Diboson production at ATLAS and CMS

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on behalf of the ATLAS and CMS collaborations

31 May 2016

Parallel Session: Electroweak – Top – Higgs

focus on well-known and recent results of fully leptonic decays of dibosons:

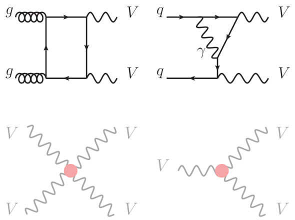
- cross section measurements
- interpretation as anomalous triple/quartic gauge couplings

$\sqrt{s}$	experiment	ZZ	$W^\pm W^\mp$	$W^\pm Z$	$(Z/W^\pm)\gamma$	$\gamma\gamma \to W^\pm W^\mp$
7 TeV	ATLAS	JHEP 03 (2013) 128	PRD 87, 112001 (2013)	EPJC 72 (2012) 2173	PLB 717 (2012) 49	
	CMS	JHEP 01 (2013) 063	EPJC 73 (2013) 2610		JHEP 10 (2013) 164 PRD 89 (2014) 092005	JHEP 07 (2013) 116
8 TeV	ATLAS	ATLAS-CONF-2013-020	arXiv:1603.01702	PRD 93, 092004 (2016)	arXiv:1604.05232	preliminary plots
	CMS	PLB 721 (2013) 190 PLB 740 (2015) 250	arXiv:1507.03268		CMS-PAS-SMP-14-018 JHEP 04 (2015) 164 CMS-PAS-SMP-14-011 arXiv:1602.07152	
7/8 TeV	CMS	EPJC 75 (2015) 511		CMS-PAS-SMP-12-006		arXiv:1604.04464
13 TeV	ATLAS	PRL 116, 101801 (2016)		preliminary plots		
	CMS	CMS-PAS-SMP-16-001		CMS-PAS-SMP-16-002		

results of semi-leptonic decays and like-sign WW production are not presented

$\sqrt{s}$	experiment	WW/WZ	WZ/ZZ	$W^\pm W^\pm$
7 TeV	ATLAS	JHEP 01 (2015) 049		
	CMS	EPJC 73 (2013) 2283		
8 TeV	ATLAS			PRL 113, 141803 (2014)
	CMS		EPJC 74 (2014) 2973	PRL 114, 051801 (2015)

- measurement of total and differential cross sections to ...
  - ... probe validity of Standard Model at TeV scale
  - ... compare with modeling of higher order QCD and EW effects
  - ... understand irreducible diboson background in Higgs analyses



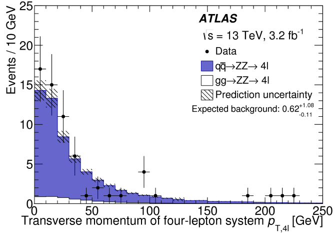
- exploration of self-coupling structure of gauge bosons will ...
  - ... improve our understanding of electroweak symmetry breaking and unitarity
  - ... intersect with determination of Higgs couplings
  - ... indicate new physics if anomalous triple/quartic couplings are present

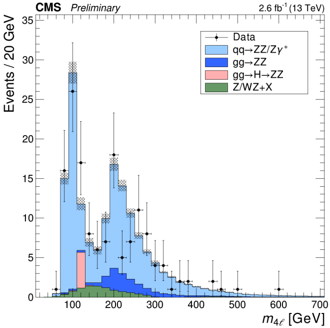
effective Lagrangian:

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_{\text{dimension d}} \sum_{i} \frac{c_i^{(d)}}{\Lambda^{d-4}} \mathcal{O}_i^{(d)}$$

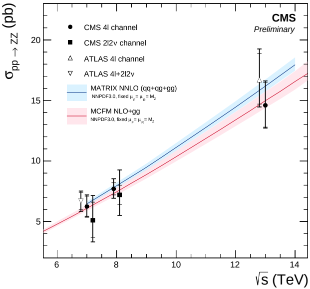
- production mechanisms:
  - $q\bar{q}$ annihilation via t-channel
  - with gg initial state and box diagram or s-channel Higgs (contributing together $\mathcal{O}(4-10)\%$ depending on the center-of-mass energy)
- two pairs of oppositely charged, pairwise same flavor leptons (τ only for CMS at 7/8 TeV)
  - minimal background of $< 1\%$ to 5%
  - small experimental uncertainties
  - slightly different fiducial selections between experiments (mass window, pairing, ...)
- total measured cross sections at 13 TeV

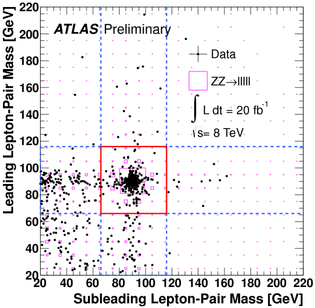
	$\sigma(pp \to ZZ)$ [fb]
ATLAS	$16.7^{+2.2}_{-2.0}(\text{stat})^{+0.9}_{-0.7}(\text{syst})^{+1.0}_{-0.7}(\text{lumi})$
CMS	$14.6^{+1.9}_{-1.8}(\text{stat})^{+0.5}_{-0.3}(\text{syst}) \pm 0.2(\text{theo}) \pm 0.4(\text{lumi})$



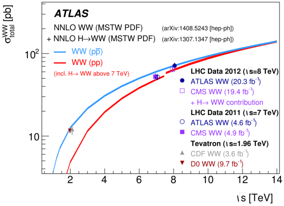


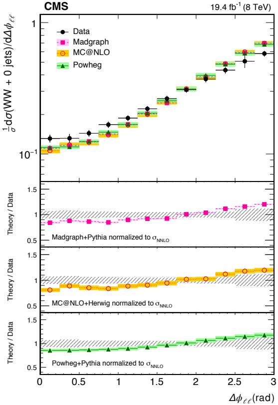
- $e^+e^-/\mu^+\mu^-$ plus missing transverse energy
  - elaborated fiducial phase space definitions
  - jet veto in common for both experiments
  - more than $\mathcal{O}(50\%)$ background dominated by WZ and Z+jets
  - increased experimental uncertainties
- measurements still agree within uncertainties with SM predictions at NLO QCD accuracy:
  - recent calculations at NNLO QCD show cross section enhancement of $q\bar{q}$ initial state
  - production via gg is predicted to increase $\mathcal{O}(70\%)$ at higher orders in QCD
  - higher order electroweak effects decrease production via $q\bar{q}$ initial state by $\mathcal{O}(8\%)$
  - predictions for other diboson pairs suggest similar effects



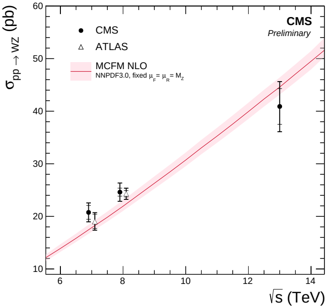


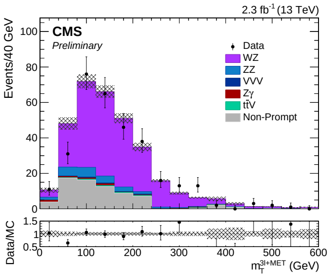
- production mechanisms:
  - $q\bar{q}$ annihilation via t-channel or s-channel
  - with gg initial state and box diagram [$\mathcal{O}(5\%)$] (or s-channel Higgs [$\mathcal{O}(3\%)$])
- event selection and backgrounds:
  - pair of isolated leptons: e^+e^-, $\mu^+\mu^-$, $\mu^\pm e^\mp$
  - missing transverse energy
  - $m(\ell^+\ell^-)/p_T(\ell^+\ell^-)$ cut to reduce Drell-Yan and Z+jets (remaining $1-7\%$)
  - jet-veto to reduce $t\bar{t}$ (remaining $11-18\%$)
  - requirements on combined quantities (remaining W+jets $1-6\%$, other diboson $2-5\%$)
- supplementary for CMS analysis
  - 1-jet fiducial volume enters the analysis
  - Higgs portion is not considered as signal



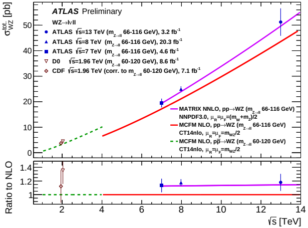


- production mechanisms:
  - $q\bar{q}$ annihilation via t-channel or s-channel
  - EW or QCD production of $WZ + 2$jets
  - no gg initial state at NNLO QCD
- various fiducial volumes:
  - three leptons $\ell^{(\prime)\pm}\ell^{+}\ell^{-}$ with $\ell = e,\mu$ assigned to gauge bosons by basic algorithm up to "resonant shape" approach
  - multiple jet requirements particularly for measurements at 8 TeV
    - b-jet veto (to suppress $t\bar{t}$ background)
    - di-jet orientation/separation to optimize for VBS production or aQGC sensitivity
- dominant backgrounds are ZZ (prompt leptons) as well as V+jets and $t\bar{t}$ (lepton misidentification)





- unfolded differential cross sections sensitive to W polarization or WZ helicity amplitude as well as further differential distributions are available for 8 TeV center-of-mass energy



- measurement of $WZ + 2$jet production:
  - CMS in fiducial volume inspired by "$W^{\pm}W^{\pm}$+2jet" analysis:

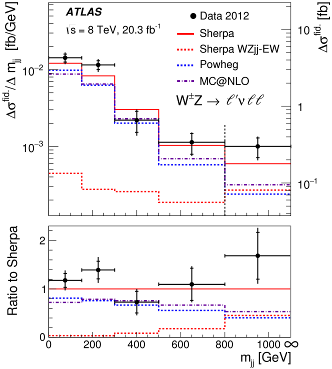
    $\sigma^{\text{fid}}_{WZjj} = 10.8 \pm 4.0(\text{stat}) \pm 1.3(\text{syst})$ fb

    expected: 14.4 ± 4.0 fb

  - ATLAS translates observed events in VBS fiducial phase space in cross section for electroweak production:

    $\sigma^{\text{fid}}_{WZjj-\text{EW}\rightarrow\ell'\nu\ell\ell} = 0.29^{+0.14}_{-0.12}(\text{stat})^{+0.09}_{-0.1}(\text{syst})$ fb

    expected: 0.13 ± 0.01 fb



- production mechanisms:
  - V plus initial/final state photon radiation
  - V plus final state quark fragmentation
  - electroweak production via VBS

- multiple fiducial volumes:
  - visible (invisible) $Z \to e^+e^-/\mu^+\mu^-$ ($\to \nu\nu$) or
  - W decay to e/μ and missing transverse energy
  - isolated photon
  - ATLAS: exclusive ($N_{\text{jets}} = 0$) and inclusive
  - CMS: various VBS di-jet selections

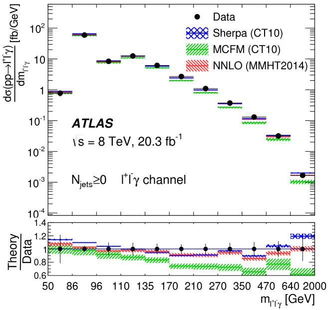
- measured $\sigma_{\text{fiducial}}(pp \to \nu\nu\gamma)$ in fb

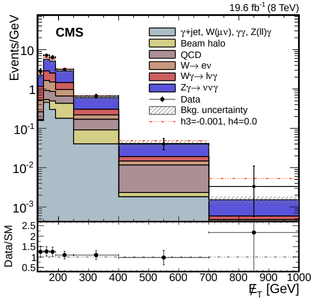
$$\sigma^{\text{ATLAS}}_{\text{exclusive}} = 43 \pm 2(\text{stat}) \pm 10(\text{syst}) \pm 1(\text{lumi}) \qquad [49.21^{+0.61}_{-0.52}]$$

$$\sigma^{\text{CMS}} = 52.7 \pm 2.1(\text{stat}) \pm 6.4(\text{syst}) \pm 1.4(\text{lumi}) \qquad [50.0^{+2.4}_{-2.2}]$$

- electroweak $W\gamma$ production with significance of 2.67 (expected 1.52) measured by CMS:

$$\sigma^{\text{CMS}}_{\text{fiducial EWK}} = 10.8 \pm 4.1(\text{stat}) \pm 3.4(\text{syst}) \pm 0.3(\text{lumi})\ \text{fb}$$





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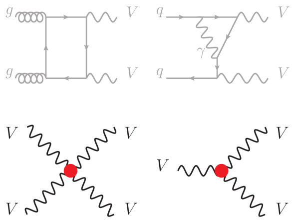

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effective Lagrangian:

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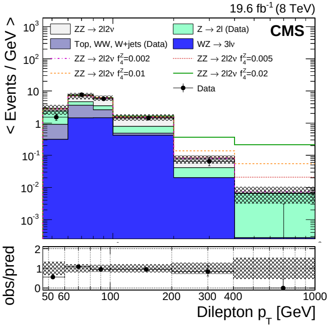
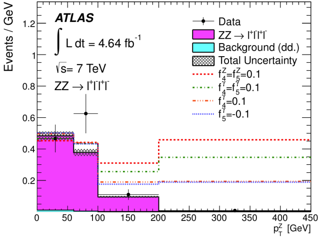
- neutral trilinear couplings f_4^V (CP-violating) and f_5^V (CP-conserving) with $V = Z, \gamma$ are forbidden on tree-level in the Standard Model

- CMS interprets measured $p_T^{\ell^+\ell^-}$ distributions for $ZZ \to 2\ell 2\nu$ and $p_T^{4\ell}$ for $ZZ \to 4\ell$:
  - combined results of 7 and 8 TeV data
  - SM prediction includes higher order EW effects
  - no form factor scaling of couplings applied
  - 1-/2-dim. 95% confidence intervals available

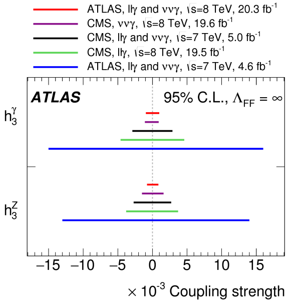
	f_4^Z $[\times 10^{-3}]$	f_4^γ $[\times 10^{-3}]$	f_5^Z $[\times 10^{-3}]$	f_5^γ $[\times 10^{-3}]$
combined	$[-2.2, 2.6]$	$[-2.9, 2.6]$	$[-2.3, 2.3]$	$[-2.6, 2.7]$
expected	$[-3.6, 3.9]$	$[-4.6, 4.1]$	$[-3.6, 3.7]$	$[-4.3, 4.3]$

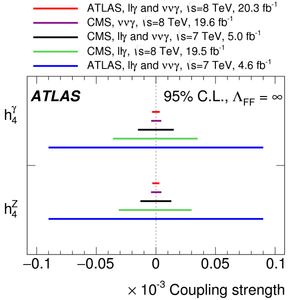
- CMS results by factor $\mathcal{O}(4-9)$ tighter than ATLAS interpretation of differential $p_T^{\text{leading }\ell^+\ell^-}$ measurement at 7 TeV or CMS limits at 7 TeV



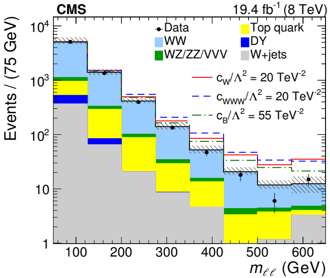


- limits expressed in terms of CP-conserving parameters $h^V_{(3/4)}$ with $V = Z,\gamma$ since CP-violating couplings do not interfere and have similar sensitivity to aTGCs
- both experiments interpret high energy tail of differential E^{γ}_{T} measurement in terms of anomalous couplings
  - ATLAS: exclusive ($N_{\mathrm{jets}} = 0$) fiducial selection
  - CMS: central photon with $|\eta^{\gamma}| < 1.44$
- limits are available as 1-/2-dim. 95% confidence intervals and as function of form factor Λ_{FF}



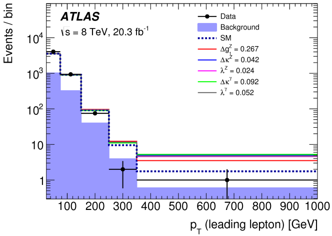


- CMS (ATLAS) interprets differential $m(\ell^+\ell^-)$ (p_T(leading ℓ)) results at 8 TeV in context of
  - coefficients $\mathcal{C}_{WWW}/\Lambda^2$, $\mathcal{C}_W/\Lambda^2$, $\mathcal{C}_B/\Lambda^2$ of C-/P-conserving effective dimension-6 operators
  - different (constrained) scenarios of coupling (deviations) Δg_1^Z, Δk^Z, Δk^γ, λ^γ and λ^Z with form factor Λ (ATLAS)



- 95% confidence intervals on couplings are given 2-dimensional and 1-dimensional:

	$\frac{\mathcal{C}_{WWW}}{\Lambda^2}$ [TeV^{-2}]	$\frac{\mathcal{C}_W}{\Lambda^2}$ [TeV^{-2}]	$\frac{\mathcal{C}_B}{\Lambda^2}$ [TeV^{-2}]
CMS	$[-5.7, 5.9]$	$[-11.4, 5.4]$	$[-29.2, 23.9]$
ATLAS	$[-4.61, 4.60]$	$[-5.87, 10.54]$	$[-20.9, 26.3]$
world average	5.5 ± 4.8	$-3.9^{+3.9}_{-4.8}$	$-1.7^{+13.6}_{-13.9}$



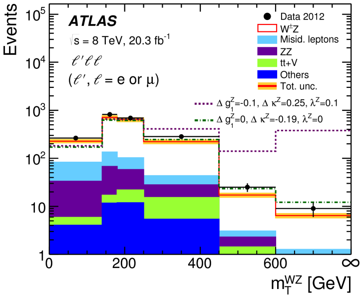
- results are more stringent than for 7 TeV and competitive with LEP findings

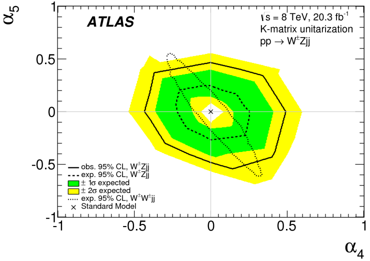
- complementary probe of triple and quartic couplings via WZ because access to other phase space regions

- ATLAS uses m_T^{WZ} to place limits on ETF coefficients for aTGCs and provides 1-/2-dim. 95% confidence intervals

	$\frac{c_{WWW}}{\Lambda^2}$ [TeV^{-2}]	$\frac{c_W}{\Lambda^2}$ [TeV^{-2}]	$\frac{c_B}{\Lambda^2}$ [TeV^{-2}]
observed	$[-3.9, 4.0]$	$[-4.3, 6.8]$	$[-320, 210]$
expected	$[-3.9, 3.8]$	$[-3.6, 7.6]$	$[-270, 180]$

- further optimized selection of VBS fiducial volume of ATLAS WZ analysis is used to investigate coefficients $\alpha_{4/5}$ of linear independent dimension-4 operators of effective $ZWZW$ coupling

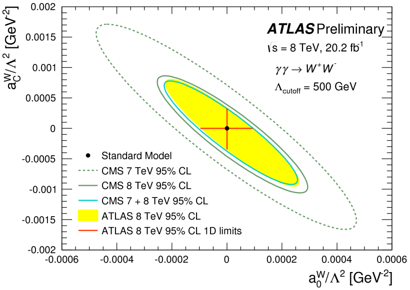


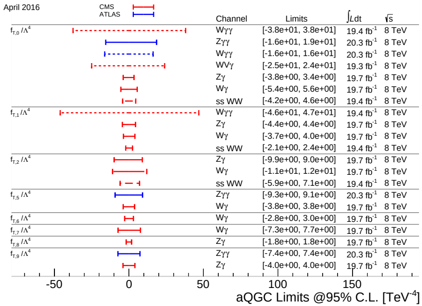


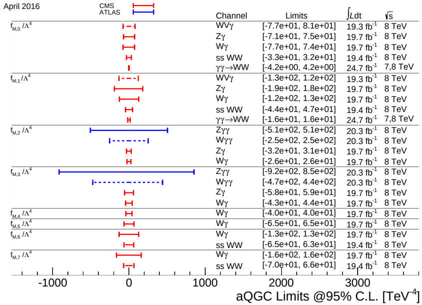
Anomalous Quartic Gauge Couplings

Studies Using $pp \to (W)V\gamma$, $W^{\pm}W^{\pm}$, $\gamma\gamma \to WW$

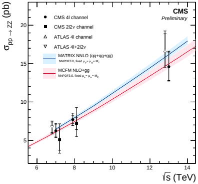
- interpretation of high transverse momentum tail p_T^W in $W\gamma$ analysis as dimension-8 couplings
- differential $p_T^{e\mu}$ obtained in exclusive $\gamma\gamma \to W(\to e^{\pm}\nu)W(\to \mu^{\mp}\nu)$ analysis used to constrain couplings $\alpha^W_{(0,C)}/\Lambda^2$

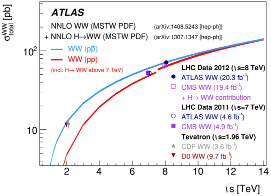


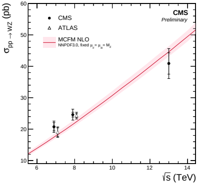


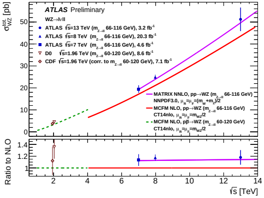


diboson measurements ...

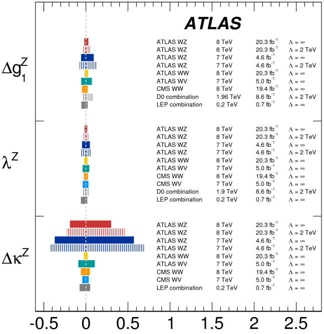








... and their interpretation



aTGC Limits at 95% CL