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Multi-boson production at the LHC

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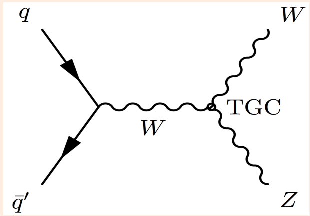
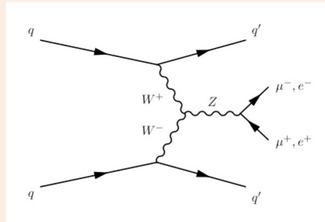
On behalf of the
ATLAS and CMS collaborations

Multi-boson final states

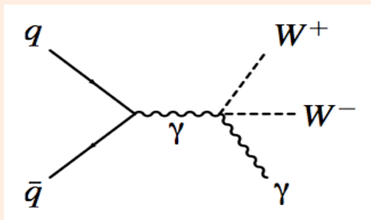
- Rich physics program to test the **electro-weak self-coupling.**
- Constrain new physics in the framework of **effective Lagrangian** and **anomalous gauge couplings**.
- Main background to many Higgs channels and BSM searches.
- Accessible couplings

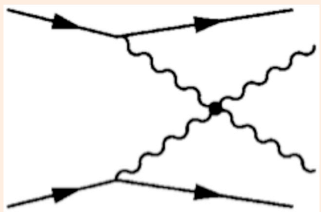
- Triple gauge couplings (TGC)
  - Di-boson final states.
  - Vector Boson Fusion



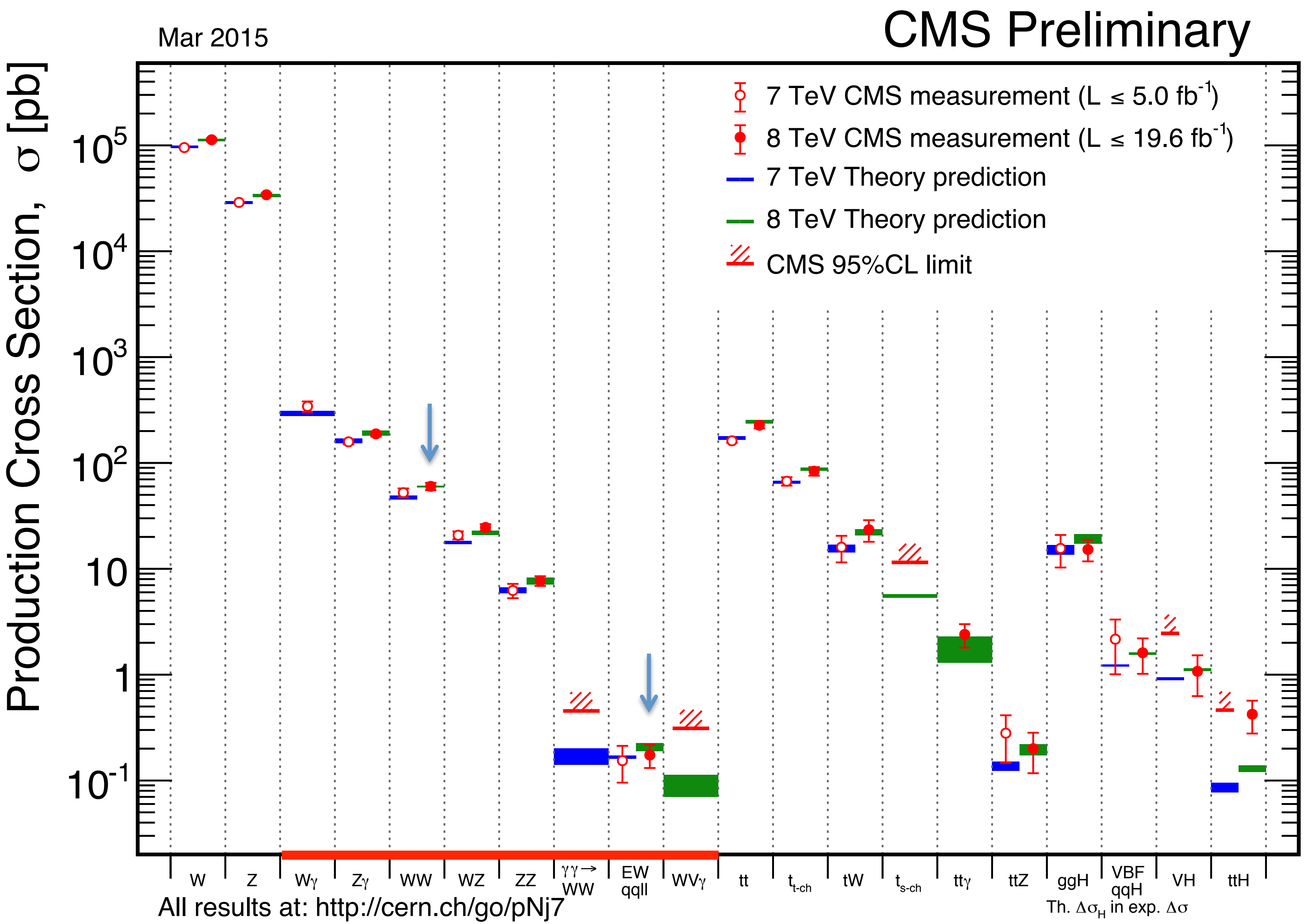


- Quartic gauge couplings (QGC)
  - Tri-boson final states.
  - Vector Boson scattering / gamma-gamma induced exclusive production.



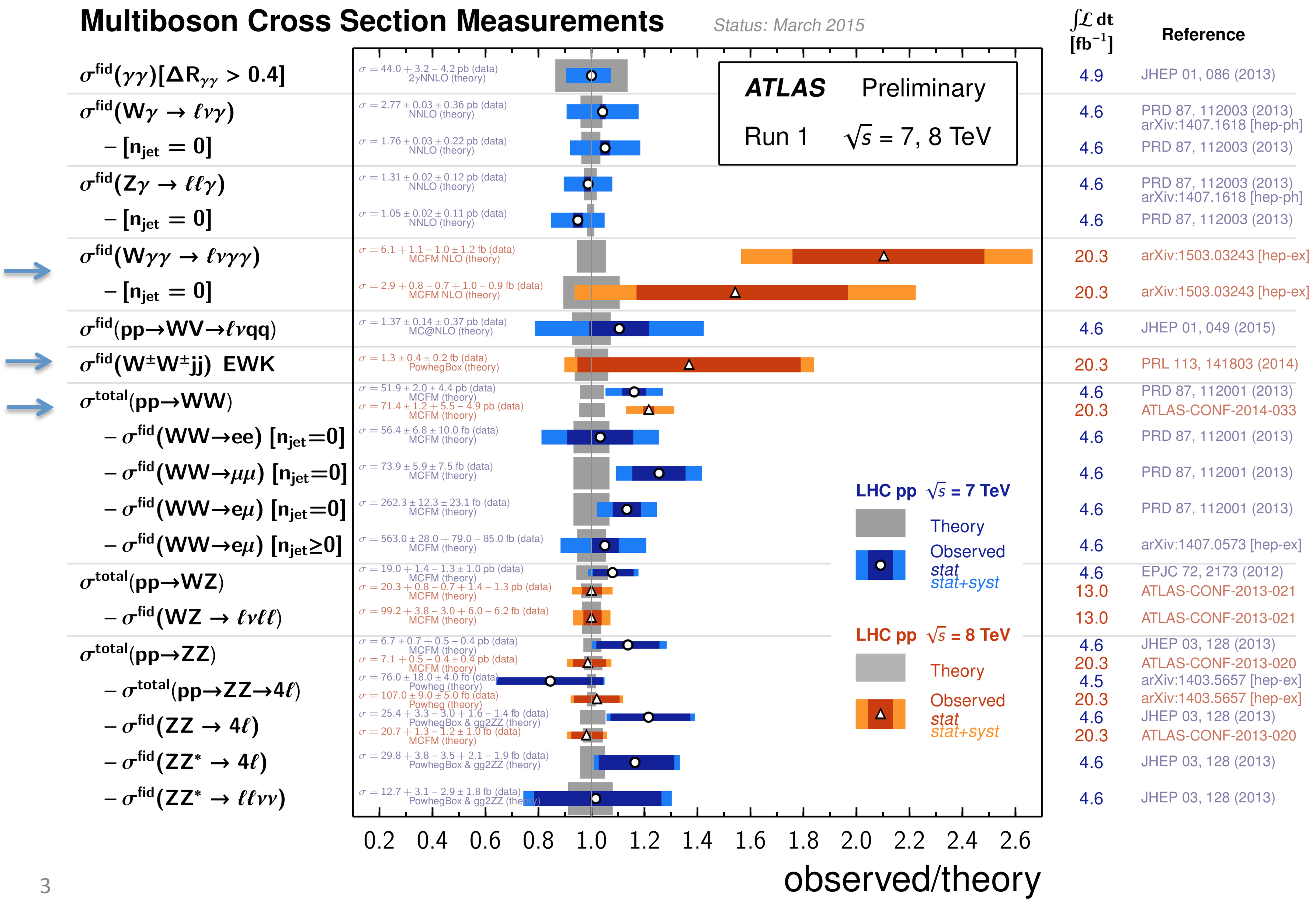


Overview



Mar 2015
CMS Preliminary
Production Cross Section, σ [pb]
7 TeV CMS measurement (L ≤ 5.0 fb-1)
8 TeV CMS measurement (L ≤ 19.6 fb-1)
7 TeV Theory prediction
8 TeV Theory prediction
CMS 95%CL limit
W
Z
Wγ
Zγ
WW
WZ
ZZ
γγ→WW
EW qqll
WVγ
tt
tt-ch
tW
ts-ch
ttγ
ttZ
ggH
VBF qqH
VH
ttH
All results at: http://cern.ch/go/pNj7
Th. ΔσH in exp. Δσ

Overview



Multiboson Cross Section Measurements
Status: March 2015
ATLAS Preliminary
Run 1 $\sqrt{s}$ = 7, 8 TeV
$\int\mathcal{L}\,dt$ [fb^{-1}]
Reference
$\sigma^{fid}(\gamma\gamma)[\Delta R_{\gamma\gamma} > 0.4]$
$\sigma^{fid}(W\gamma \to \ell\nu\gamma)$
$-[n_{jet} = 0]$
$\sigma^{fid}(Z\gamma \to \ell\ell\gamma)$
$-[n_{jet} = 0]$
$\sigma^{fid}(W\gamma\gamma \to \ell\nu\gamma\gamma)$
$-[n_{jet} = 0]$
$\sigma^{fid}(pp\to WV\to \ell\nu qq)$
$\sigma^{fid}(W^{\pm}W^{\pm}jj)$ EWK
$\sigma^{total}(pp\to WW)$
$-\sigma^{fid}(WW\to ee)\ [n_{jet}=0]$
$-\sigma^{fid}(WW\to \mu\mu)\ [n_{jet}=0]$
$-\sigma^{fid}(WW\to e\mu)\ [n_{jet}=0]$
$-\sigma^{fid}(WW\to e\mu)\ [n_{jet}\geq 0]$
$\sigma^{total}(pp\to WZ)$
$-\sigma^{fid}(WZ \to \ell\nu\ell\ell)$
$\sigma^{total}(pp\to ZZ)$
$-\sigma^{total}(pp\to ZZ\to 4\ell)$
$-\sigma^{fid}(ZZ \to 4\ell)$
$-\sigma^{fid}(ZZ^{*} \to 4\ell)$
$-\sigma^{fid}(ZZ^{*} \to \ell\ell\nu\nu)$
4.9 JHEP 01, 086 (2013)
4.6 PRD 87, 112003 (2013) arXiv:1407.1618 [hep-ph]
4.6 PRD 87, 112003 (2013)
4.6 PRD 87, 112003 (2013) arXiv:1407.1618 [hep-ph]
4.6 PRD 87, 112003 (2013)
20.3 arXiv:1503.03243 [hep-ex]
20.3 arXiv:1503.03243 [hep-ex]
4.6 JHEP 01, 049 (2015)
20.3 PRL 113, 141803 (2014)
4.6 PRD 87, 112001 (2013)
20.3 ATLAS-CONF-2014-033
4.6 PRD 87, 112001 (2013)
4.6 PRD 87, 112001 (2013)
4.6 PRD 87, 112001 (2013)
4.6 arXiv:1407.0573 [hep-ex]
4.6 EPJC 72, 2173 (2012)
13.0 ATLAS-CONF-2013-021
13.0 ATLAS-CONF-2013-021
4.6 JHEP 03, 128 (2013)
20.3 ATLAS-CONF-2013-020
4.5 arXiv:1403.5657 [hep-ex]
20.3 arXiv:1403.5657 [hep-ex]
4.6 JHEP 03, 128 (2013)
20.3 ATLAS-CONF-2013-020
4.6 JHEP 03, 128 (2013)
4.6 JHEP 03, 128 (2013)
LHC pp $\sqrt{s}$ = 7 TeV
Theory
Observed
stat
stat+syst
LHC pp $\sqrt{s}$ = 8 TeV
Theory
Observed
stat
stat+syst
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
observed/theory

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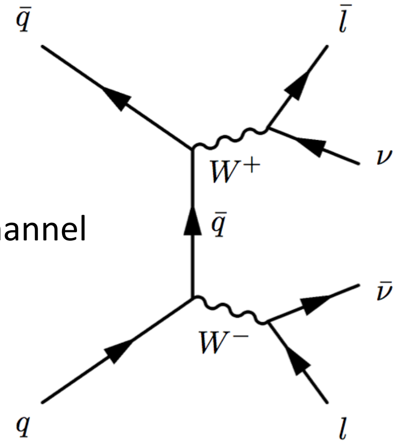
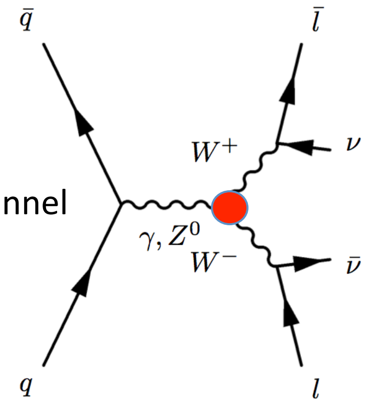
WW production

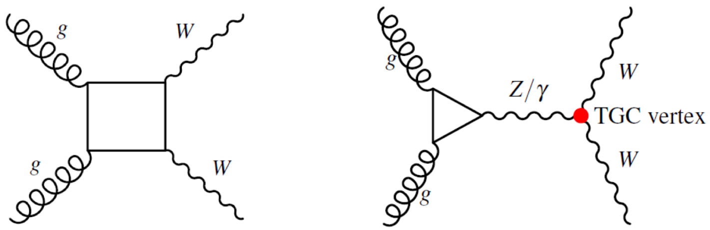
t-channel



s-channel



- Signature two leptons and MET.
- Small contribution (3%) from gg:



- Important background to H->WW.
- Study of charge triple gauge boson vertex.
- Run-1 results:
  ATLAS (20ifb 8TeV), CONF-2014-033
  CMS (20ifb 8TeV), CMS-PAS-SMP-14-016

WW production

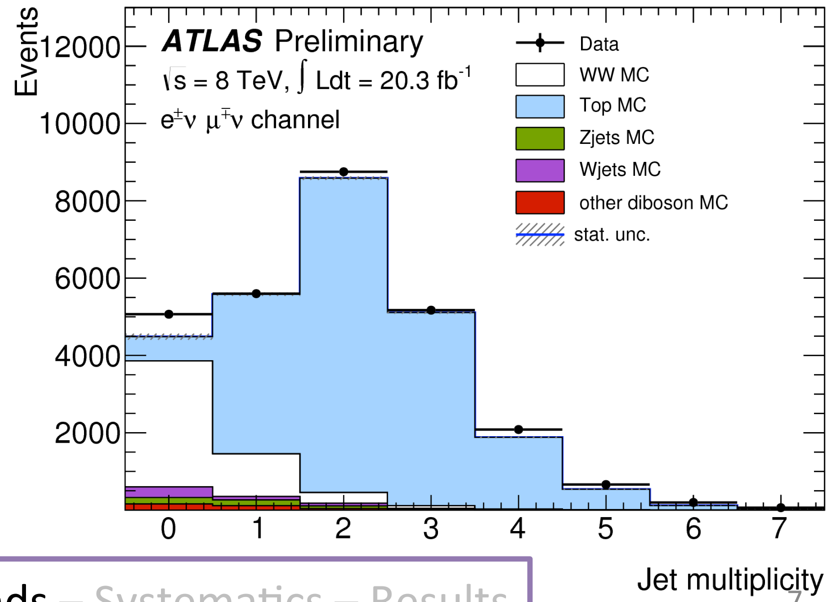
	ATLAS	CMS
Fiducial and total cross section.		
H→WW	signal	background
Signal Acceptance	~5%	~4.2%

Selection	ATLAS	CMS
2 leptons OS	e,μ : p_T >20 GeV	e,μ : p_T >20 GeV
	$p_T(l_1)$ >25 GeV	
m(ll)	> 15 GeV (ee, $\mu\mu$), > 10 GeV (eμ)	> 12 GeV
Z veto ($\lvert m_{ll}-m_Z \rvert$	< 15GeV	< 15GeV
E_T^{miss} (rel)	> (45,45,15) GeV, ($\mu\mu$,ee,eμ)	> 20 GeV
additional cuts	p_T^{miss} > (45,45,20) GeV, ($\mu\mu$,ee,eμ) $\Delta\phi$ (p_T^{miss},E_T^{miss})<0.6	MVA to reduce Drell Yan
Jet veto	N>0, pT>25GeV, |eta|<4.5,anti-kt,DR=0.4	N>1, pT>25GeV, |eta|<4.5,anti-kt,DR=0.4
heavy flavour	-	top veto

Backgrounds WW

- Dominant backgrounds
  - Top pair
    - Use control regions to estimate top contribution.
  - V+jets
    - Estimate probability of jets being identified as leptons.
  - diboson
    - Use MC prediction (ATLAS).
    - Wγ* normalised to control regions in data (CMS).

Background	ATLAS	CMS
top	52%	42%
W+j	15%	26%
Z+j	20%	10%
diboson	14%	12%
other (higgs)		10%
total bkg	28%	26%
total events exp	5787	6981



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Systematic uncertainties WW

- Cross section uncertainty
  - Theory 3-4%
    - dominant
      Jet veto (ATLAS)
      Jet counting (CMS)
  - Experimental 4-6%
    - dominant
      Jet, MET related (ATLAS)
      lepton efficiency (CMS)
      background

Source	Uncertainty (%)
Statistical uncertainty	1.5
Luminosity	2.6
Lepton efficiency	3.8
Lepton momentum scale	0.5
E_T^{miss} resolution	0.7
Jet energy scale	1.7
$t\bar{t}$+tW normalization	2.2
W + jets normalization	1.3
$Z/\gamma^* \to \ell^+\ell^-$ normalization	0.6
$Z/\gamma^* \to \tau^+\tau^-$ normalization	0.2
$W\gamma$ normalization	0.3
$W\gamma^*$ normalization	0.4
VV normalization	3.0
$H \to$ WW normalization	0.8
Jet counting theory model	4.3
PDFs	1.2
MC statistics	0.9
Total uncertainty	7.9

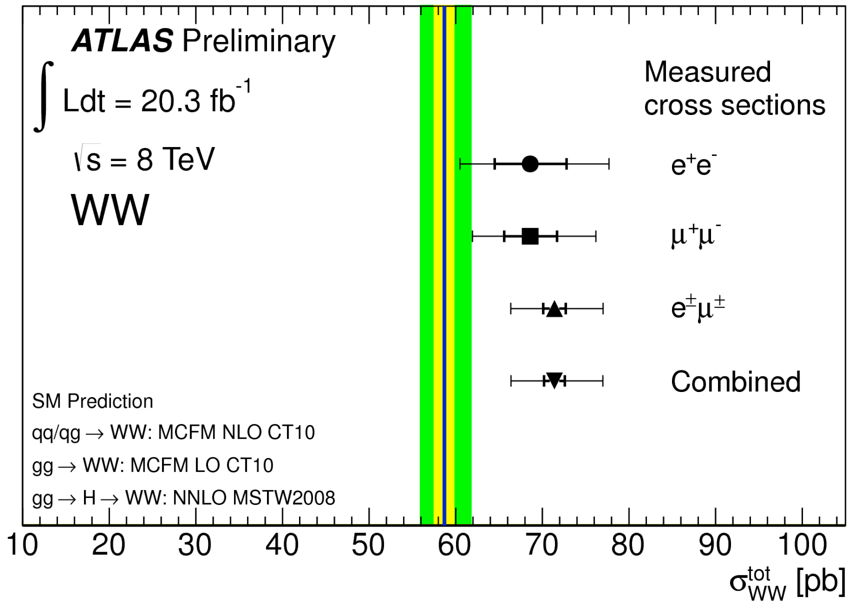
CMS

Results WW

- Total cross section

CMS $60.1 \pm 0.9\,(\text{stat.}) \pm 3.2\,(\text{exp.}) \pm 3.1\,(\text{th.}) \pm 1.6\,(\text{lum.})\,\text{pb}.$

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



ATLAS and CMS in agreement.

<u>Theoretical predictions cited:</u>

59.8 ± 1.2 pb (CMS)

NNLO "qqbar+qq" (no H)

58.7 ± 2.9 pb (ATLAS)

NLO qqbar + LO gg + NNLO H

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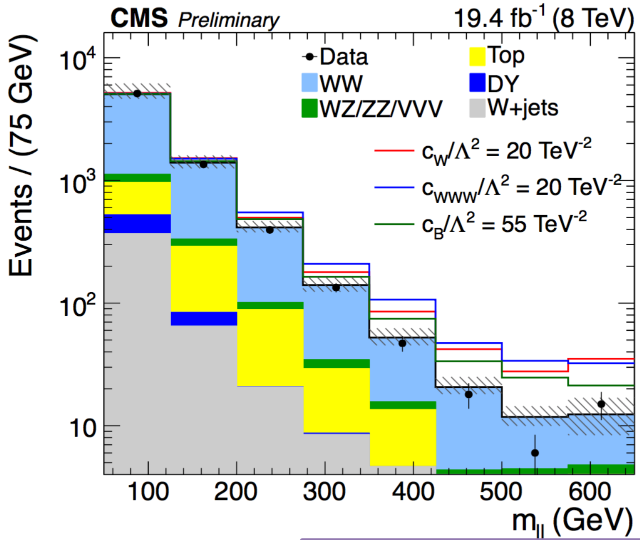
Results WW

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

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)

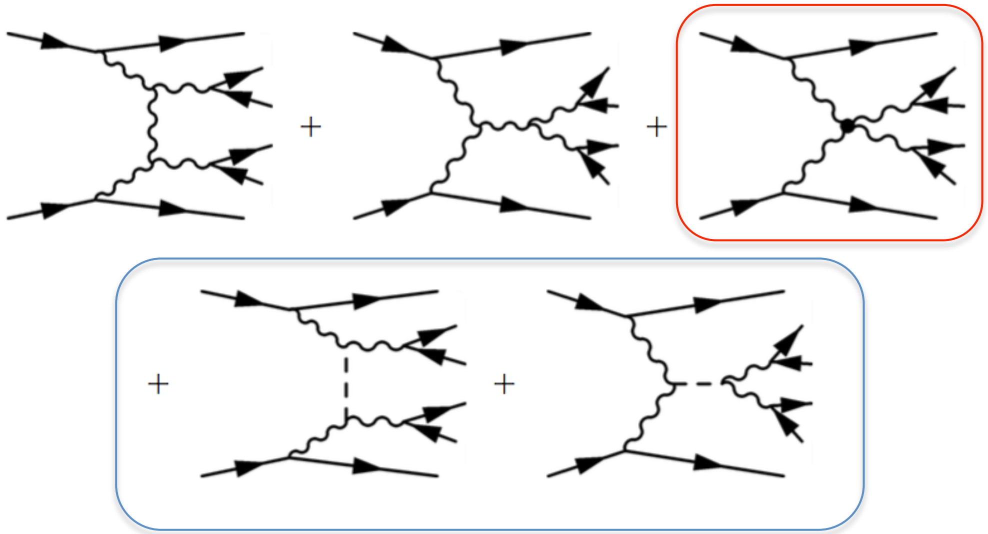


$$\mathcal{O}_{WWW} = \frac{c_{WWW}}{\Lambda^2}\mathrm{Tr}[W_{\mu\nu}W^{\nu\rho}W_\rho^{\ \mu}],$$
$$\mathcal{O}_W = \frac{c_W}{\Lambda^2}(D^\mu\Phi)^\dagger W_{\mu\nu}(D^\nu\Phi),$$
$$\mathcal{O}_B = \frac{c_B}{\Lambda^2}(D^\mu\Phi)^\dagger B_{\mu\nu}(D^\nu\Phi).$$

Dim 6 EFT operators

Multi-boson + 2 jets

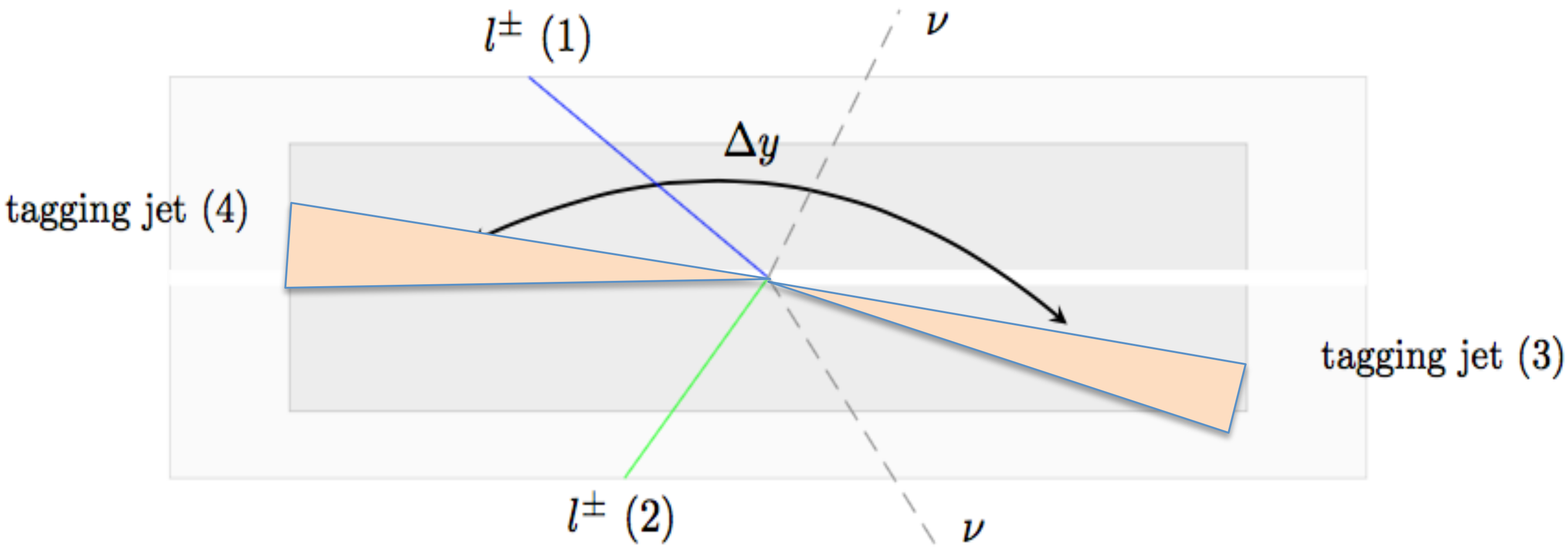
- Study Vector Boson Scattering



Quartic vertex and Higgs tame the cross section at high *s*.
Motivation: Discover VBS, set limits on BSM.
Signature: Two jets and two same sign W.

Multi-boson + 2 jets

- VBS topology: Two tagging jets, l^+l^+, missing energy



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Multi-boson + 2 jets

- Experimental results:

ATLAS – 8 TeV, 20 fb^{-1}
Phys. Rev. Lett. 113, 141803 (2014),
http://arxiv.org/abs/1405.6241

σ(QCD+EWK)
σ(EWK only)
anomalous couplings

CMS – 8 TeV, 20 fb^{-1}
Phys. Rev. Lett. 114, 051801 (2015),
http://arxiv.org/abs/1410.6315

σ(EWK only)
anomalous couplings
limits H^{++}, H^{--}

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Multi-boson + 2 jets

- VBS topology: Two tagging jets, l^+l^+, missing energy

Object	ATLAS	CMS
2 leptons	e,μ	e,μ,(τ→e,μ)
lepton pT	> 25 GeV	> 20 GeV
η l(e, μ)	< 2.5	<2.5 (2.4)
m(ll)	> 20 GeV	> 50 GeV
ΔR(l,l/j)	> 0.3	> 0.3
2 jets anti-kT	R=0.4	R=0.5
pT(j)	> 30 GeV	> 30 GeV
η(j)	< 4.5	< 4.7
m(jj)	> 500 GeV	> 500 GeV
E_T^{miss}	> 40 GeV	> 40 GeV

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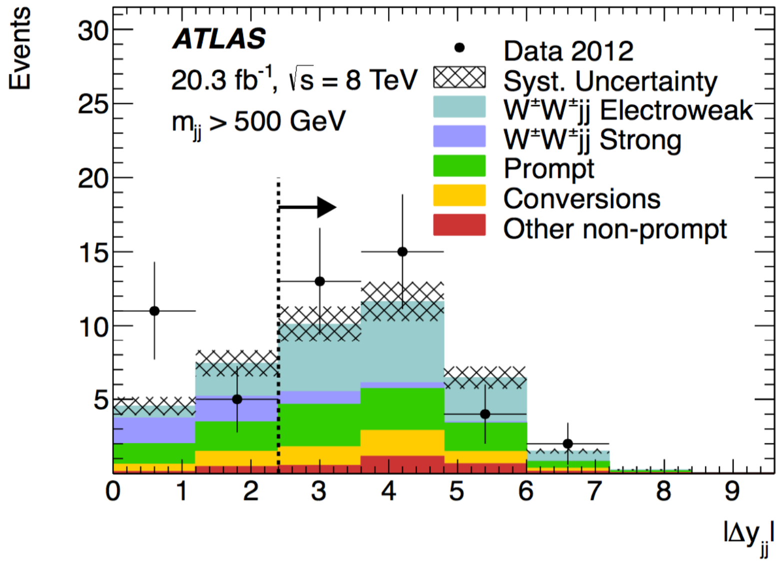
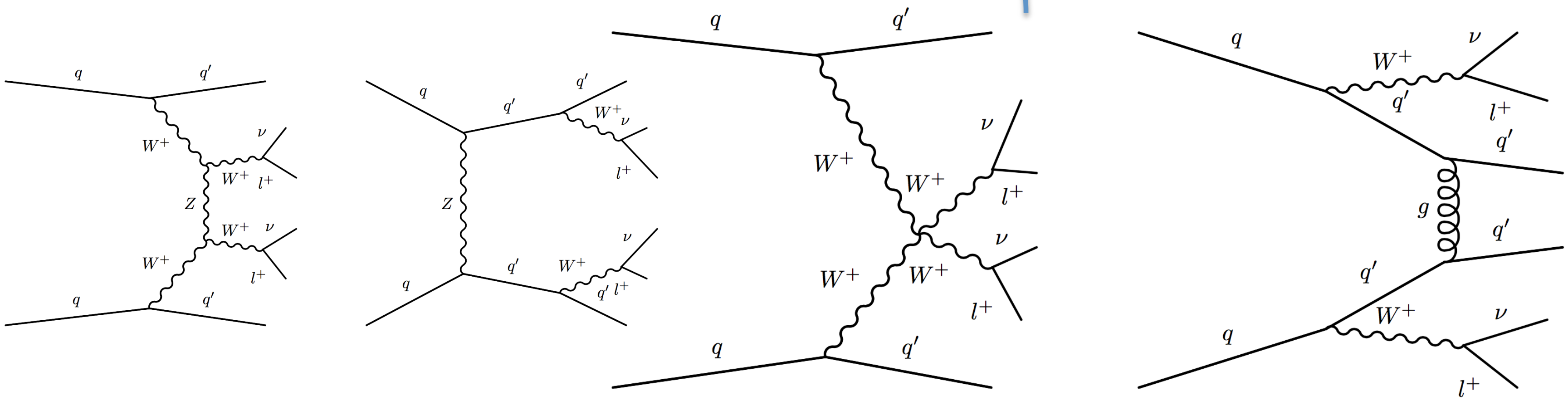
- Signal

EWK production:
Δy(jj) > 2.4, ATLAS
Δeta(jj) > 2.5, CMS





EWK + QCD production (ATLAS)

Multi-boson + 2 jets

Main background sources:
prompt, conversions, other non-prompt.

- MC-based estimation:
  - *WZ* + jets
  - *Wγjj, tt+W/Z, ZZ*
  - Double parton scattering (negligible)
- Data-driven estimation:
  - *Z* + jets for *ee* and *eμ* channels (*e* charge miss identification)
  - Background with one or two jets mis-reconstructed as isolated leptons
- Top rejection (CMS)
  - Soft μ and *b*-jet detection to reduce top related backgrounds (*tt*, *tW*)

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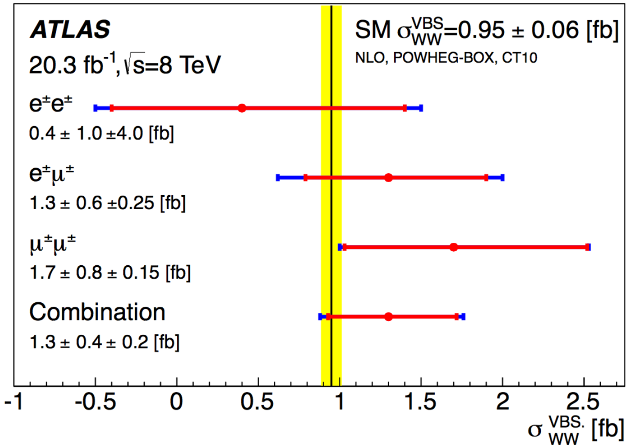
Multi-boson + 2 jets

- **Cross section extraction**
  - Profile likelihood ratio method, simultaneous fit over all three channels.
  - CMS : Fiducial volume definition extrapolating from signal selection:
  - ATLAS: Inclusive and VBS fiducial volumes corresponding to event selection.

$p_T(l) > 10$ GeV
$|\eta(l)| < 2.5$
$p_T(j) > 20$ GeV
$|\eta(j)| < 5.0$
$m(jj) > 300$ GeV
$|\Delta y(jj) > 2.5$



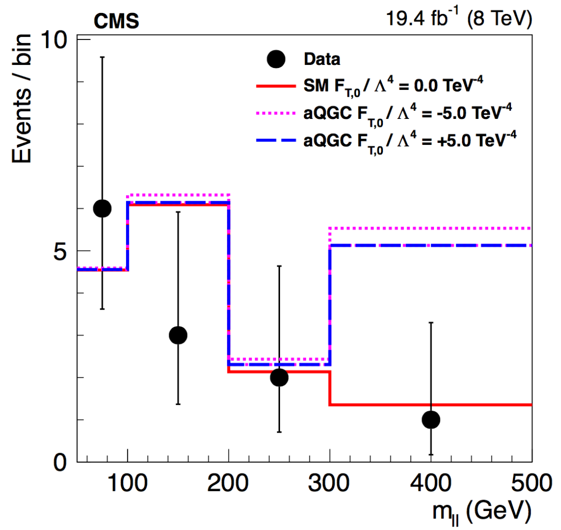
$$\sigma_{\text{fid}}(\mathrm{W}^{\pm}\mathrm{W}^{\pm}jj) = 4.0^{+2.4}_{-2.0}\,(\text{stat})^{+1.1}_{-1.0}\,(\text{syst})\text{ fb}$$

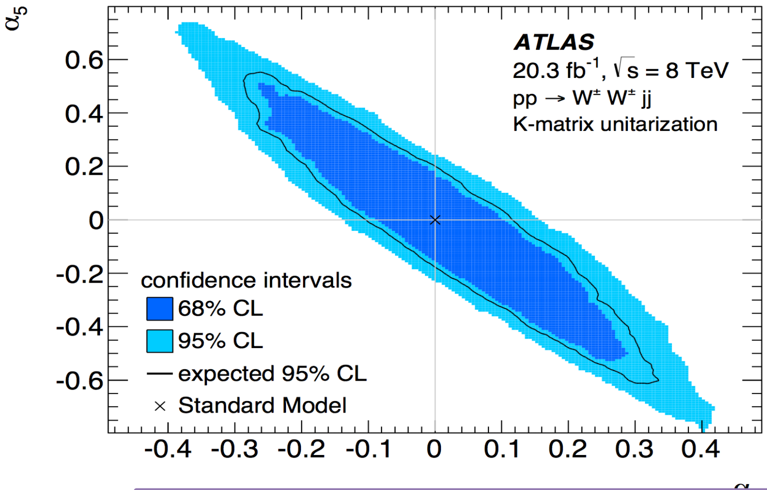
Expected : 5.8 ± 1.2 fb

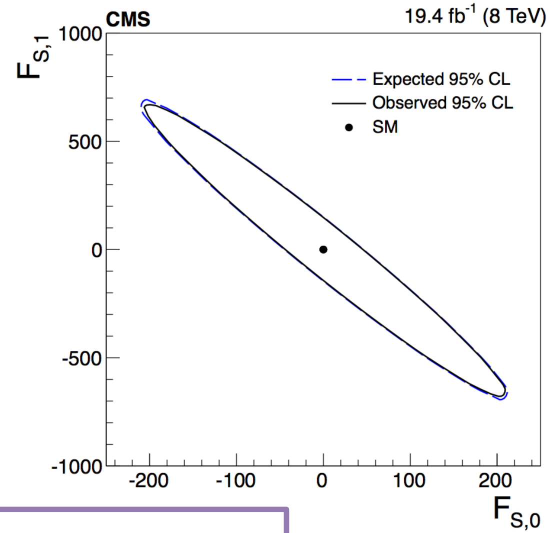
CMS

Multi-boson + 2 jets

- **Anomalous couplings**
  - Effective theory to assess agreement with SM.
  - Constrain additional operators to guard unitarity
  - CMS :
    Dim-8 operators, C,P conserving.
    m(ll) differential cross section.
  - ATLAS:
    k-matrix unitarisation and α parameterisation
    VBS fiducial cross section.







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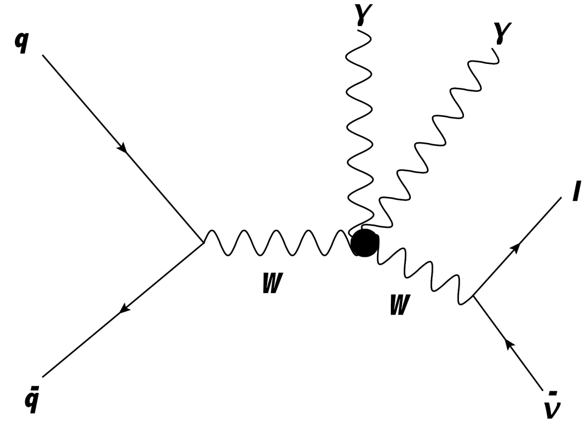
W γγ

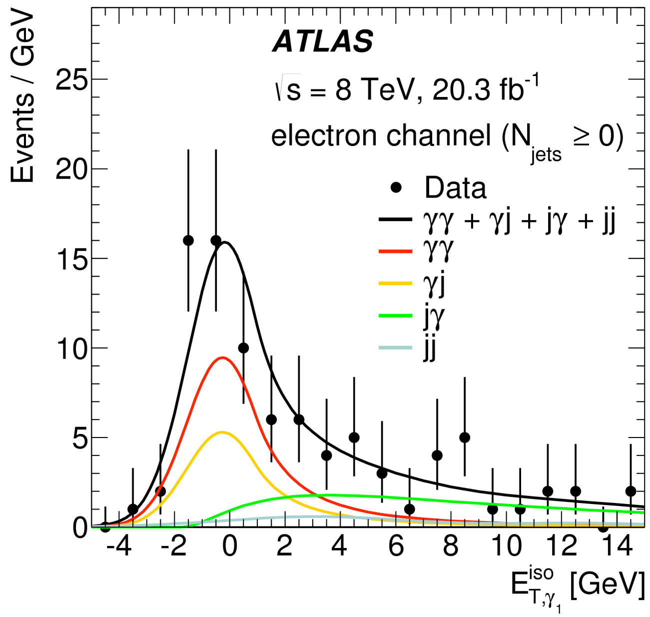


- **Tri-boson final state**
  - *γγ(W→lν), l=e,μ*
  - First cross section measurement of tri-boson production.
    - Inclusive
    - Exclusive (no jets)
  - Access to anomalous quartic gauge boson couplings.

Cuts	$pp \to \ell\nu\gamma\gamma$
Lepton	$p_T^{\ell} > 20$ GeV
	$p_T^{\nu} > 25$ GeV
	$\lvert\eta^{\ell}\rvert < 2.5$
W-Boson	$m_T > 40$ GeV
Photon	$E_T^{\gamma} > 20$ GeV
	$\lvert\eta^{\gamma}\rvert < 2.37$
	$\Delta R(\ell, \gamma) > 0.7$
	$\Delta R(\gamma, \gamma) > 0.4$
	iso. fraction $\epsilon_h^p < 0.5$
Jets	$p_T^{\text{jet}} > 30$ GeV
	$\lvert\eta^{\text{jet}}\rvert < 4.4$
	$\Delta R(\ell, \text{jet}) > 0.3$
	$\Delta R(\gamma, \text{jet}) > 0.3$
	Exclusive selection: $N_{\text{jet}} = 0$

W γγ

- **Backgrounds**
  <u>from MC</u>
  – *Zγ, Zγγ, WZ, W(τν)γγ*
  – *tt, WW*
  <u>from Data</u>
  – *Wj, Wγj, γγj*



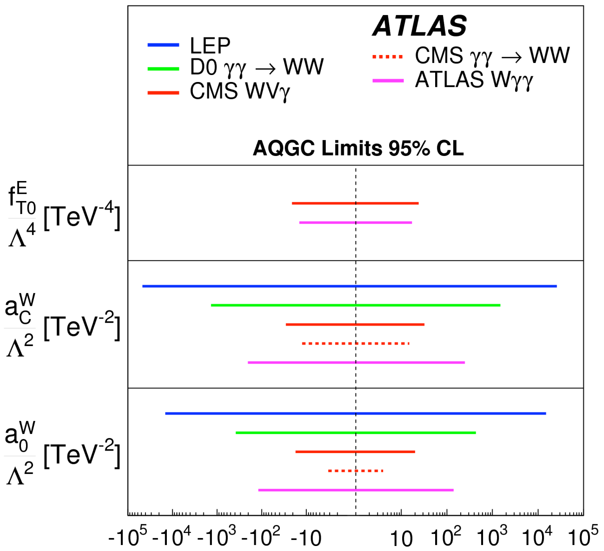
Fake photon estimated with two-dimensional template fit to transverse isolation distribution. Fake estimate dominant systematic ~ 20%.

W γγ

- **Cross section**

	$\sigma^{\rm fid}$ [fb]	$\sigma^{\rm MCFM}$ [fb]
Inclusive ($N_{\rm jet} \geq 0$)		
$\mu\nu\gamma\gamma$	$7.1\ ^{+1.3}_{-1.2}$ (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 ($N_{\rm jet} = 0$)		
$\mu\nu\gamma\gamma$	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.)	

- **Anomalous couplings**



Limits provided for non-unitarised and unitarised with dipol-formfactor.

Summary

- **Run-1** allowed to explore di-boson production processes.
  - Most di-boson measurements systematically limited.
  - Rich legacy of 8TeV cross sections and unfolded distributions.
  - Tri-boson and VBS processes accessible.
- Awaiting combinations and Run-2 analysis.