EWK Diboson production at ATLAS

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on behalf of ATLAS collaboration

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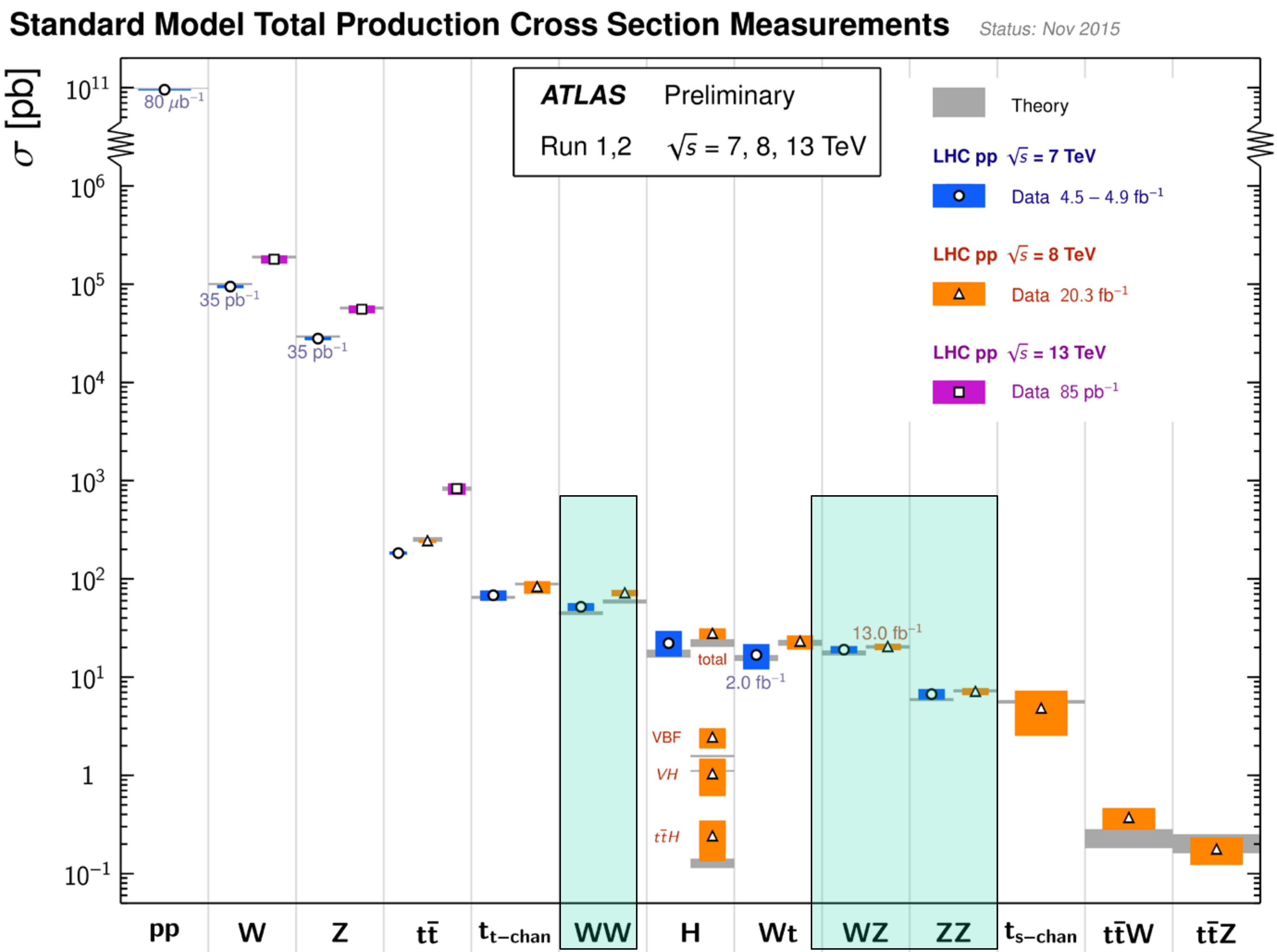
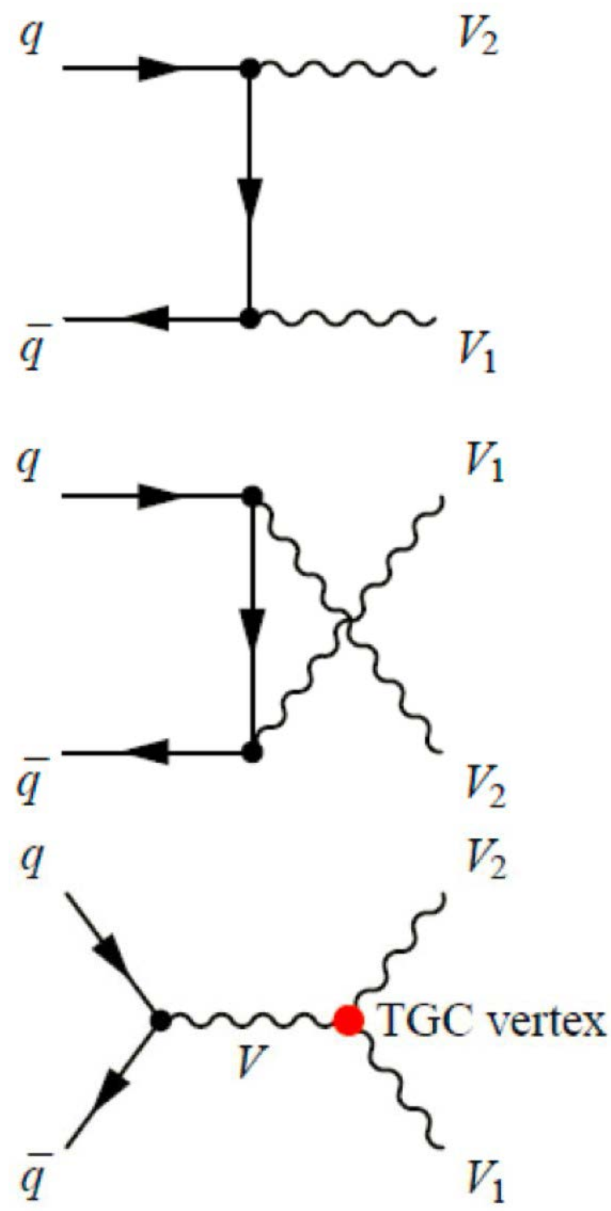
La Thuile, Aosta Valley, Italy


Standard Model Total Production Cross Section Measurements
Status: Nov 2015
ATLAS Preliminary
Run 1,2 $\sqrt{s}$ = 7, 8, 13 TeV
Theory
LHC pp $\sqrt{s}$ = 7 TeV
Data 4.5 – 4.9 fb^{-1}
LHC pp $\sqrt{s}$ = 8 TeV
Data 20.3 fb^{-1}
LHC pp $\sqrt{s}$ = 13 TeV
Data 85 pb^{-1}
σ [pb]
80 μb^{-1}
35 pb^{-1}
35 pb^{-1}
total
2.0 fb^{-1}
13.0 fb^{-1}
VBF
VH
$t\bar{t}H$
pp
W
Z
$t\bar{t}$
t_{t-chan}
WW
H
Wt
WZ
ZZ
t_{s-chan}
$t\bar{t}W$
$t\bar{t}Z$

Motivation

- Diboson production cross-section measurements
  - important test of electroweak sector of Standard Model (SM) at TeV scale
  - Precision tests of theory
  - Important background for Higgs
  - Sensitivity to new physics, new heavy particles decaying to diboson
- Anomalous Triple Gauge Coupling (aTGC)
  - Vector boson self-couplings fundamental prediction of the Electroweak Sector of the SM
  - Probe to new physics through deviations of measured cross sections from predictions
- NB: mostly qq channel, gg contribution is below 10%



Cross-section measurement strategy

- "Cut and count" analysis of observed events
- Signal selection:
  - At least one boson decays to leptons to get better background suppression
  - Select high p_T leptons/jets, require high missing E_T (if ν) + m_T cut for W
- Background estimation
  - Data-driven or simulation-only (in case of irreducible background)

$$\sigma_{tot}^{fid} = \frac{N_{data} - N_{backg.}}{A * BR * C * \int Ldt}$$

acceptance

branching ratio

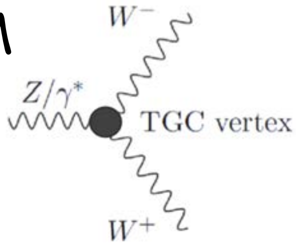
efficiency

integrated luminosity

$$A = \frac{N_{MC,gen}^{fid}}{N_{MC,gen}^{tot}} \qquad C = \frac{N_{Reco}^{Selected}}{N_{MC,gen}^{fid}}$$

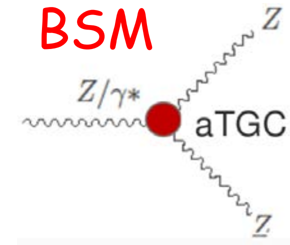
- Uncertainties
  - Experimental: energy resolution/scale, reconstruction ID, luminosity …
  - Theoretical: PDFs, parton shower, renormalization/factorization scale, …

SM



Anomalous couplings

BSM



- The non-abelian nature of the EWK sector of the SM predicts the self-interaction of gauge bosons in the form of triple and quartic couplings
- General Lagrangian for WWZ or WWγ vertex that conserves C and P separately (V = Z or γ):

$$\mathcal{L}_{WWV} = -i\, g_{WWV}\Big[g_1^V\left(W^\dagger_{\mu\nu}W^\mu V^\nu - W^\dagger_\mu V_\nu W^{\mu\nu}\right) + \kappa_V W^\dagger_\mu W_\nu V^{\mu\nu} + \frac{\lambda_V}{M_W^2} W^\dagger_{\lambda\mu} W^\mu_\nu V^{\nu\lambda}\Big]$$

  - 5 parameters $\Delta g_1^Z = g_1^Z - 1,\ \Delta\kappa_\gamma = \kappa_\gamma - 1,\ \Delta\kappa_Z = \kappa_Z - 1,\ \lambda_\gamma,\ \lambda_Z$
    - all should be 0 in SM
  - LEP parametrization: $\Delta\kappa_Z = \Delta g_1^Z - \Delta\kappa_\gamma tan^2\theta_W$ and $\lambda_\gamma = \lambda_Z$
    only 3 independent parameters left
- To set aTGC/aQGC limits
  - look for deviations in cross section measurements
  - look for enhancements in high p_T or high invariant mass regions

coupling	parameters	channel
$WW\gamma$	$\lambda_\gamma, \Delta k_\gamma$	$WW, W\gamma$
WWZ	$\lambda_Z, \Delta k_Z, \Delta g_1^Z$	WW, WZ
$ZZ\gamma$	h_3^Z, h_4^Z	$Z\gamma$
$Z\gamma\gamma$	h_3^γ, h_4^γ	$Z\gamma$
$Z\gamma Z$	f_{40}^Z, f_{50}^Z	ZZ
ZZZ	$f_{40}^\gamma, f_{50}^\gamma$	ZZ

Effective field theory

- Alternative description with Effective Field Theory (EFT)

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \sum_d \sum_i \frac{c_i^{(d)}}{\Lambda^{d-4}} \mathcal{O}_i^{(d)}$$

arXiv:1205.4231

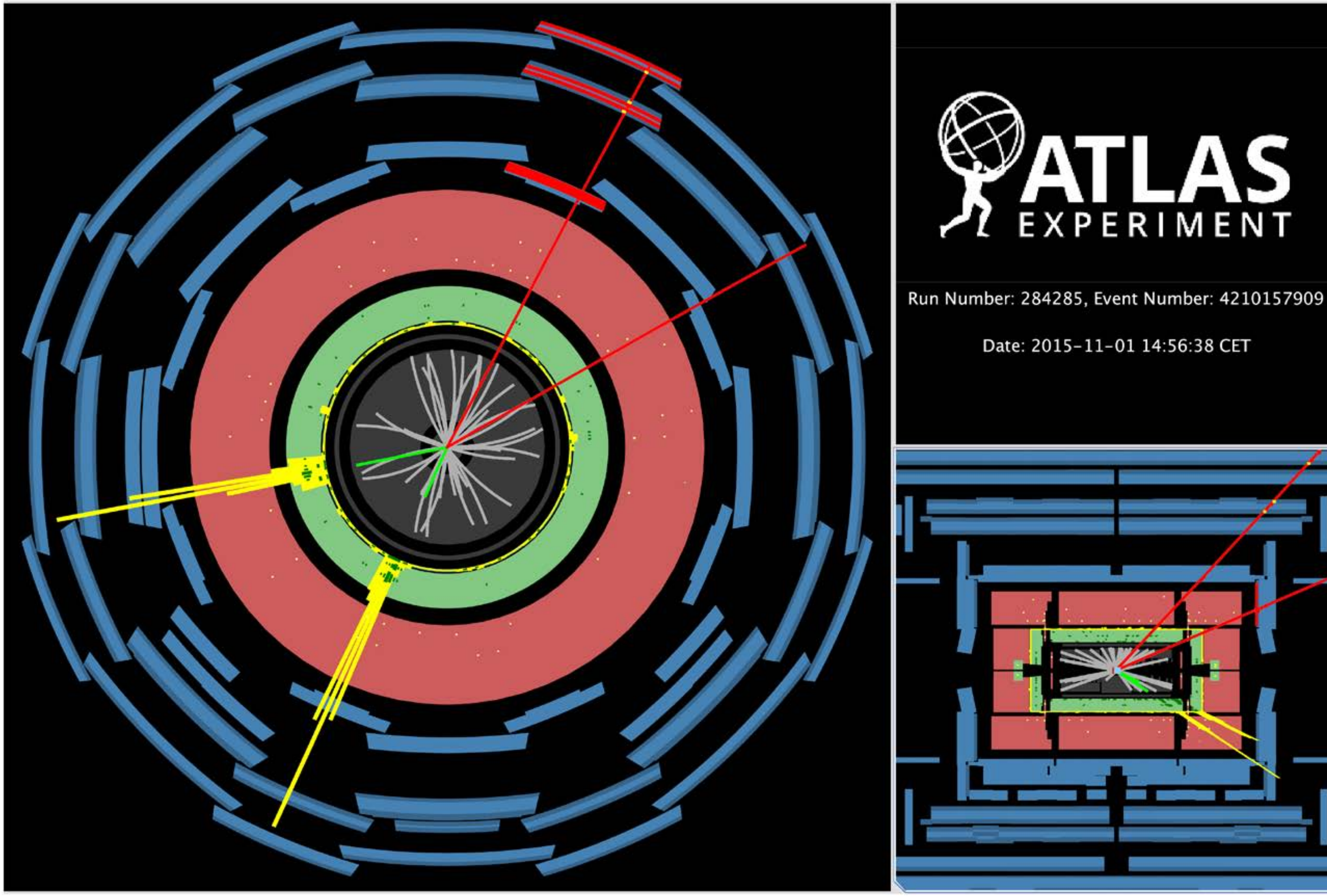
Λ *- scale of new physics*
$O_i^{(d)}$ *– new operators of higher dimensions*

- aTGC parameters can be converted to EFT couplings strengths, e.g. for d=6

$$\frac{c_W}{\Lambda^2} = \frac{2}{m_Z^2}\Delta g_1^Z ,$$
$$\frac{c_B}{\Lambda^2} = \frac{2}{m_W^2}\Delta\kappa_\gamma - \frac{2}{m_Z^2}\Delta g_1^Z ,$$
$$\frac{c_{WWW}}{\Lambda^2} = \frac{2}{3g^2 m_W^2}\lambda ,$$

Recent RUN2 results

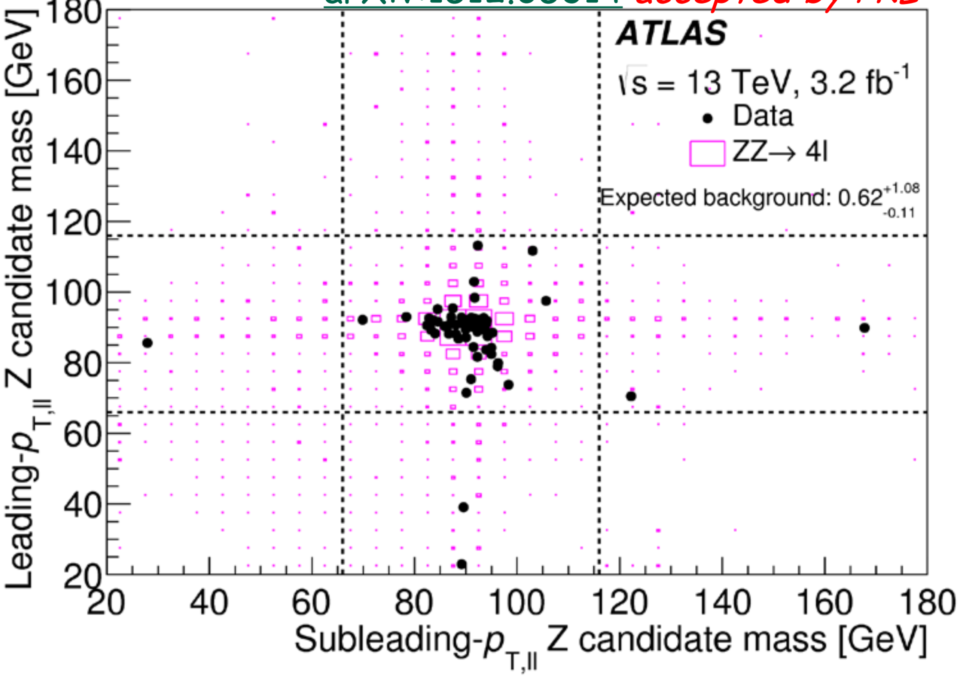
ZZ @ 13 TeV

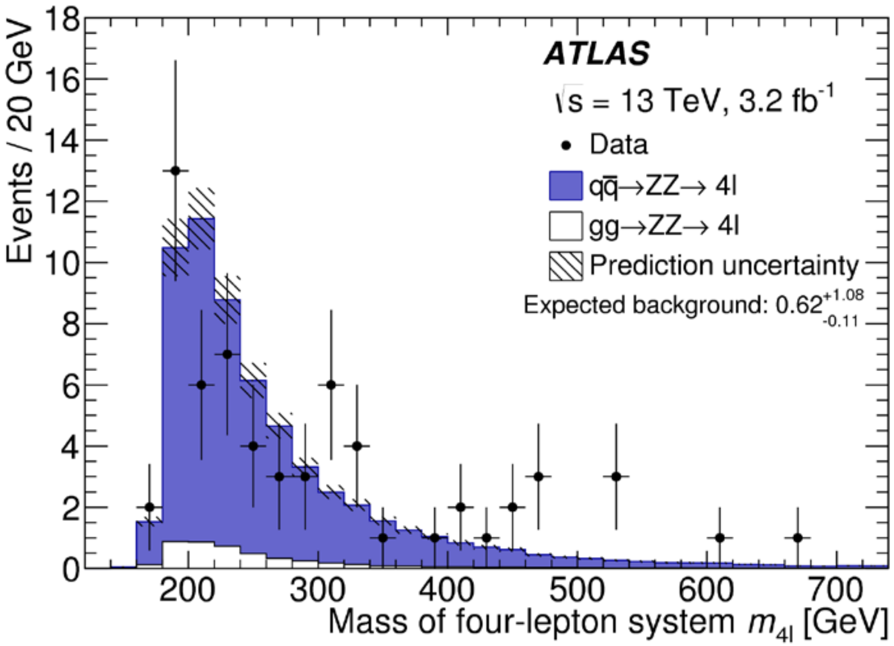

ATLAS
EXPERIMENT
Run Number: 284285, Event Number: 4210157909
Date: 2015-11-01 14:56:38 CET

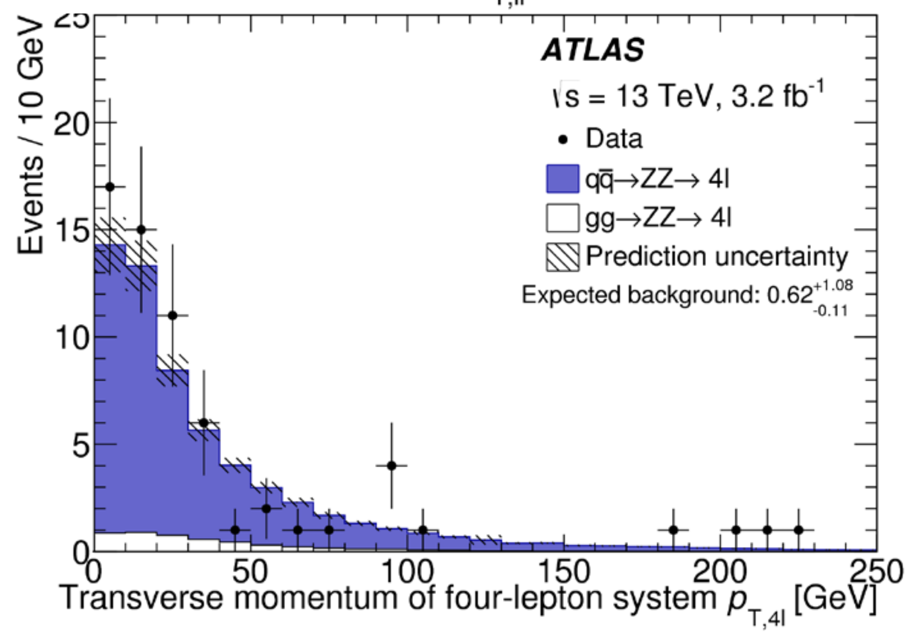
ZZ @ 13 TeV

arXiv:1512.05314 *accepted by PRL*

- First diboson result at 13 TeV!
- 4l channel, 2 OS-SF [e,μ] pairs
- $p_T > 20$ GeV, $66 < m_{ll} < 116$ GeV
- 63 events in 3 channels
- total exp. background: $0.62^{+1.08}_{-0.11}$







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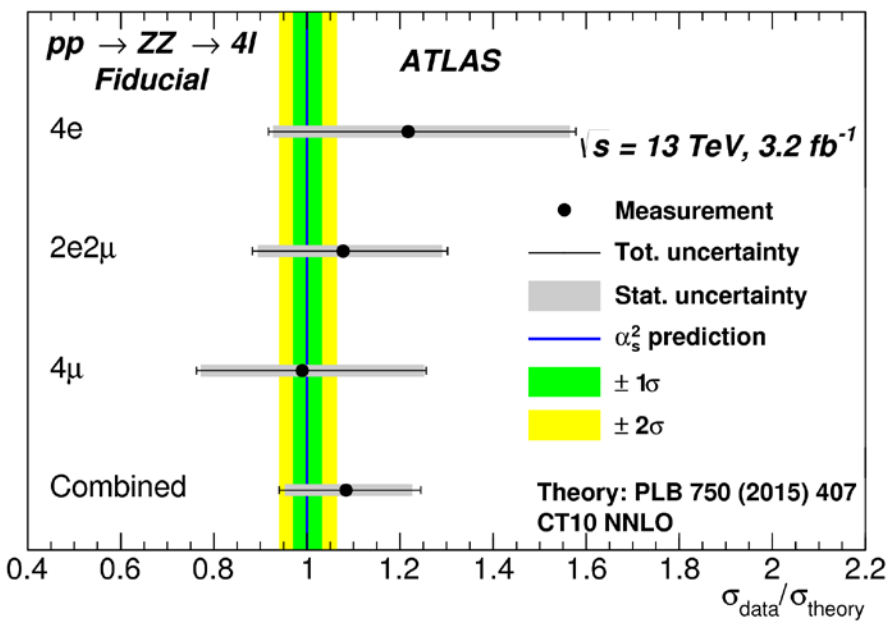
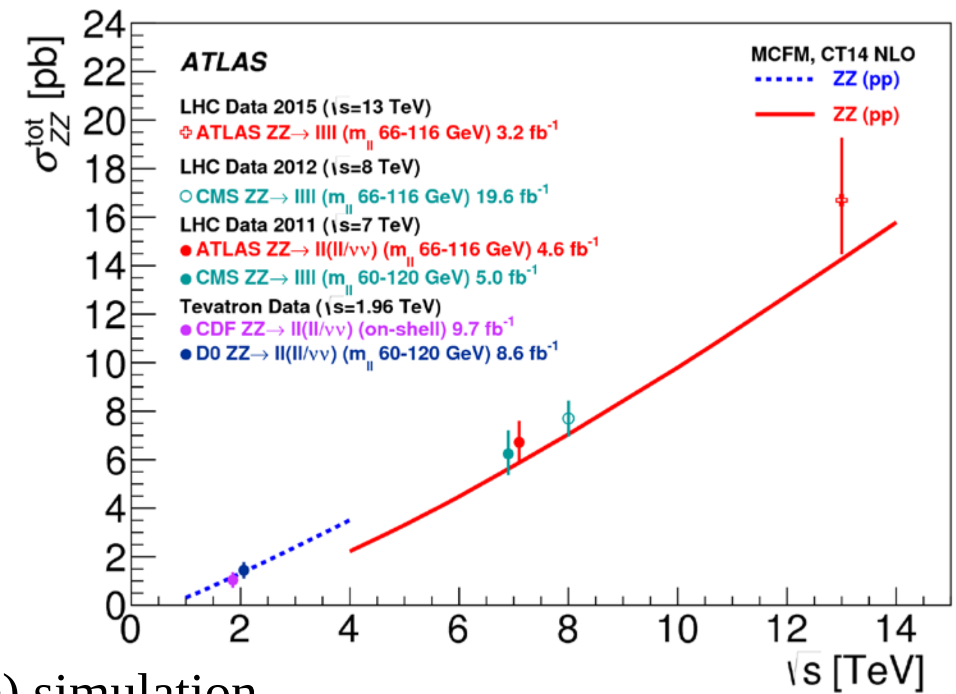
ZZ @ 13 TeV





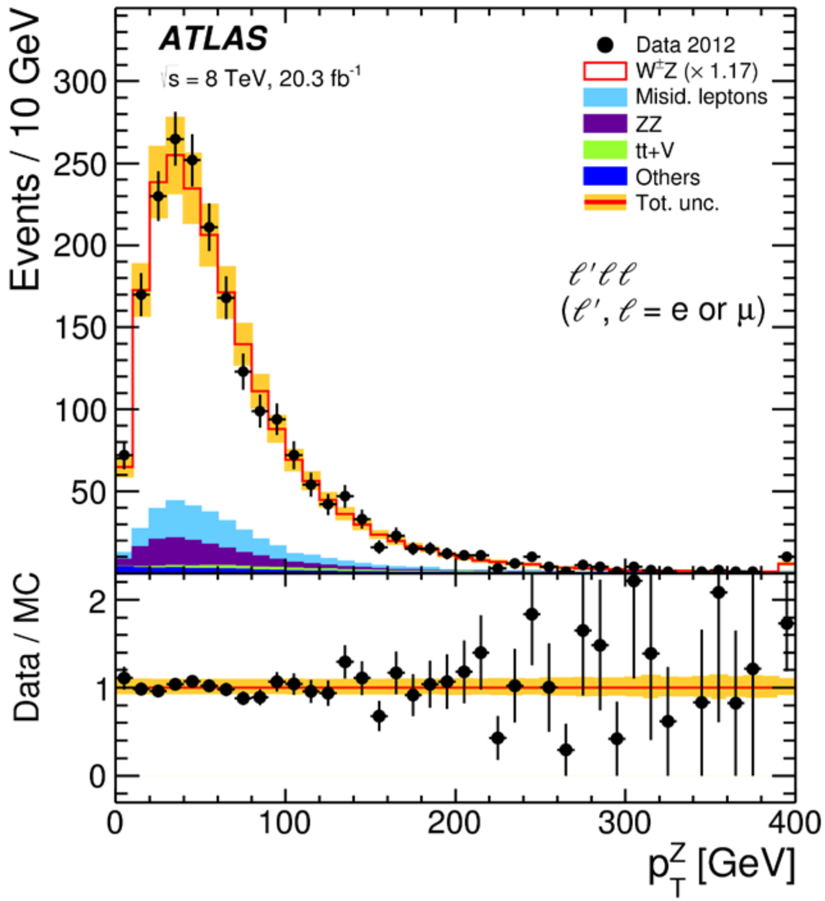
- ZZ: predictions still miss a full $O(\alpha_s^2)$ simulation

	Measurement	$\mathcal{O}(\alpha_s^2)$ prediction
$\sigma^{\text{fid}}_{ZZ\to e^+e^-e^+e^-}$	$8.4\ ^{+2.4}_{-2.0}(\text{stat.})\ ^{+0.4}_{-0.2}(\text{syst.})\ ^{+0.5}_{-0.3}(\text{lumi.})$ fb	$6.9^{+0.2}_{-0.2}$ fb
$\sigma^{\text{fid}}_{ZZ\to e^+e^-\mu^+\mu^-}$	$14.7\ ^{+2.9}_{-2.5}(\text{stat.})\ ^{+0.6}_{-0.4}(\text{syst.})\ ^{+0.9}_{-0.6}(\text{lumi.})$ fb	$13.6^{+0.4}_{-0.4}$ fb
$\sigma^{\text{fid}}_{ZZ\to \mu^+\mu^-\mu^+\mu^-}$	$6.8\ ^{+1.8}_{-1.5}(\text{stat.})\ ^{+0.3}_{-0.3}(\text{syst.})\ ^{+0.4}_{-0.3}(\text{lumi.})$ fb	$6.9^{+0.2}_{-0.2}$ fb
$\sigma^{\text{fid}}_{ZZ\to \ell^+\ell^-\ell'^+\ell'^-}$	$29.7\ ^{+3.9}_{-3.6}(\text{stat.})\ ^{+1.0}_{-0.8}(\text{syst.})\ ^{+1.7}_{-1.3}(\text{lumi.})$ fb	$27.4^{+0.9}_{-0.8}$ fb
σ^{tot}_{ZZ}	$16.7\ ^{+2.2}_{-2.0}(\text{stat.})\ ^{+0.9}_{-0.7}(\text{syst.})\ ^{+1.0}_{-0.7}(\text{lumi.})$ pb	$15.6^{+0.4}_{-0.4}$ pb

Recent RUN1 results

WZ Production

- Final state: : (W→) lν + (Z→) ll, l = e, mu
- Selection:
  - 3 isolated high p_T leptons, at least one lepton with p_T> 25 GeV, lepton from W with p_T> 20 GeV
  - E_T^{miss}> 25 GeV, M_T^W> 30 GeV
  - Z mass window: | M_{ll} – M_Z | < 10 GeV
- Data driven estimates for Z+jets, Zγ, WW and tt reducible backgrounds
  - fakes leptons from light flavor, heavy flavor jets and photons (for e)
- ZZ and other irreducible bkg – from MC
  - latest theoretical calculations
  - mixture of NNLO and NLO (for gg→ZZ)



Submitted to PRD

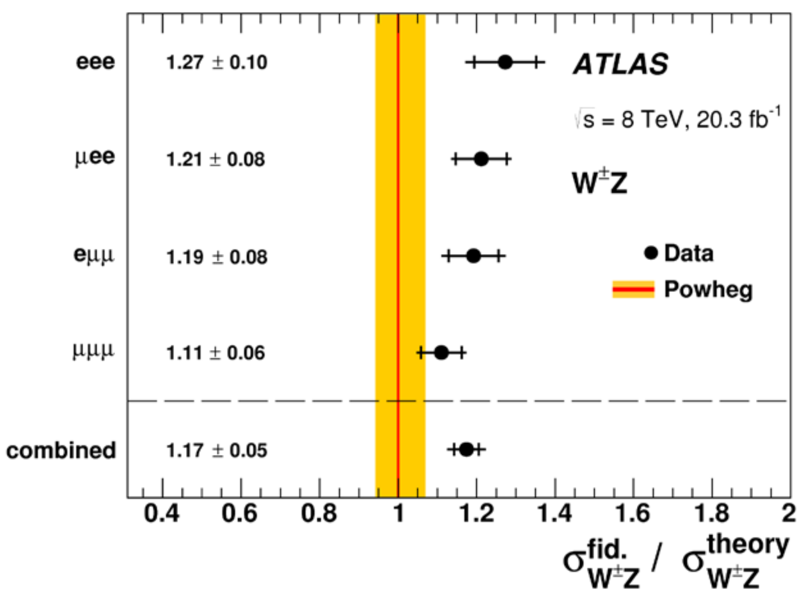
arXiv:1603.02151

WZ Production cross-section

$$\sigma^{\text{fid.}}_{W^{\pm}Z\rightarrow\ell'\nu\ell\ell} = 35.2 \pm 0.9\,(\text{stat.}) \pm 0.8\,(\text{sys.}) \pm 0.8\,(\text{lumi.})\ \text{fb},$$

$$\frac{\sigma^{\text{fid.}}_{W^{+}Z\rightarrow\ell'\nu\ell\ell}}{\sigma^{\text{fid.}}_{W^{-}Z\rightarrow\ell'\nu\ell\ell}} = 1.51 \pm 0.08\,(\text{stat.}) \pm 0.01\,(\text{sys.}) \pm 0.01\,(\text{lumi.})$$

$$\sigma^{\text{tot.}}_{W^{\pm}Z} = 24.3 \pm 0.6\,(\text{stat.}) \pm 0.6\,(\text{sys.}) \pm 0.4\,(\text{th.}) \pm 0.5\,(\text{lumi.})\ \ \text{pb}$$

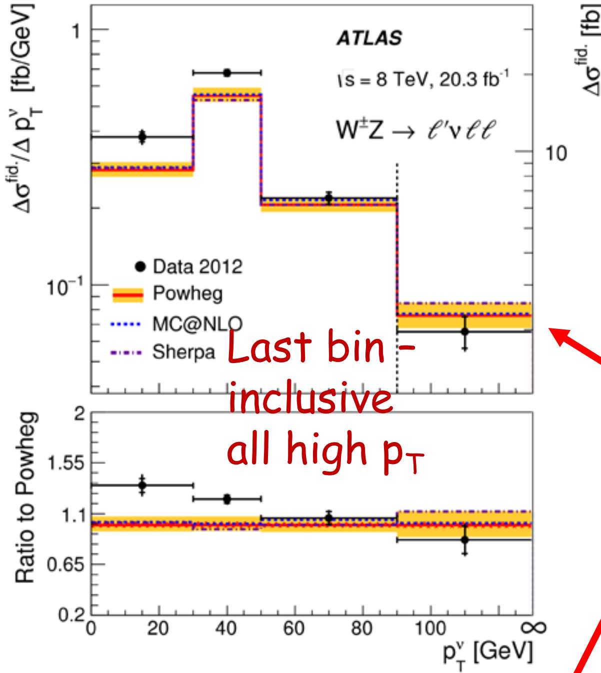


- Results are 20% higher than theory
  - Not covered by systematics
- Situation might improve with NNLO calculations
  - The only diboson channel for which we do not have NNLO predictions

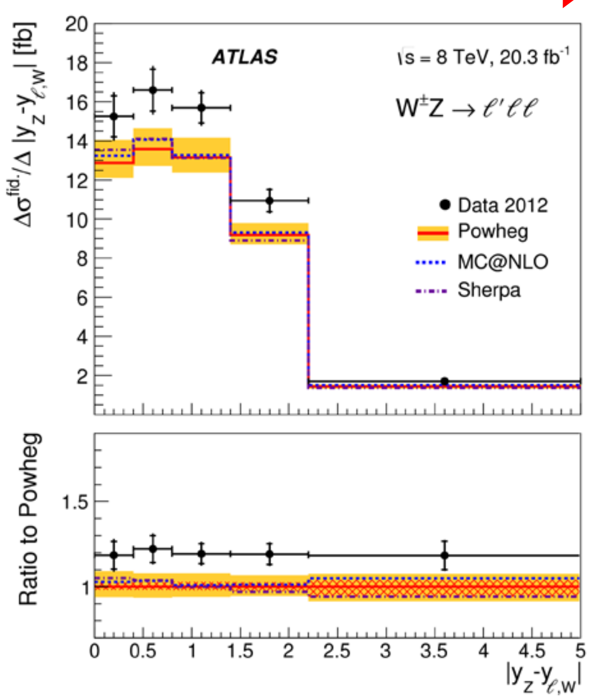
arXiv:1603.02151

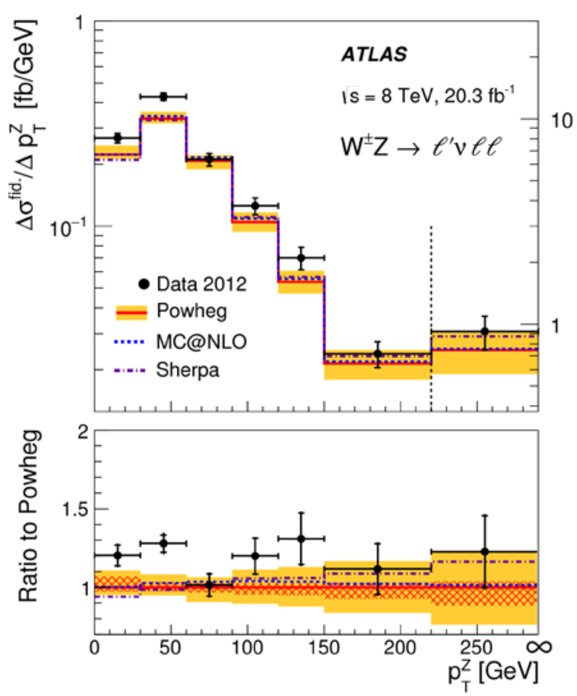
WZ differential x-section

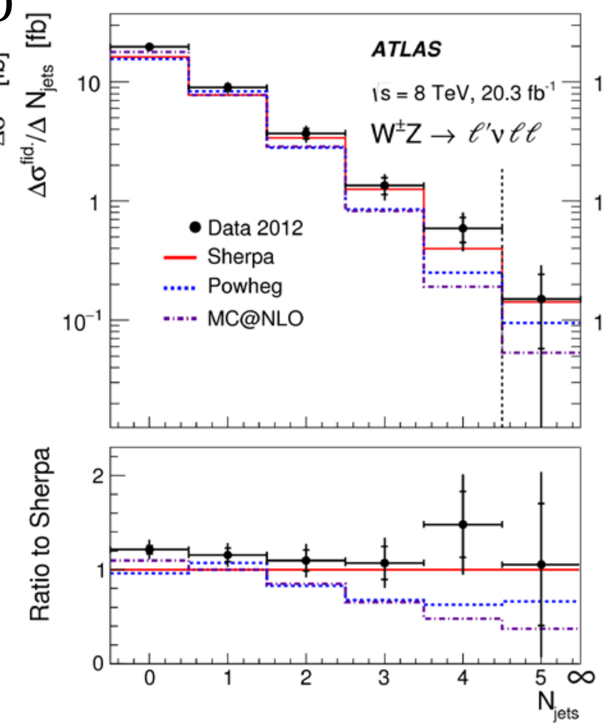
- Various differential cross-sections were measured
  - all decay channels are added together
  - unfolded and divided by 4 (= x-sec for single chan)
- X-sec vs p_T^{ν} – probe very low p_T
- X-sec vs $|y_Z - y_W|$ -first measurement for WZ events
- Fair agreement with LO and NLO is observed
- Might be better with NNLO



Last bin - inclusive all high p_T







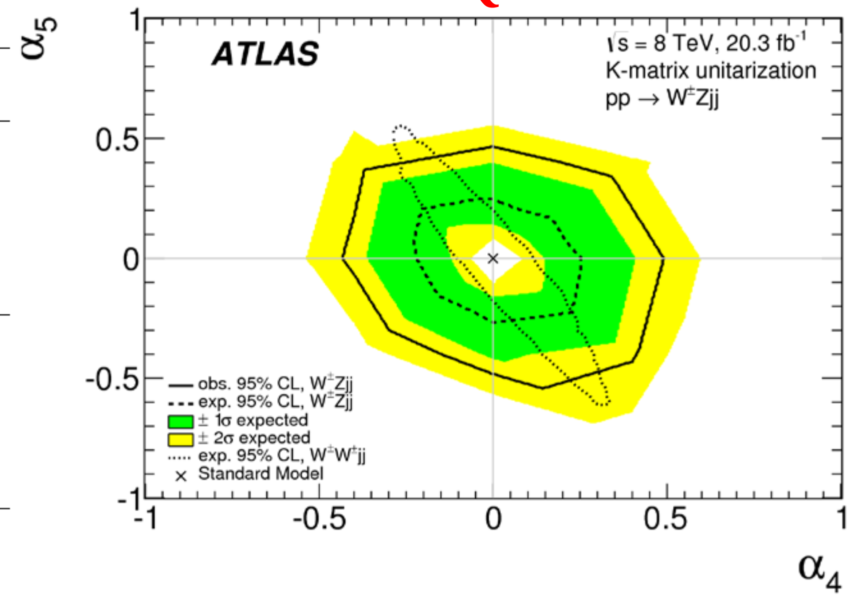
WZ Production – aTGC and aQGC

aTGC

Λ_{co}	Coupling	Expected	Observed
2 TeV	Δg_1^Z	[−0.023 ; 0.055]	[−0.029 ; 0.050]
	$\Delta\kappa^Z$	[−0.22 ; 0.36]	[−0.23 ; 0.46]
	λ^Z	[−0.026 ; 0.026]	[−0.028 ; 0.028]
15 TeV	Δg_1^Z	[−0.016 ; 0.033]	[−0.019 ; 0.029]
	$\Delta\kappa^Z$	[−0.17 ; 0.25]	[−0.19 ; 0.30]
	λ^Z	[−0.016 ; 0.016]	[−0.017 ; 0.017]
∞	Δg_1^Z	[−0.016 ; 0.032]	[−0.019 ; 0.029]
	$\Delta\kappa^Z$	[−0.17 ; 0.25]	[−0.19 ; 0.30]
	λ^Z	[−0.016 ; 0.016]	[−0.016 ; 0.016]

EFT coupling	Expected [TeV^{-2}]	Observed [TeV^{-2}]
c_W/Λ^2	[−3.7 ; 7.6]	[−4.3 ; 6.8]
c_B/Λ^2	[−270 ; 180]	[−320 ; 210]
c_{WWW}/Λ^2	[−3.9 ; 3.8]	[−3.9 ; 4.0]

aQGC

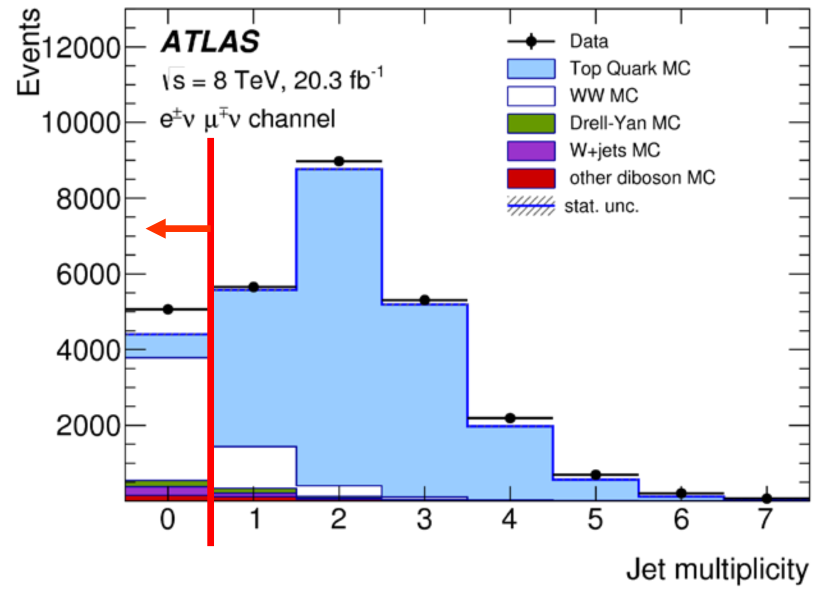


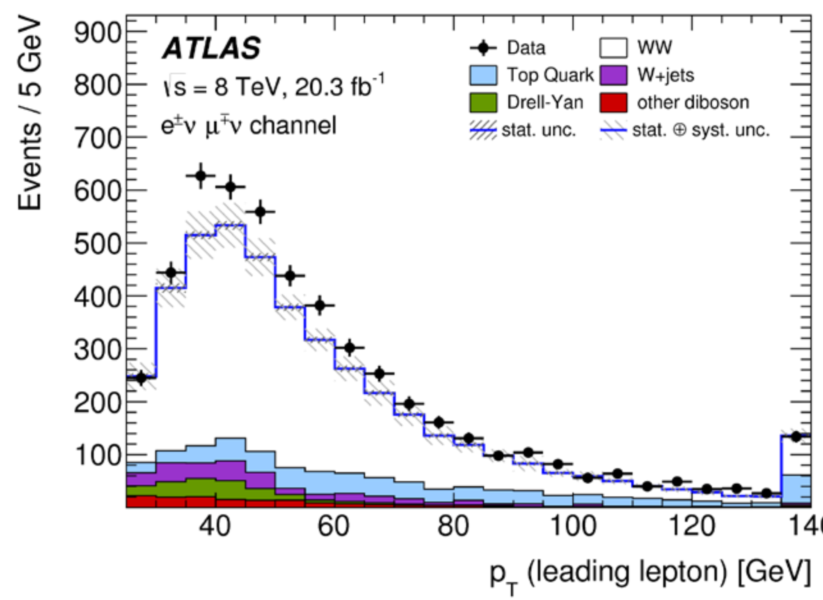
- Limits extracted from m_T^{WZ} distribution
- Calculated for different values of cutoff scale Λ_{co}

$$\alpha(\hat{s}) = \alpha(0)/(1 + \hat{s}/\Lambda_{co}^2)^2$$

$W^{\mp}W^{\pm}$ Production

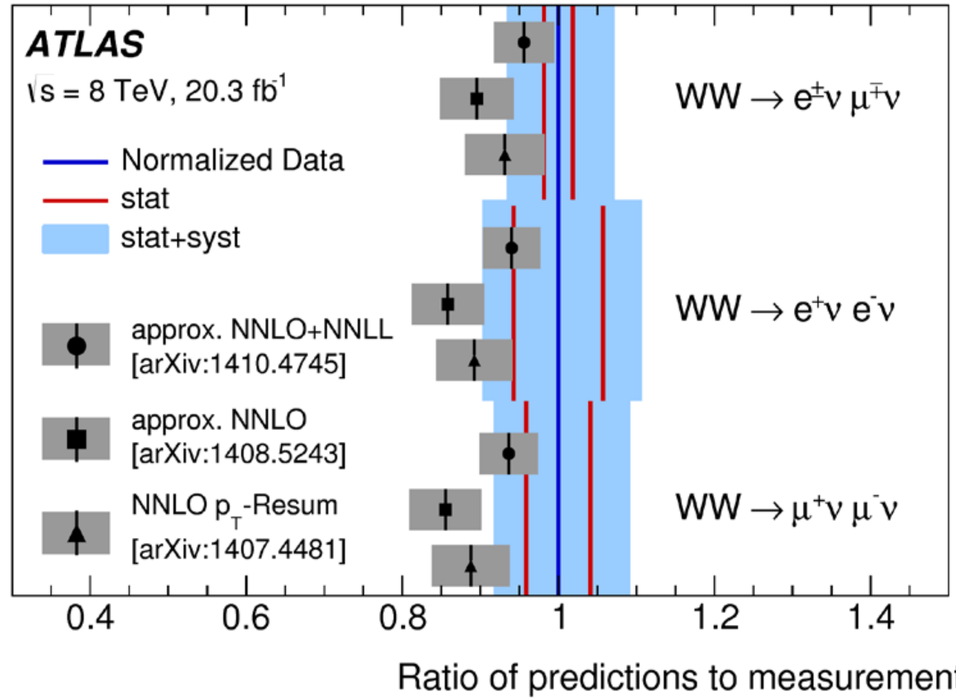
- Final state: lvlv, l = e, mu in 0-jet bin
- Selection:
  - 2 opposite sign leptons
  - Z veto in same flavor channels:
    - $| M_{ll} - M_Z | > 15$ GeV
  - Large E_t^{miss} to further suppress Drell-Yan (~5% of total)
  - Hard Jet Veto to suppress top (~15%)
- Backgrounds
  - Top, Drell-Yan, W+jets, multijets – data driven estimates
  - Diboson (WZ(γ *), ZZ, W/Z+γ) – from MC





$W^{\mp}W^{\pm}$ Production – cross-section

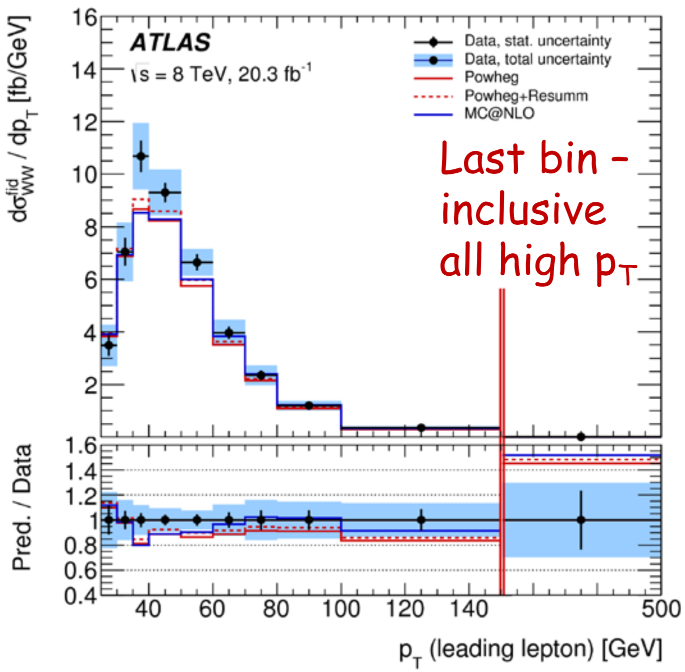
- Measurement is dominated by systematic uncertainties
  - Jet energy scale (4%)
  - Background uncertainty (3%)
  - Jet Veto requirement (3%)
- Measured cross section higher than SM prediction by ~1.5 σ
  - Situation improved with NNLO and NNLL corrections w.r.t. preliminary results from a year ago



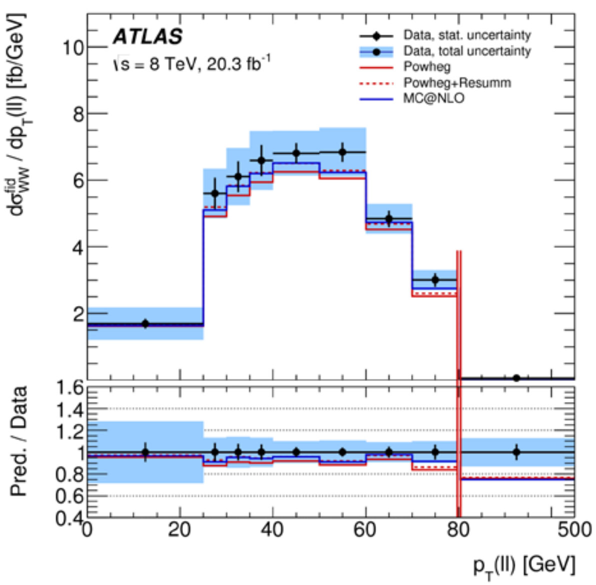
Final state	Total Cross section $pp \rightarrow WW$ [pb]
$e\mu$	$70.5^{+1.3}_{-1.3}(\text{stat})\ ^{+5.8}_{-5.1}(\text{syst})\ ^{+2.1}_{-2.0}(\text{lumi})$
ee	$73.5^{+4.2}_{-4.1}(\text{stat})\ ^{+7.5}_{-6.4}(\text{syst})\ ^{+2.3}_{-2.1}(\text{lumi})$
$\mu\mu$	$73.9^{+3.0}_{-3.0}(\text{stat})\ ^{+7.1}_{-5.9}(\text{syst})\ ^{+2.2}_{-2.1}(\text{lumi})$
combined	$71.0^{+1.1}_{-1.1}(\text{stat})\ ^{+5.7}_{-5.0}(\text{syst})\ ^{+2.1}_{-2.0}(\text{lumi})$
NNLO theory prediction	$63.2^{+1.6}_{-1.4}(\text{scale})\pm 1.2(\text{PDF})$

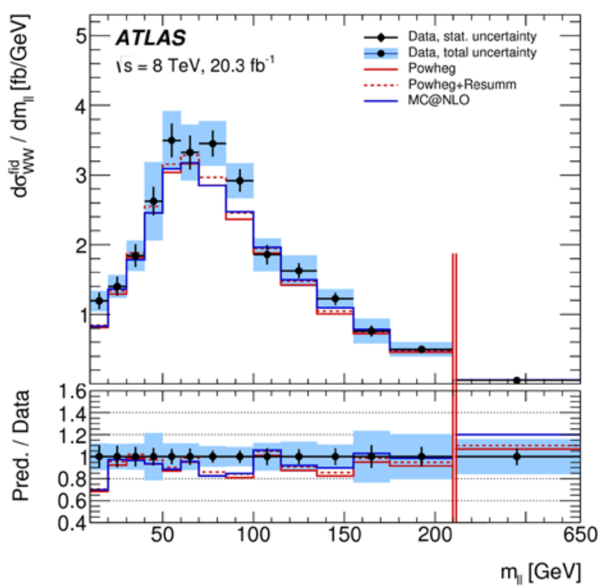
arXiv:1603.01702

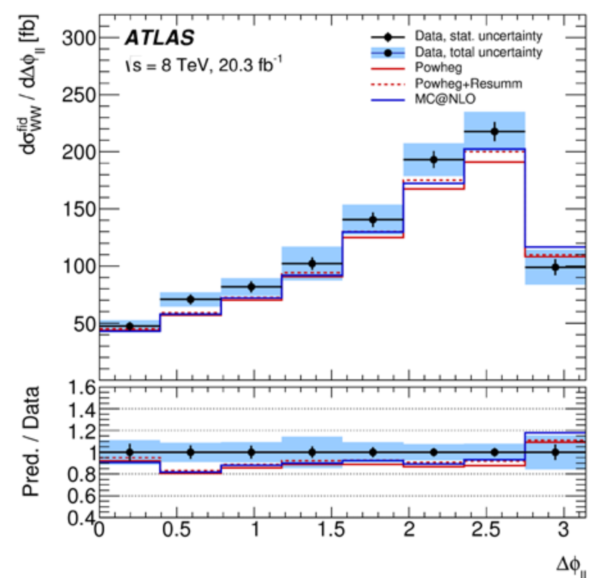
$W^{\mp}W^{\pm}$ diff. X-section



- Various differential cross section predictions generally agree with data
  - All MCs are normalized to NNLO prediction for cross section
- All differences are accounted for in aTGC limits settings







arXiv:1603.01702

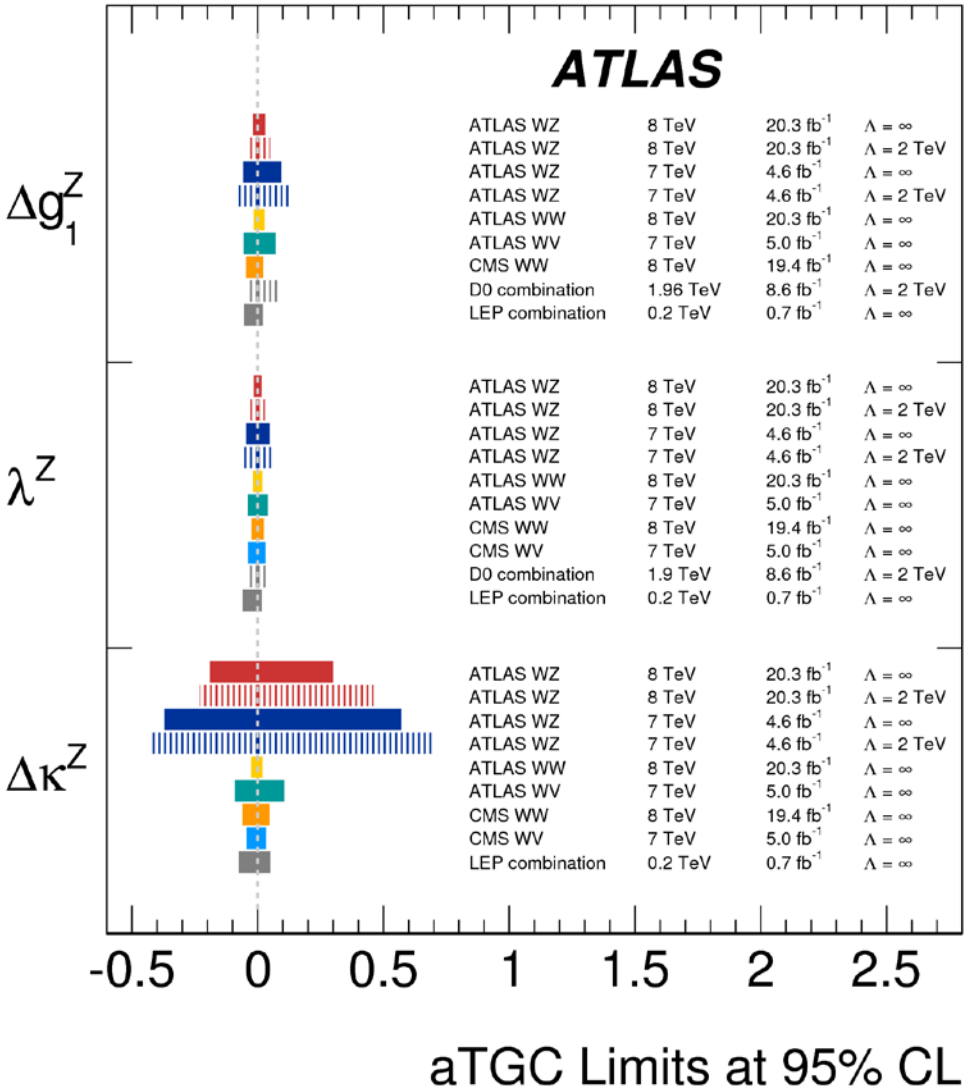
$W^{\mp}W^{\pm}$ Production – aTGC

Scenario	Parameter	Expected $\Lambda = \infty$	Observed $\Lambda = \infty$	Expected Λ = 7 TeV	Observed Λ = 7 TeV
No constraints scenario	Δg_1^Z	[-0.498,0.524]	[-0.215,0.267]	[-0.519,0.563]	[-0.226,0.279]
	Δk^Z	[-0.053,0.059]	[-0.027,0.042]	[-0.057,0.064]	[-0.028,0.045]
	λ^Z	[-0.039,0.038]	[-0.024,0.024]	[-0.043,0.042]	[-0.026,0.025]
	Δk^γ	[-0.109,0.124]	[-0.054,0.092]	[-0.118,0.136]	[-0.057,0.099]
	λ^γ	[-0.081,0.082]	[-0.051,0.052]	[-0.088,0.089]	[-0.055,0.055]
LEP	Δg_1^Z	[-0.033,0.037]	[-0.016,0.027]	[-0.035,0.041]	[-0.017,0.029]
	Δk^Z	[-0.037,0.035]	[-0.025,0.020]	[-0.041,0.038]	[-0.027,0.021]
	λ^Z	[-0.031,0.031]	[-0.019,0.019]	[-0.033,0.033]	[-0.020,0.020]
HISZ	Δk^Z	[-0.026,0.030]	[-0.012,0.022]	[-0.028,0.033]	[-0.013,0.024]
	λ^Z	[-0.031,0.031]	[-0.019,0.019]	[-0.033,0.034]	[-0.020,0.020]
Equal Couplings	Δk^Z	[-0.041,0.048]	[-0.020,0.035]	[-0.045,0.052]	[-0.021,0.037]
	λ^Z	[-0.030,0.030]	[-0.019,0.019]	[-0.034,0.033]	[-0.020,0.020]

Scenario	Parameter	Expected	Observed
EFT	C_{WWW}/Λ^2	[-7.62,7.38]	[-4.61,4.60]
	C_B/Λ^2	[-35.8,38.4]	[-20.9,26.3]
	C_W/Λ^2	[-12.58,14.32]	[-5.87,10.54]

- Limits extracted from p_T (leading lepton) distr. of eμ final state
- Many different scenarios considered !

aTGC limits summary



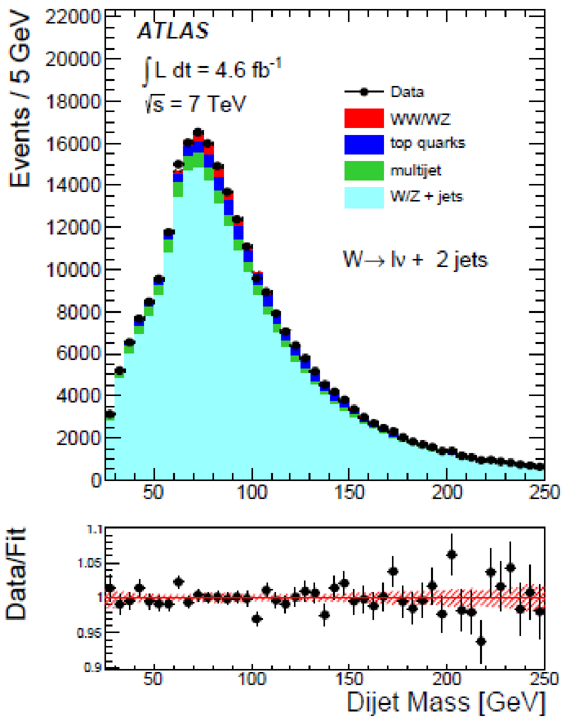
- Limits at 8 TeV are 1.5-2.5 times better than at 7 TeV
- Measurements of WW and WZ diboson production provide complementary results
- Combined together give the most stringent limits on WWZ couplings

Other RUN1 results

JHEP 1501 (2015) 049

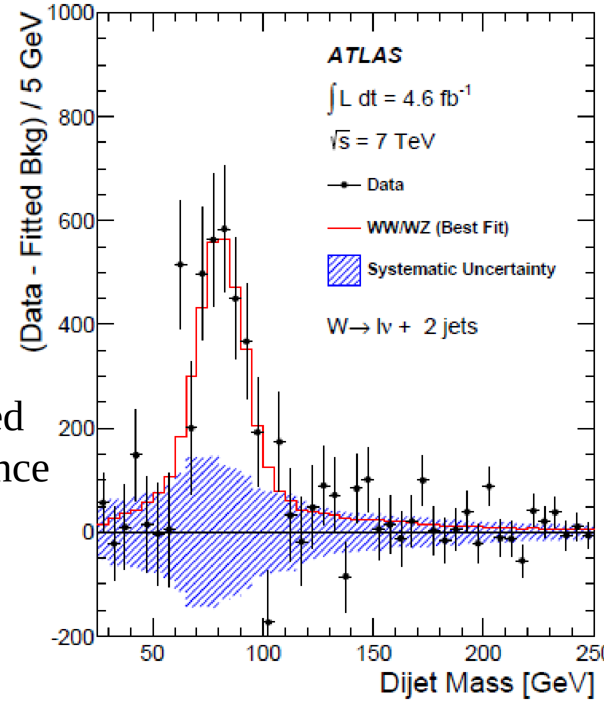
WW/WZ Semileptonic Production (7TeV)

- Final state: (W→) lν (W/Z →) jj, l = e, mu
- Selection:
  - Exactly one lepton
  - Two jets with |ΔR| > 0.7 if $p_T(jj) < 250$ GeV, |Δη| < 1.5, and $25 < m_{jj} < 250$ GeV
  - $E_T^{miss} > 30$ GeV, $m_T^W > 40$ GeV, | Δφ(leading jet E_T,E_T^{miss}) | > 0.8



- Backgrounds:
  - W+jets (~85%),Z+jets (~4%), Multijet (~4%), Top (~5%)

Observed Significance 3.4σ



$$\sigma_{\text{fid}} = 1.37 \pm 0.14\ (\text{stat.}) \pm 0.37\ (\text{syst.})\ \text{pb}$$

$$\sigma_{\text{tot}} = 68 \pm 7\ (\text{stat.}) \pm 19\ (\text{syst.})\ \text{pb}\,,$$

MC@NLO prediction: 61.1±2.2 pb

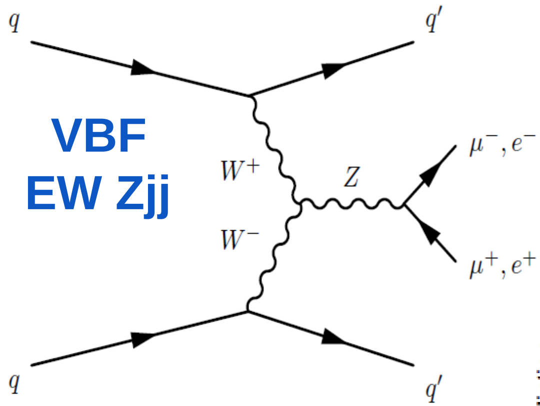
NNLO prediction ~ 4% higher

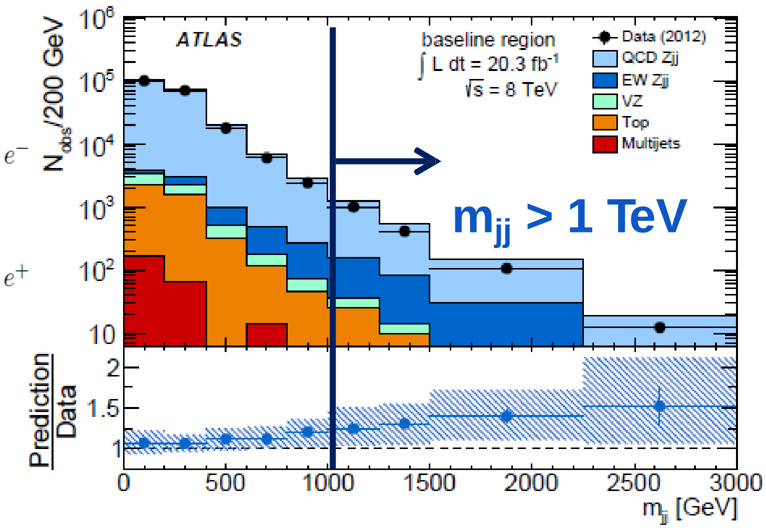
JHEP 1404 (2014) 031

Vector Boson Fusion Production of Zjj

- Final state: $(Z \rightarrow)\ l^+l^-\ jj$
- Signature:
  - Two leptons with $m(ll)$ consistent with m_Z
  - Two high p_T jets
  - Search region:
    - $p_T(ll) > 20$ GeV
    - $m_{jj} > 250$ GeV, $p_T^{balance} < 0.15$
    - No jets in rapidity gap between the two high p_T jets

VBF
EW Zjj





- Fiducial cross sections measured in several regions, including a search region with $m_{jj} > 1$ TeV to obtain high sensitivity to EW production of Zjj (35% of events)
  - Reject background only hypothesis at $> 5\sigma$

$$\sigma_{\mathrm{EW}}\,(m_{jj} > 1\ \mathrm{TeV}) = 10.7 \pm 0.9\,(\mathrm{stat}) \pm 1.9\,(\mathrm{syst}) \pm 0.3\,(\mathrm{lumi})\ \mathrm{fb},$$

$$\text{theoretical prediction} \quad 9.38 \pm 0.05\,(\mathrm{stat})\ ^{+0.15}_{-0.24}\,(\mathrm{scale}) \pm 0.24\,(\mathrm{PDF}) \pm 0.09\,(\mathrm{model})\ \mathrm{fb}.$$

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

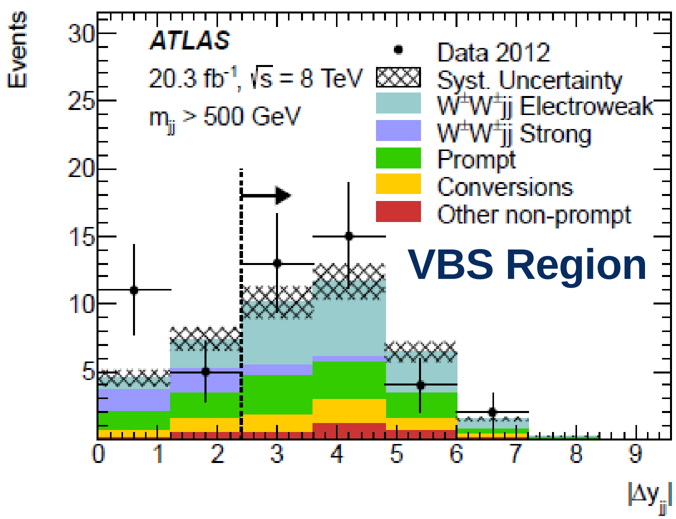
Phys.Rev.Lett. 113 (2014) 141803

Vector boson scattering: $W^{\pm}W^{\pm}jj$

- Final state: $l^{\pm}\nu\ l^{\pm}\nu$ jj
- Selection
  - Two high p_T leptons, ≥2 jets
  - m(ll) > 20 GeV
  - | m(ee) – m_Z | > 10 GeV
  - E_T^{miss} > 40 GeV
  - b-jet veto
  - Inclusive: m(jj) > 500 GeV
  - VBS: $|\Delta y_{jj}|$ > 2.4

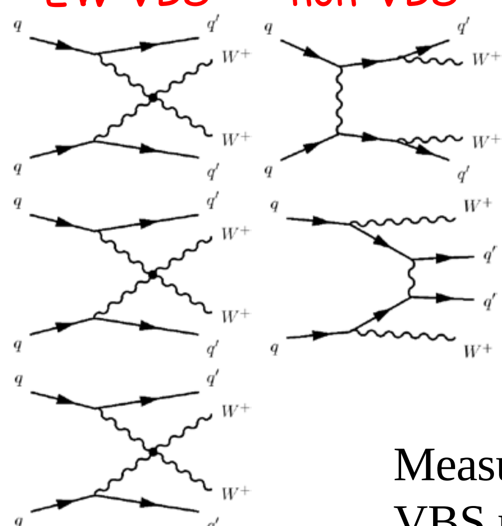
First evidence of VBS WWjj at LHC !

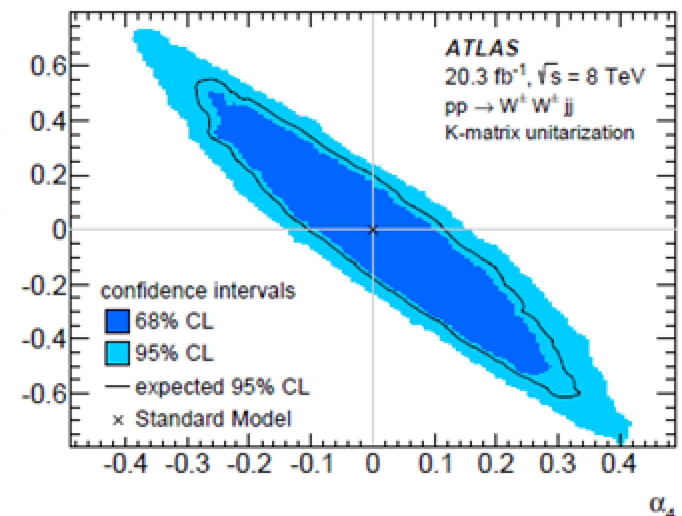
Fiducial Cross section			
Strong and Electroveak W±W±jj	SM prediction	1.52 ± 0.11 fb	
	Observed	2.1 ± 0.5(stat) ± 0.3(syst) fb	
	Significance	observed: 4.5σ	expected: 3.4σ
Electroveak W±W±jj VBS region	SM prediction	0.95 ± 0.06 fb	
	Observed	1.3 ± 0.4(stat) ± 0.2(syst) fb	
	Significance	observed: 3.6σ	expected: 2.8σ



EW VBS

non-VBS



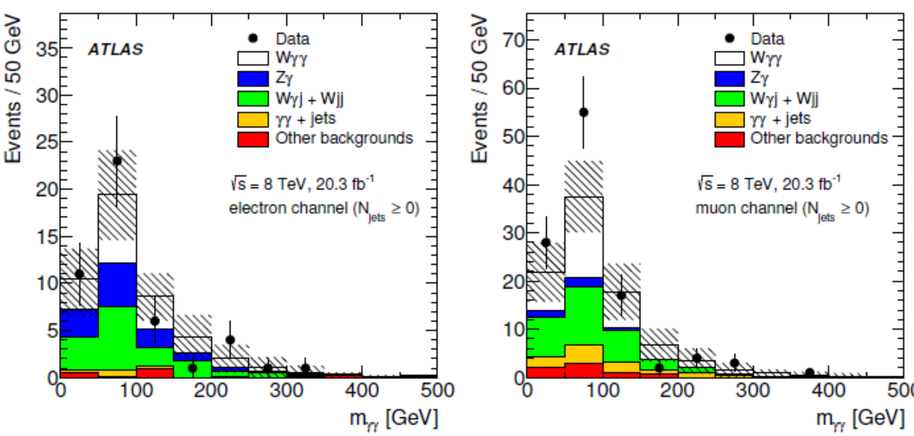


Measured fiducial cross section in VBS region used to set limits on aQGC's

Phys. Rev. Lett. 115, 031802 (2015)

$W\gamma\gamma$ Production

- Final state $(W\rightarrow)l\nu\ \gamma\gamma$
- Selection:
  - Lepton/photon $p_T > 20$ GeV
  - $E_T^{miss} > 25$ GeV
  - $m_T > 40$ GeV
  - Restrictions on $e\gamma\gamma$ system to reduce electron mis-id. (mainly from $Z\gamma$)
- Backgrounds:
  - Data driven estimates for photon fakes ($W\gamma j+Wjj$) and lepton fakes ($\gamma\gamma$+jets)



First evidence of triboson production !

Fiducial Cross section		
Inclusive ($N_{jet} \geq 0$)	Measured	$6.1\ ^{+1.1}_{-1.0}$(stat) ± 1.2 (syst) ± 0.2(lumi.) fb Significance >**3σ**
	MCFM	2.90 ± 0.16 fb
Exclusive ($N_{jet} = 0$)	Measured	$2.9\ ^{+0.8}_{-0.7}$(stat) $^{+1.0}_{-0.9}$(syst) ± 0.1(lumi.) fb
	MCFM	1.88 ± 0.20 fb

Big data/MCFM discrepancy in inclusive
Maybe NNLO will be closer to data ?

		Observed [TeV^{-4}]	Expected [TeV^{-4}]
$n=0$	f_{T0}/Λ^4	$[-0.9, 0.9]\times 10^2$	$[-1.2, 1.2]\times 10^2$
	f_{M2}/Λ^4	$[-0.8, 0.8]\times 10^4$	$[-1.1, 1.1]\times 10^4$
	f_{M3}/Λ^4	$[-1.5, 1.4]\times 10^4$	$[-1.9, 1.8]\times 10^4$
$n=1$	f_{T0}/Λ^4	$[-7.6, 7.3]\times 10^2$	$[-9.6, 9.5]\times 10^2$
	f_{M2}/Λ^4	$[-4.4, 4.6]\times 10^4$	$[-5.7, 5.9]\times 10^4$
	f_{M3}/Λ^4	$[-8.9, 8.0]\times 10^4$	$[-11.0, 10.0]\times 10^4$
$n=2$	f_{T0}/Λ^4	$[-2.7, 2.6]\times 10^3$	$[-3.5, 3.4]\times 10^3$
	f_{M2}/Λ^4	$[-1.3, 1.3]\times 10^5$	$[-1.6, 1.7]\times 10^5$
	f_{M3}/Λ^4	$[-2.9, 2.5]\times 10^5$	$[-3.7, 3.3]\times 10^5$

Exclusive cross section measurement with $m(\gamma\gamma) > 300$ GeV used to extract aQGC limits with different exponents in form factor

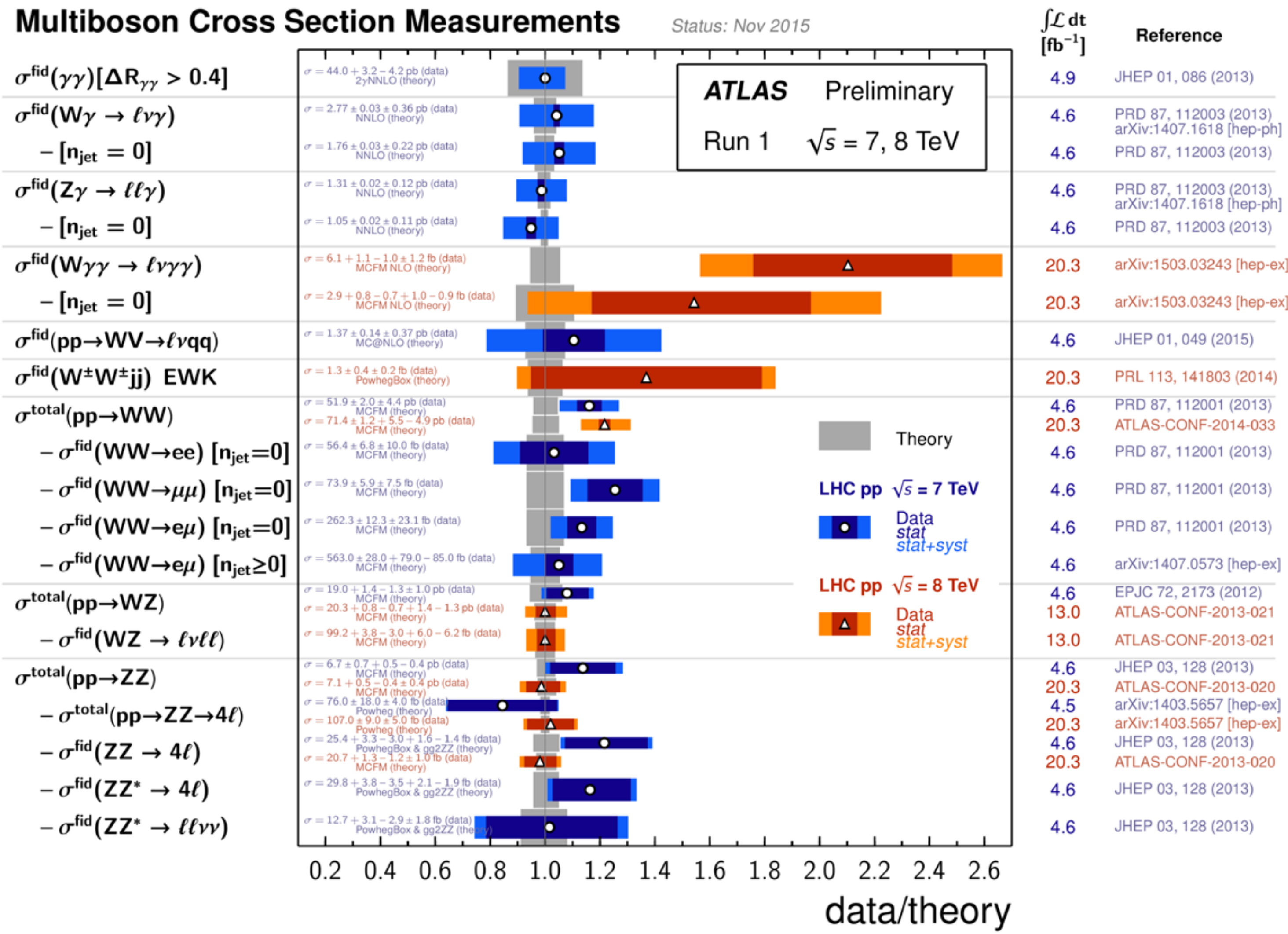
Conclusions

- Fiducial, total and differential cross-section measurements for diboson processes at ATLAS allow precision comparisons to state-of-the-art theory predictions
- In some cases have reached sensitivity to NNLO corrections!
- 8 TeV LHC data for the first time gives us evidence for vector boson scattering
- Also seeing evidence for tri-boson production!
- RUN1 data allow to set competitive limits on aTGCs and aQGCs
- Measurements with different final states give complementary results

- Measurements at 8 TeV are almost finished
- Analysis of 13 TeV data has been started, first results already available, a lot of new interesting results expected

BACKUP

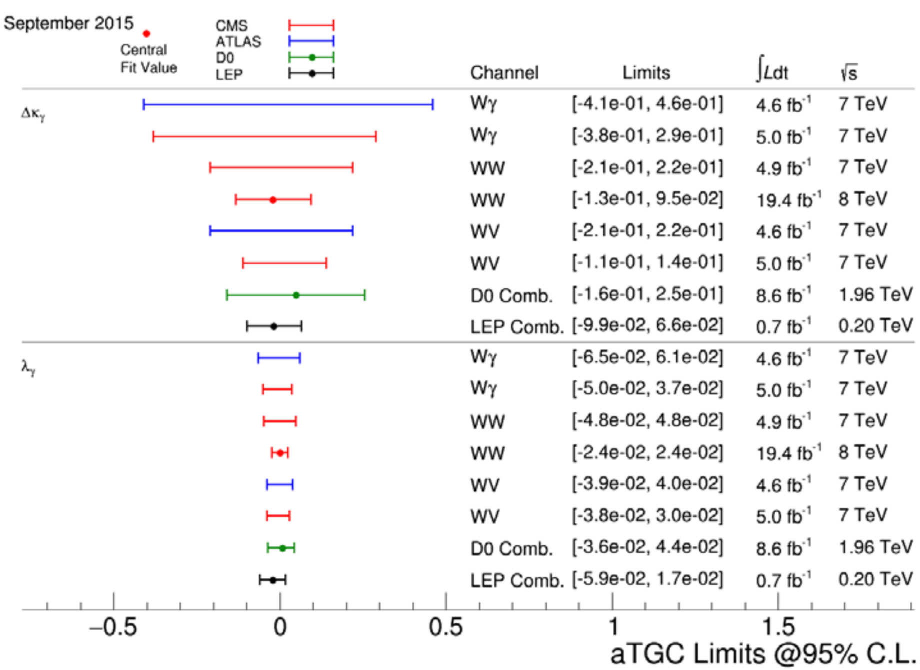
Summary of Diboson measurements in RUN1 (recent results missing)



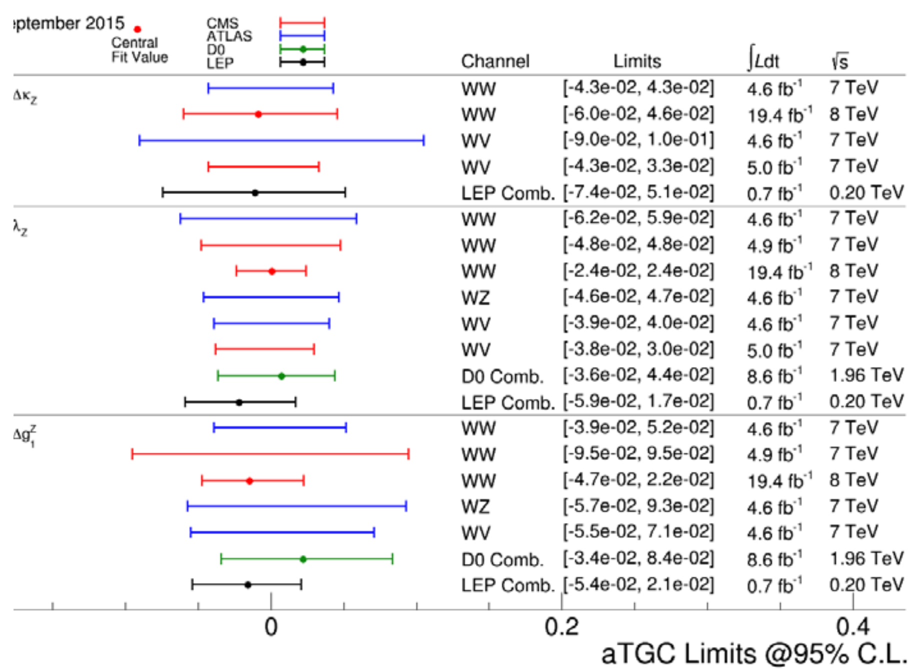
Summary of charged aTGC limits (recent results missing)

- No deviation from SM observed

Charged aTGC WWγ



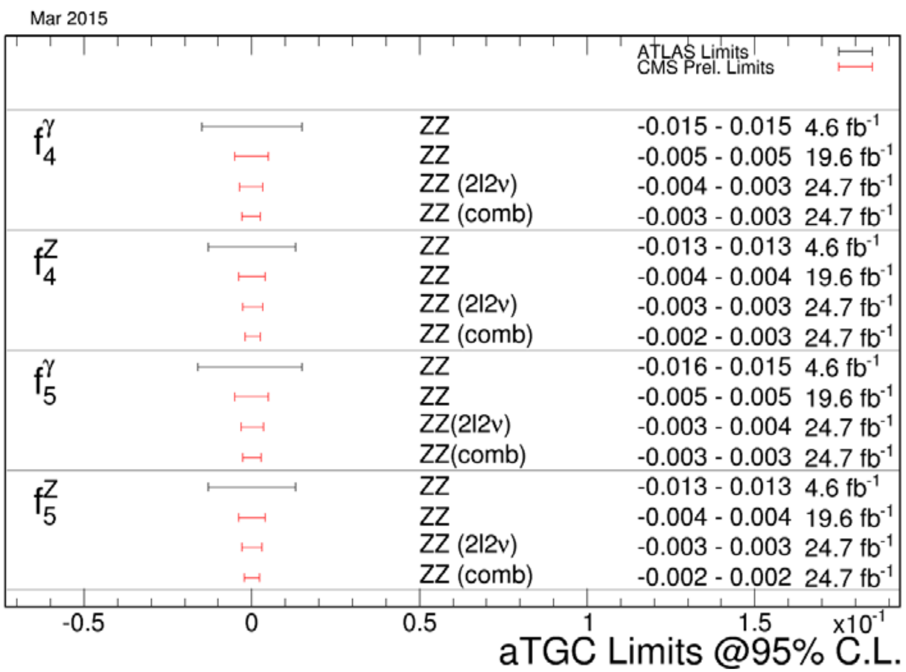
Charged aTGC WWZ



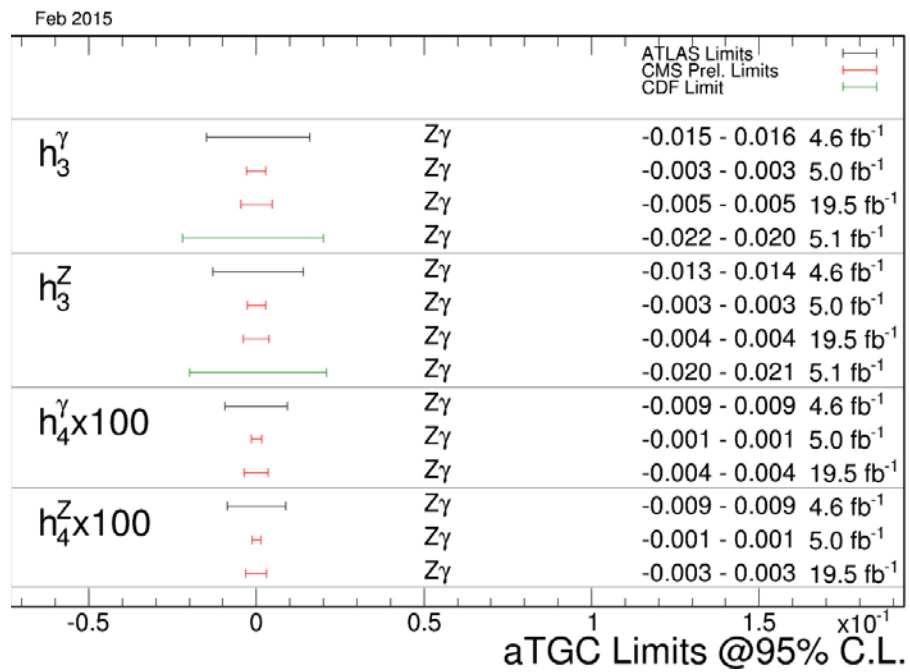
Summary of neutral aTGC limits (recent results missing)

- No deviation from SM observed

Neutral aTGC $Z\gamma Z$, ZZZ

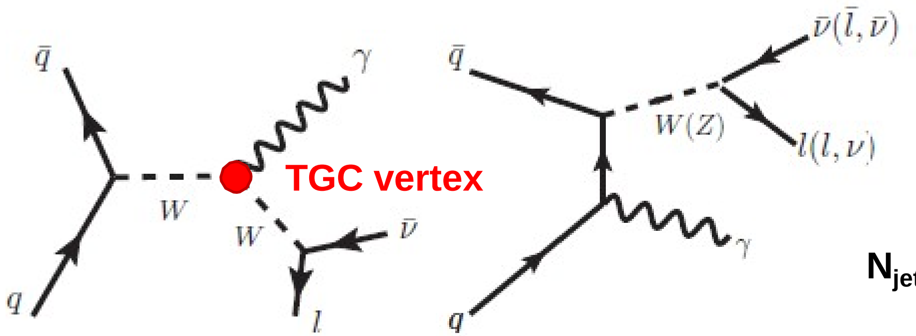


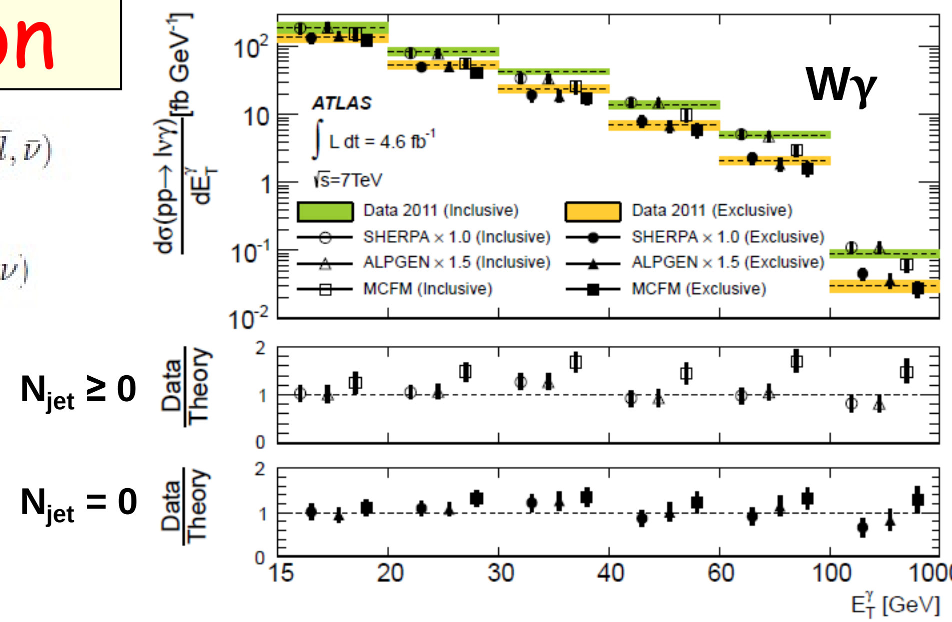
Neutral aTGC $ZZ\gamma$, $Z\,\gamma\,\gamma$



Phys. Rev. D 87, 112003

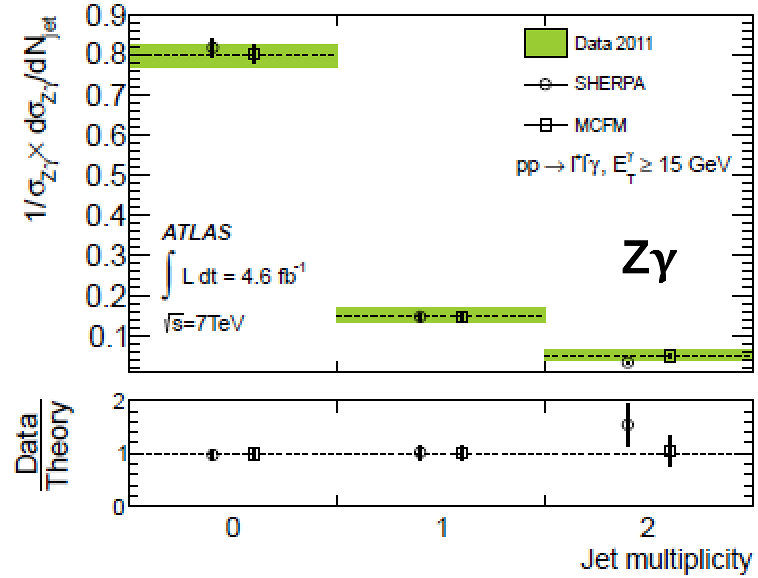
Wγ / Zγ Production





Selection Highlights

(W→) lν γ	(Z→) ll γ	(Z→) νν γ
p_T^{lep} > 25 GeV, E_T^γ > 15 GeV		E_T^γ > 100 GeV
E_T^{miss} > 35 GeV	-	E_T^{miss} > 90 GeV
m_T > 40 GeV	M(ll) > 40 GeV	-
p_T^{jet} > 30 GeV		



- Differential cross section measurements in photon E_T (top) and jet multiplicity (bottom).
  - Exclusive: $N_{jet} = 0$, Inclusive: $N_{jet} \geq 0$

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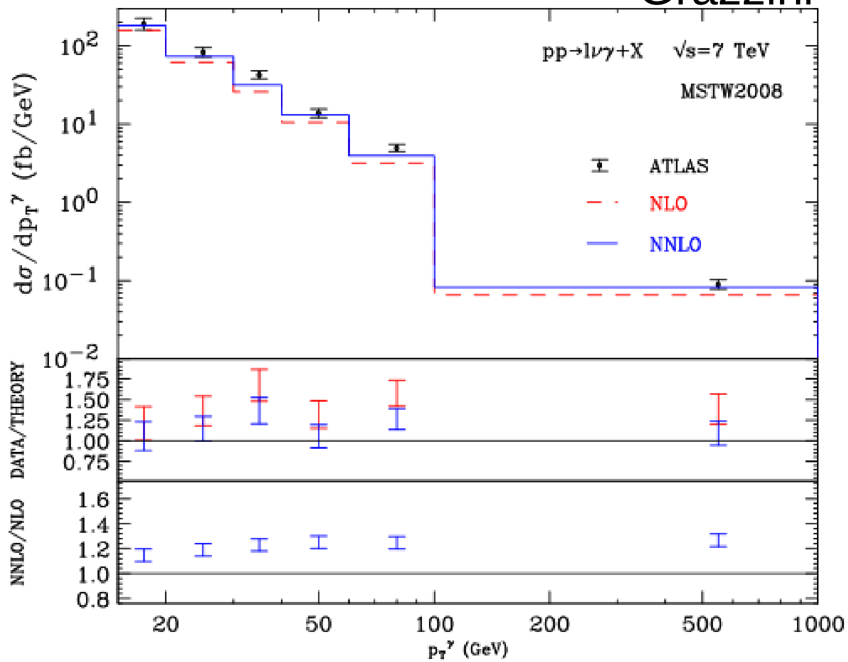
Wγ / Zγ Production – NNLO calculations

- NNLO calculation (arXiv:1407.1618)
  - Large radiative corrections for Wγ
  - 19% correction for Wγ
  - 6% increase for Zγ
- Agreement with data is improved
- Fiducial cross section with NLO and NNLO calculations below

Grazzini

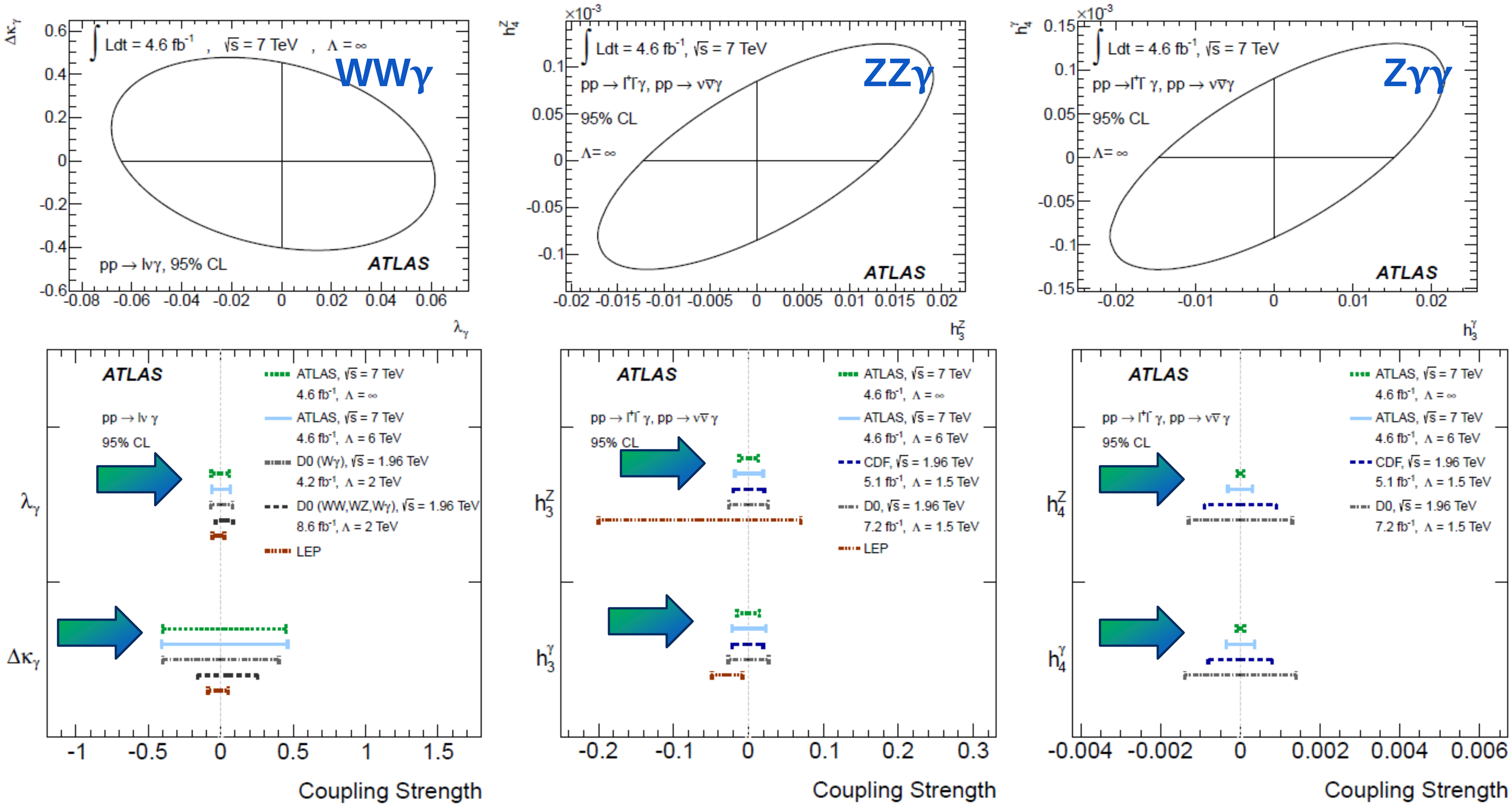


Process	NLO (fb)	NNLO (fb)	Measurement (fb)
Wγ	2065.2 ± 0.9	2456 ± 6	2770 ± 30(stat) ± 330(syst) ± 140(lumi)
Zγ	1226.2 ± 0.4	1305 ± 3	1310 ± 20(stat) ± 110(syst) ± 50(lumi)

Phys. Rev. D 87, 112003

Wγ / Zγ Production - aTGC

- Limits on anomalous couplings from fiducial measurement with $E_T^{\gamma} > 100$ GeV



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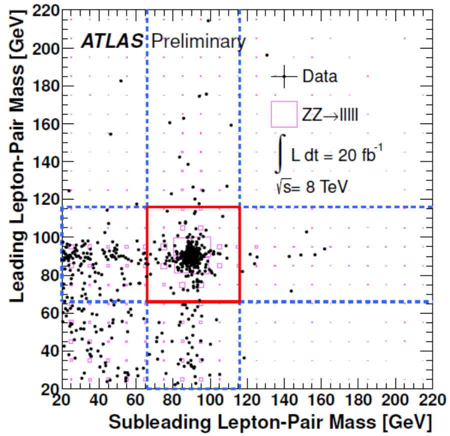
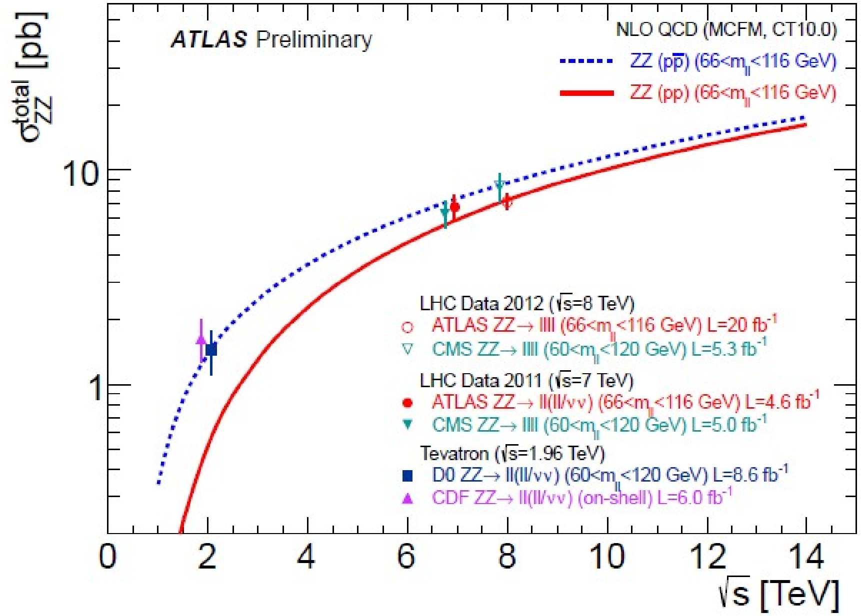
ZZ Production

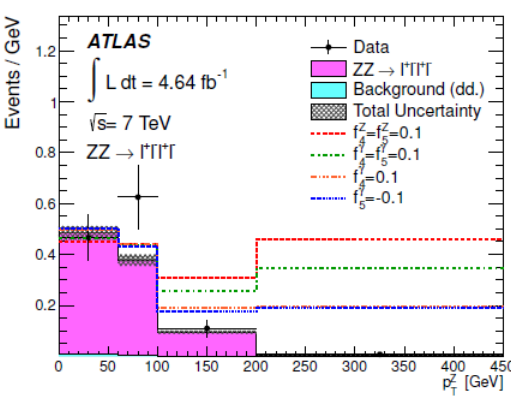
- Final state: ZZ→l^+l^- l^+l^- and ZZ→l^+l^- νν
- Selection:
  - Opposite sign lepton pair(s) with M(ll) within Z mass window
  - For l+l- νν: jet veto

  axial-E_T^{miss} > 75 GeV

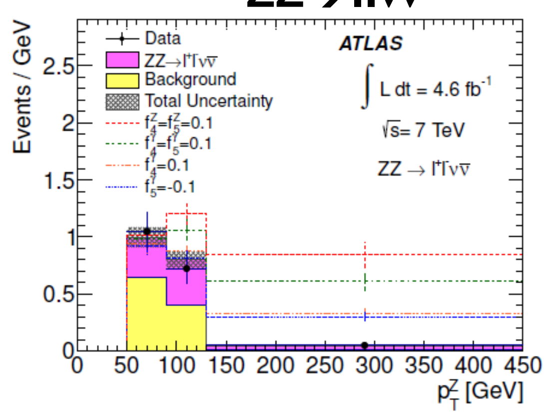


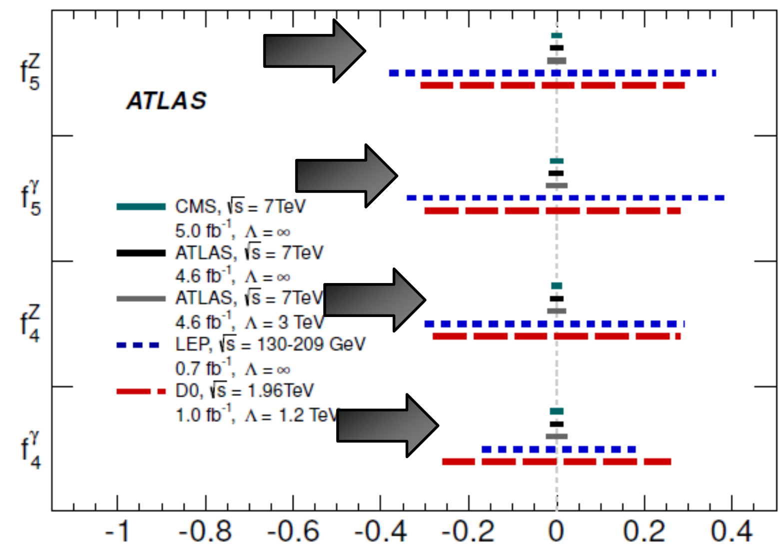


ZZ→llll



ZZ→llνν

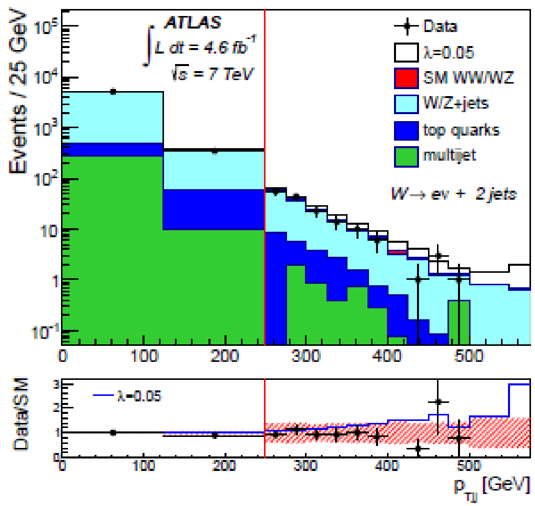




JHEP 1501 (2015) 049

WW/WZ Semileptonic (7TeV) - aTGC

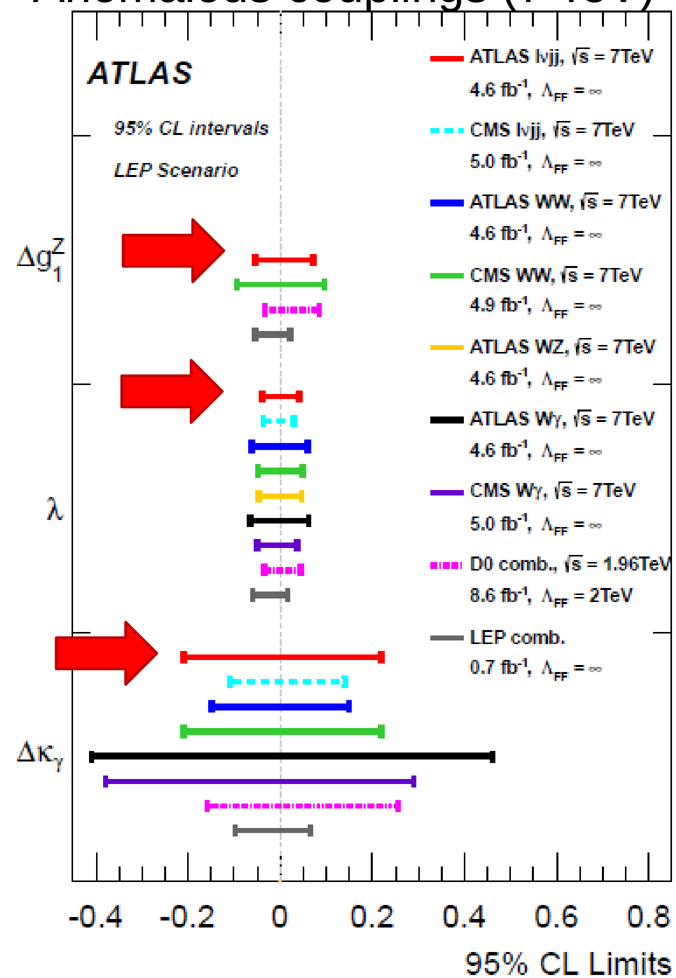
- $p_T(jj)$ used to extract limits on parameters in anomalous couplings framework and Effective Field Theory



EFT limits have been calculated (first at LHC!)

Parameter	Observed Limit
c_{WWW}/Λ^2	$[-9.5, 9.6]\ \mathrm{TeV}^{-2}$
c_B/Λ^2	$[-64, 69]\ \mathrm{TeV}^{-2}$
c_W/Λ^2	$[-13, 18]\ \mathrm{TeV}^{-2}$

Anomalous couplings (7 TeV)

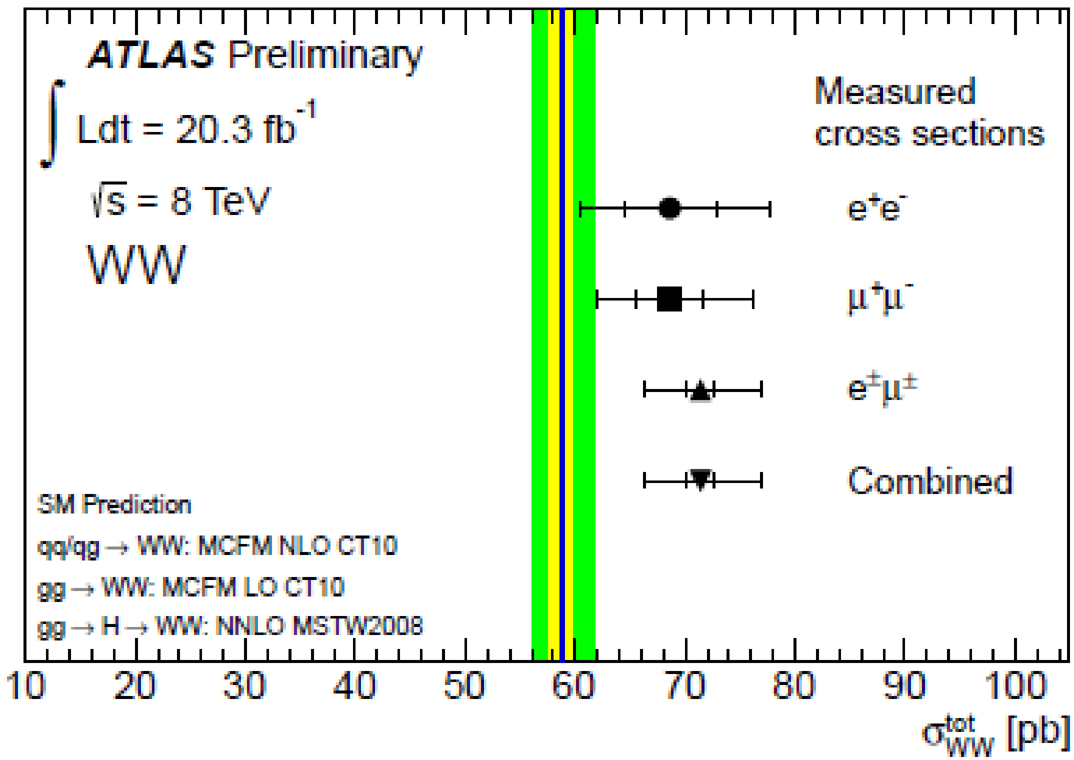


8 TeV WW/WZ paper in preparation

Phys.Rev. D87 (2013) 112001

$W^{\mp}W^{\pm}$ Production (older result)

- Previois results (NLO only)
  bigger disagreement with data



NNLO prediction for WW: 63.2 pb (+7%) (arxiv:1408.5243)