EWK measurements from ATLAS and CMS: Run1 legacy, prospects

Luca Perrozzi (ETHZ)
for the CMS and ATLAS collaborations

50th Rencontres de Moriond, EWK session
La Thuile, March 14th-21st 2015

I would like to thank the organizers…

ATLAS+CMS: Other EW measurements; Run1 legacy, prospects

Plenary given at Moriond/EW: 50th Rencontres de Moriond on "EW Interactions and Unified Theories", 14-21 Mar 2015, La Thuile (Italy) The talk is selected (cms speaker). The talk length was 15 minutes.

Speakers

Luca Perrozzi (ETH Zürich)

Abstract

W mass covered in a different talk by ATLAS. The ATLAS talk is meant at covering all measurements that are currently being done, as well as all the new techniques that are being developed, to reduce the systematic uncertainties on the W mass measurement at the LHC.

Content Review

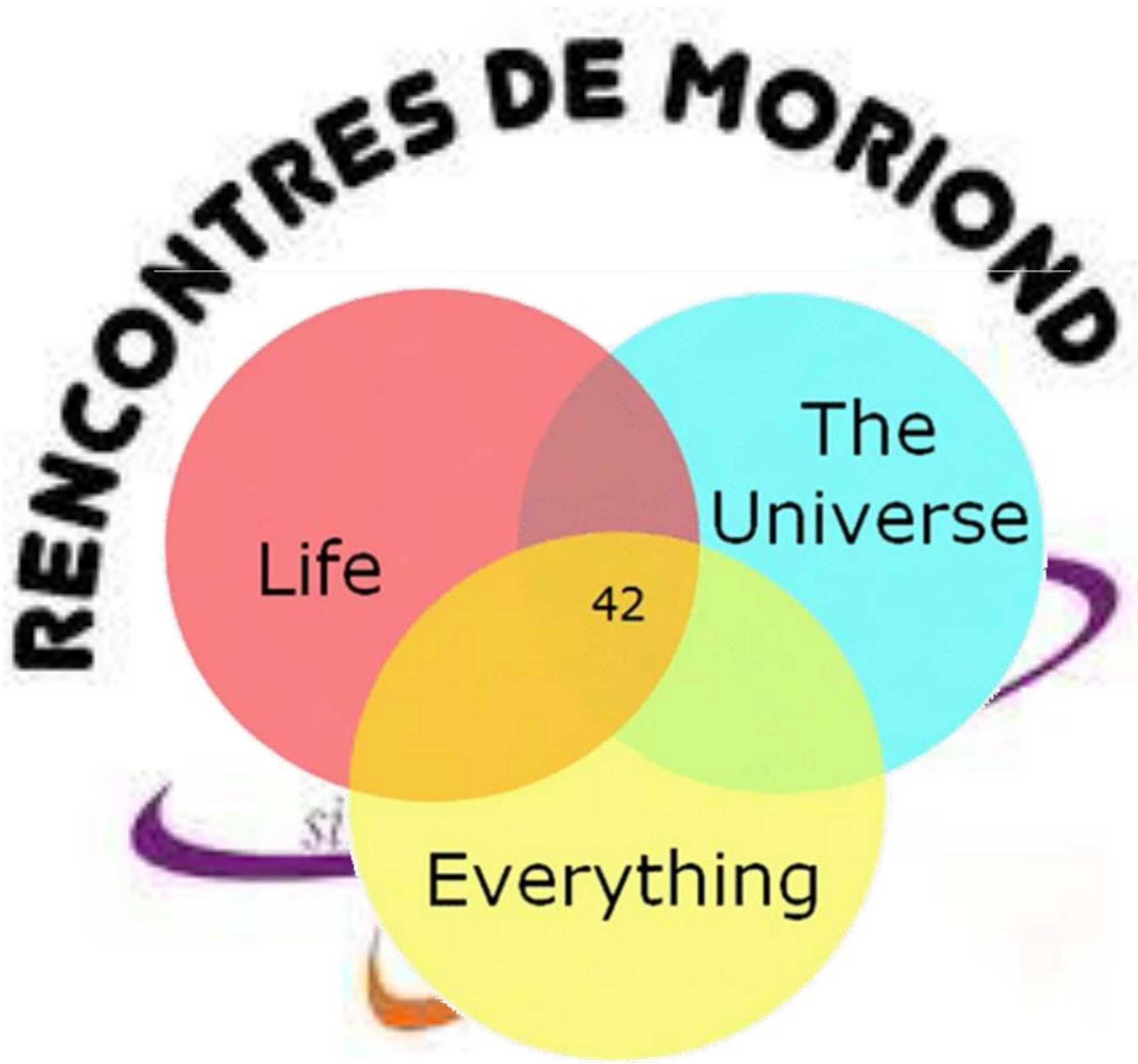
The content of this talk is related to the groups listed below.

- CMS: Physics Overview
- CMS: B physics
- CMS: Standard Model
- CMS: Top
- ATLAS: "Standard Model, QCD, W,Z,DIFF,FW"
- ATLAS: Top
- ATLAS: B physics

Luca: what should I include?

Conveners: whatever has been publicly released since the Moriond EWK 2014

Proposal for a new Moriond logo…

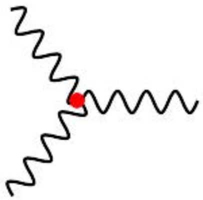


Electroweak Multi-boson Measurements

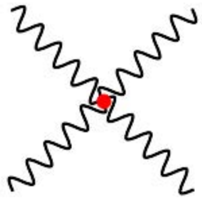
- Measurements of the multi-boson production cross section test the Standard Model (SM) at the TeV scale

- Irreducible background for Higgs studies and many beyond SM searches
  - No explicit mention of Higgs production in this talk

- Probe boson self-interactions, searching for anomalous couplings



TGC



QGC

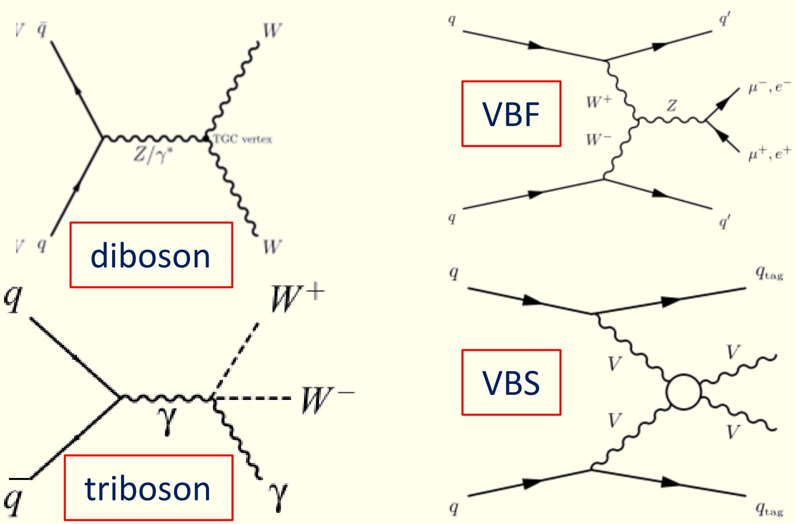
- Triple gauge couplings probed by
  - Diboson production
  - EW production of single vector bosons

- Quartic gauge couplings probed by
  - Triboson production
  - EW diboson production

Signatures and backgrounds

Signatures (i.e. combinations of γ,W,Z)

- σ(γ) > σ(W) > σ(Z)
- Leptons/photons
  - High pT, isolated, electrons/muons and/or photons
- Z bosons
  - Invariant mass window cut around Z pole
- W bosons
  - Large missing E_T from the undetected neutrino (computed from jets, leptons and calorimeter information)
  - Transverse mass selection cut



Backgrounds

- V+jets
  - High pT leptons from boson or heavy flavour decays
  - Jets misidentified as lepton/photons
  - Particles outside acceptance → missing E_T
- tt-bar and single top
  - Prompt isolated leptons from W bosons
  - Large missing E_T
- Other multi-boson processes
  - Act as background for each other
- Estimated from MC or with data-driven methods

Signatures and backgrounds

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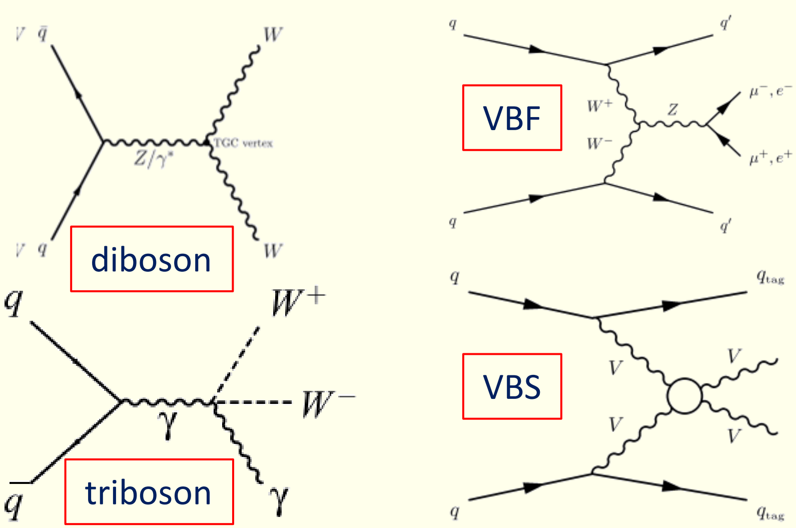

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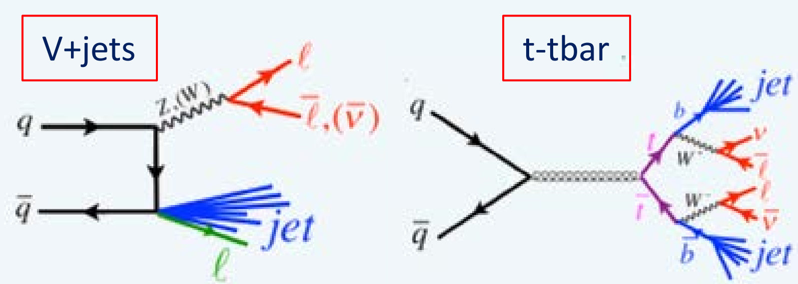

Effective Theory Approach to BSM

taken from A. Falkowski http://indico.cern.ch/event/378967/

Basic assumptions

- New physics scale Λ separated from EW scale v, $\Lambda \gg v$
- Linearly realized SU(3)xSU(2)xU(1) local symmetry spontaneously broken by VEV of Higgs doublet field

EFT Lagrangian beyond the SM expanded in operator dimension D

$$\mathcal{L}_{\mathrm{EFT}} = \mathcal{L}_{\mathrm{SM}} + \cancel{\frac{1}{\Lambda}\mathcal{L}^{D=5}} + \frac{1}{\Lambda^2}\mathcal{L}^{D=6} + \cancel{\frac{1}{\Lambda^3}\mathcal{L}^{D=7}} + \frac{1}{\Lambda^4}\mathcal{L}^{D=8} + \ldots$$

Lepton number violating, hence too small to probe at LHC

Subleading to D=6

For D=6 Lagrangian several complete non-redundant set of operators (so-called basis) proposed in the literature

Any complete basis leads to completely equivalent physics description

Warsaw Basis	Grządkowski et al. 1008.4884 Alonso et al 1312.2014
SILH basis	Giudice et al hep-ph/0703164 Contino et al 1303.3876
Primary/Higgs basis	Gupta et al 1405.0181 LHCHXSWG-INT-2015-001

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- Most of CMS and ATLAS anomalous coupling interpretation use:
  - Vertex function approach for NEUTRAL triple couplings (ZZZ,Zγγ,ZZγ)
  - Effective Lagrangian approach (no operaror basis) for CHARGED triple couplings (WWW, WWγ)
- Only recently EFT approach starting to be used for QUARTIC gauge couplings
  (SS WW EWK, WWγ, γγ->WW)

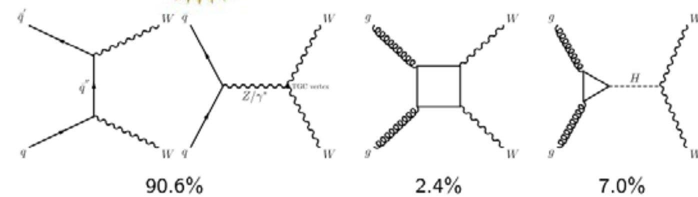
New results

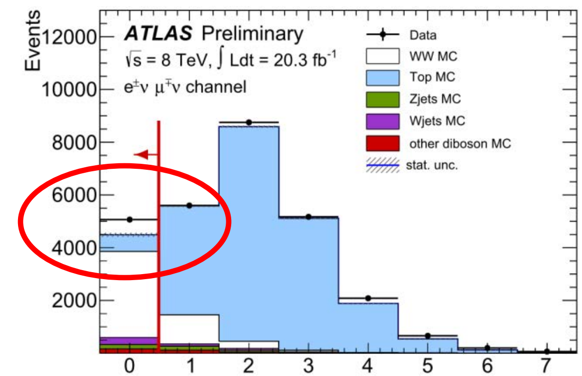
W^+W^- production and aTGC at 8 TeV in CMS

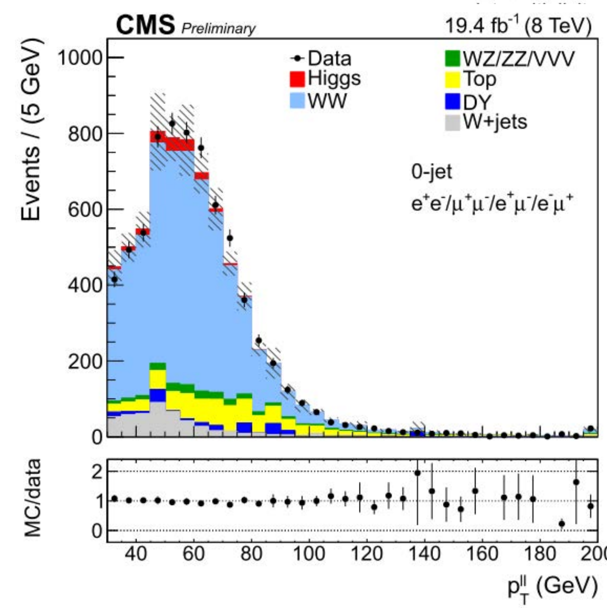
NEW! CMS-PAS-SMP-14-016

- ATLAS (ATLAS-CONF-2014-033) reports 2σ excess wrt to NLO (also previous CMS meas., see backup)

- Measurement in electron and muon channels, with 19.4 fb^{-1} at 8 TeV
  - Selection: 2 isolated leptons, kinematic range $p_{T,l}$>20 GeV, $|\eta_{ele}|$<2.5 , $|\eta_{\mu}|$<2.4, *projected* missing E_T>20 GeV, $p_{T,ll}$>45 GeV
- Several techniques to reduce the large background
  - Anti b-tagging and jet veto (N_{jets} < 2) for t-tbar
  - Dilepton boost and Z mass veto to reject Z→ll events
  - Third lepton veto for WZ and ZZ contamination
  - Multiple control regions to estimate the yields
- Systematics dominated by jet veto and lepton efficiency uncertainties







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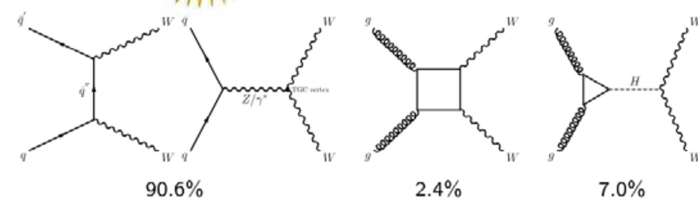
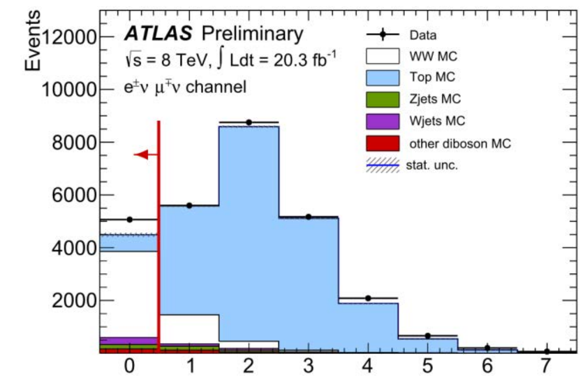
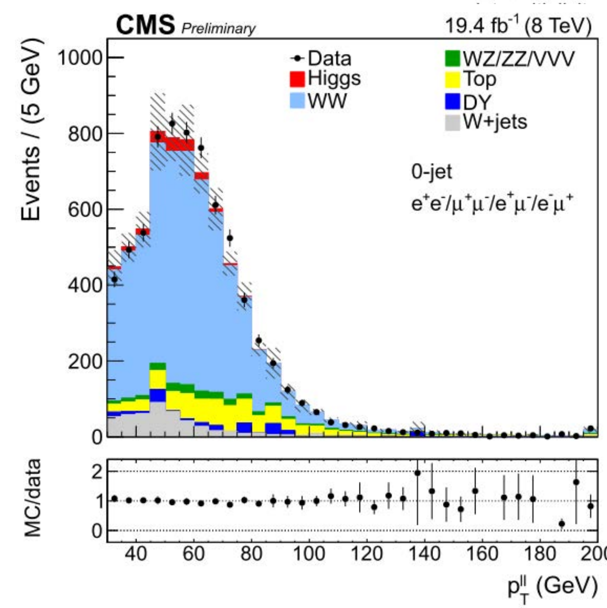
  - Dilepton boost and Z mass veto to reject Z→ll events
  - Third lepton veto for WZ and ZZ contamination
  - Multiple control regions to estimate the yields
- Systematics dominated by jet veto and lepton efficiency uncertainties
- Total measured cross section (after removing Higgs contribution)

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

compatible with NNLO theory prediction: $59.8^{+1.3}_{-1.1}$ pb







W^+W^- production and aTGC at 8 TeV in CMS

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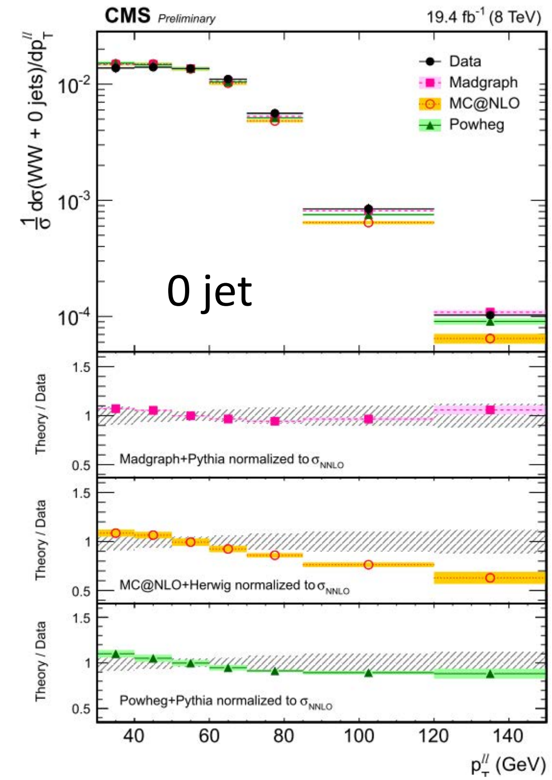
- W^+W^- unfolded (normalized) differential cross section measured as a function of kinematic variables ($p_{T,l}$, m_{ll}, $p_{T,ll}$, $\Delta\phi_{ll}$) and compared with theory predictions
  - Some shape trends both at low and high p_T
  - Comparison of fiducial volume cross sections in 0 jet bin

p_T^{jet} threshold (GeV)	$\sigma_{0jet,W\to\ell\nu}$ measured (pb)	$\sigma_{0jet,W\to\ell\nu}$ predicted (pb)
20	0.223 ± 0.004 (stat.) ± 0.013 (exp.) ± 0.007 (th.) ± 0.006 (lum.)	0.228 ± 0.001 (stat.)
25	0.253 ± 0.005 (stat.) ± 0.014 (exp.) ± 0.008 (th.) ± 0.007 (lum.)	0.254 ± 0.001 (stat.)
30	0.273 ± 0.005 (stat.) ± 0.015 (exp.) ± 0.009 (th.) ± 0.007 (lum.)	0.274 ± 0.001 (stat.)



- Limits on aTGC are measured in the framework of dimension-six 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)

Corresponding ATLAS analysis in ATLAS-CONF-2014-033

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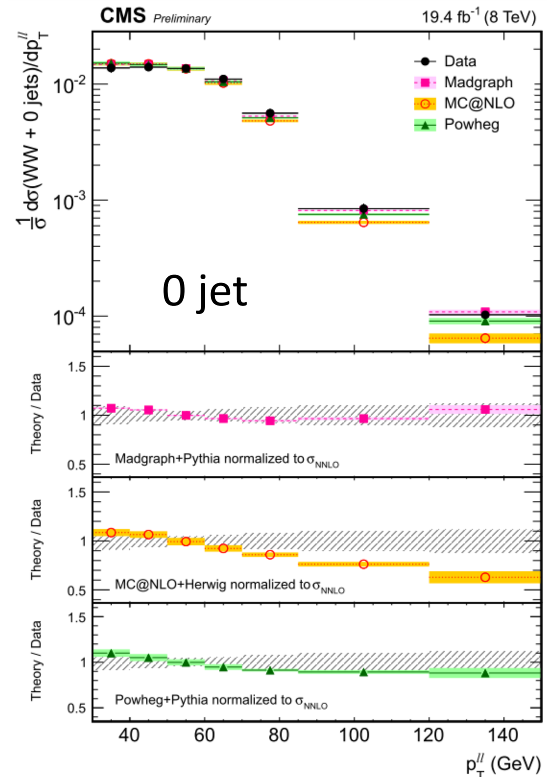

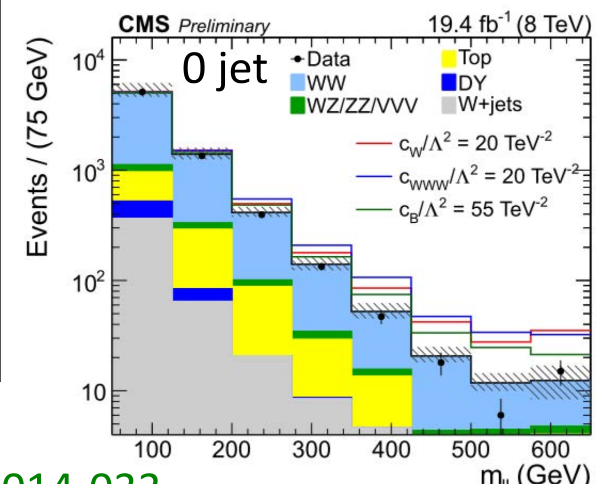

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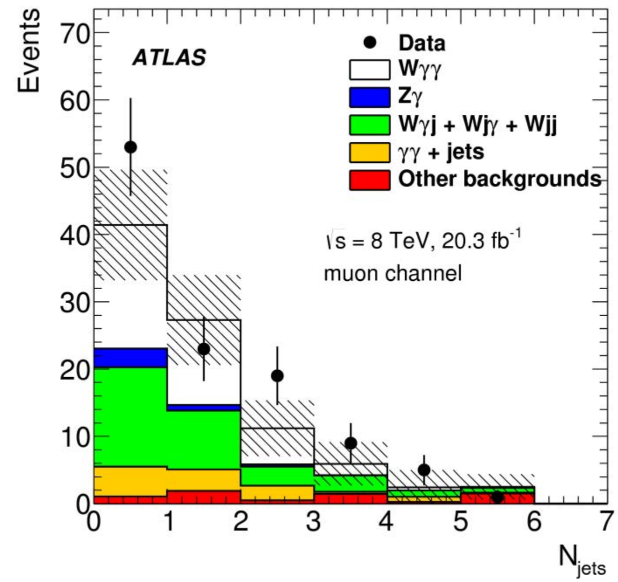
Evidence of Wγγ production in ATLAS

NEW! arXiv:1503.03243 submitted to PRL

- Cross section measured in muon and electron channels, with 20.3 fb^{-1} at 8 TeV
- Analysis performed in jet inclusive (≥0) and exclusive (=0) in the fiducial phase spaces
- Dominant systematic uncertainties from data-driven background and jet energy scale
  - Data-driven fake photon background from Wγj+Wjj estimated with 2D template fit of the isolation distributions of the two γ candidates



- Total significance is 3.7 σ in the inclusive case, and 2.2 σ in the exclusive case → first Wγγ evidence
  - Electron and muon channels are compatible within 1 σ
- The measured cross sections is 1.9 σ higher than MCFM predictions in the inclusive case, 1.3 σ in the exclusive case

	$\sigma^{\rm fid}$ [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.)	
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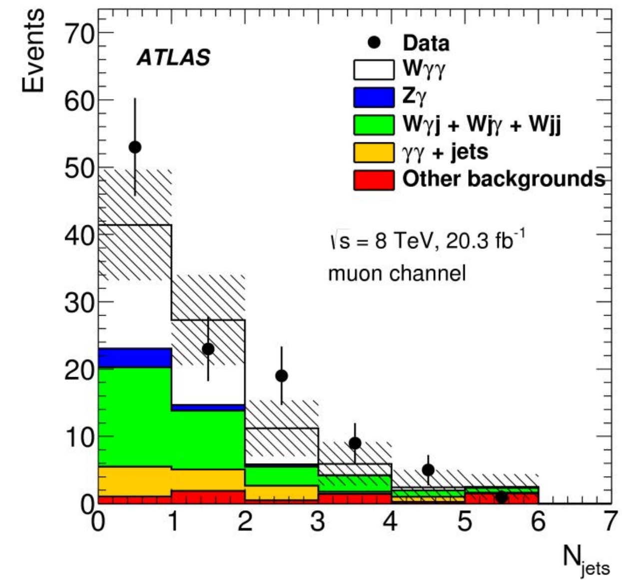

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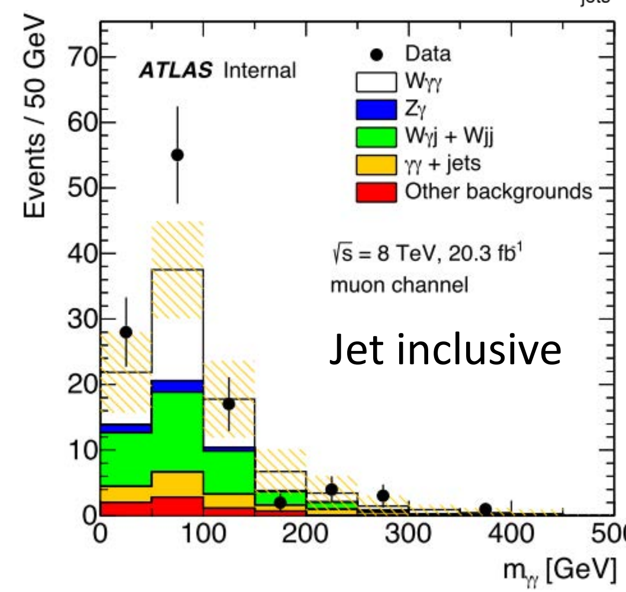

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- Fiducial region defined at particle level including jet and isolation variables

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

- aQGC computed with EFT approach for dimension 8 operators
- Deviations from the SM prediction, expected in high di-photon invariant mass: define search region with $m_{\gamma\gamma} > 300$ GeV
- Limits on f_{T0}/Λ^4 is improved with respect to the previous results published by CMS

	Observed [GeV^{-4}]	Expected [GeV^{-4}]
f_{T0}/Λ^4	$[-9.5, 9.4] \times 10^{-11}$	$[-1.2, 1.2] \times 10^{-10}$
f_{M2}/Λ^4	$[-8.2, 8.4] \times 10^{-9}$	$[-1.1, 1.1] \times 10^{-8}$
f_{M3}/Λ^4	$[-1.5, 1.4] \times 10^{-8}$	$[-1.9, 1.8] \times 10^{-8}$

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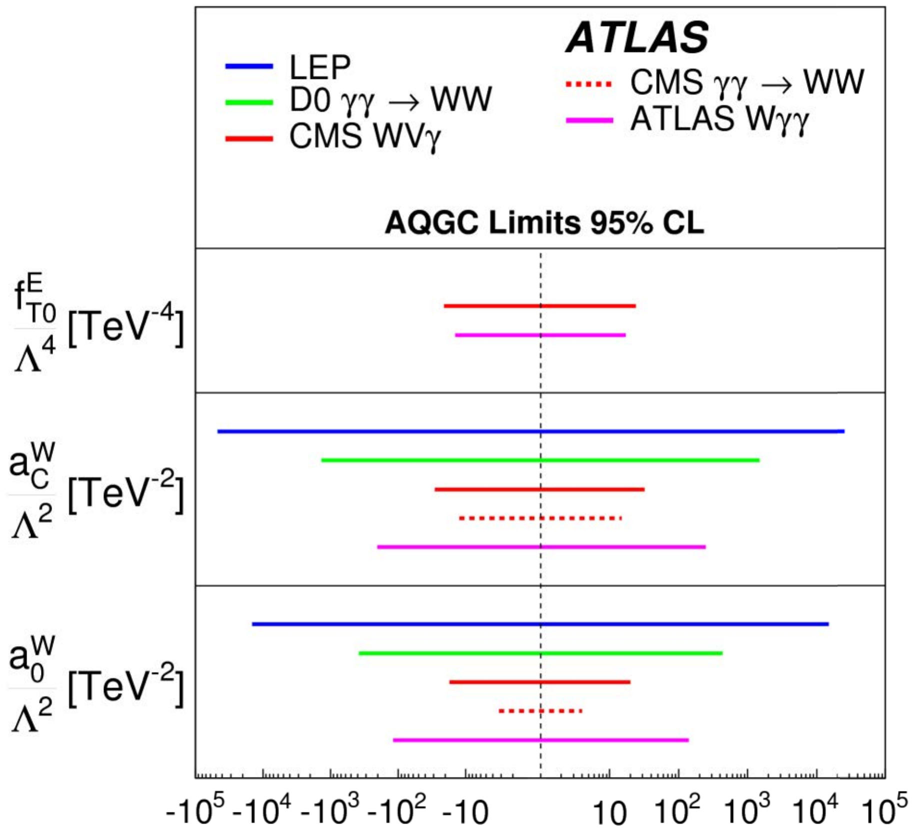

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Updates of preliminary results

Zγ production and aTGC at 8 TeV in CMS

arxiv:1502.05664
submitted to JHEP

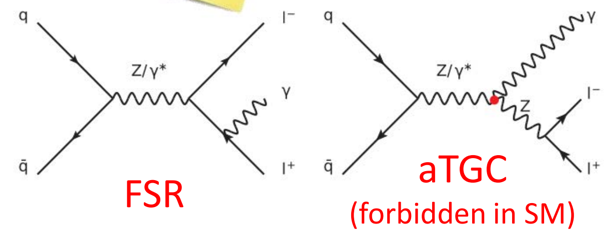
- Measurement of the Zγ production cross section in electron and muon channels, with 19.5 fb^{-1} at 8 TeV
- Kinematic range $p_{T,j}>20$ GeV, $m_{ll}>50$ GeV, $E_{T,\gamma}>15$ GeV, $\Delta R_{l,\gamma}>0.7$

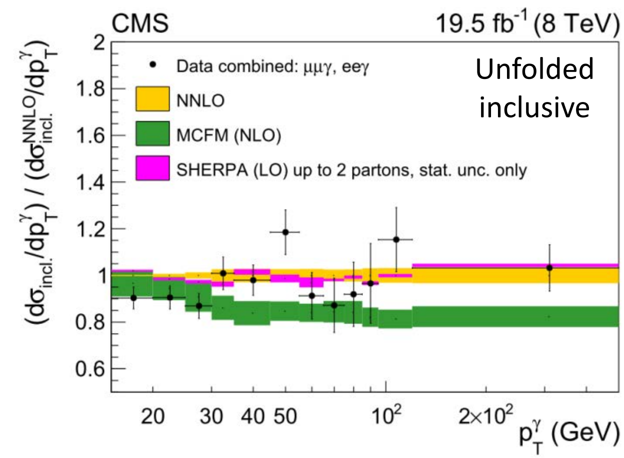
- Two template observables (shower shape, isolation) used to measure the yield independently, then combined
- Background dominated by DY + non-prompt photons

- Total inclusive cross section is in good agreement with prediction ($\sigma^{MCFM} = 2100 \pm 120$ fb)
  $\sigma = 2063 \pm 19(stat) \pm 98(syst) \pm 54(lumi)$ fb

- Uncertainties dominated by template statistics and FSR contamination

- aTGC would enhance the high $E_{T,\gamma}$ spectrum
- The data are in good agreement with the SM expectations
- aTGC limits on ZZγ and Zγγ aTGC improved by factor 3 wrt 7 TeV





Corresponding ATLAS analysis at 7 TeV in PRD 87, 112003 (2013)

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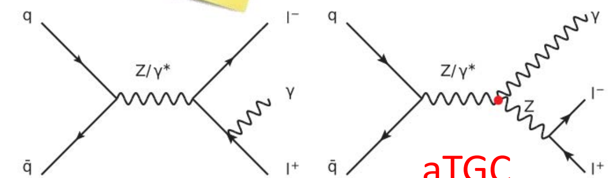
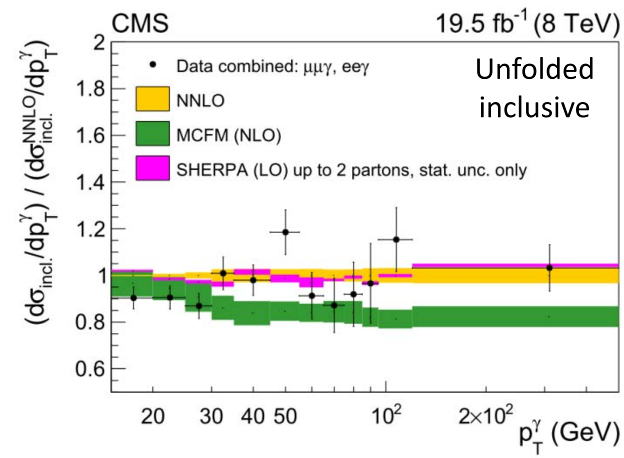
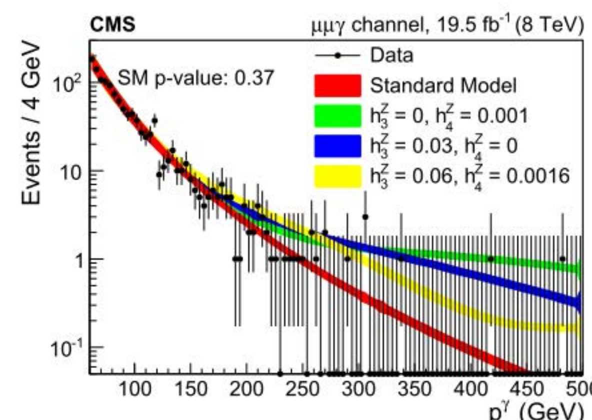


FSR

aTGC
(forbidden in SM)



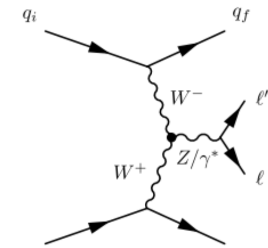


- aTGC would enhance the high $E_{T,\gamma}$ spectrum
- The data are in good agreement with the SM expectations
- aTGC limits on ZZγ and Zγγ aTGC improved by factor 3 wrt 7 TeV

Corresponding ATLAS analysis at 7 TeV in PRD 87, 112003 (2013)

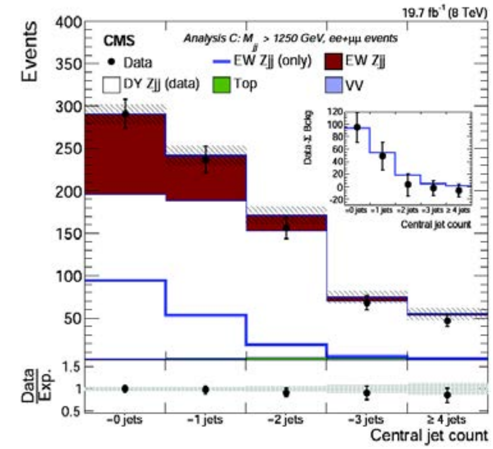
Electroweak production of Z+2jets at 7 TeV

- Vector boson fusion (VBF) of WW → Z
  - Process similar to the Higgs VBF production and sensitive to WWZ aTGC
  - Central Z decay associated with energetic forward-backward quark jets
  - Large η separation between the jets, large invariant dijet mass



VBF

- CMS - EPJC 75 (2015) 66 Updates **Dedicated YSF talk by T. Cornelis**
  - Quark/gluon discriminator used to reduce background
  - BDT used to extract signal contribution
  - Measured σ = 174 ± 15 (stat) ± 40 (syst) fb
    σ/σ_{SM} = 0.84 ± 0.07 (stat) ± 0.19 (syst)
  - Analysis precision limited by the knowledge of large interference effects between production diagrams
  - Study of the hadronic and jet activity in Z+jet events included



- ATLAS – JHEP 04 (2014) 031
  - Analysis performed in 5 different phase spaces
  - Data-to-MC ratio in control region to constrain background shapes
  - Analysis precision limted by statistics in control region
  - aTGC limits computed for the first time on VBF

aTGC	Λ = 6 TeV (obs)	Λ = 6 TeV (exp)	Λ = ∞ (obs)	Λ = ∞ (exp)
$\Delta g_{1,Z}$	[−0.65, 0.33]	[−0.58, 0.27]	[−0.50, 0.26]	[−0.45, 0.22]
λ_Z	[−0.22, 0.19]	[−0.19, 0.16]	[−0.15, 0.13]	[−0.14, 0.11]

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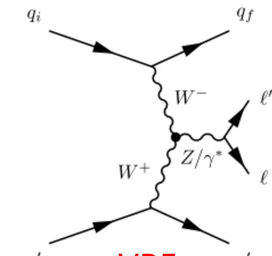

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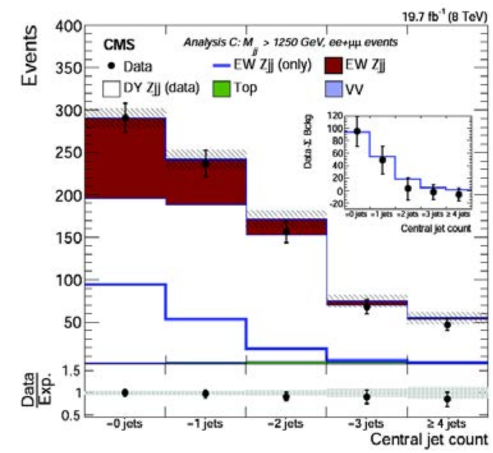

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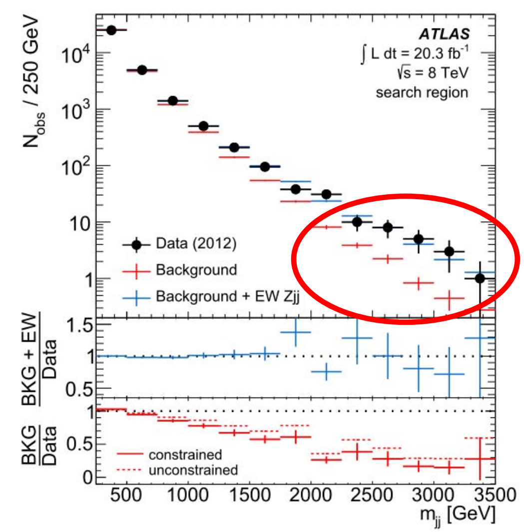
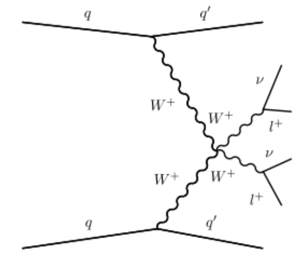
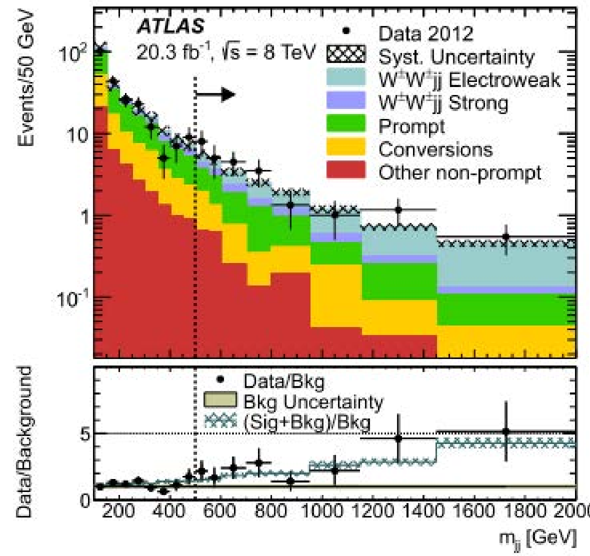


VBS : $W^{\pm}W^{\pm}$ production at 8 TeV

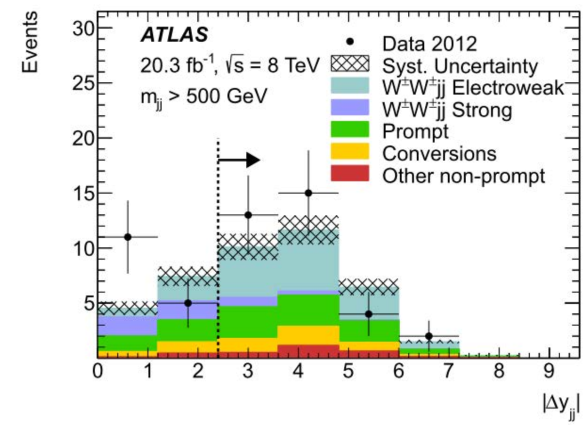
- Analysis similar to HWW in VBF channel
  - Two isolate leptons with same charge, third lepton veto to reduce WZ background
  - Two forward jets with high invariant mass and large η separation
  - m_{ll} > 50 GeV cut to reduce W+jets and top backgrounds, missing E_T > 40 GeV
  - Main backgrounds from WZ→3lν and non-prompt leptons
  - Systematics dominated by Jet and theory uncertainties



- ATLAS - PRL 113 (2014) 141803 (first evidence of VBS scattering)
  Inclusive region: σ = 2.1 ± 0.5 (stat) ± 0.3 (syst) fb, 4.5σ obs. (3.4σ exp.)
  VBS SR (m_{jj}>500 GeV): σ = 1.3 ± 0.4 (stat) ± 0.2 (syst) fb, 3.6σ obs (2.8σ exp.)



- CMS - PRL 114 (2015) 051801
  Cross section measured in fiducial region with m_{jj}>300 GeV
  $\sigma = 4.0_{-2.0}^{+2.4}$ (stat) $_{-1.0}^{+1.1}$ (syst) fb, 2.0σ obs. (3.1σ exp.)



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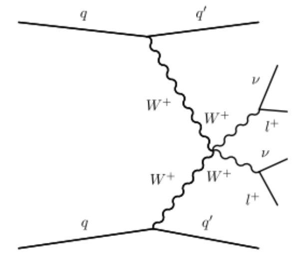

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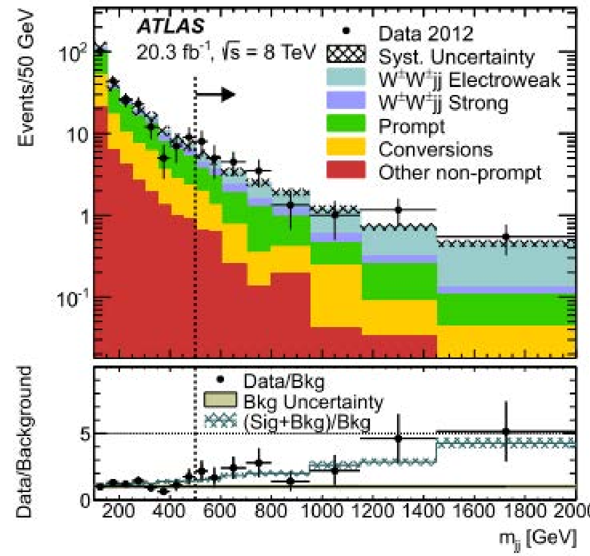
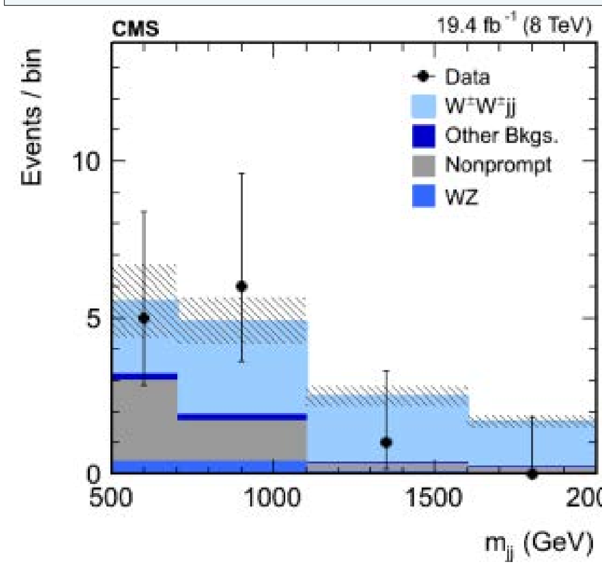
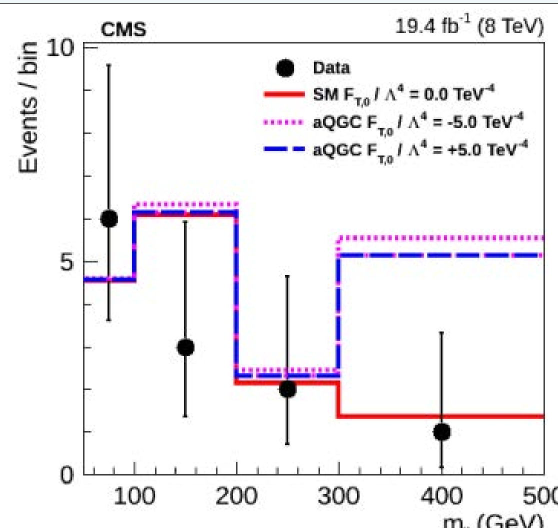
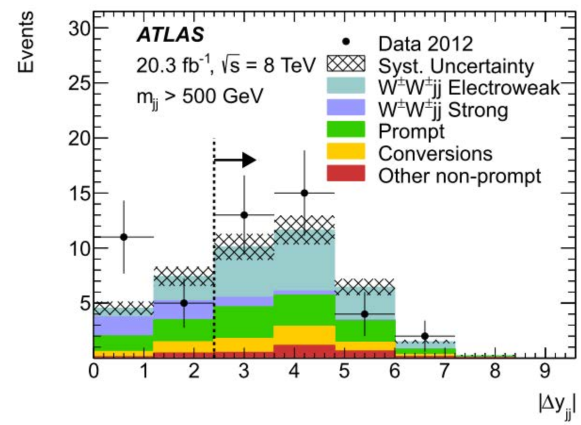


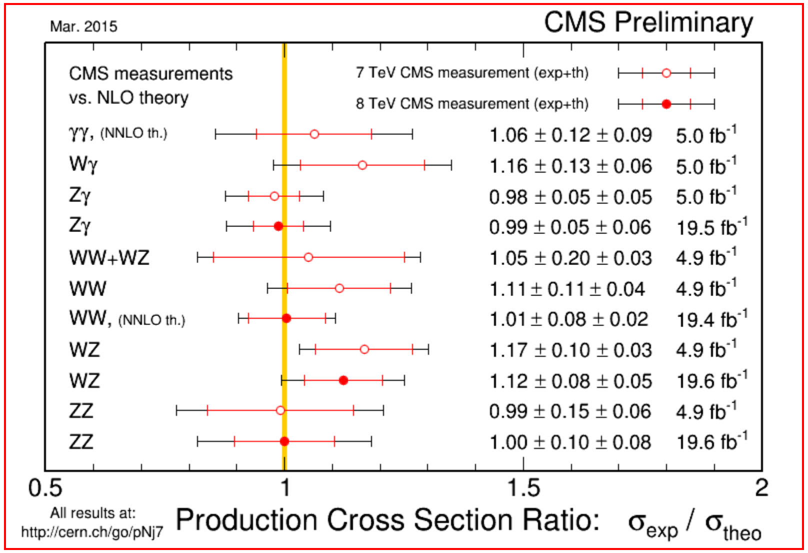


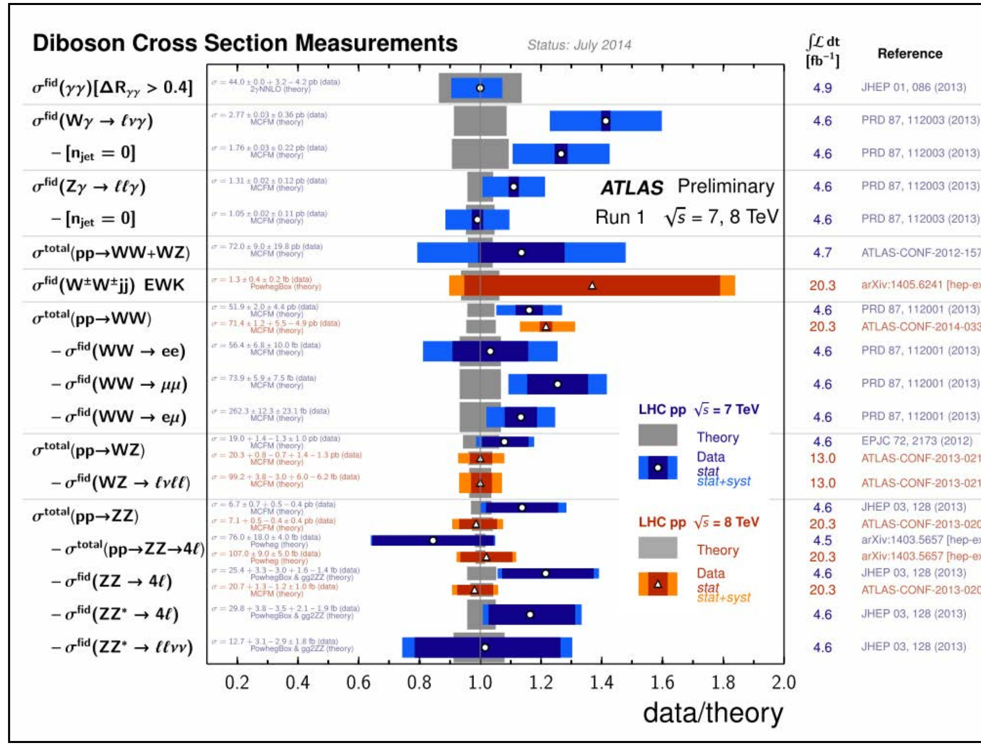


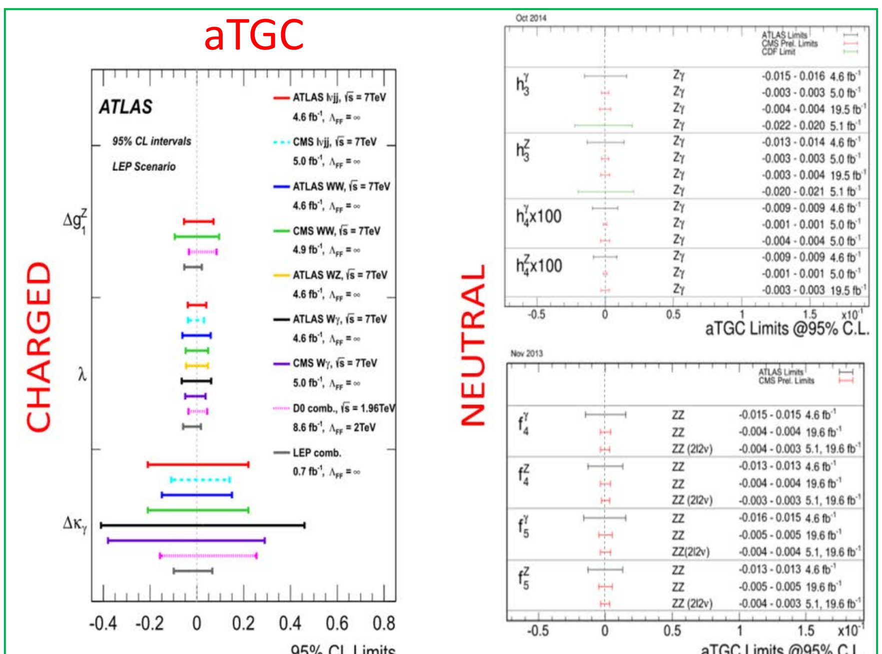


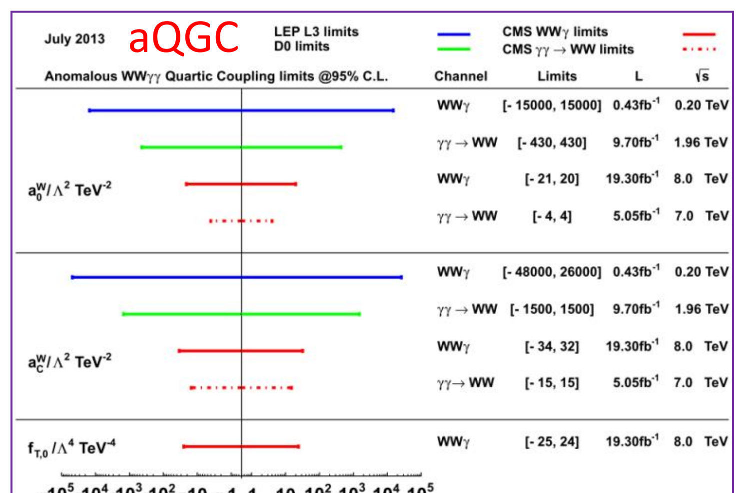
Public summary plots

[CMS public page](#) [ATLAS public page](#)









	Title	Dataset	Preliminary	Publication	arxiv	aTGC	aQGC
CMS							
ZZ, ZW, WW	ZZ differential cross section and aTGCs in the 4l channel	8 TeV, 19.6 fb^{-1}	SMP-13-005	Phys. Lett. B 740 (2015) 250	arXiv:1406.0113	●	
	ZZ cross section and aTGCs in the 2l2nu channel	7+8 TeV, 5.1+19.6 fb^{-1}	SMP-12-016			●	
	WZ cross sections in the 3l channel	7+8 TeV, 4.9+19.6 fb^{-1}	SMP-12-006				
	W^+W^- and ZZ cross sections	8 TeV, 3.5 fb^{-1} WW, 5.3 fb^{-1} ZZ	SMP-12-024	Phys. Lett. B 721 (2013) 190	arXiv:1301.4698		
	W^+W^- cross section in the lvlv channel	8 TeV, 19.4 fb^{-1}	SMP-14-016				●
	VZ cross sections in the bb channel	8 TeV, 18.9 fb^{-1}	SMP-13-011	EPJC 74 (2014) 2973	arXiv:1403.3047		
	VW cross section in the W+dijet channel	7 TeV, 5 fb^{-1}	SMP-12-015	Eur.Phys.J. C73 (2013) 2283	arXiv:1210.7544		
γV	γγ differential cross section	7 TeV, 4.9 fb^{-1}	SMP-13-001	Eur. Phys. J. C 74 (2014) 3129	arXiv:1405.7225		
	Zγ->llγ cross section	8 TeV, 19.5 fb^{-1}	SMP-13-014	Submitted to JHEP	arXiv.1502.05664	●	
	Wγ and Zγ->llγ cross sections	7 TeV, 5 fb^{-1}	EWK-11-009	Phys. Rev. D 89, 092005	arXiv:1308.6832	●	
	Zγ cross section in the MET+photon channel	7 TeV, 5 fb^{-1}	SMP-12-020	J. High Energy Phys. 10 (2013) 164	arXiv:1309.1117	●	
Triple bosons and EWK production	EWK production of $W^{\pm}W^{\pm}$ with 2 jets and WZ production with 2 jets	8 TeV, 19.4 fb^{-1}	SMP-13-015	Phys. Rev. Lett. 114 (2015) 051801	arXiv:1410.6315		●
	Electroweak production of a Z boson	8 TeV, 19.7 fb^{-1}	FSQ-12-035	Eur. Phys. J. C 75 (2015) 66	arXiv:1410.3153		
	WWγ and WZγ search and aQGCs	8 TeV, 19.3 fb^{-1}	SMP-13-009	Phys. Rev. D 90, 032008 (2014)	arXiv:1404.4619		●
Photoproduction	Exclusive γγ production of W^+W^- pairs, and aQGC		FSQ-12-010	JHEP 1307 (2013) 116	arXiv:1305.5596		●
ATLAS							
ZZ, ZW, WW, γV, Triple bosons	Evidence of Wγγ production and aQGC	8 TeV, 20.3 fb^{-1}	STDM-2013-05	Submitted to PRL	arXiv:1503.03243		●
	Semileptonic WW+WZ cross section and limits on aTGC	7 TeV, 4.6 fb^{-1}	STDM-2012-22	JHEP01(2015)049	arXiv:1410.7238	●	
	Wγ and Zγ Production	7 TeV, 4.6 fb^{-1}	STDM-2012-07	Phys. Rev. D 87, 112003 (2013)	arXiv:1302.1283	●	
	Simultaneous measurement of W^+W^-, Ztautau and ttbar	7 TeV, 4.6 fb^{-1}	TOPQ-2012-05	submitted to PRD	arXiv:1407.0573		
	ZZ production and limits on anomalous ZZZ and ZZγ couplings	7 TeV, 4.6 fb^{-1}	STDM-2012-02	JHEP03(2013)128	arXiv:1211.6096	●	
	W^+W^- Production and limits on WWZ and WWγ aTGC	7 TeV, 4.6 fb^{-1}	STDM-2012-01	Phys. Rev. D 87, 112001 (2013)	arXiv:1210.2979	●	
	A Measurement of WZ Production	8 TeV, 13 fb^{-1}	CONF-2013-021				
	WZ Production	7 TeV, 4.6 fb^{-1}	STDM-2012-09	Eur. Phys. J. C (2012) 72:2173	arXiv:1208.1390	●	
	W^+W^- cross section	8 TeV, 20.3 fb^{-1}	CONF-2014-033				
	Total ZZ production cross section	8 TeV, 20.3 fb^{-1}	CONF-2013-020				
EWK production	Evidence for electroweak production of WWjj same sign	8 TeV, 20.3 fb^{-1}	STDM-2013-06	Phys. Rev. Lett. 113, 141803 (2014)	arXiv:1405.6241		●
	Electroweak production of a Z boson	8 TeV, 20.3 fb^{-1}	STDM-2013-02	JHEP04(2014)031	arXiv:1401.7610	●	
Future prospects	Vector Boson Scattering And Triboson Production with Upgraded ATLAS Det. at a High-Luminosity LHC	300 fb-1, 3000 fb-1	PHYS-PUB-2013-006				
Snowmass future prospects	Study of Electroweak Interactions at the Energy Frontier				arXiv:1310.6708		

Towards Run2

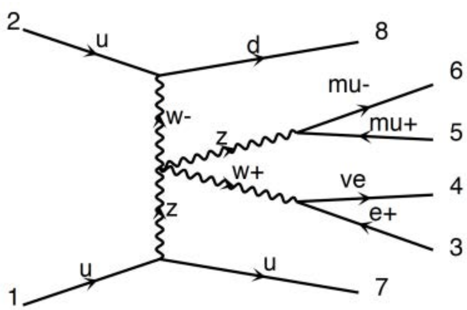
- Measurements are currently statistically limited
  - Either in control regions or in signal regions (high pT/mass)
- Major improvement expected at 13 TeV due to large increases of signal cross section
  - The anomalous coupling dependence on the energy depends on the parameter

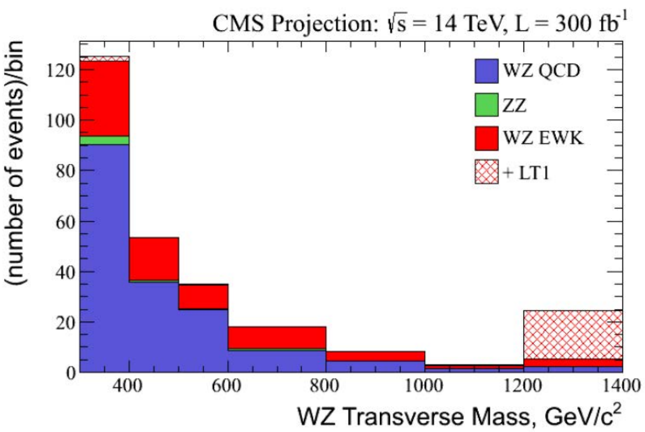
- Inputs needed for 13 TeV analyses
  - Higher order MC tools to reduce QCD scale uncertainty on the boson pt
  - NLO EWK corrections NOT available in most cases (contributions important at high pT/mass region)
  - NLO MC tools to generate anomalous couplings

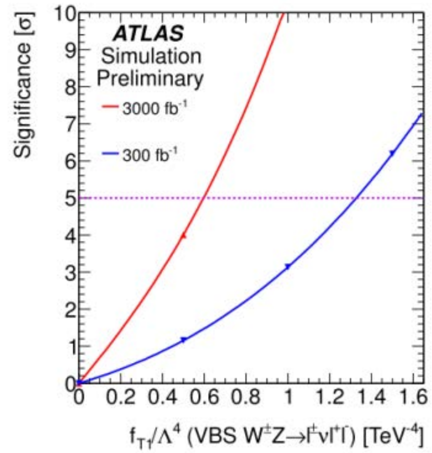
- Anomalous couplings for 13 TeV analyses
  - EFT approach will become the standard
  - Unfolded spectra: important to define the background subtracted “signal”
  - Multi-boson and Higgs production probe the same physics: consistent interpretation frameworks to combine
  - Discussions ongoing with Higgs community (http://indico.cern.ch/event/378967/)

Long term projections

- ATLAS ATL-PHYS-PUB-2013-006: aQCG projections quoting 5s discovery for dim-6 $c_{\phi W}/\Lambda^2$ and dim-8 f_{S0}/Λ^4, f_{T1}/Λ^4, f_{T8}/Λ^4 and f_{T9}/Λ^4 parameters in EFT context
  - Channels: VBS WZ→3l, VBS ZZ →4l, VBS $W^\pm W^\pm$→2l2ν, VBS WZ→3l, Zγγ →2l+2γ
- CMS FTR-13-006: projections for aQGC parameter f_{T1}/Λ^4
  - Channels: VBS WZ→3l







CMS

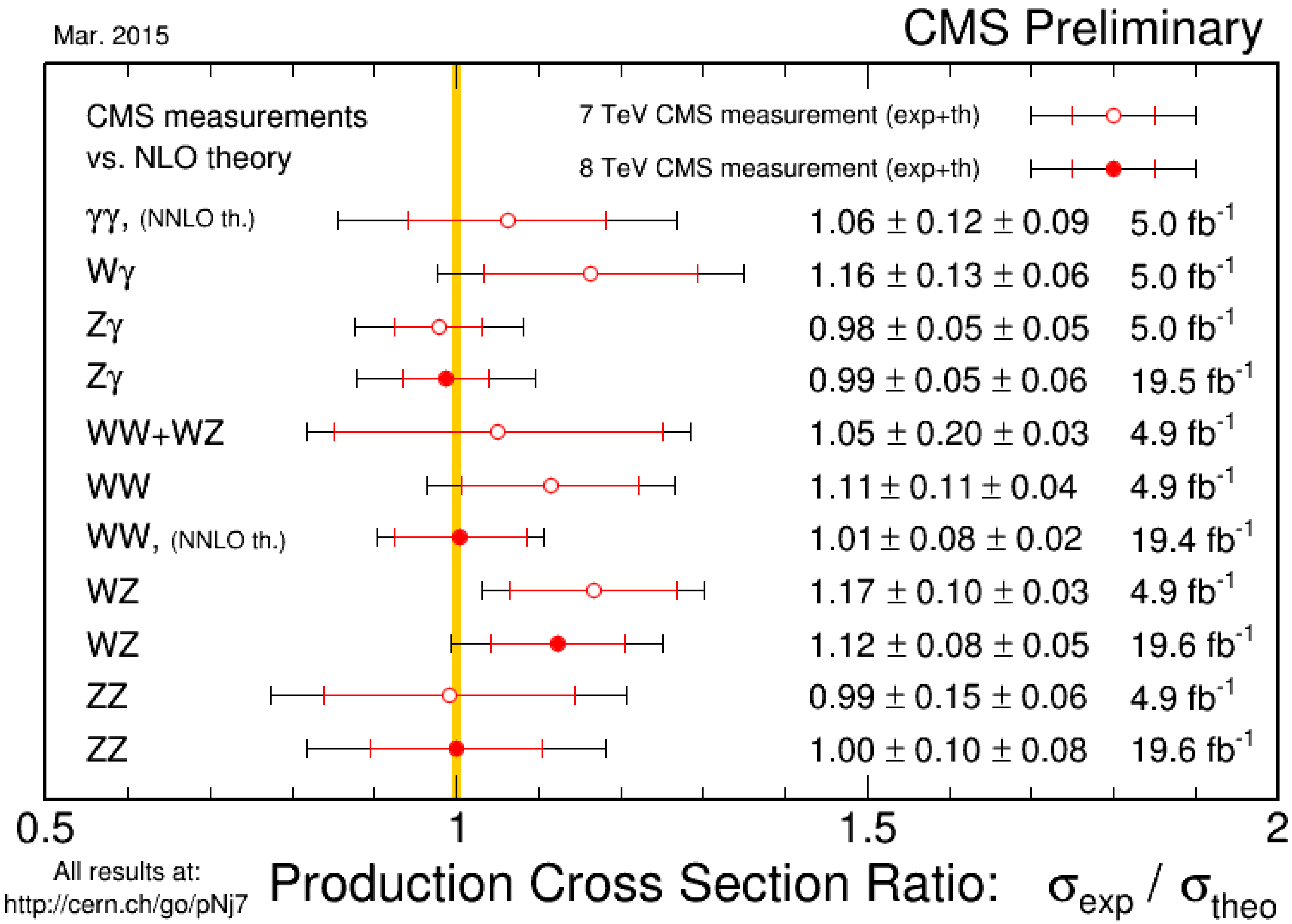
Significance	3σ	5σ
SM EWK scattering discovery	75 fb^{-1}	185 fb^{-1}
f_{T1}/Λ^4 at 300 fb^{-1}	0.8 TeV^{-4}	1.0 TeV^{-4}
f_{T1}/Λ^4 at 3000 fb^{-1}	0.45 TeV^{-4}	0.55 TeV^{-4}

ATLAS

Parameter	dimension	channel	Λ_{UV} [TeV]	300 fb^{-1}		3000 fb^{-1}	
				5σ	95% CL	5σ	95% CL
$c_{\phi W}/\Lambda^2$	6	ZZ	1.9	34 TeV^{-2}	20 TeV^{-2}	16 TeV^{-2}	9.3 TeV^{-2}
f_{S0}/Λ^4	8	$W^\pm W^\pm$	2.0	10 TeV^{-4}	6.8 TeV^{-4}	4.5 TeV^{-4}	0.8 TeV^{-4}
f_{T1}/Λ^4	8	WZ	3.7	1.3 TeV^{-4}	0.7 TeV^{-4}	0.6 TeV^{-4}	0.3 TeV^{-4}
f_{T8}/Λ^4	8	$Z\gamma\gamma$	12	0.9 TeV^{-4}	0.5 TeV^{-4}	0.4 TeV^{-4}	0.2 TeV^{-4}
f_{T9}/Λ^4	8	$Z\gamma\gamma$	13	2.0 TeV^{-4}	0.9 TeV^{-4}	0.7 TeV^{-4}	0.3 TeV^{-4}

Backup slides

Diboson cross sections (CMS)



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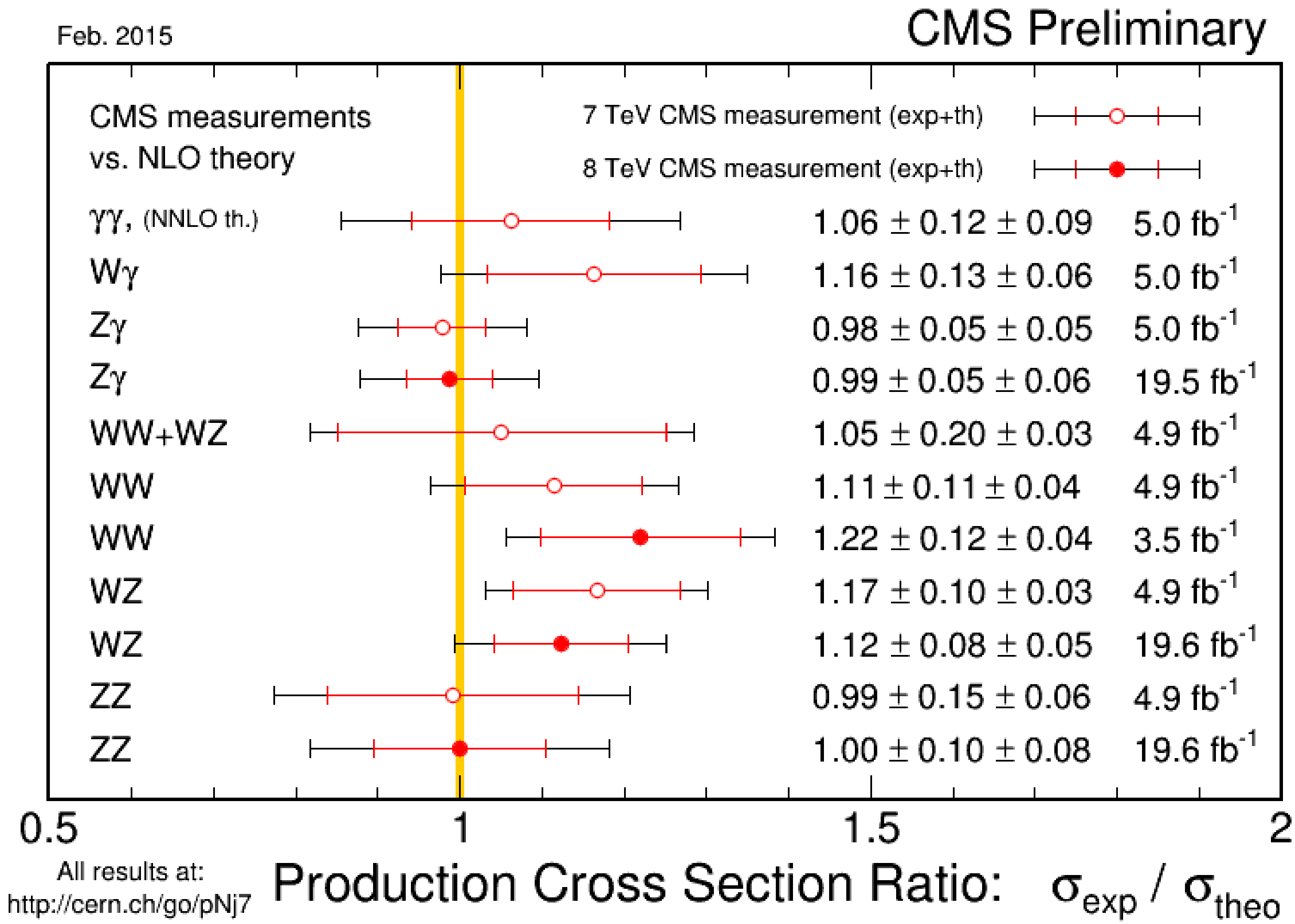
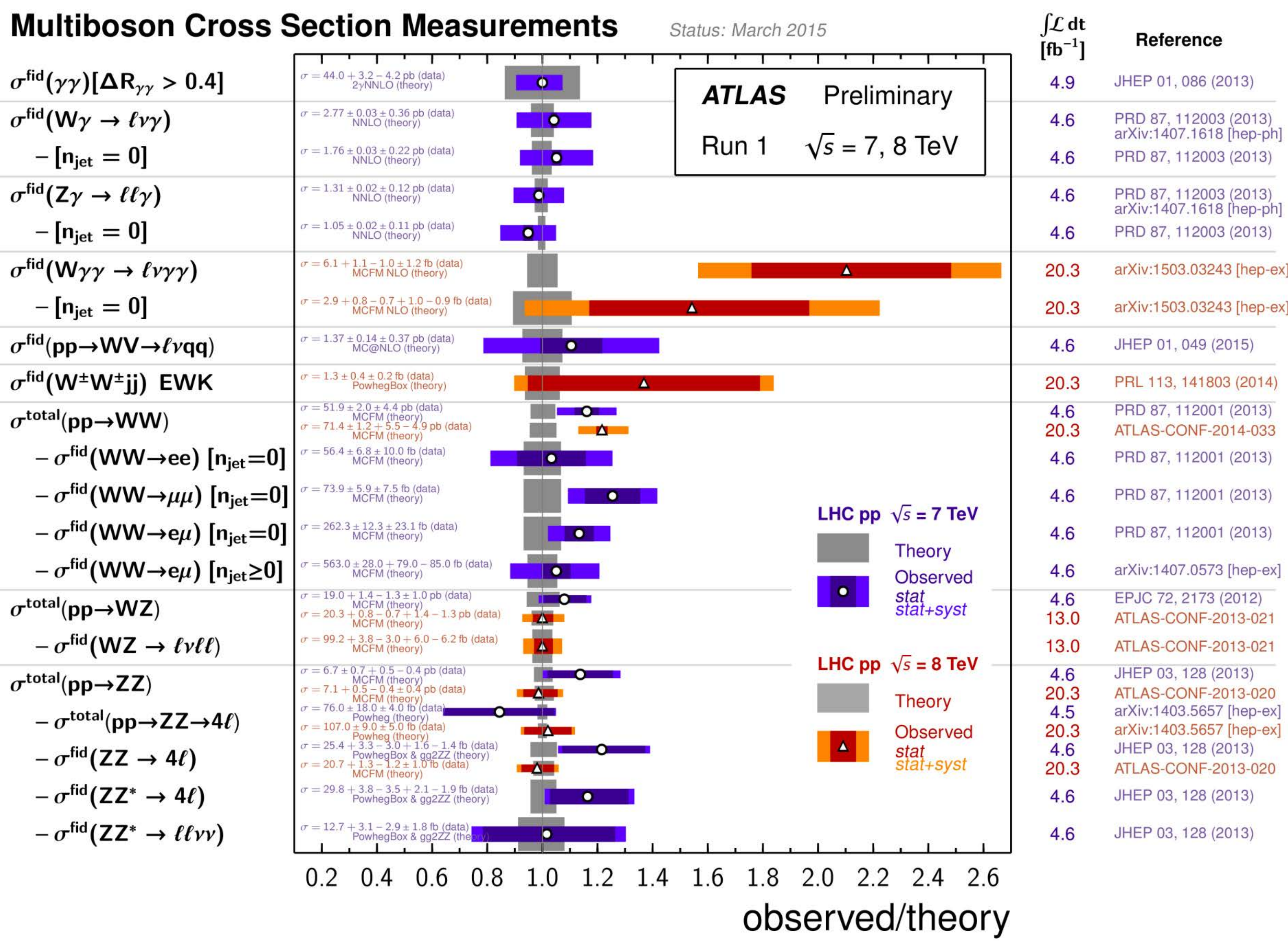
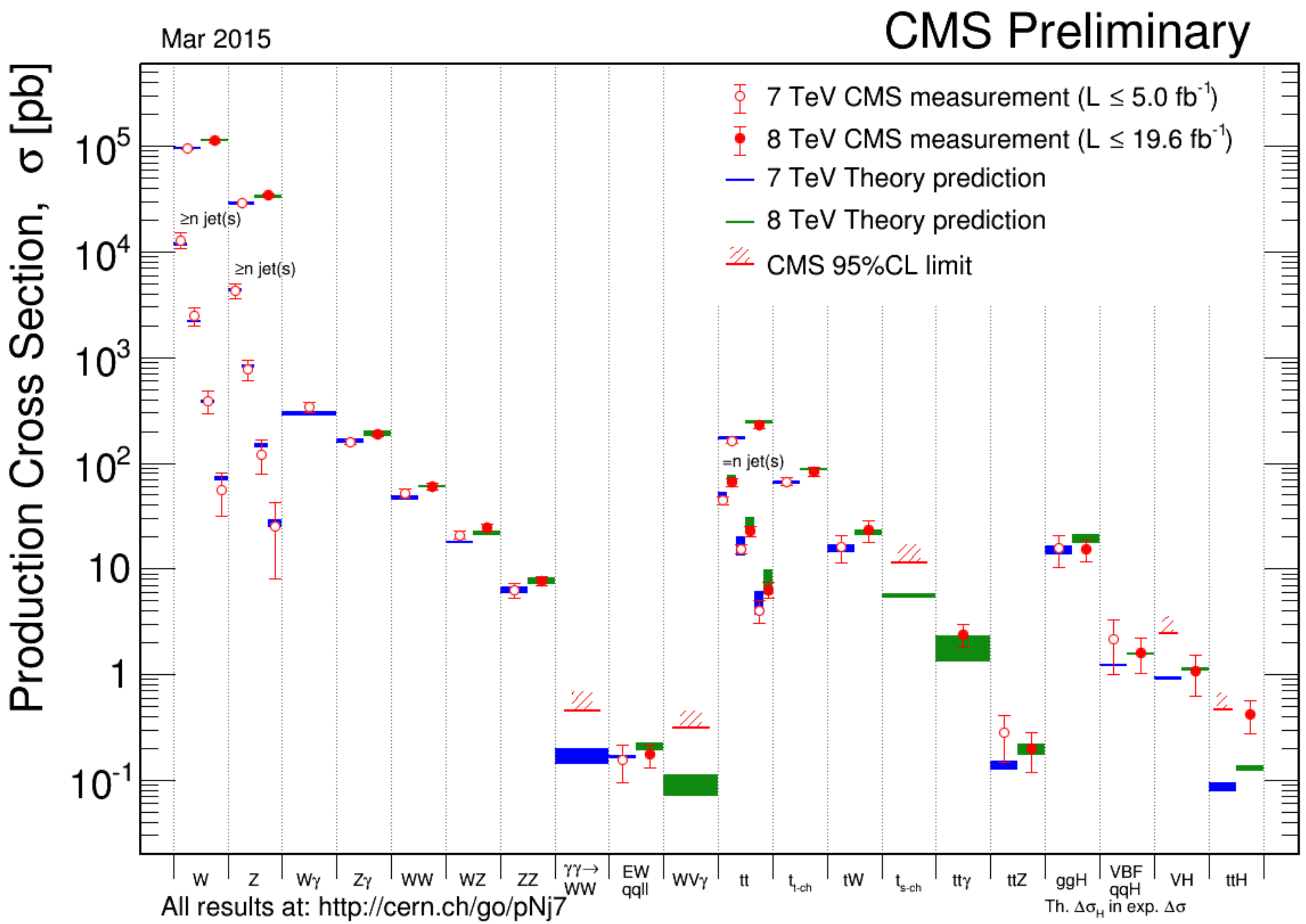


Diboson cross sections (ATLAS)



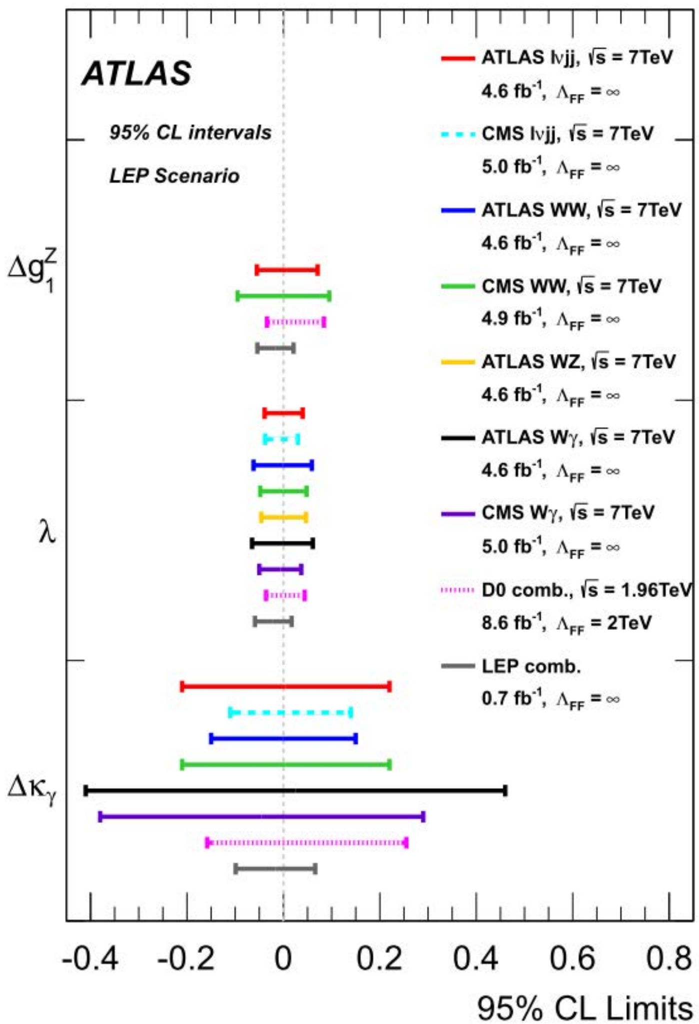
EWK cross sections (CMS)



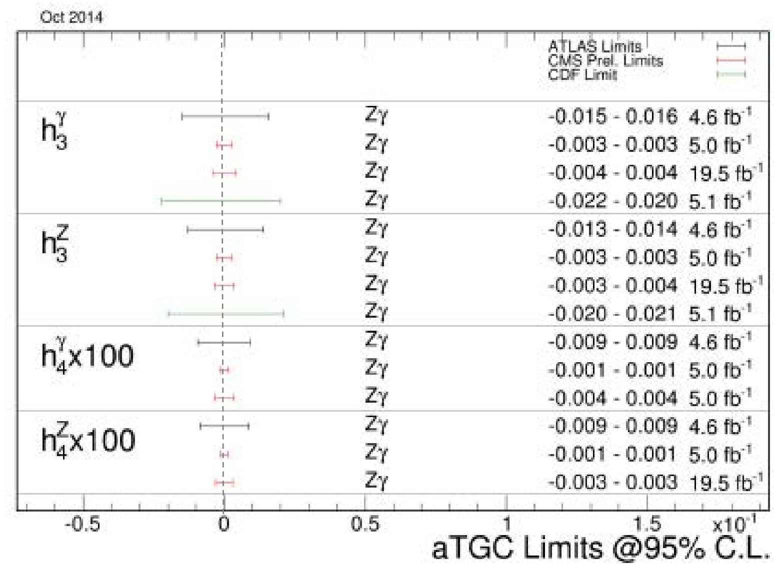
Anomalous Triple Gauge Couplings

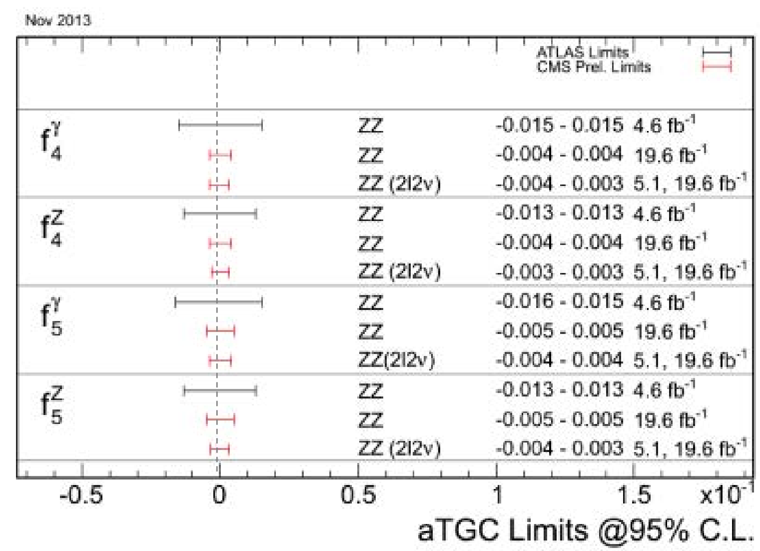
- Limits on the charged aTGC: WWγ and WWZ vertices
- Any deviation would be an indication of new physics
- Results reaching LEP sensitivity

CHARGED

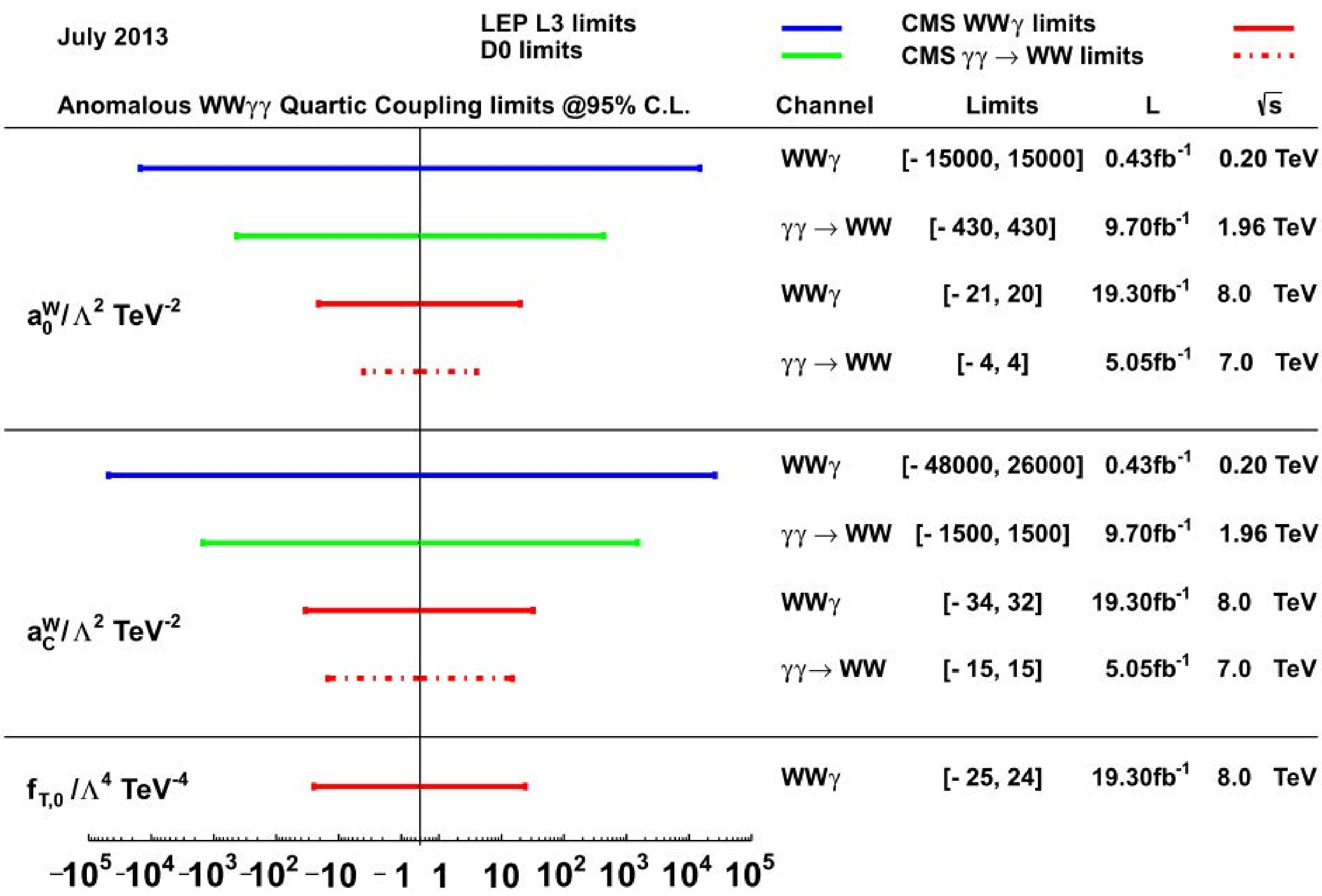


NEUTRAL





Anomalous Quartic Gauge Couplings



Standard Model measurements @ LHC

- 4 macro areas with different final states:
  - Jets , Single boson , Single boson + jets , Multi bosons (+ jets)
    - Also other topologies like VBF, VBS, Very Forward jets, forward proton tagging…

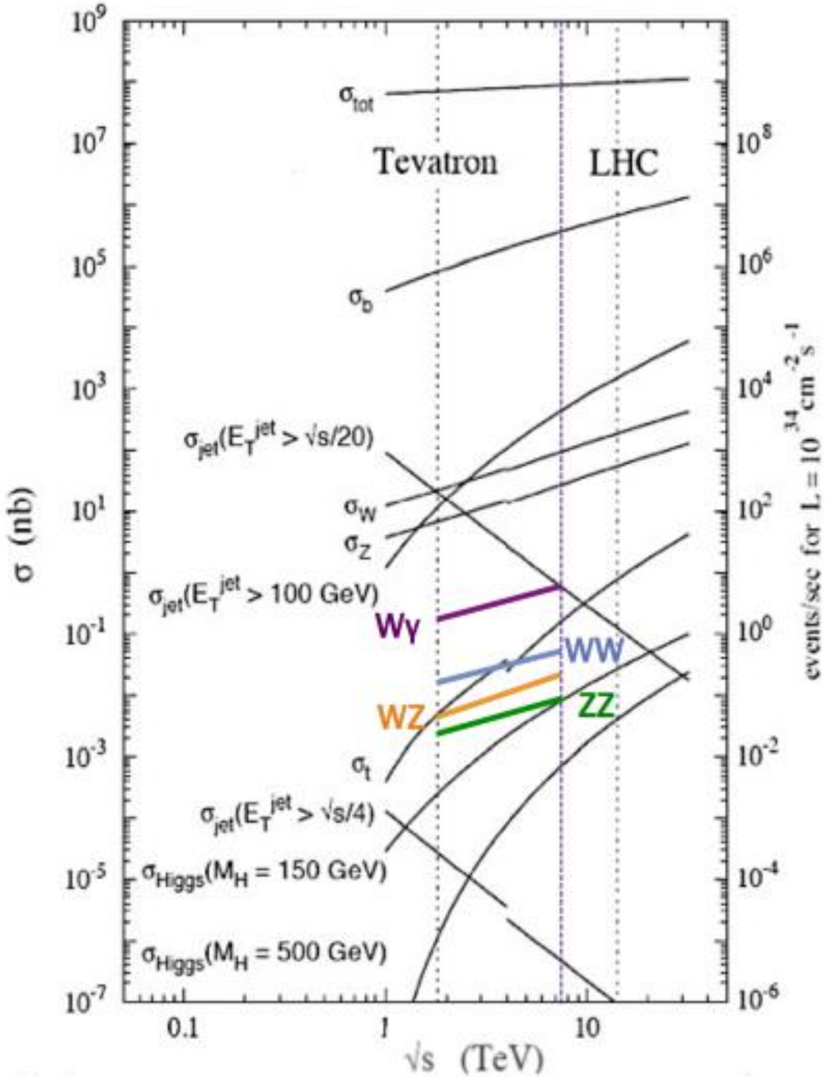
- Large span of physics interests
  - pQCD: Rigorously test perturbative QCD, its limitations
  - PDF: Significantly constrain parton distribution functions
  - EWK: Precision tests of electroweak interactions and BSM
  - Tails: At each step in energy and lumi, validate SM for highest PT/mass events
  - Higgs: Validate background modeling for Higgs analysis
  - BSM: Validate background modeling for BSM analysis

Considered hereafter (EWK, Tails, Higgs, BSM)

- Measurements evolve with the needs of search groups

Example: diboson production at the LHC

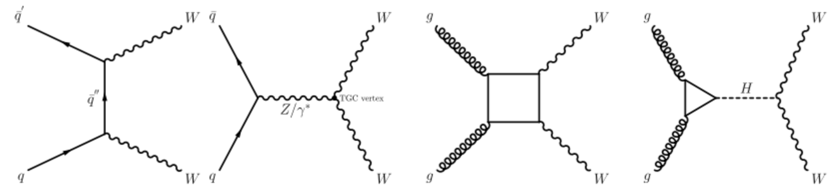
- Measurements of di-boson processes involve combinations of W, Z, γ
  - Opposite sign WW, WZ, ZZ, W/Z γ, Same sign WW
- Measured mainly trough their leptonic final states
  - Pros: relatively low backgrounds
  - Cons: low Branching Ratios BR(W→lν) = 0.108 , BR(Z→ll) = 0.034
  - For ZZ and Zg also Z->νν used
- Small cross sections O(1-100 pb)
- Tri-boson cross sections even lower O(1 fb)



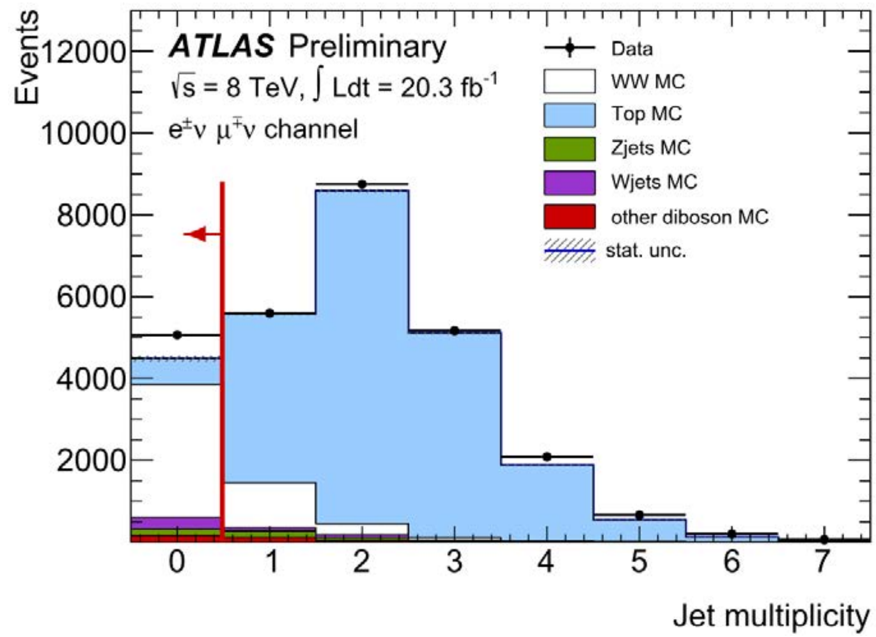
$W^+W^- \rightarrow l\nu l\nu$ cross section in ATLAS

ATLAS-CONF-2014-033

- Hard selection-criteria on E_t^{miss} and a jet-veto to suppress t-tbar background
- Dominant uncertainty comes from jet-veto and backgrounds
- Measured cross-section at 8 TeV is 2.1σ higher than NLO calculation
- Might be explained by missing:
  - NNLO contribution to total cross-section (enhancement by ~ 10%, cfr arXiv:1408.5243)
  - Resummation effects in the fiducial cross-section (cfr arXiv:1407.4537, arXiv:1407.4481, arXiv:1407.4745)



90.6% 2.4% 7.0%



$\sqrt{s}$	$\int \mathcal{L}dt$ [fb^{-1}]	Measured total cross-section [pb]	Theory [pb]	
7 TeV	4.6	$51.9 \pm 2.0(\text{stat.}) \pm 3.9(\text{syst.}) \pm 2.0(\text{lumi})$	$44.7^{2.1}_{-1.9}$	
8 TeV	20.3	$71.4 \pm 1.2(\text{stat.})^{5.0}_{-4.4}(\text{syst.})^{2.2}_{2.1}(\text{lumi})$	$58.7^{3.0}_{-2.7}$	incl. Higgs

W^+W^- production and aTGC at 8 TeV in CMS

NEW! SMP-14-016

Event category		Signal efficiency (%)
0-jet category	Different-flavor	3.02 ± 0.02 (stat.) ± 0.22 (syst.)
	Same-flavor	1.21 ± 0.01 (stat.) ± 0.09 (syst.)
1-jet category	Different-flavor	0.96 ± 0.01 (stat.) ± 0.11 (syst.)
	Same-flavor	0.34 ± 0.01 (stat.) ± 0.04 (syst.)

Process	0-jet category		1-jet category	
	Different-flavor	Same-flavor	Different-flavor	Same-flavor
$qq \to W^+W^-$	3516 ± 271	1390 ± 109	1113 ± 137	386 ± 49
$gg \to W^+W^-$	162 ± 50	91 ± 28	62 ± 19	27 ± 9
W^+W^-	3678 ± 276	1481 ± 113	1174 ± 139	413 ± 50
ZZ + WZ	84 ± 10	89 ± 11	86 ± 4	42 ± 2
VVV	33 ± 17	17 ± 9	28 ± 14	14 ± 7
Top-quark	522 ± 83	248 ± 26	1398 ± 156	562 ± 128
$Z/\gamma^* \to \ell^+\ell^-$	38 ± 4	141 ± 63	136 ± 14	65 ± 33
$W\gamma^*$	54 ± 22	12 ± 5	18 ± 8	3 ± 2
$W\gamma$	54 ± 20	20 ± 8	36 ± 14	9 ± 6
W + jets(e)	189 ± 68	46 ± 17	114 ± 41	16 ± 6
W + jets(μ)	81 ± 40	19 ± 9	63 ± 30	17 ± 8
Higgs	125 ± 25	53 ± 11	75 ± 22	22 ± 7
Total bkg.	1179 ± 123	643 ± 73	1954 ± 168	749 ± 133
W^+W^- + Total bkg.	4857 ± 302	2124 ± 134	3128 ± 217	1162 ± 142
Data	4847	2233	3114	1198

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

Event category		W^+W^- production cross section (pb.)
0-jet category	Different-flavor	59.7 ± 1.1 (stat.) ± 3.3 (exp.) ± 3.5 (th.) ± 1.6 (lum.)
	Same-flavor	64.3 ± 2.1 (stat.) ± 4.6 (exp.) ± 4.3 (th.) ± 1.7 (lum.)
1-jet category	Different-flavor	59.1 ± 2.8 (stat.) ± 6.0 (exp.) ± 6.2 (th.) ± 1.6 (lum.)
	Same-flavor	65.1 ± 5.5 (stat.) ± 8.3 (exp.) ± 8.0 (th.) ± 1.7 (lum.)

Total

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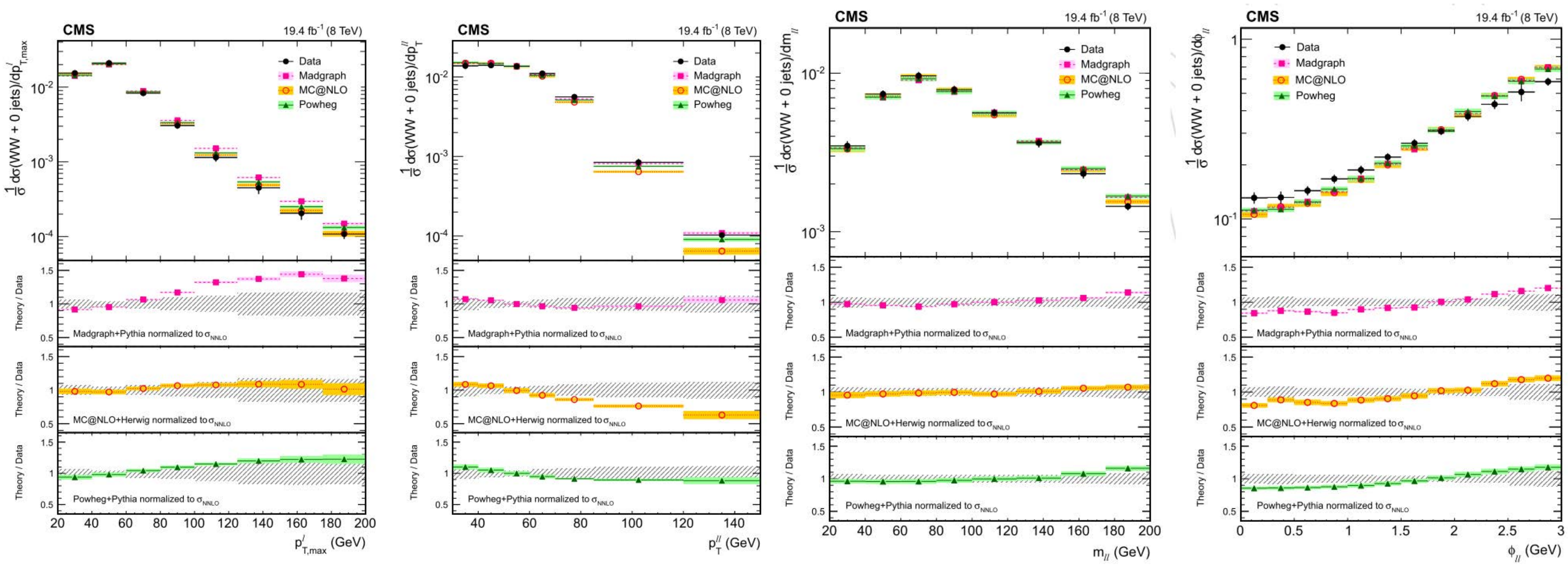
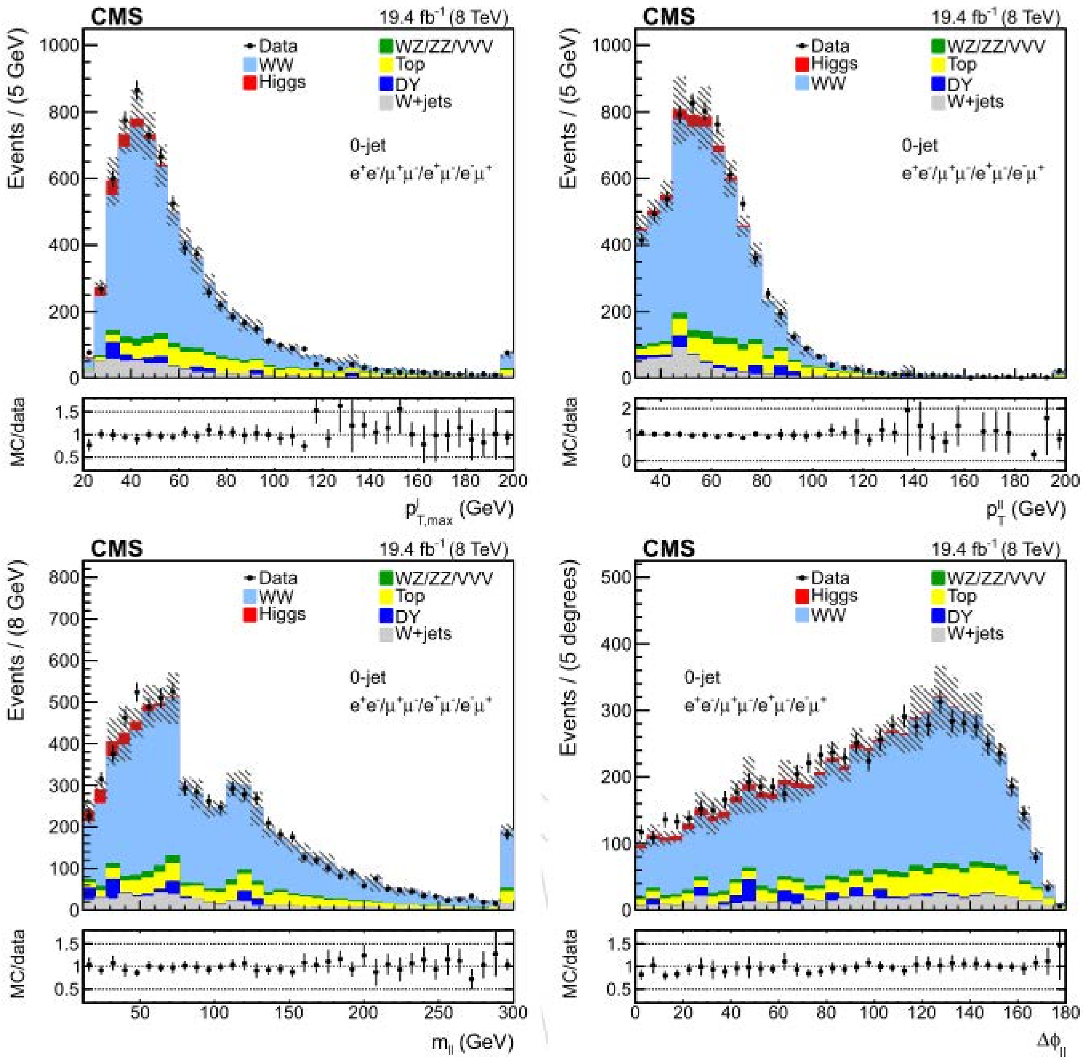
p_T^{jet} threshold (GeV)	$\sigma_{0jet,W\to\ell\nu}$ measured (pb)	$\sigma_{0jet,W\to\ell\nu}$ predicted (pb)
20	0.223 ± 0.004 (stat.) ± 0.013 (exp.) ± 0.007 (th.) ± 0.006 (lumi.)	0.228 ± 0.001 (stat.)
25	0.253 ± 0.005 (stat.) ± 0.014 (exp.) ± 0.008 (th.) ± 0.007 (lumi.)	0.254 ± 0.001 (stat.)
30	0.273 ± 0.005 (stat.) ± 0.015 (exp.) ± 0.009 (th.) ± 0.007 (lumi.)	0.274 ± 0.001 (stat.)

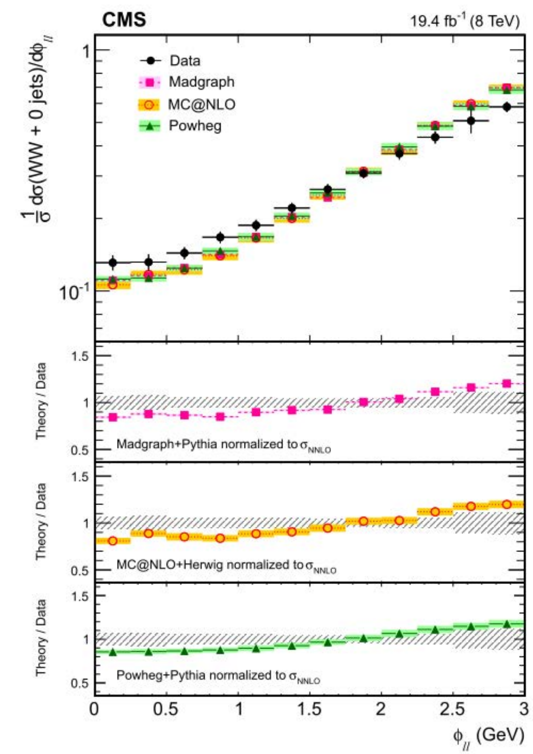
Fiducial



W^+W^- production and aTGC at 8 TeV in CMS

SMP-14-016





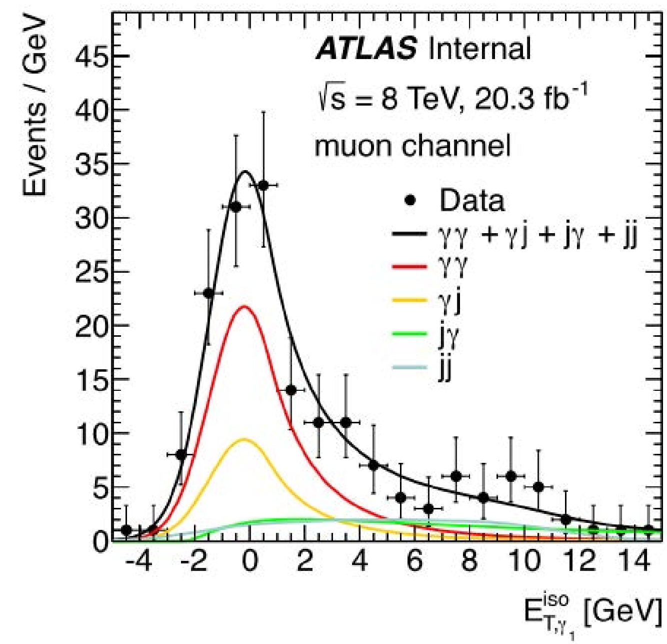
Evidence of Wγγ production in ATLAS

arXiv:1503.03243
submitted to PRL

Definition of the fiducial region
$p_{\mathrm{T}}^{\ell} > 20\,\mathrm{GeV},\ p_{\mathrm{T}}^{\nu} > 25\,\mathrm{GeV},\ \lvert\eta_\ell\rvert < 2.5$
$m_{\mathrm{T}} > 40\,\mathrm{GeV}$
$E_{\mathrm{T}}^{\gamma} > 20\,\mathrm{GeV},\ \lvert\eta^{\gamma}\rvert < 2.37$, iso. fraction $\epsilon_{\mathrm{h}}^{\mathrm{p}} < 0.5$
$\Delta R(\ell,\gamma) > 0.7,\ \Delta R(\gamma,\gamma) > 0.4,\ \Delta R(\ell/\gamma,\mathrm{jet}) > 0.3$
exclusive: no anti-k_t jets with $p_{\mathrm{T}}^{\mathrm{jet}} > 30\,\mathrm{GeV},\ \lvert\eta^{\mathrm{jet}}\rvert < 4.4$

	Electron channel	Muon channel
	$\mathrm{N_{jets}} \geq 0$	
Data	47	110
$W\gamma$j + Wjj	15 ± 5(stat.) ± 5(syst.)	30 ± 8(stat.) ± 7(syst.)
$\gamma\gamma$ + jets	1.5 ± 0.6(stat.) ± 1.0(syst.)	11 ± 4(stat.) ± 5(syst.)
$Z\gamma$	11.2 ± 1.1(stat.)	3.9 ± 0.2(stat.)
Other backgrounds	2.2 ± 0.6(stat.)	6.7 ± 2.0(stat.)
Total background	29.9 ± 5.2(stat.) ± 5.1(syst.)	51.6 ± 9.2(stat.) ± 8.6(syst.)

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



aQGC

Evidence of $W\gamma\gamma$ production in ATLAS

arXiv:1503.03243
submitted to PRL

Selection criteria	$e\nu\gamma\gamma$	$\mu\nu\gamma\gamma$
Lepton p_{T}	$p_{\mathrm{T}}^{e} > 20\,GeV$	$p_{\mathrm{T}}^{\mu} > 20\,GeV$
Lepton η	$\lvert\eta_e\rvert < 2.47$ excl. $1.37 < \lvert\eta_e\rvert < 1.52$	$\lvert\eta_\mu\rvert < 2.4$
W transverse mass	$m_{\mathrm{T}} > 40\,GeV$	
Missing E_{T}	$> 25\,GeV$	
Lepton track isolation	$p_{\mathrm{T}}^{\mathrm{iso}}(\Delta R = 0.2) < 0.15\,p_{\mathrm{T}}^{\mathrm{lepton}}$	
Lepton calo isolation	$E_{\mathrm{T}}^{\mathrm{iso}}(\Delta R = 0.2) < 0.20\,p_{\mathrm{T}}^{\mathrm{lepton}}$	–
Lepton $\lvert d_0\rvert/\sigma(d_0)$	< 6	< 3
Lepton $\lvert z_0 \cdot \sin\theta\rvert$	< 0.5 mm	
Photons	$E_{\mathrm{T}}^{\gamma} > 20\,GeV$ $\lvert\eta_\gamma\rvert < 2.37$ (excluding $1.37 < \lvert\eta_\gamma\rvert < 1.52$) $\Delta R(l,\gamma) > 0.7$ $\Delta R(\gamma,\gamma) > 0.4$ $E_{\mathrm{T}}^{\mathrm{iso}}(\Delta R = 0.4) < 4\,GeV$	
Z rejection cuts	$m(e\gamma\gamma) - m(Z) < -10\,GeV$ or $> 5\,GeV$ $m(e\gamma_1) - m(Z) < -10\,GeV$ or $> 3\,GeV$ $m(e\gamma_2) - m(Z) < -5\,GeV$ or $> 3\,GeV$ $p_{\mathrm{T}}(e\gamma\gamma) > 30\,GeV$	– – – –
	inclusive: $\mathrm{N_{jet}} > 0$; exclusive: $\mathrm{N_{jet}} = 0$	
Jet	anti-k_t with R=0.4 $p_{\mathrm{T}^{\mathrm{jet}}} > 30\,GeV$, $\lvert\eta^{\mathrm{jet}}\rvert < 4.4$ $\Delta R(\mathrm{lepton}/\gamma, \mathrm{jet}) > 0.3$ jet vertex fraction > 0.5 for jets with $p_{\mathrm{T}} < 50\,GeV$ and $\lvert\eta\rvert < 2.4$	

ZZ→lll'l' at 8 TeV

CMS-PAS-SMP-13-005
Phys. Lett. B 740 (2015) 250

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

Cross section in agreement with MCFM NLO expectation.

Signature

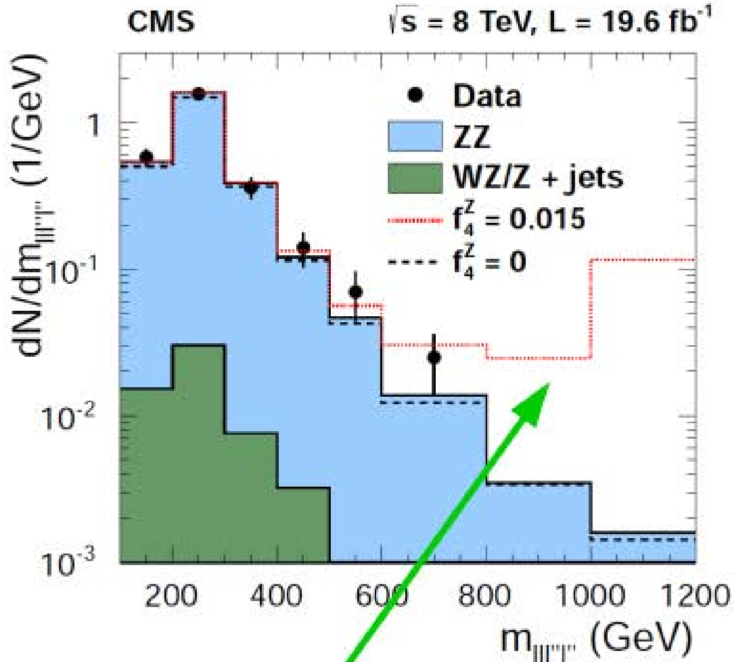
- Two lepton pairs peaking at M_Z.
- l=e,μ l'=e,μ,τ

Selections

- Two same-flavor and opposite-sign isolated leptons from each Z.
- Lepton pair retained if $60 < M_{ll} < 120$ GeV.
- At least one lepton with $p_T > 20$ GeV and one with $p_T > 10$ GeV.

Backgrounds

- Mostly rejected by isolation and identification criteria.
- The remnants are Z/WZ+jets.

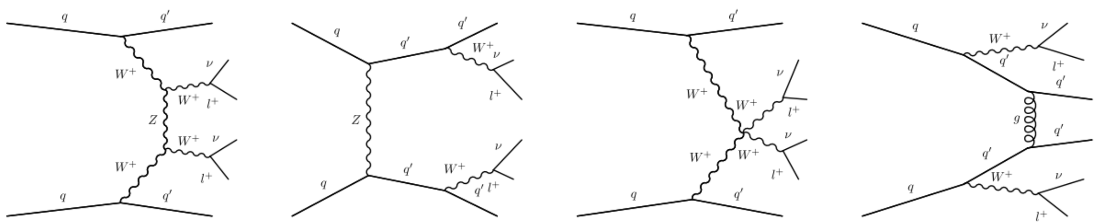


Anomalous couplings effects simulated with SHERPA and used to set limits on ZZZ and ZZγ couplings.

ZZ→2l2ν: expected to be published within next few weeks.

VBS : $W^{\pm}W^{\pm}$ production

- Golden channel to probe the nature of the EWK symmetry breaking
- Without SM Higgs, longitudinally polarized VBS amplitude violates unitarity at energies around 1 TeV
- Higgs discovery suggests which mechanism should unitarize the VBS
- Many BSM scenarios predict enhancements in VBS production
- Sjgnal receives contributions from EW, QCD and interference



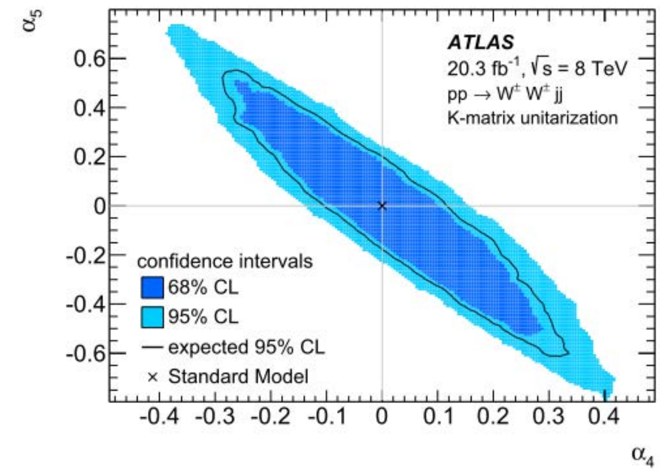
VBS **QCD** **VBS** **QCD**

Final state	Process	VVjj-EW	VVjj-QCD	Ratio
$\ell^{\pm}\nu\ell'^{\pm}\nu' jj$ (same sign, arbitrary flavor)	$W^{\pm}W^{\pm}$	19.5 fb	18.8 fb	1.04
$\ell^{\pm}\nu\ell'^{\mp}\nu' jj$ (opposite sign)	$W^{\pm}W^{\mp}$	91.3 fb	3030 fb	0.03
$\ell^{+}\ell^{-}\nu'\nu' jj$	ZZ	2.4 fb	162 fb	0.015
$\ell^{\pm}\ell^{\mp}\ell'^{\pm}\nu' jj$	$W^{\pm}Z$	30.2 fb	687 fb	0.04
$\ell^{\pm}\ell^{\mp}\ell'^{\pm}\ell'^{\mp} jj$	ZZ	1.5 fb	106 fb	0.014

Sherpa inclusive predictions at 8 TeV

VBS : $W^{\pm}W^{\pm}$ production and aQGC

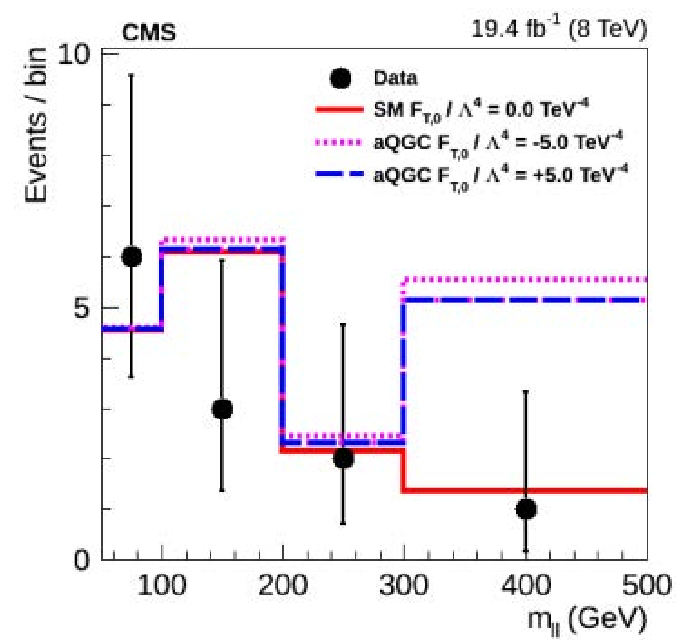
- Various extensions of the SM that can alter the WWVV couplings → aQGC



- ATLAS - PRL 113 (2014) 141803
- Deviations from SM parametrized in terms of parameters α4 and α5
- Limits extracted in VBS region

- CMS - PRL 114 (2015) 051801

- Nine independent C and P conserving EFT dim 8 operators to model



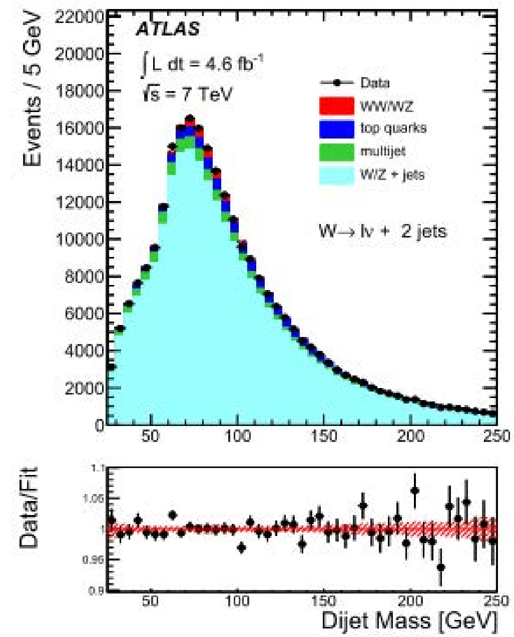
Operator coefficient	Exp. lower	Exp. upper	Obs. lower	Obs. upper	Unitarity limit
$F_{S,0}/\Lambda^4$	−42	43	−38	40	0.016
$F_{S,1}/\Lambda^4$	−129	131	−118	120	0.050
$F_{M,0}/\Lambda^4$	−35	35	−33	32	80
$F_{M,1}/\Lambda^4$	−49	51	−44	47	205
$F_{M,6}/\Lambda^4$	−70	69	−65	63	160
$F_{M,7}/\Lambda^4$	−76	73	−70	66	105
$F_{T,0}/\Lambda^4$	−4.6	4.9	−4.2	4.6	0.027
$F_{T,1}/\Lambda^4$	−2.1	2.4	−1.9	2.2	0.022
$F_{T,2}/\Lambda^4$	−5.9	7.0	−5.2	6.4	0.08

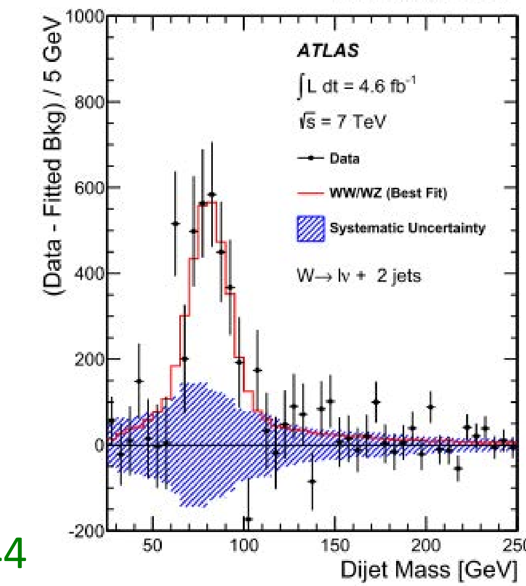
WW/WZ → lνjj cross section in ATLAS

arxiv:1410.7238

- Measurement of combined WW/WZ cross-section in semi-leptonic final state
- Large background from W+jets (89%)
- Signal yield extracted from a fit to m_{jj} distribution
- Large m_{jj} range allows to constraint the W+jets rate in signal free regions
- The observed significance is 3.4σ
- σ_{obs} = 68 ±7(stat) ± 19(syst) pb, compared to
  σ_{th} = 61.1 ± 2.2 pb
- Large uncertainties from W+jets modeling and jet uncertainties
- aTGC coupling have been extracted

Parameter	Observed Limit	Expected Limit
c_{WWW}/Λ^2	$[-9.5, 9.6]$ TeV^{-2}	$[-11.6, 11.5]$ TeV^{-2}
c_B/Λ^2	$[-64, 69]$ TeV^{-2}	$[-73, 79]$ TeV^{-2}
c_W/Λ^2	$[-13, 18]$ TeV^{-2}	$[-17, 21]$ TeV^{-2}

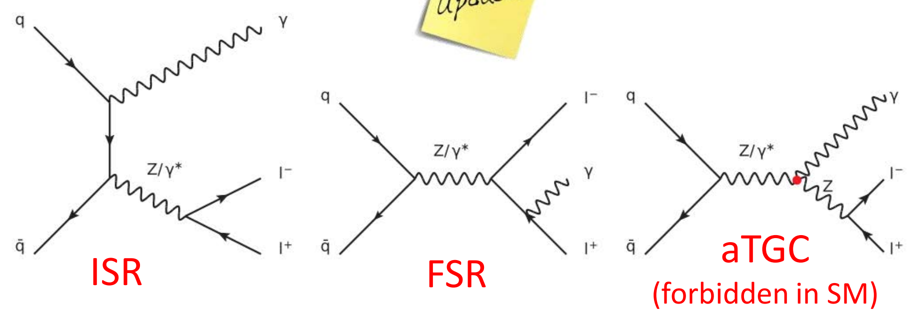




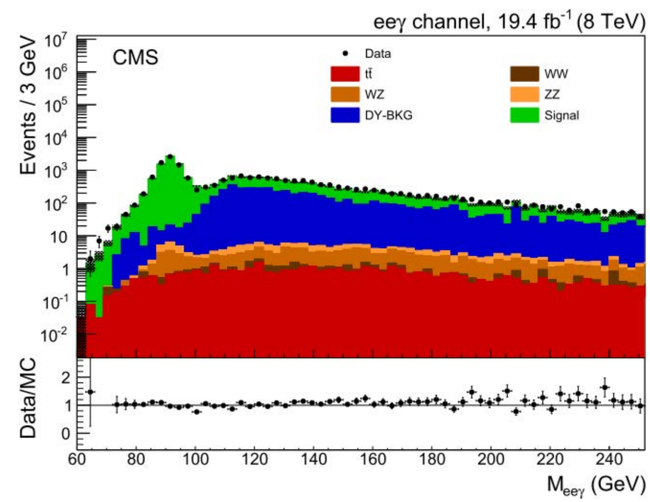
Corresponding CMS analysis in arXiv:1210.7544

Zγ production and aTGC in CMS

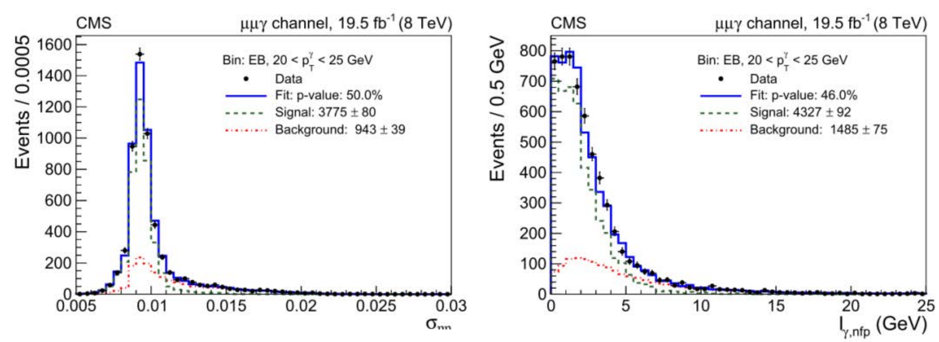
arxiv:1502.05664



- Measurement of the Zγ production cross section in electron and muon channels, with 19.5 fb^{-1} at 8 TeV
- Kinematic range $p_{T,j}$>20 GeV, m_{ll}>50 GeV, $E_{T,\gamma}$>15 GeV, $\Delta R_{l,\gamma}$>0.7



- The dominant background is DY+Jets
  - non-prompt photons from π^0 or η decays or misidentified hadrons
- Two template observables used to measure the yield independently, then combined
  - $\sigma_{i\eta i\eta}$ (shower shape spread along η): larger for background photons, included in EM showers
  - $I_{\gamma,nfp}$: p_T sum of all photon-like PF candidates in ΔR<0.4 around photon, i.e. no “footprint” of the photon



Corresponding ATLAS analysis at 7 TeV in PRD 87, 112003 (2013)

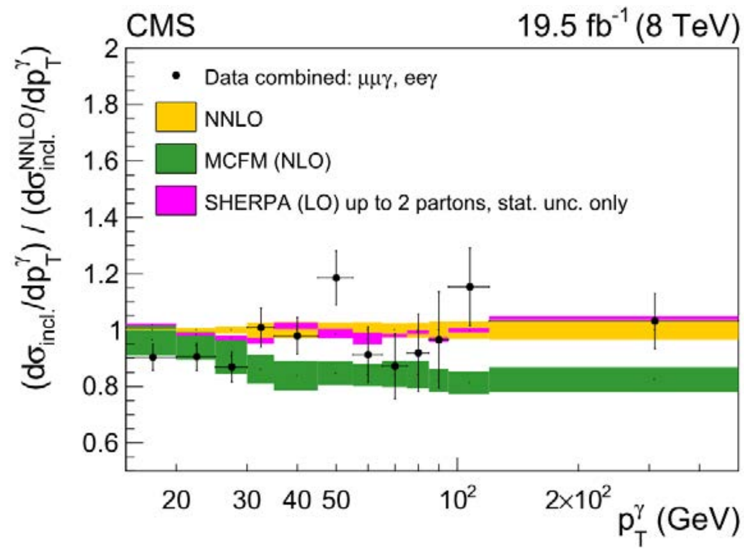
Zγ production and aTGC in CMS

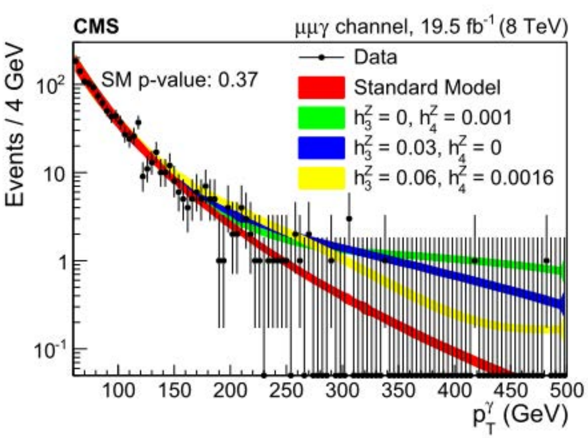
arxiv:1502.05664

- Total inclusive cross section

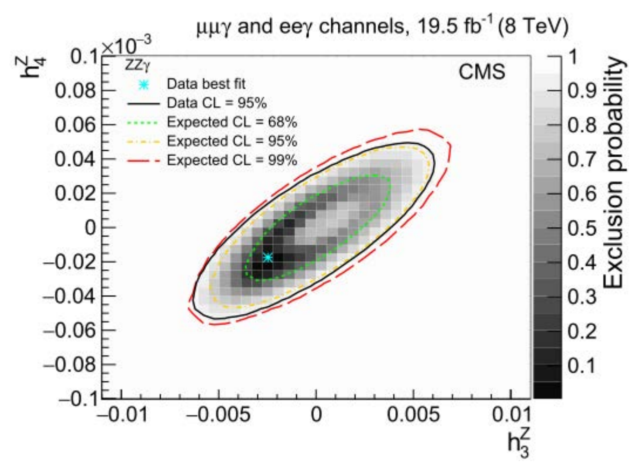
σ(incl) = 2063 ± 19 (stat.) ± 98 (syst.) ± 54 (lumi.) fb

- Uncertainties dominated by template statistics and FSR contamination
- At high pT_{γ} best a greement with NNLO and SHERPA, worse with MCFM
- aTGC would enhance the high $E_{T,\gamma}$ spectrum
- The data are in good agreement with the SM expectations
- Limits on the strenght of ZZγ and Zγγ aTGC are extracted
- Improvement up to factor 3 wrt previous 7 TeV results





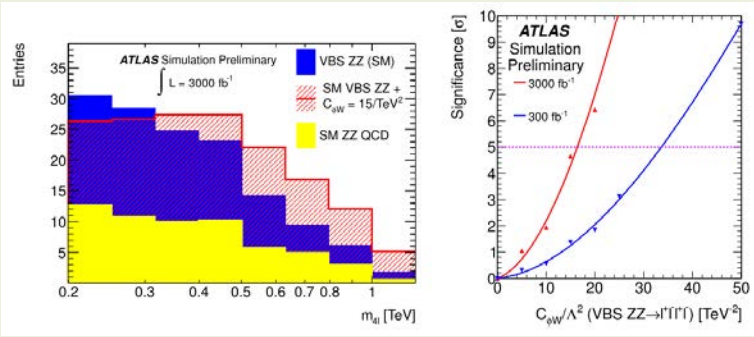
$$-3.8 \times 10^{-3} < h_3^Z < 3.7 \times 10^{-3}$$
$$-3.1 \times 10^{-5} < h_4^Z < 3.0 \times 10^{-5}$$
$$-4.6 \times 10^{-3} < h_3^{\gamma} < 4.6 \times 10^{-3}$$
$$-3.6 \times 10^{-5} < h_4^{\gamma} < 3.5 \times 10^{-5}.$$



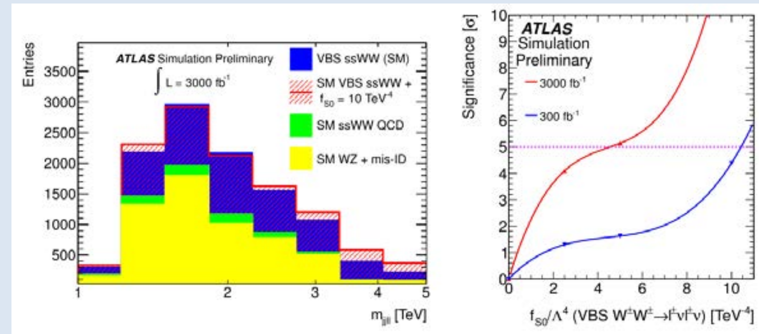
Long term projections for ATLAS

ATL-PHYS-PUB-2013-006: aQCG projections quoting 5s discovery for dim-6 $c_{\phi W}/\Lambda^2$ and dim-8 f_{S0}/Λ^4, f_{T1}/Λ^4, f_{T8}/Λ^4 and f_{T9}/Λ^4 parameters in EFT context

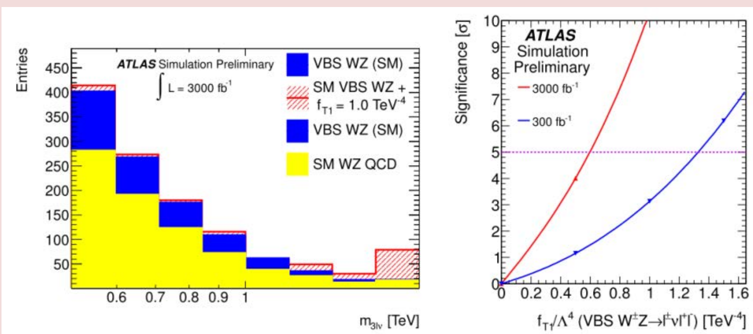
VBS ZZ →4l



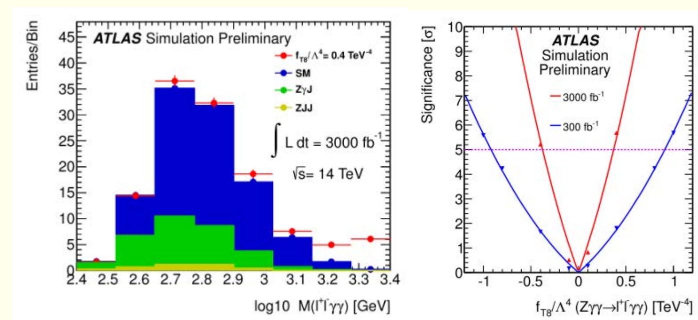
VBS W±W±→2l2ν



VBS WZ→3l



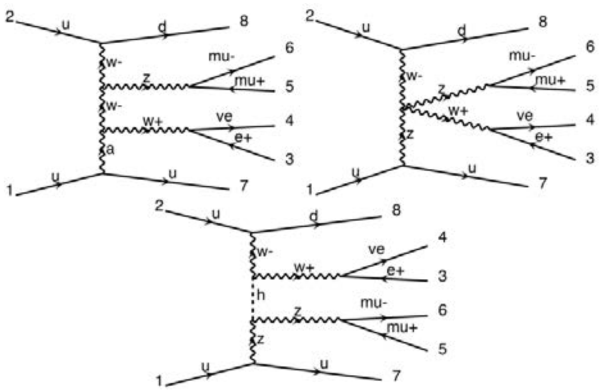
Zγγ →2l+2γ

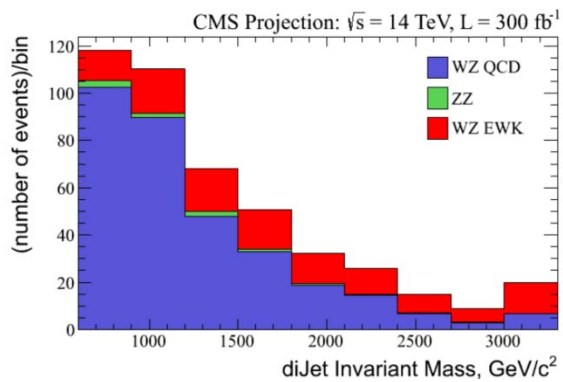


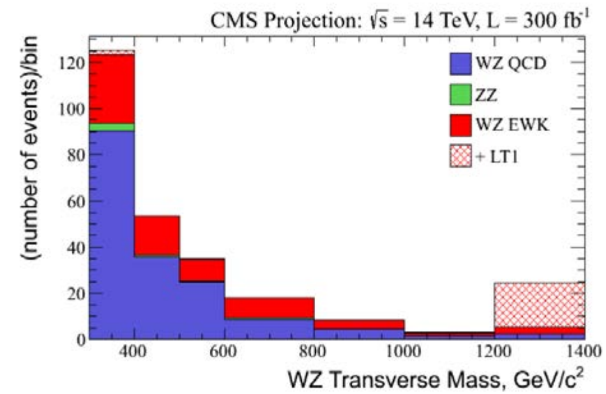
Parameter	dimension	channel	Λ_{UV} [TeV]	300 fb^{-1}		3000 fb^{-1}	
				5σ	95% CL	5σ	95% CL
$c_{\phi W}/\Lambda^2$	6	ZZ	1.9	34 TeV^{-2}	20 TeV^{-2}	16 TeV^{-2}	9.3 TeV^{-2}
f_{S0}/Λ^4	8	$W^\pm W^\pm$	2.0	10 TeV^{-4}	6.8 TeV^{-4}	4.5 TeV^{-4}	0.8 TeV^{-4}
f_{T1}/Λ^4	8	WZ	3.7	1.3 TeV^{-4}	0.7 TeV^{-4}	0.6 TeV^{-4}	0.3 TeV^{-4}
f_{T8}/Λ^4	8	$Z\gamma\gamma$	12	0.9 TeV^{-4}	0.5 TeV^{-4}	0.4 TeV^{-4}	0.2 TeV^{-4}
f_{T9}/Λ^4	8	$Z\gamma\gamma$	13	2.0 TeV^{-4}	0.9 TeV^{-4}	0.7 TeV^{-4}	0.3 TeV^{-4}

Long term projections for CMS

FTR-13-006: projections for aQGC parameter $L_{T1} = (f_{T1}/\Lambda^4) Tr[\hat{W}_{\alpha\nu}\hat{W}^{\mu\beta}] Tr[\hat{W}_{\mu\beta}\hat{W}^{\alpha\nu}]$ using VBS WZ$\rightarrow$3l







Comparison with ATLAS shows slightly better projection by CMS

CMS

Significance	3σ	5σ
SM EWK scattering discovery	75 fb^{-1}	185 fb^{-1}
f_{T1}/Λ^4 at 300 fb^{-1}	0.8 TeV^{-4}	1.0 TeV^{-4}
f_{T1}/Λ^4 at 3000 fb^{-1}	0.45 TeV^{-4}	0.55 TeV^{-4}

ATLAS

Parameter	dimension	channel	Λ_{UV} [TeV]	300 fb^{-1}		3000 fb^{-1}	
				5σ	95% CL	5σ	95% CL
$c_{\phi W}/\Lambda^2$	6	ZZ	1.9	34 TeV^{-2}	20 TeV^{-2}	16 TeV^{-2}	9.3 TeV^{-2}
f_{S0}/Λ^4	8	$W^\pm W^\pm$	2.0	10 TeV^{-4}	6.8 TeV^{-4}	4.5 TeV^{-4}	0.8 TeV^{-4}
f_{T1}/Λ^4	8	WZ	3.7	1.3 TeV^{-4}	0.7 TeV^{-4}	0.6 TeV^{-4}	0.3 TeV^{-4}
f_{T8}/Λ^4	8	$Z\gamma\gamma$	12	0.9 TeV^{-4}	0.5 TeV^{-4}	0.4 TeV^{-4}	0.2 TeV^{-4}
f_{T9}/Λ^4	8	$Z\gamma\gamma$	13	2.0 TeV^{-4}	0.9 TeV^{-4}	0.7 TeV^{-4}	0.3 TeV^{-4}