection:

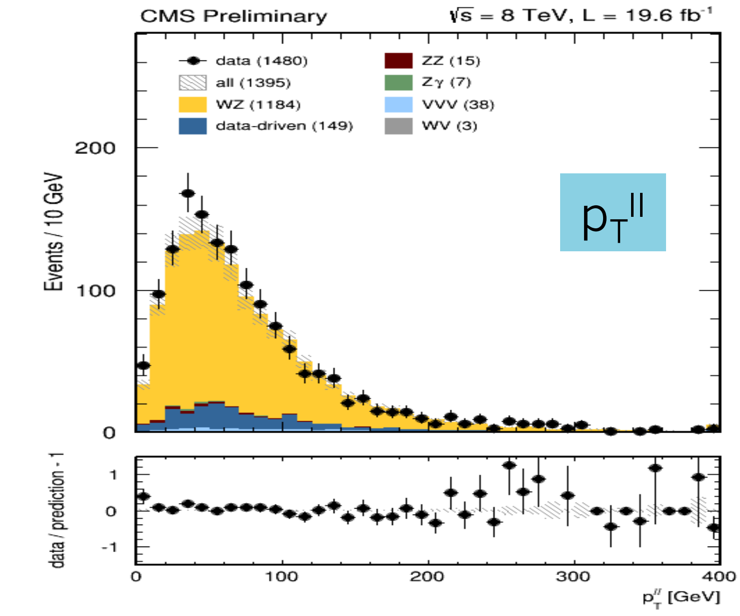
- Two opposite charge leptons + 3rd lepton+ E_T^{miss}
- Z reconstruction:
- p_T^l > 20 (10) GeV
- |mll − m_Z| < 20 GeV (and closest to m_Z)
- W reconstruction:
- p_T^l > 20 GeV, E_T^{miss} > 30 GeV

Background:

- ✧ Fake lepton - real Z plus a jet faking a lepton – the dominant background
- ✧ Non Peaking - no Z boson (e.g. tt)
- ✧ Prompt Lepton –ZZ -> 4l (lost 1 lepton).

Systematic:

- Dominated by data-driven (Z+jets,tt)
- E_T^{miss} energy scales and resolution



W+Z/W-Z ratio measurement

$$\frac{\sigma_{W^+Z}}{\sigma_{W^-Z}} = \frac{N_S^+}{N_S^-} \cdot \frac{(\mathcal{A}\cdot\varepsilon)^-}{(\mathcal{A}\cdot\varepsilon)^+}$$

$$\left(\frac{\sigma_{W^+Z}}{\sigma_{W^-Z}}\right)_{7\ \mathrm{TeV}} = 1.94 \pm 0.25\ (\mathrm{stat.}) \pm 0.04\ (\mathrm{syst.})$$

With theoretical prediction: $1.776^{+0.006}_{-0.0034}$

$$\left(\frac{\sigma_{W^+Z}}{\sigma_{W^-Z}}\right)_{8\ \mathrm{TeV}} = 1.81 \pm 0.12\ (\mathrm{stat.}) \pm 0.03\ (\mathrm{syst.})$$

With theoretical prediction: 1.724 ± 0.003

Measured pp->WZ cross section (71<m_{ll}<111 GeV):

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

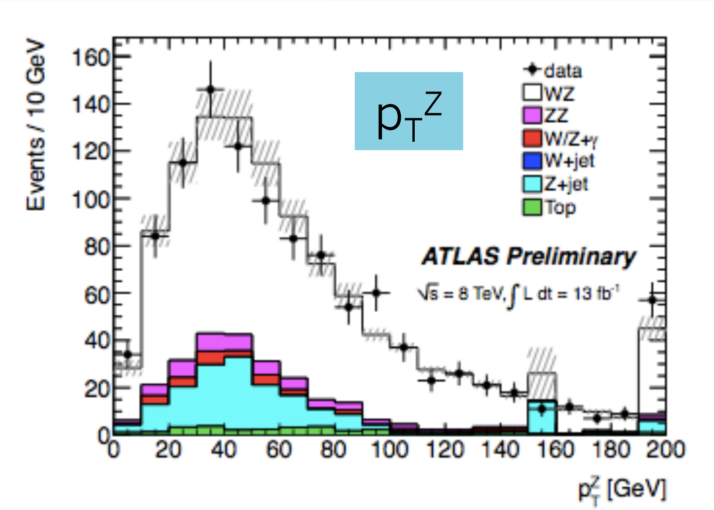
SM: σ_{WW}(MCFM, NLO) = 17.8 $^{+0.7}_{-0.5}$ pb @ 7 TeV

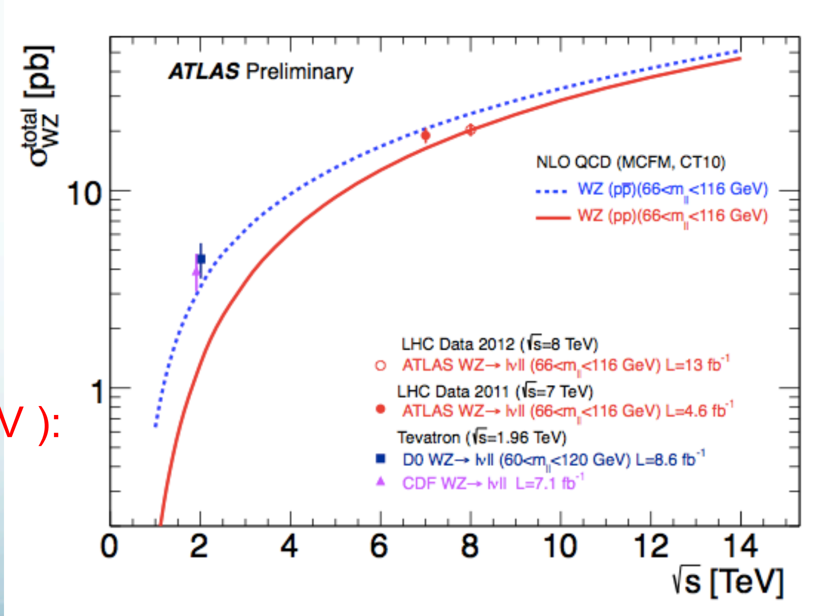
SM: σ_{WW}(MCFM, NLO) = 21.91 $^{+1.17}_{-0.88}$ pb @ 8 TeV

ATLAS 8 TeV WZ($lll'\nu$)

CONF-2013-021

- Event selection:
  - Two opposite charge leptons + 3rd lepton+ E_T^{miss}
  - Z reconstruction:
  - p_T^l > 20 (10) GeV
  - $|m_{ll} - m_Z| < 10$ GeV (and closest to m_Z)
  - W reconstruction:
  - p_T^l > 20 GeV, E_T^{miss} > 25 GeV, m_T^W>20 GeV
- Background:
  - two hard leptons and a fake lepton: Z+jets, tt (data-driven) (dominate)
  - ZZ(3 real leptons), W/Z+γ(photon conversion) (MC simulation)
- Systematic:
  - Dominated by data-driven (Z+jets,tt)





Measured pp->WZ total cross section (66<m_{ll}<116 GeV):

$$20.3^{+0.8}_{-0.7}(\text{stat.})\ ^{+1.2}_{-1.1}(\text{syst.})\ ^{+0.7}_{-0.6}(\text{lumi.})$$

SM: σ_{WZ}(MCFM, NLO) = 20.3 ± 0.8 pb

Anomalous Quartic Gauge Couplings

- New physics may appear as gauge boson self-interaction at low energy scale with high energy degrees of freedom
- SM lagrangian can be extended with 8 dimensional operators remaining SU(2)×U(1) gauge symmetry

Higgs field

$$\mathcal{L}_{S,0} = \left[(D_\mu\Phi)^\dagger D_\nu\Phi\right] \times \left[(D^\mu\Phi)^\dagger D^\nu\Phi\right]$$
$$\mathcal{L}_{S,1} = \left[(D_\mu\Phi)^\dagger D^\mu\Phi\right] \times \left[(D_\nu\Phi)^\dagger D^\nu\Phi\right]$$

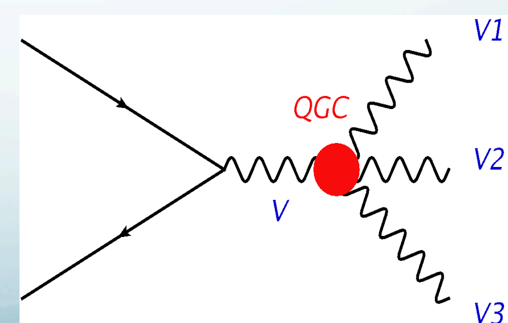
Higgs - Gauge boson field(L)

$$\mathcal{L}_{M,0} = \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right] \times \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right]$$
$$\mathcal{L}_{M,1} = \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\nu\beta}\right] \times \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right]$$
$$\mathcal{L}_{M,2} = \left[B_{\mu\nu}B^{\mu\nu}\right] \times \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right]$$
$$\mathcal{L}_{M,3} = \left[B_{\mu\nu}B^{\nu\beta}\right] \times \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right]$$
$$\mathcal{L}_{M,4} = \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu} D^\mu\Phi\right] \times B^{\beta\nu}$$
$$\mathcal{L}_{M,5} = \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu} D^\nu\Phi\right] \times B^{\beta\mu}$$
$$\mathcal{L}_{M,6} = \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu}\hat{W}^{\beta\nu} D^\mu\Phi\right]$$
$$\mathcal{L}_{M,7} = \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu}\hat{W}^{\beta\mu} D^\nu\Phi\right]$$

Gauge boson field (L)

$$\mathcal{L}_{T,0} = \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right] \times \mathrm{Tr}\left[\hat{W}_{\alpha\beta}\hat{W}^{\alpha\beta}\right]$$
$$\mathcal{L}_{T,1} = \mathrm{Tr}\left[\hat{W}_{\alpha\nu}\hat{W}^{\mu\beta}\right] \times \mathrm{Tr}\left[\hat{W}_{\mu\beta}\hat{W}^{\alpha\nu}\right]$$
$$\mathcal{L}_{T,2} = \mathrm{Tr}\left[\hat{W}_{\alpha\mu}\hat{W}^{\mu\beta}\right] \times \mathrm{Tr}\left[\hat{W}_{\beta\nu}\hat{W}^{\nu\alpha}\right]$$
$$\mathcal{L}_{T,5} = \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right] \times B_{\alpha\beta}B^{\alpha\beta}$$
$$\mathcal{L}_{T,6} = \mathrm{Tr}\left[\hat{W}_{\alpha\nu}\hat{W}^{\mu\beta}\right] \times B_{\mu\beta}B^{\alpha\nu}$$
$$\mathcal{L}_{T,7} = \mathrm{Tr}\left[\hat{W}_{\alpha\mu}\hat{W}^{\mu\beta}\right] \times B_{\beta\nu}B^{\nu\alpha}$$
$$\mathcal{L}_{T,8} = B_{\mu\nu}B^{\mu\nu}B_{\alpha\beta}B^{\alpha\beta}$$
$$\mathcal{L}_{T,9} = B_{\alpha\mu}B^{\mu\beta}B_{\beta\nu}B^{\nu\alpha}$$

	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
$\mathcal{L}_{T,9}, \mathcal{L}_{T,9}$	0	0	X	0	0	X	X	X	X



Triple and Quartic Anomalous Gauge Couplings

Process (l=e,μ)	aTGC/QGC Parameters		Limit Setting variable
Wγ	WWγ	$\lambda_{\gamma,}$ ΔK_{γ} (charged)	E_T
Zγ	ZZγ, Zγγ	$h_3^{Z,\gamma}$, $h_4^{Z,\gamma}$ (neutral)	E_T
Zγ	ZZγ, Zγγ	$h_3^{Z,\gamma}$, $h_4^{Z,\gamma}$ (neutral)	E_T
WW(lvlv)	WWγ, WWZ	(EFT) c_{WWW}/Λ^2, c_W/Λ^2 ,c_B/Λ^2 (CMS 8 TeV) $\lambda_{z/\gamma,}$ $\Delta K_{z/\gamma,}\Delta g^Z_1$ (ATLAS,CMS 7 TeV)	M_{ll} (CMS 8 TeV) Max P_T^l
ZZ(4l, 2l2v)	ZZZ, ZZγ	$f_4^{Z,\gamma}$, $f_5^{Z,\gamma}$ (neutral)	M_{4l}
WZ->lvjj	WWγ, WWZ	$\lambda_{z,}$ $\Delta K_{\gamma,}$	$P_t^{di\text{-}jet}$
WVγ	WWγγ, WZγγ	a_0^w, a^w_c ,f_{T0}, K_0^w, K_c^w	E_t
WW(lvjj)	WWWW	α_4, α_5 (ATLAS), $f_{S0,}$ f_{S1} (CMS)	m_{ll}
Wγγ	WWγγ	f_{T0}/Λ^4, f_{M2}/Λ^4, and f_{M3}/Λ^4	$m_{\gamma\gamma}$

- With or without form factor, K Matrix for unitarization
- deltaNLL, CLs or profile likelihood methods used to set the upper limit