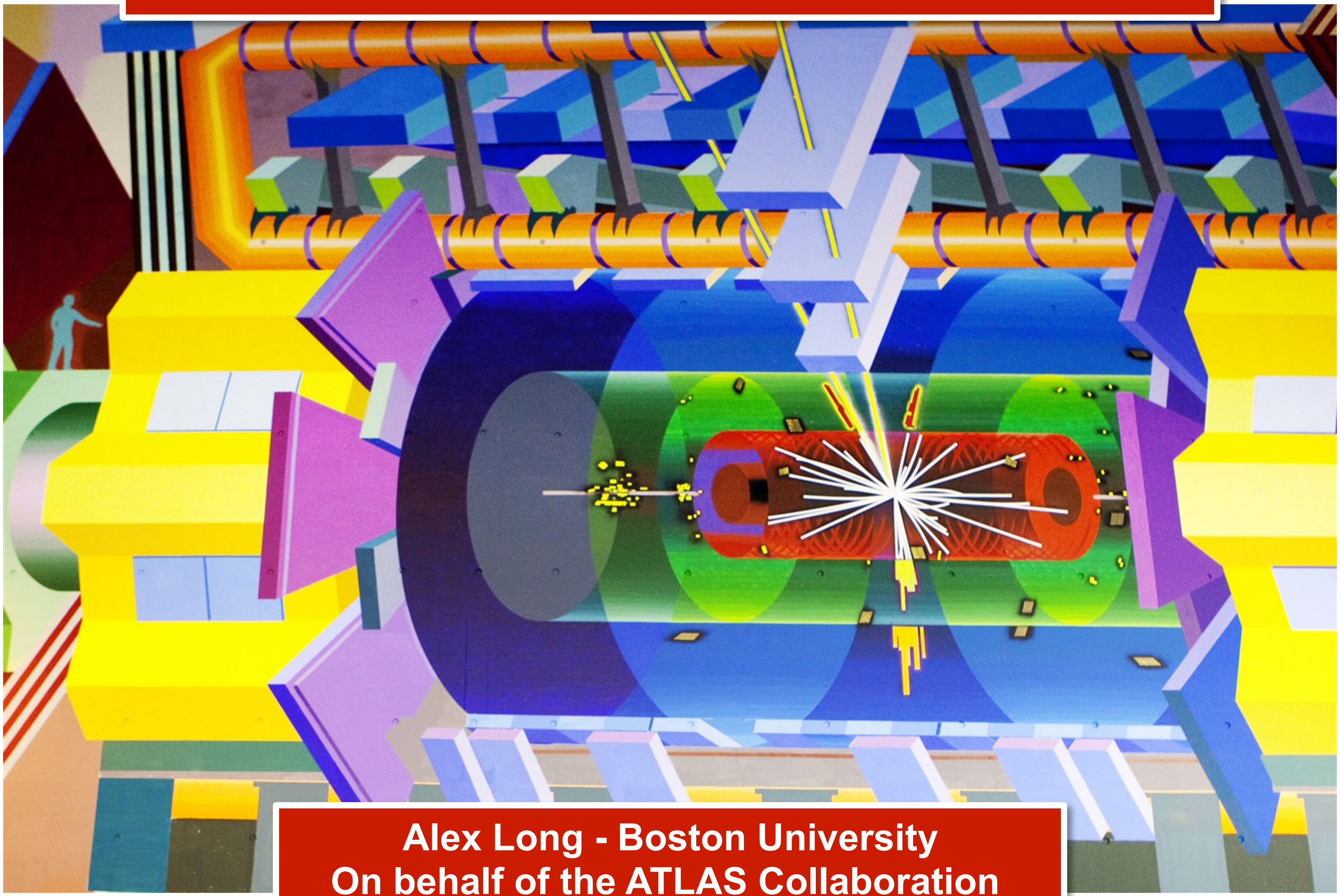
Recent Electroweak Results from ATLAS



Alex Long - Boston University
On behalf of the ATLAS Collaboration

Lake Louise Winter Institute
7th - 13th February 2016

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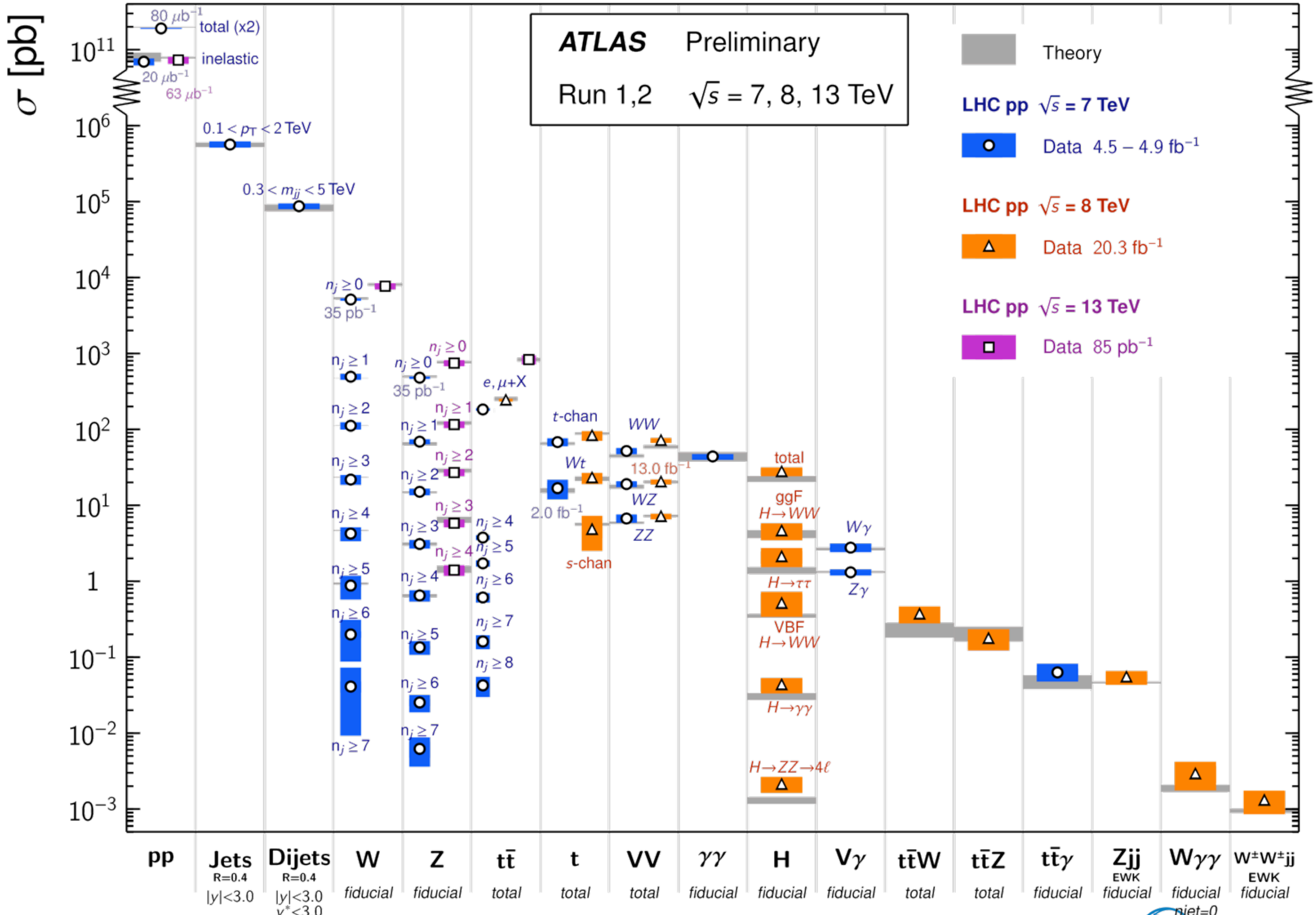
ATLAS EXPERIMENT

Standard Model Production Cross Section Measurements

Status: Nov 2015



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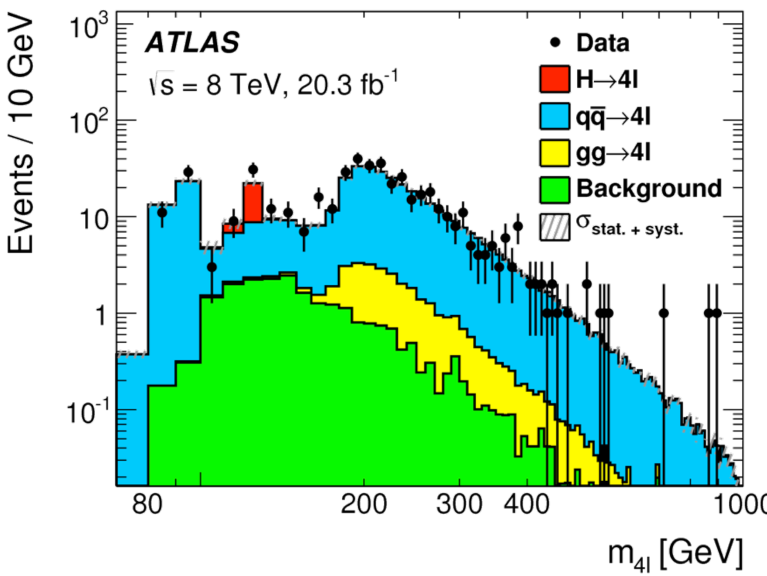
ATLAS EXPERIMENT

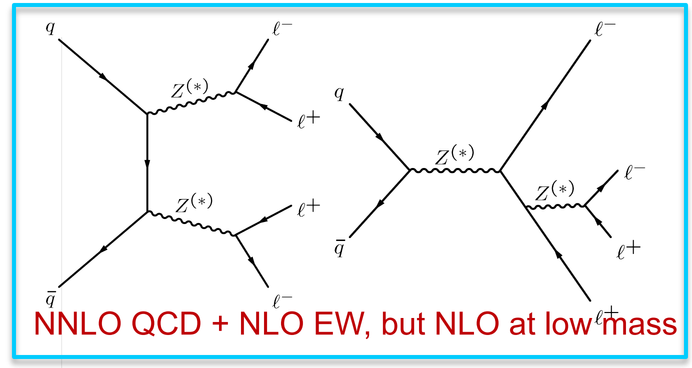
Inclusive 4l Production - 8 TeV

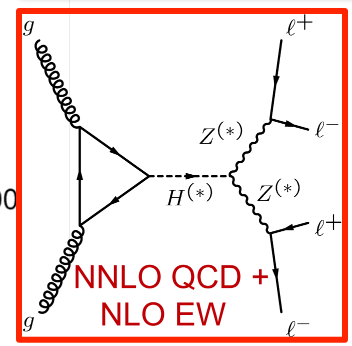
PLB 753 (2016) 552-572

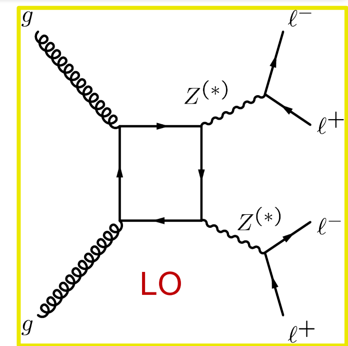
Total cross-section measured in range 0.08 < m(4l) < 1 TeV

Includes Higgs production and interference with non-resonant gluon fusion processes at high mass.







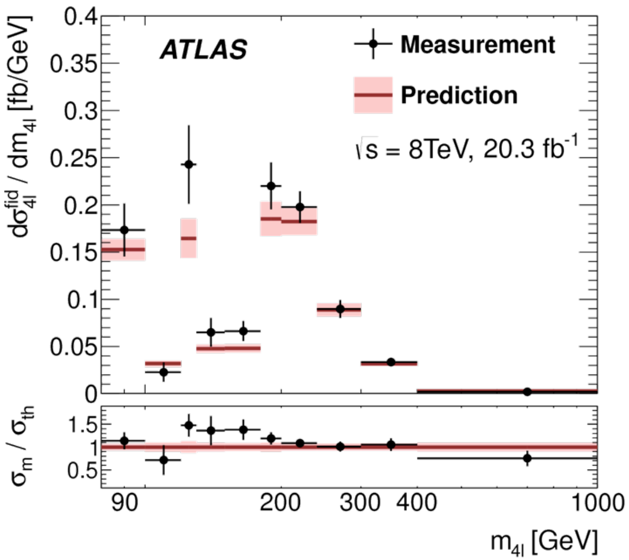


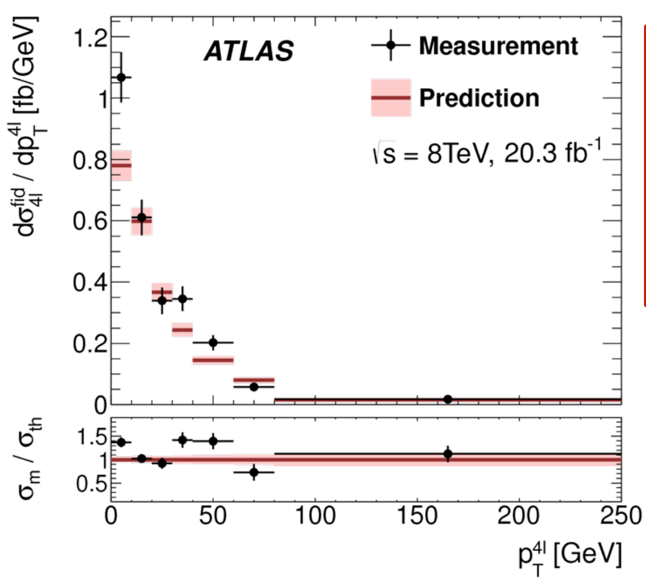
4ℓ	Measured σ^{fid} [fb]	SM σ^{fid} [fb]	Measured σ^{ext} [fb]	SM σ^{ext} [fb]
$4e$	$7.4^{+0.9}_{-0.8}$ (stat) $^{+0.4}_{-0.3}$ (syst) $^{+0.2}_{-0.2}$ (lumi)	6.9 ± 0.4	$17.8^{+2.1}_{-2.0}$ (stat) $^{+1.5}_{-1.1}$ (syst) $^{+0.5}_{-0.5}$ (lumi)	16.4 ± 1.0
4μ	$8.7^{+0.8}_{-0.7}$ (stat) $^{+0.2}_{-0.2}$ (syst) $^{+0.3}_{-0.2}$ (lumi)	8.3 ± 0.5	$17.3^{+1.5}_{-1.4}$ (stat) $^{+0.9}_{-0.7}$ (syst) $^{+0.5}_{-0.5}$ (lumi)	16.4 ± 1.0
$2e2\mu$	$15.9^{+1.1}_{-1.1}$ (stat) $^{+0.5}_{-0.4}$ (syst) $^{+0.5}_{-0.4}$ (lumi)	13.7 ± 0.9	$37.7^{+2.7}_{-2.6}$ (stat) $^{+2.5}_{-2.0}$ (syst) $^{+1.1}_{-1.1}$ (lumi)	32.1 ± 2.0
Total			73^{+4}_{-4} (stat) $^{+4}_{-4}$ (syst) $^{+2}_{-2}$ (lumi)	65 ± 4

Inclusive 4l Production - 8 TeV

PLB 753 (2016) 552-572

Continued

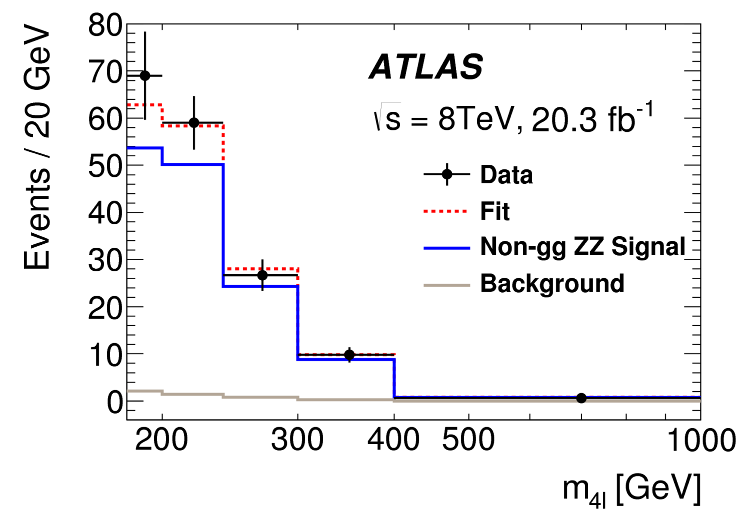




Differential measurements of m(4l) and p_T(4l) are performed after unfolding to particle level.

The gluon-gluon signal strength, μ_{gg}, is measured with respect to the LO prediction using the reconstructed m(4l) distribution from m(4l) > 180 GeV. It is measured to be:

$$\mu_{gg} = 2.4 \pm 1.0\ (\text{Stat.}) \pm 0.5\ (\text{Syst.}) \pm 0.8 (\text{Theory})$$



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Z/γ^* p_T^{ll} and ϕ_η^* - 8 TeV

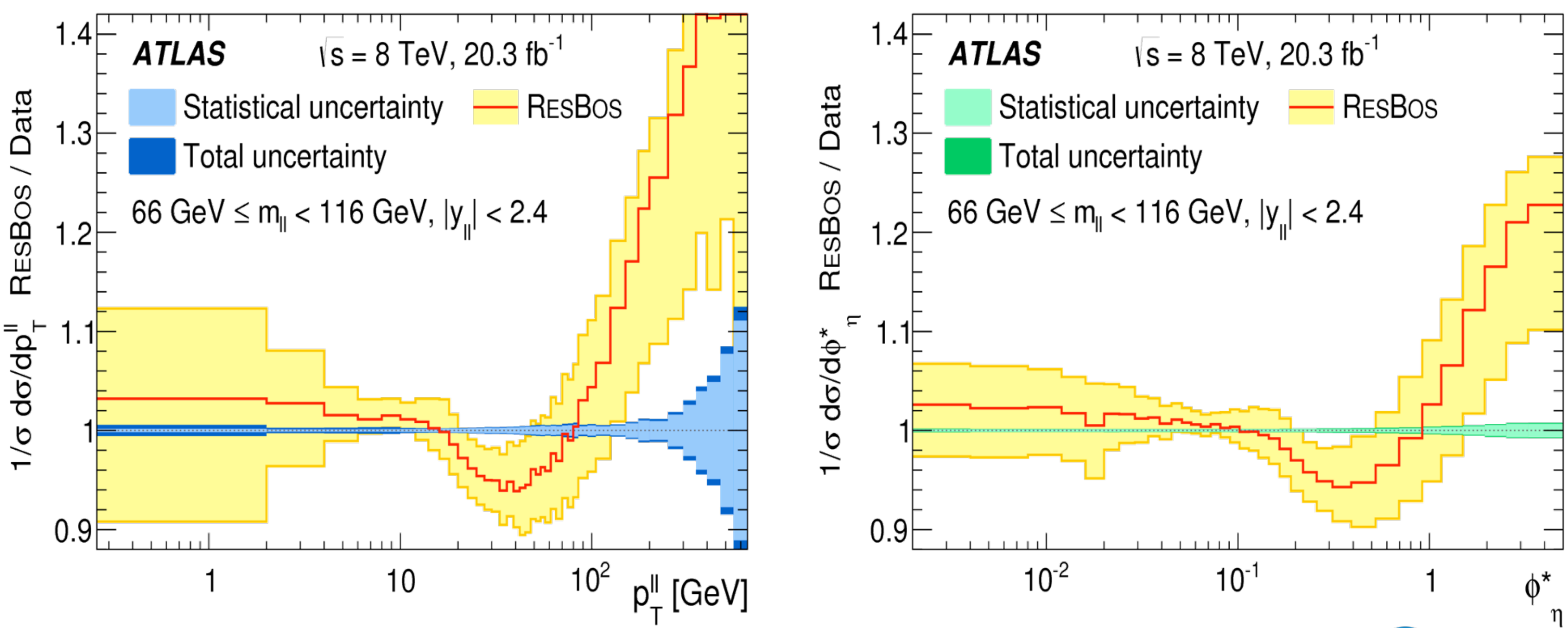
Submitted to EPJC
arXiv:1512.02192

Born-level differential distributions for Drell-Yan processes compared to a variety of generators

ϕ_η^* is a useful proxy to p_T^{ll} with a better precision, in particular at low values.

ResBos comparisons corrected to QCD NNLO

$$\sqrt{2} m_Z \phi_\eta^* \approx p_T^{\ell\ell}$$



$$\phi_\eta^* = \tan\left(\frac{\pi - \Delta\phi}{2}\right) \cdot \sin(\theta_\eta^*), \quad \cos(\theta_\eta^*) = \tanh\left(\frac{\eta^- - \eta^+}{2}\right)$$

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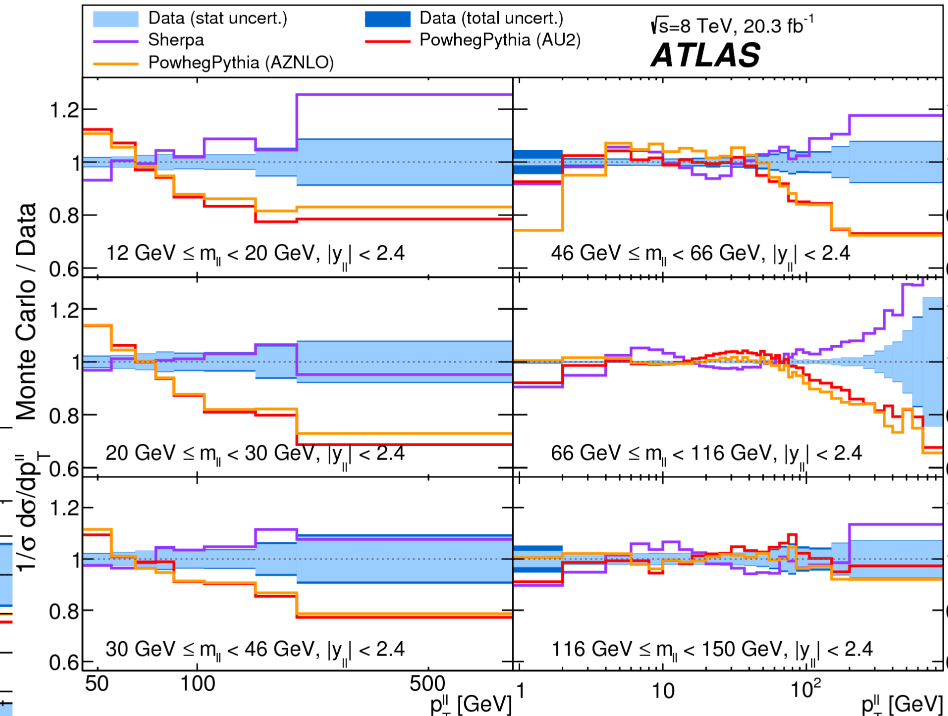
ATLAS EXPERIMENT

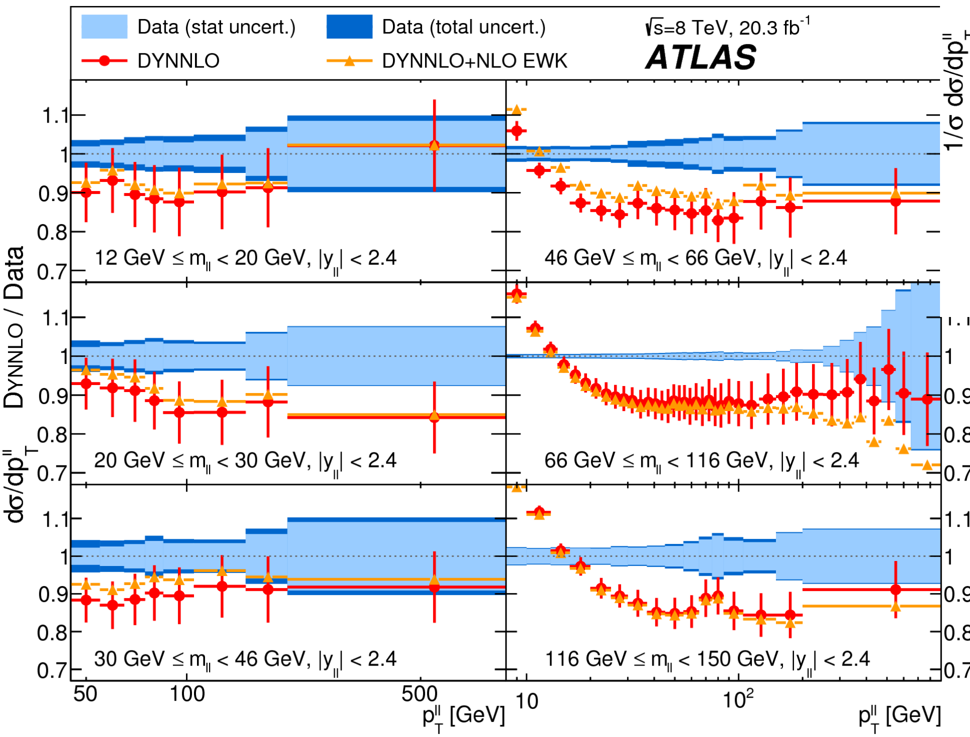
Z/γ^* p_T^{ll} and ϕ_η^* - 8 TeV Continued

Submitted to EPJC
arXiv:1512.02192

Normalized p_T^{ll} distributions compared to Sherpa and Powheg+Pythia

Absolute p_T^{ll} distributions compared to DYNNLO at QCD NNLO and QCD NNLO + NLO EWK. Normalization differences might be fixed by $O(\alpha_s^3)$ corrections.





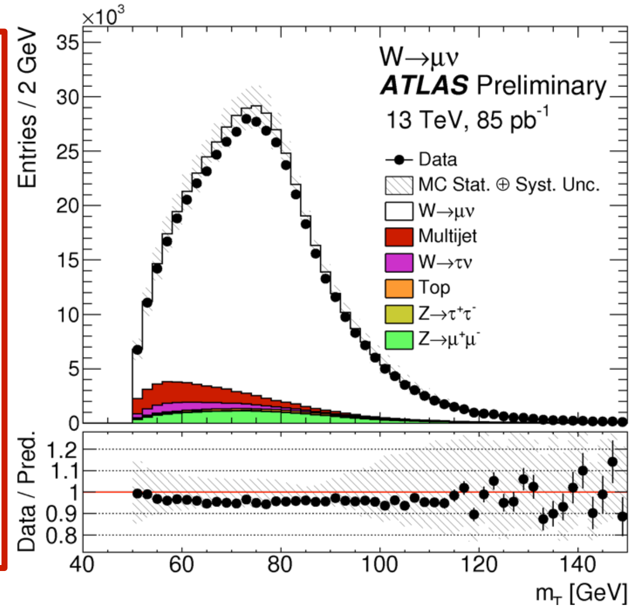
Many more di-lepton mass and rapidity bins have been compared.

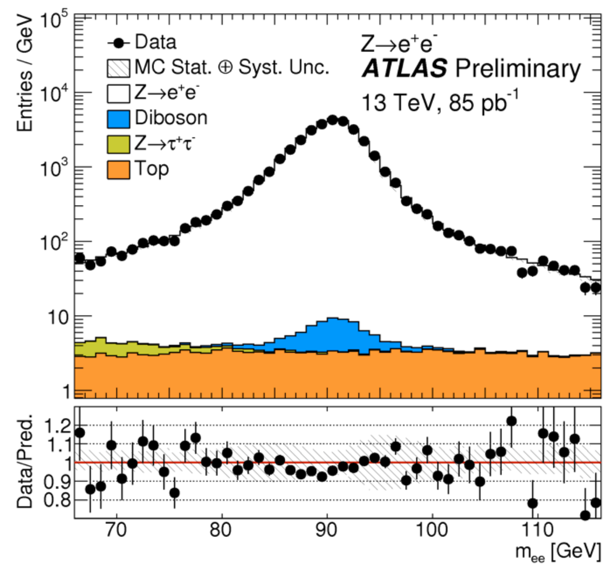
Also have performed measurements of integrated cross-sections in bins of m(ll)

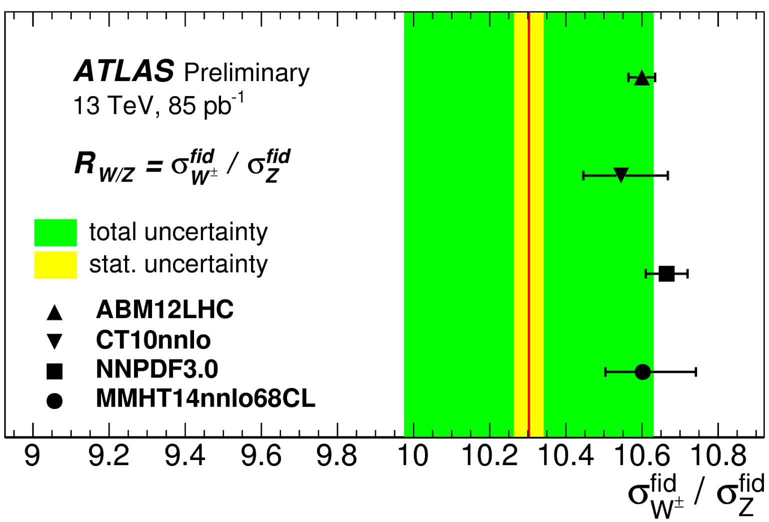
W/Z Cross-sections and Ratios – 13 TeV

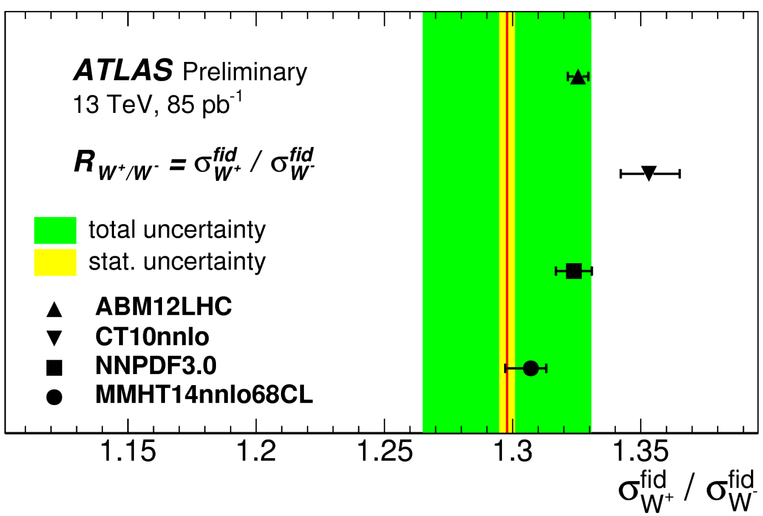
Note public on 8/2015
ATLAS-CONF-2015-039

- W and Z cross-sections measured at 13 TeV using first Run 2 data.
- Measured cross-sections are consistent with NNLO QCD + NLO EW predictions
- Ratios of cross-sections allows for good comparison of PDFs





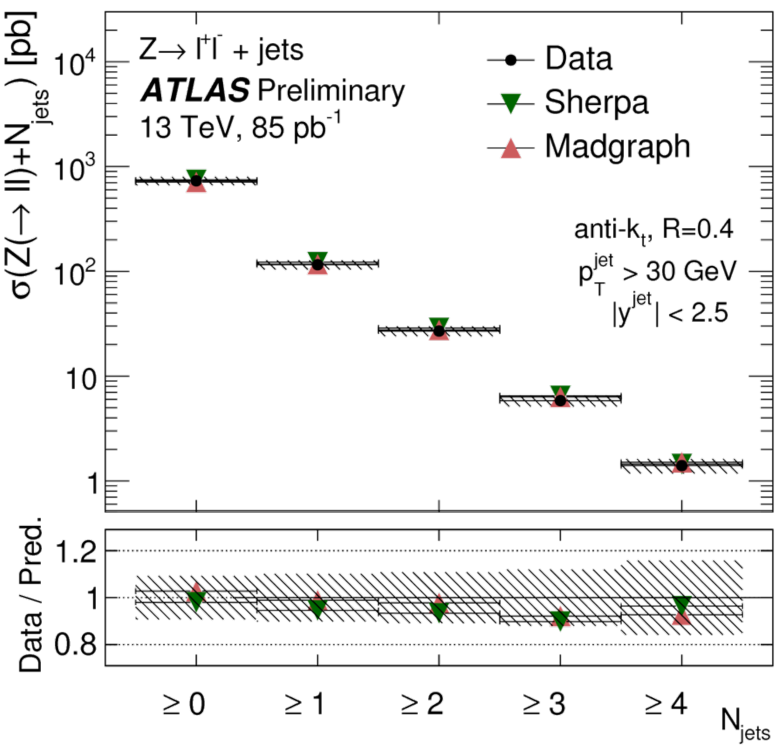


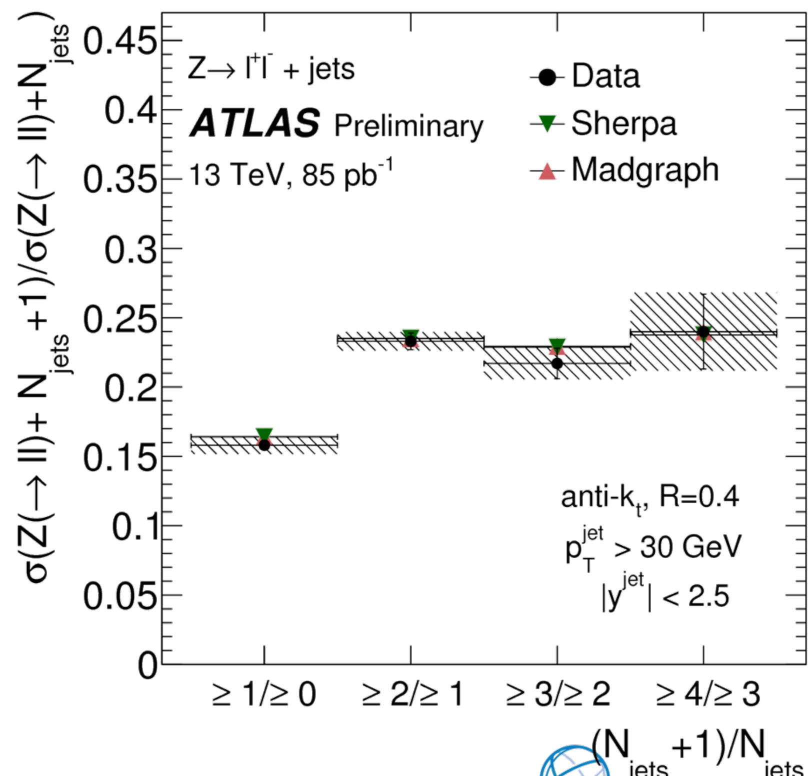


Z+Jets – 13 TeV

Note public on 8/2015
ATLAS-CONF-2015-041

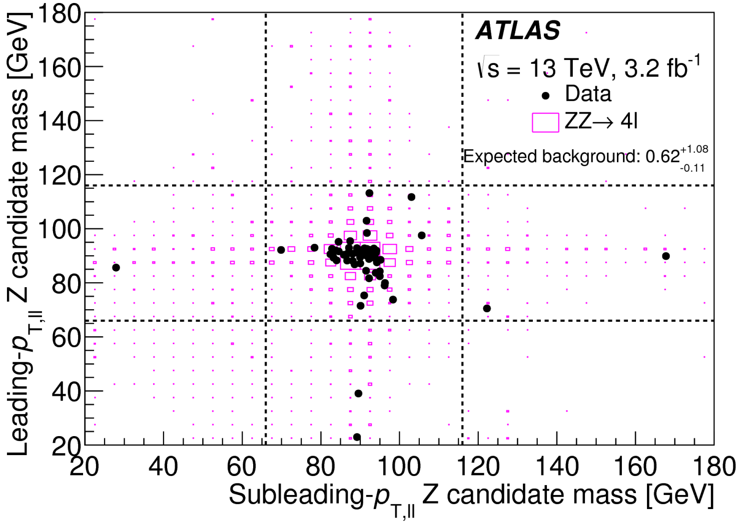
- Same inclusive selection as in W/Z study
- Fiducial cross-sections measured in bins of inclusive N_{jets}
- Cross-section ratios with neighboring bin improve precision
- Results consistent with SM predictions normalized to QCD NNLO





ZZ→4l - 13 TeV

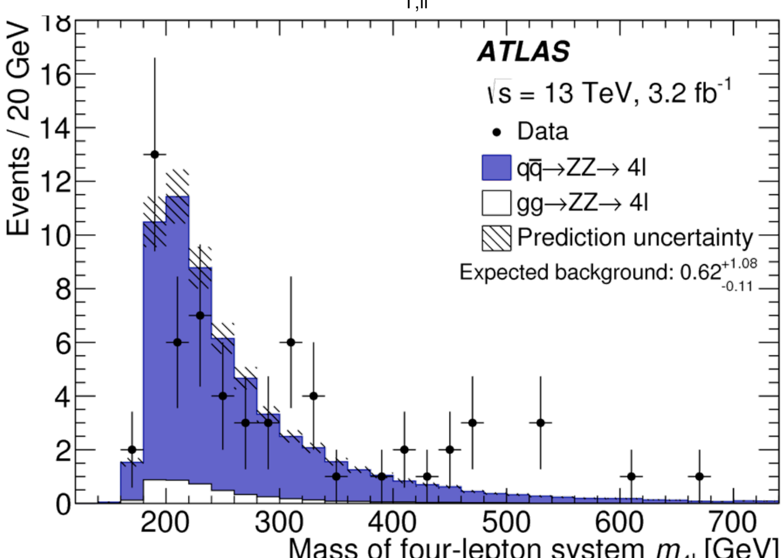
Submitted to PRL 12/2015
arXiv:1512.05314

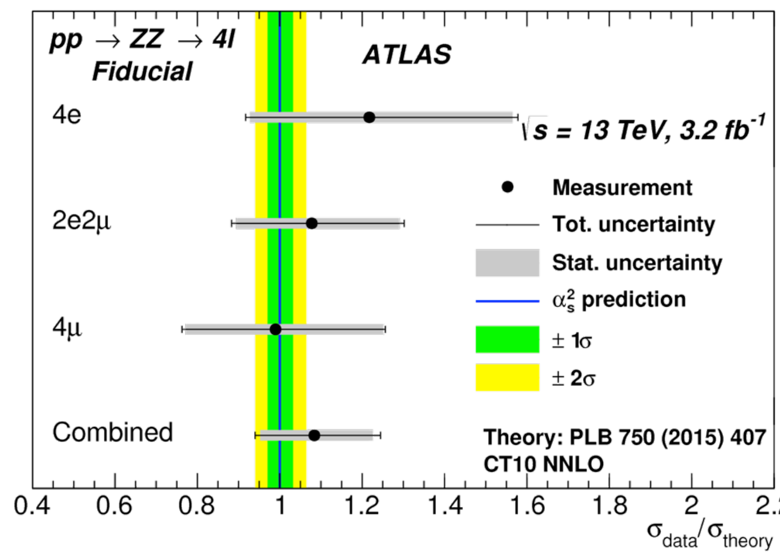


- First 13 TeV di-boson measurement from ATLAS!
- Z candidates required to be on-shell.
- 63 events observed in data.
- Measured cross-section consistent with SM

$$\sigma(ZZ\ \text{Total Obs.}) = 16.7\ ^{+2.2}_{-2.0}\ (\text{Stat.})\ ^{+0.9}_{-0.7}\ (\text{Syst.})\ ^{+1.0}_{-0.7}\ (\text{Lumi.})\ \text{pb}$$

$$\sigma(ZZ\ \text{NNLO Total Exp.}) = 15.6 \pm 0.4\ \text{pb}$$





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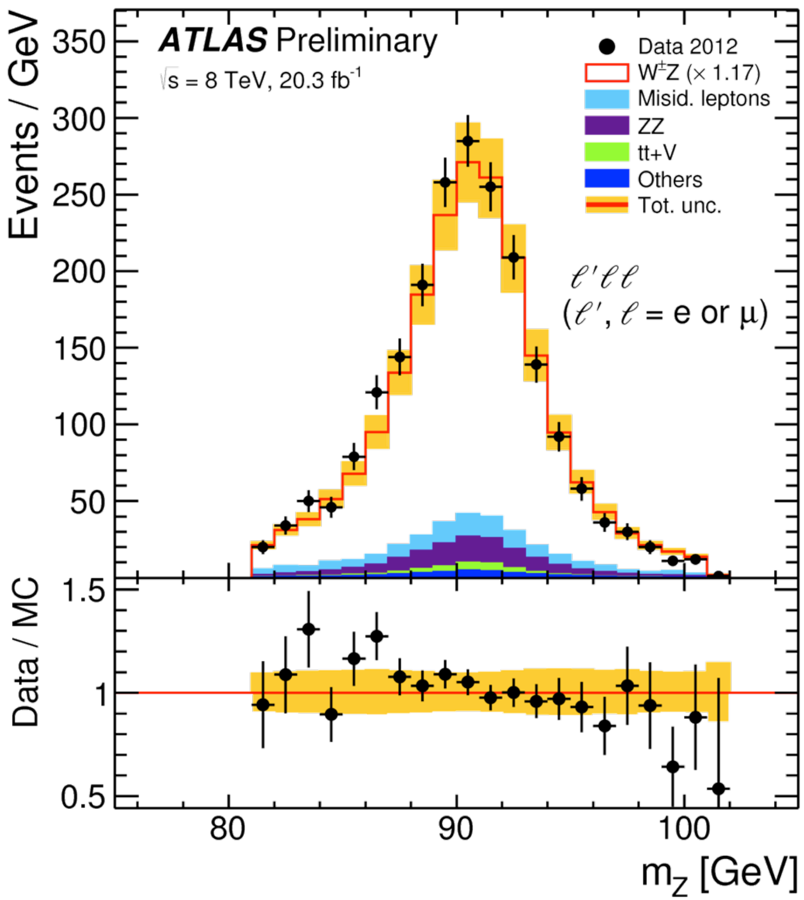
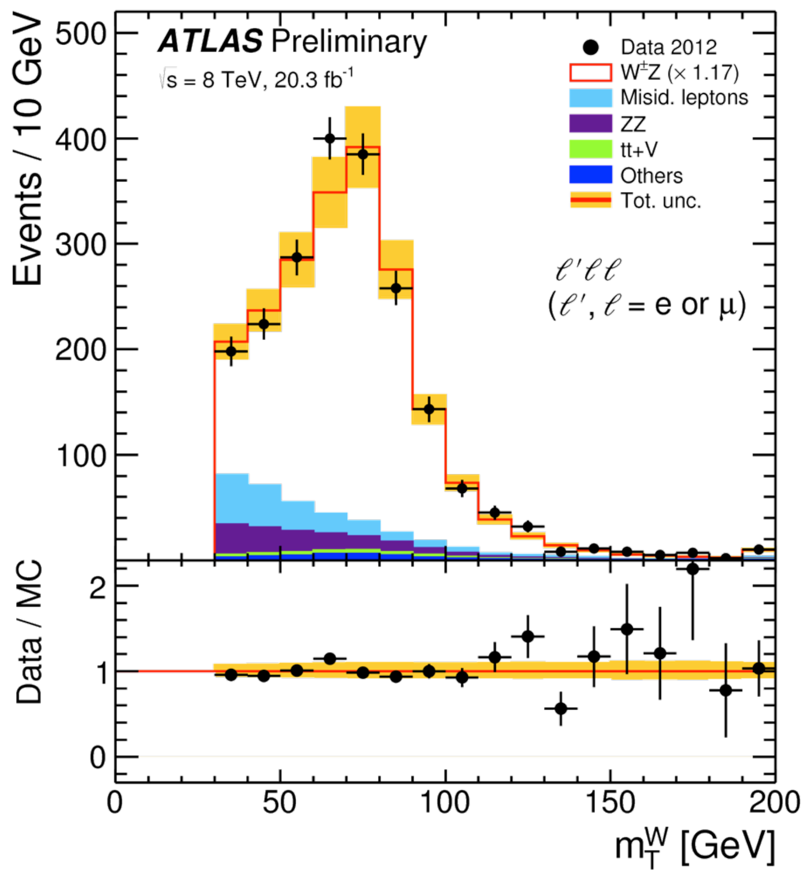
ATLAS EXPERIMENT

WZ - 8 TeV

Hot off the press!
To be submitted to PRD
STDM-2014-02

- Brand new result for WZ production at 8 TeV in leptonic final state
- Many important new measurements/limits presented.





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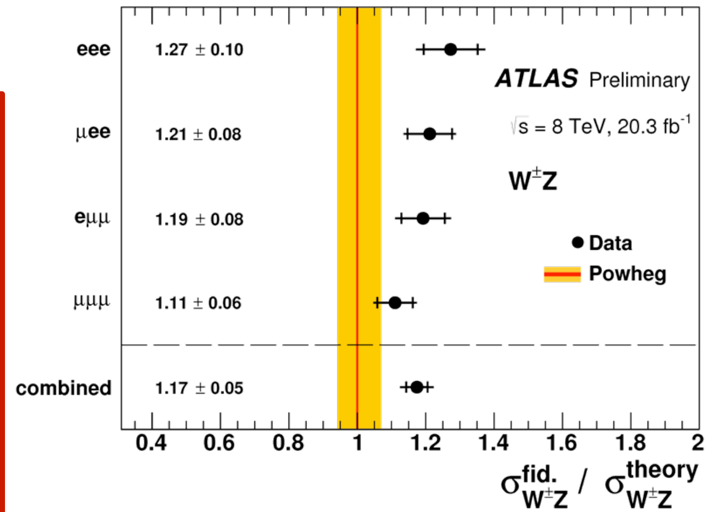
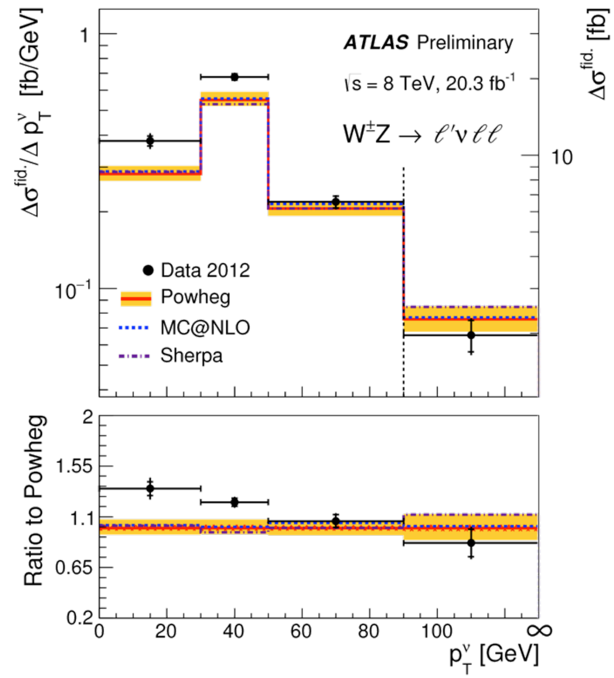
ATLAS EXPERIMENT

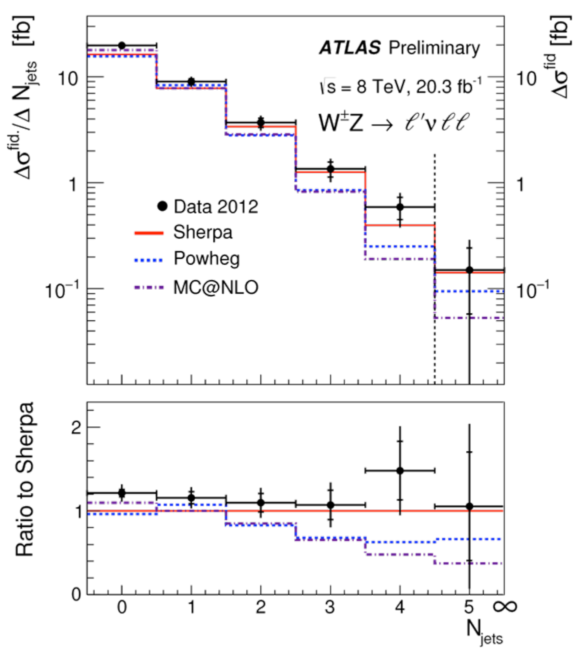
WZ - 8 TeV

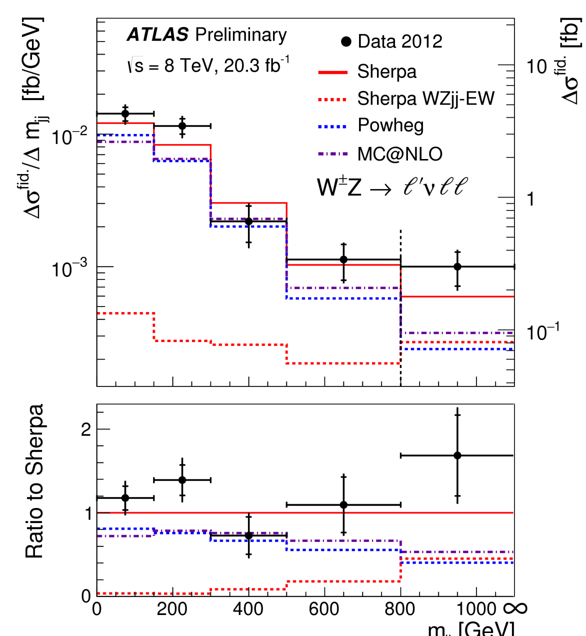
Hot off the press!
To be submitted to PRD
STDM-2014-02

- Fiducial and total cross-sections observed to be above QCD NLO SM prediction. (Full NNLO calculation unavailable)
- Unfolded differential cross-section measurements of $p_T(W)$, $p_T(Z)$, $m_T(WZ)$, $p_T(nu)$, $|y_{l,W}-y_Z|$, jet multiplicity, m(jj)
- Differences mainly at low p_T
- Study of EW VBS also performed.









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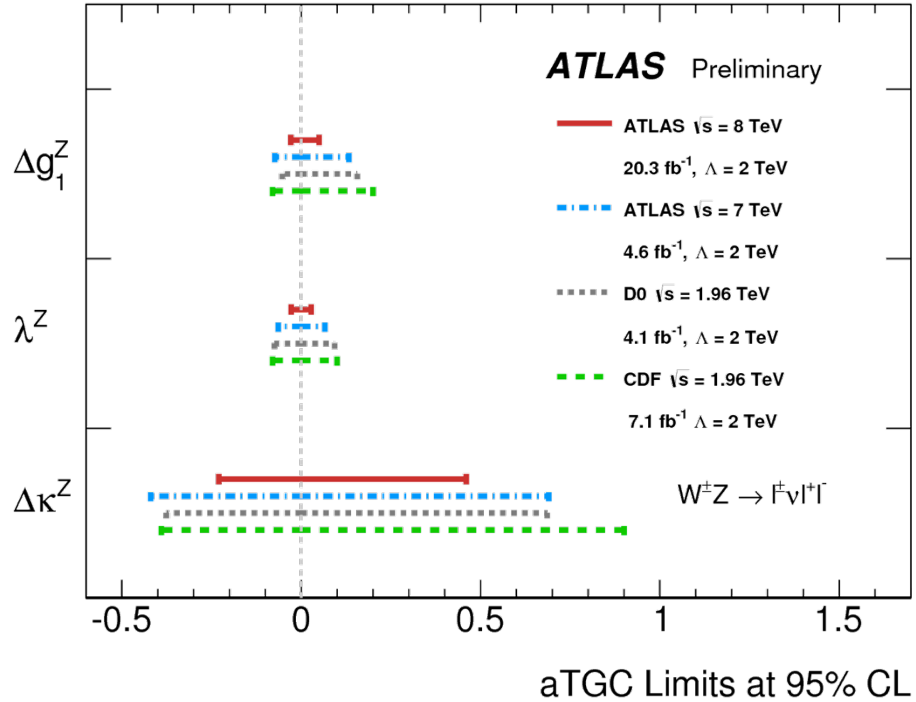
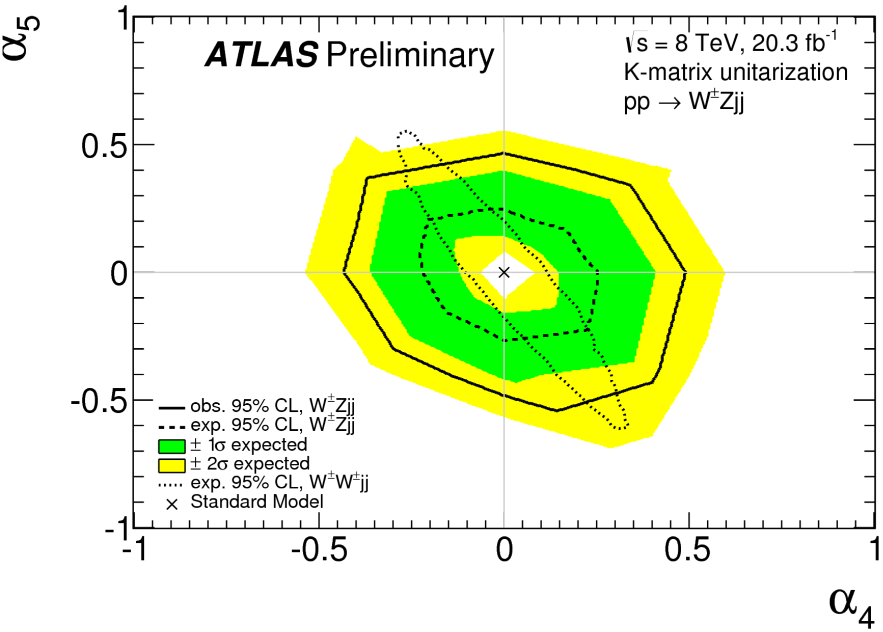
Hot off the press!
To be submitted to PRD
STDM-2014-02

WZ - 8 TeV
Continued

New limits set on aTGC parameters strongly improve on previous limits





aQGC limits also set on α_4 and α_5 parameters

$$\frac{f_{S,0(1)}}{\Lambda^4} = \alpha_{4(5)} \times \frac{16}{\nu^4}$$

ATLAS EXPERIMENT

Conclusions

- A summary of recent studies of electroweak processes in ATLAS were presented with new results at 8 TeV and the first results at 13 TeV.
- A wide survey of results show we are consistent with the SM. Any differences could likely be resolved by higher order corrections.
- There is more to come from the 8 TeV and latest 13 TeV runs. And we have an exciting year ahead with much more 13 TeV data coming from the LHC!

BACKUP

4l Production - 8 TeV

4l Production - 8 TeV

Selection

Fiducial

Lepton selection	
Muons:	$p_T > 6$ GeV, $\lvert\eta\rvert < 2.7$
Electrons:	$p_T > 7$ GeV, $\lvert\eta\rvert < 2.5$
Lepton pairing	
Leading pair:	SFOS lepton pair with smallest $\lvert m_Z - m_{\ell\ell}\rvert$
Sub-leading pair:	The remaining SFOS with the largest $m_{\ell\ell}$
For both pairs:	$p_T^{\ell^+\ell^-} > 2$ GeV
Event selection	
Lepton $p_T^{\ell_1,\ell_2,\ell_3}$:	$> 20, 15, 10 (8 \text{ if } \mu)$ GeV
Mass requirements:	$50 < m_{12} < 120$ GeV $12 < m_{34} < 120$ GeV
Lepton separation:	$\Delta R(\ell_i, \ell_j) > 0.1\ (0.2)$ for same- (different-) flavour leptons
J/ψ veto:	$m(\ell_i^+, \ell_j^-) > 5$ GeV
4ℓ mass range:	$80 < m_{4\ell} < 1\,000$ GeV

Extended

4 leptons each with p_T > 5 GeV and |η|<2.8 (no flavor dependence)
80 < m(4l) < 1000 GeV
M(l+l-) > 4 GeV
$p_T(Z_1)$,$p_T(Z_2)$ > 2 GeV

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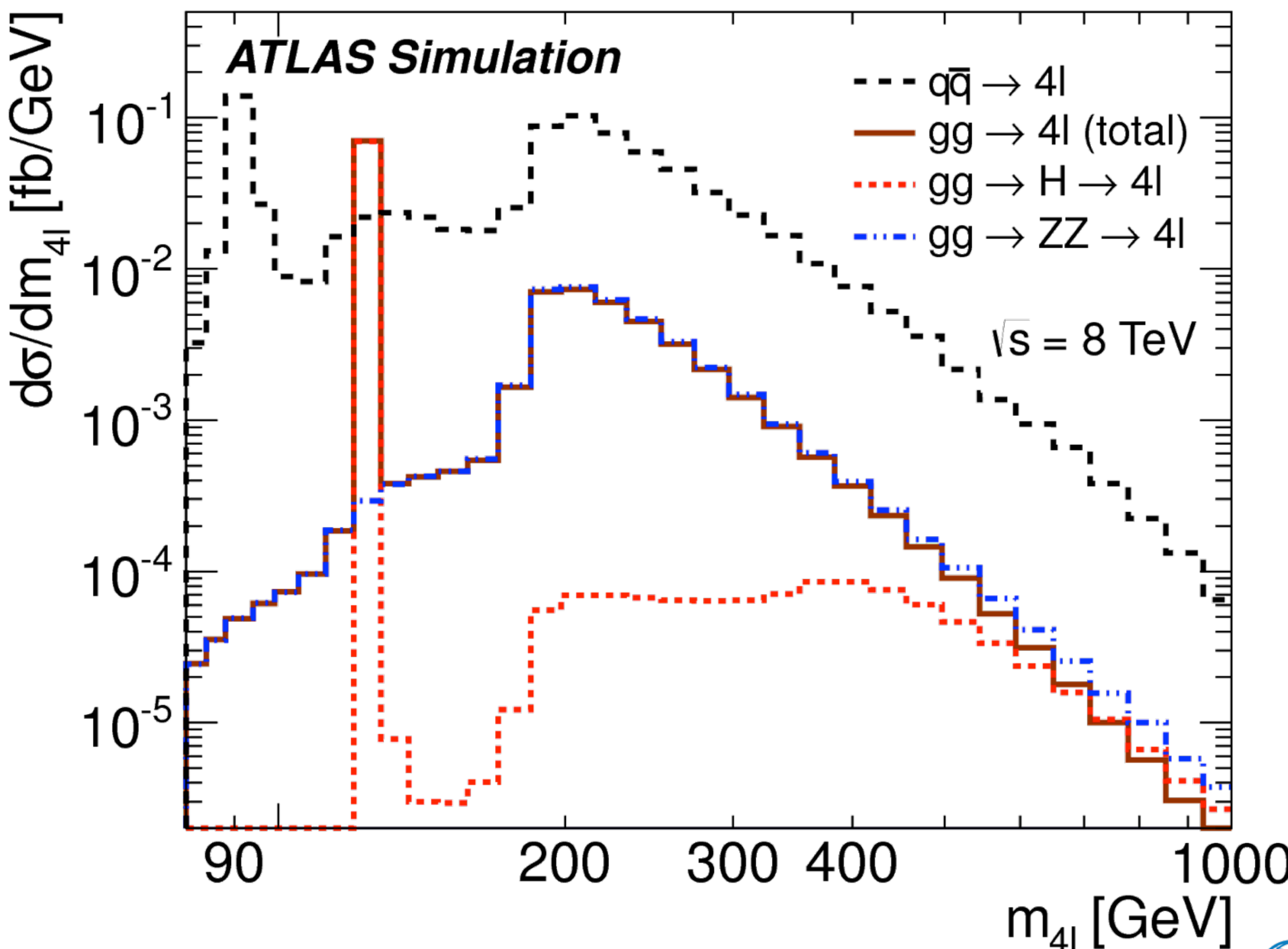
ATLAS EXPERIMENT

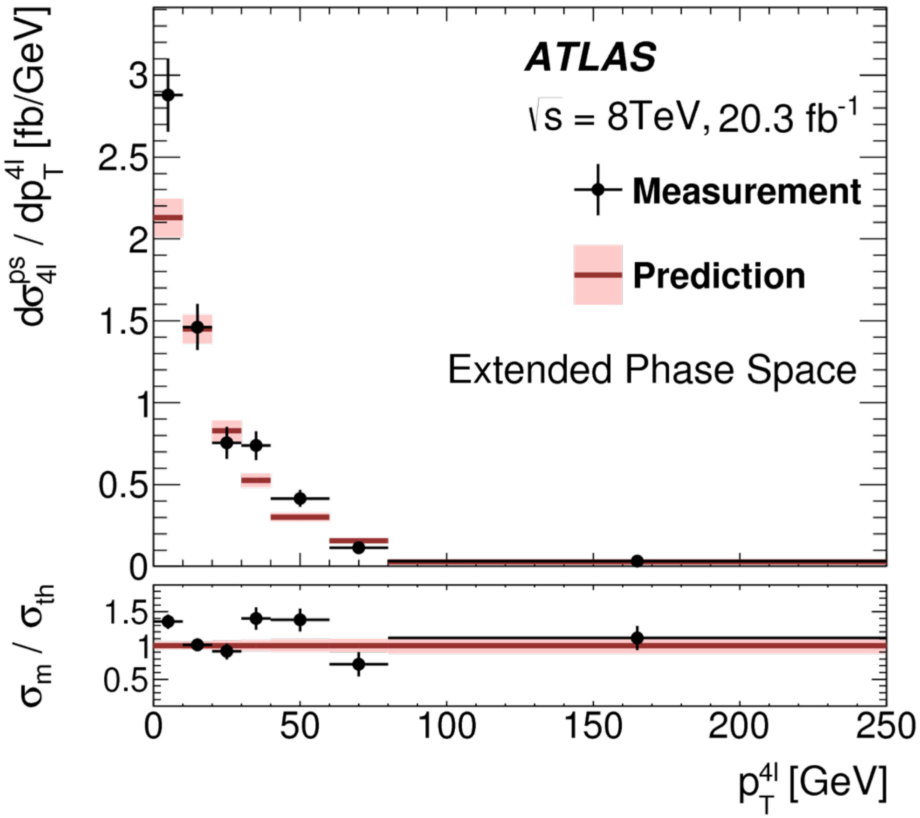
4l Production - 8 TeV

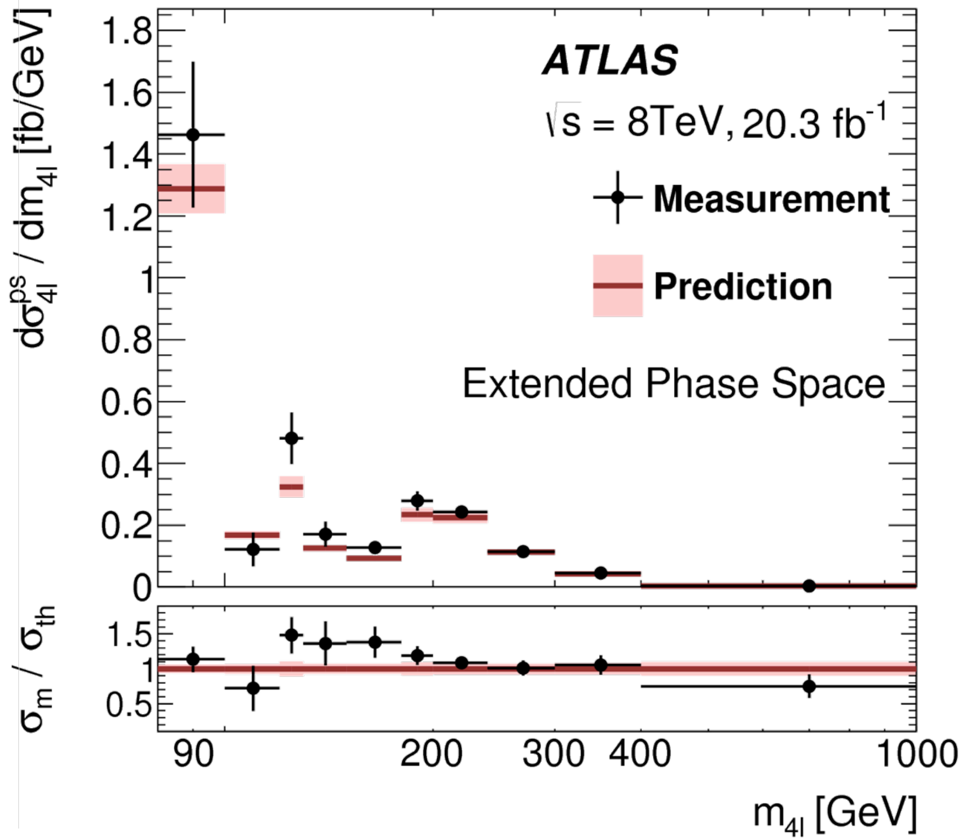
Signal



4l Production - 8 TeV

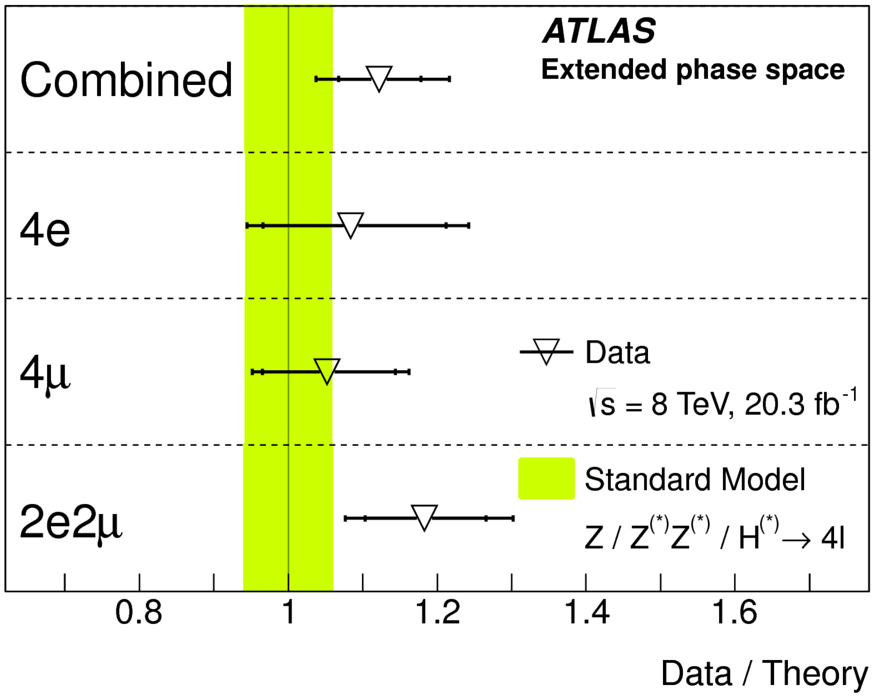
Unfolded distributions in extended phase space

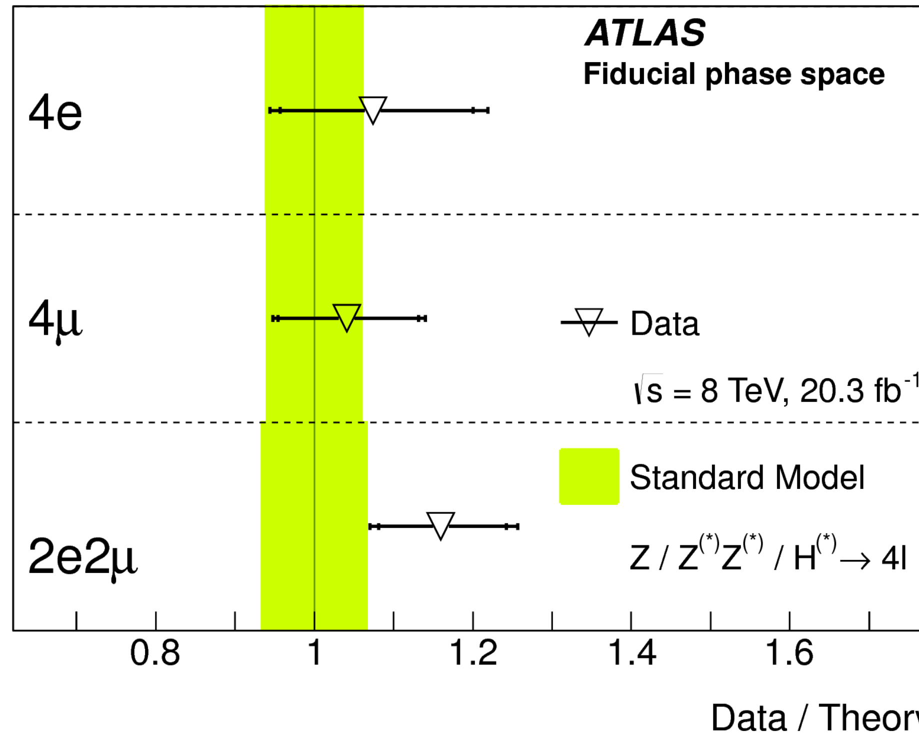




4l Production - 8 TeV

Measured cross-sections





Z/γ^* p_T^{ll} and ϕ_η^* - 8 TeV

Z/γ* p_T^{ll} and ϕ_η^* - 8 TeV

Selection

Particle-level definitions (Treatment of final-state photon radiation)	
electron pairs	dressed; Born
muon pairs	bare; dressed; Born
combined	Born
Fiducial region	
Leptons	$p_T > 20$ GeV; $\lvert\eta\rvert < 2.4$
Lepton pairs	$\lvert y_{\ell\ell}\rvert < 2.4$
	$\Delta R > 0.15$ ($p_{\mathrm{T}}^{\ell\ell}$ measurements of dressed electrons only)
Mass and rapidity regions	
$46\,\mathrm{GeV} < m_{\ell\ell} < 66\,\mathrm{GeV}$	$\lvert y_{\ell\ell}\rvert < 0.8$; $0.8 < \lvert y_{\ell\ell}\rvert < 1.6$; $1.6 < \lvert y_{\ell\ell}\rvert < 2.4$ (ϕ_η^* measurements only)
$66\,\mathrm{GeV} < m_{\ell\ell} < 116\,\mathrm{GeV}$	$\lvert y_{\ell\ell}\rvert < 0.4$; $0.4 < \lvert y_{\ell\ell}\rvert < 0.8$; $0.8 < \lvert y_{\ell\ell}\rvert < 1.2$; $1.2 < \lvert y_{\ell\ell}\rvert < 1.6$; $1.6 < \lvert y_{\ell\ell}\rvert < 2.0$; $2.0 < \lvert y_{\ell\ell}\rvert < 2.4$
$116\,\mathrm{GeV} < m_{\ell\ell} < 150\,\mathrm{GeV}$	$\lvert y_{\ell\ell}\rvert < 0.8$; $0.8 < \lvert y_{\ell\ell}\rvert < 1.6$; $1.6 < \lvert y_{\ell\ell}\rvert < 2.4$ (ϕ_η^* measurements only)
$\lvert y_{\ell\ell}\rvert < 2.4$	$46\,\mathrm{GeV} < m_{\ell\ell} < 66\,\mathrm{GeV}$; $66\,\mathrm{GeV} < m_{\ell\ell} < 116\,\mathrm{GeV}$; $116\,\mathrm{GeV} < m_{\ell\ell} < 150\,\mathrm{GeV}$
Very-low mass regions	
$12\,\mathrm{GeV} < m_{\ell\ell} < 20\,\mathrm{GeV}$; $20\,\mathrm{GeV} < m_{\ell\ell} < 30\,\mathrm{GeV}$; $30\,\mathrm{GeV} < m_{\ell\ell} < 46\,\mathrm{GeV}$	
($p_{\mathrm{T}}^{\ell\ell} > 45\,\mathrm{GeV}$, $p_{\mathrm{T}}^{\ell\ell}$ measurements only)	

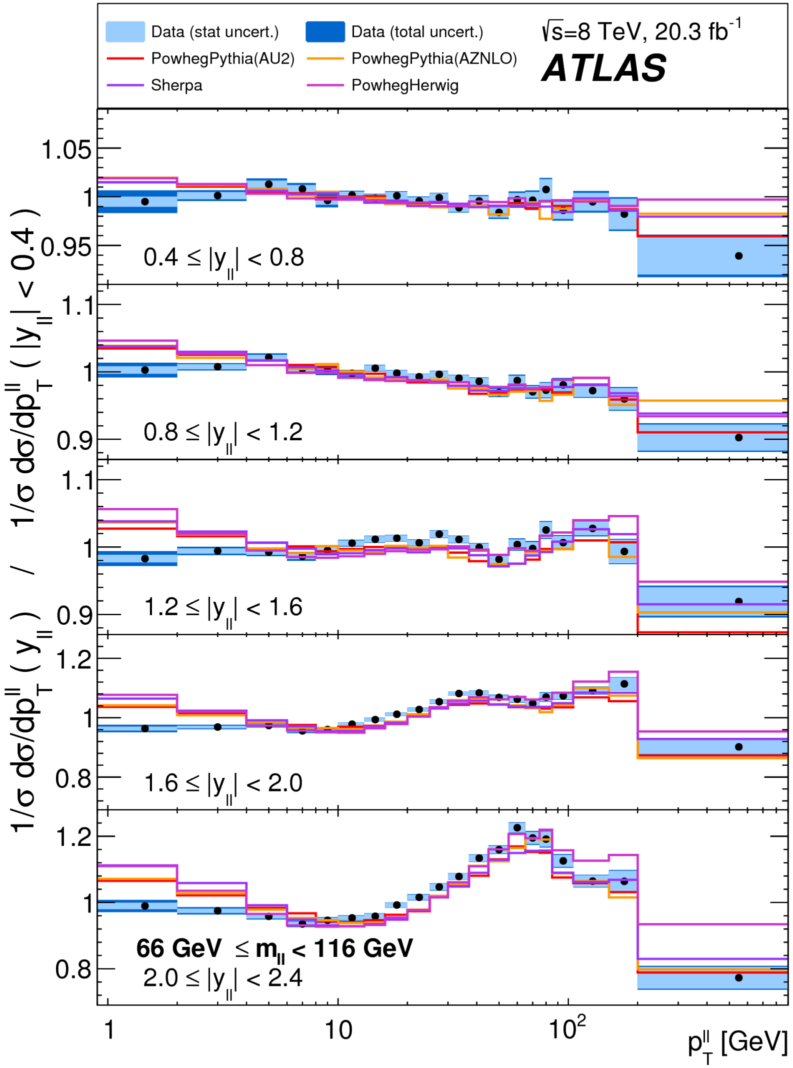
Z/γ^* p_T^{ll} and ϕ_η^* - 8 TeV

Integrated cross-sections

$m_{\ell\ell}$ [GeV]	12–20	20–30	30–46	46–66	66–116	116–150
$\sigma(Z/\gamma^* \to e^+e^-)$ [pb]	1.42	1.04	1.01	15.16	537.64	5.72
Statistical uncertainty [%]	0.91	1.05	1.13	0.28	0.04	0.41
Detector uncertainty [%]	2.28	2.12	1.79	3.47	0.83	0.87
Background uncertainty [%]	3.16	1.97	2.36	2.77	0.14	0.83
Model uncertainty [%]	5.11	4.38	3.59	1.59	0.16	0.74
Total systematic uncertainty [%]	6.43	5.25	4.66	4.72	0.86	1.41
$\sigma(Z/\gamma^* \to \mu^+\mu^-)$ [pb]	1.45	1.04	0.97	14.97	535.25	5.48
Statistical uncertainty [%]	0.69	0.82	0.91	0.21	0.03	0.37
Detector uncertainty [%]	1.07	1.08	1.01	1.10	0.71	0.84
Background uncertainty [%]	0.75	2.19	2.00	1.48	0.04	0.97
Model uncertainty [%]	2.59	1.81	2.36	0.75	0.31	0.31
Total systematic uncertainty [%]	2.90	3.04	3.25	2.00	0.78	1.32
$\sigma(Z/\gamma^* \to \ell^+\ell^-)$ [pb]	1.45	1.03	0.97	14.96	537.10	5.59
Statistical uncertainty [%]	0.63	0.75	0.83	0.17	0.03	0.31
Detector uncertainty [%]	0.84	0.99	0.87	1.05	0.40	0.56
Background uncertainty [%]	0.18	0.85	1.42	1.28	0.06	0.77
Model uncertainty [%]	1.84	2.24	2.27	0.89	0.19	0.50
Total systematic uncertainty [%]	2.06	2.44	2.38	1.82	0.45	1.03

Z/γ* p_T^{ll} and ϕ_η^* - 8 TeV

Evolutions



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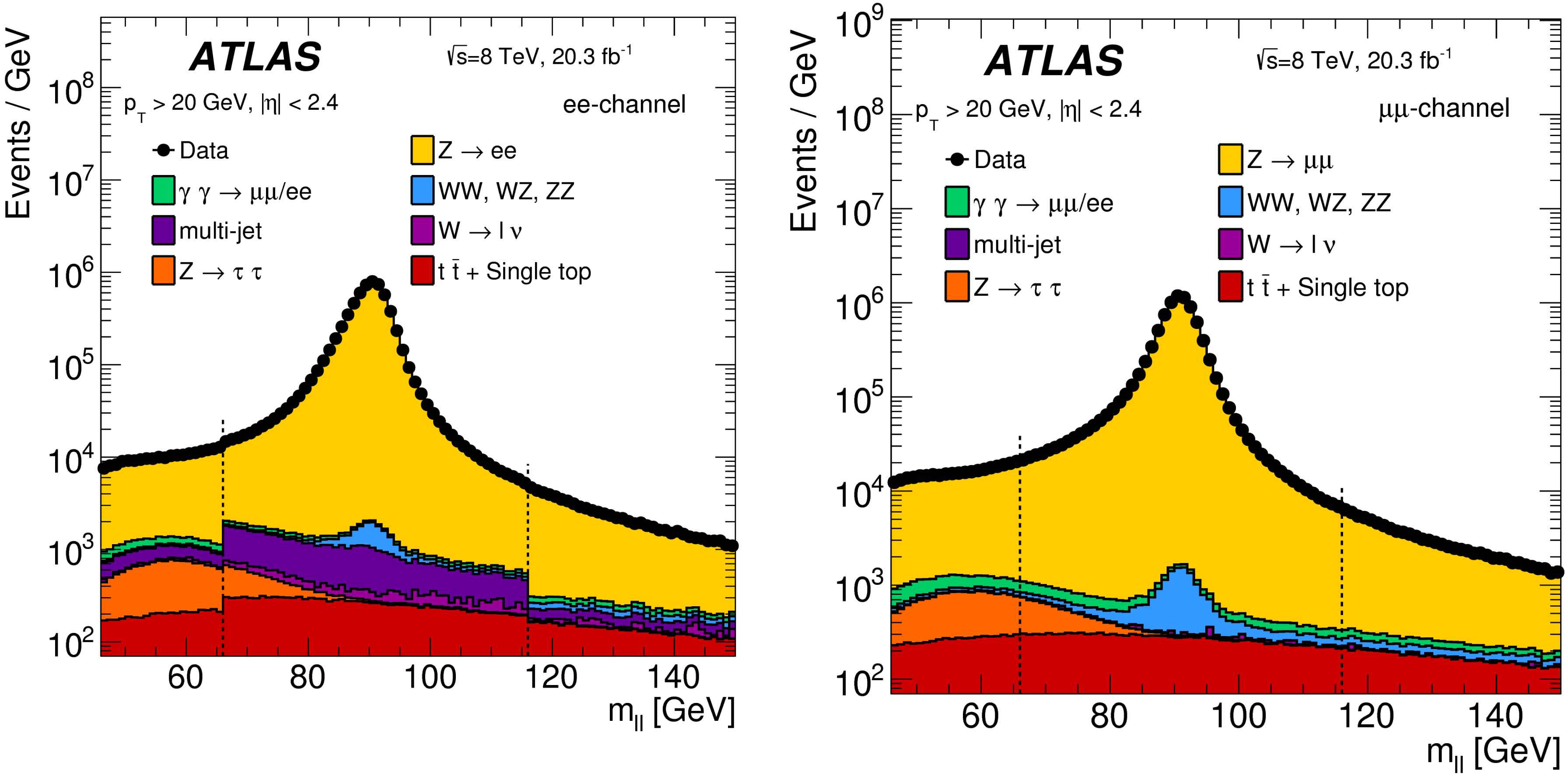
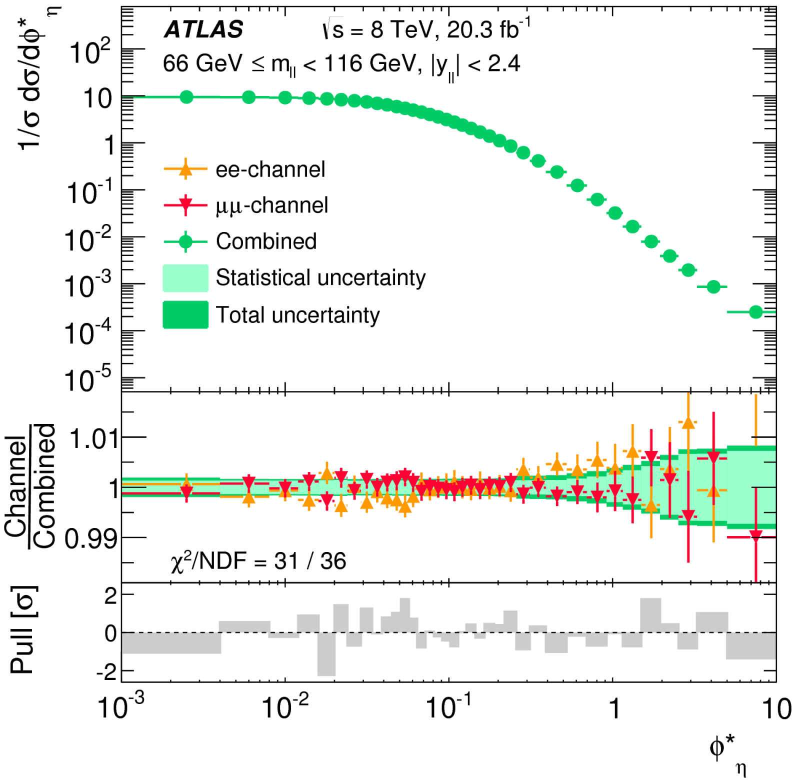
Z/γ* p_T^{ll} and ϕ_η^* - 8 TeV

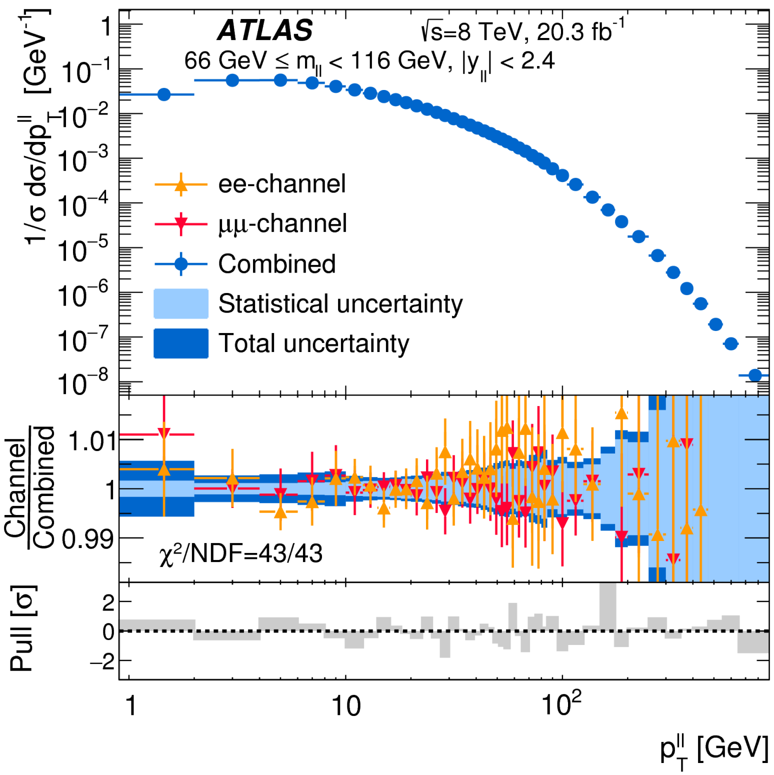
Data to background comparisons



Z/γ^* p_T^{ll} and ϕ_η^* - 8 TeV

Electron and Muon channel combinations





WZ - 8 TeV

WZ - 8 TeV

Selection

Variable	Total	Fiducial and aTGC	VBS	aQGC
Lepton $\|\eta\|$	—	≤ 2.5	≤ 2.5	≤ 2.5
p_T of ℓ_Z, p_T of ℓ_W [GeV]	—	$\geq 15, \geq 20$	$\geq 15, \geq 20$	$\geq 15, \geq 20$
m_Z range [GeV]	66 – 116	$\|m_Z - m_Z^{\mathrm{PDG}}\| < 10$	$\|m_Z - m_Z^{\mathrm{PDG}}\| < 10$	$\|m_Z - m_Z^{\mathrm{PDG}}\| < 10$
m_T^W [GeV]	—	≥ 30	≥ 30	≥ 30
$\Delta R(\ell_Z^-, \ell_Z^+)$, $\Delta R(\ell_Z, \ell_W)$	—	$\geq 0.2, \geq 0.3$	$\geq 0.2, \geq 0.3$	$\geq 0.2, \geq 0.3$
p_T two leading jets [GeV]	—	—	≥ 30	≥ 30
$\|\eta_j\|$ two leading jets	—	—	≤ 4.5	≤ 4.5
Jet multiplicity	—	—	≥ 2	≥ 2
m_{jj} [GeV]	—	—	≥ 500	≥ 500
$\Delta R(j, \ell)$	—	—	≥ 0.3	≥ 0.3
$\|\Delta\phi(W, Z)\| > 2$	—	—	—	≥ 2
$\sum \|p_T^\ell\|$ [GeV]	—	—	—	≥ 250

Table 1: Phase-space definitions used for the total, fiducial, VBS cross-section measurements and for the extraction of limits on the aTGC and aQGC. The symbols ℓ_Z and ℓ_W refer to the leptons associated to the Z and W boson, respectively. The symbol m_Z^{PDG} refers to the mean experimental mass of the Z boson from the Particle Data Group [16]. The other symbols are defined in the text.

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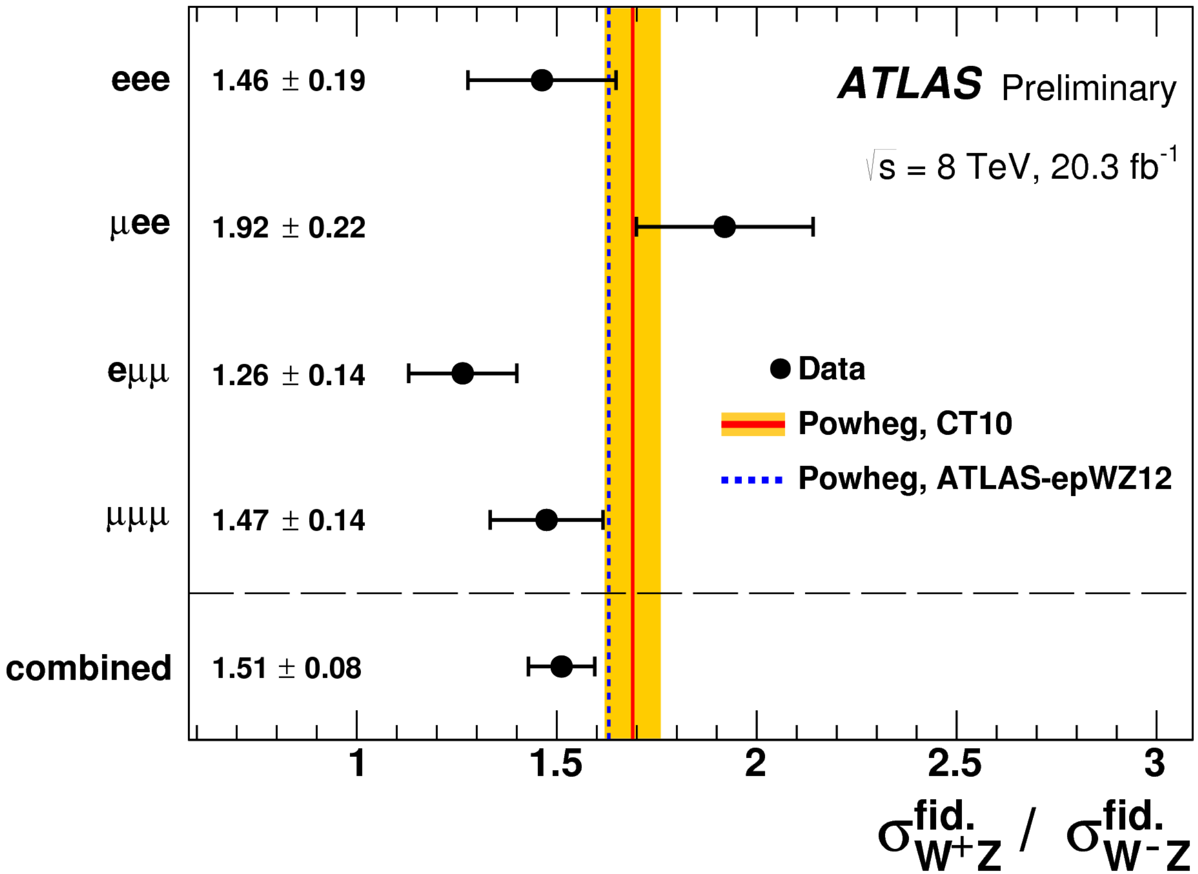
ATLAS EXPERIMENT

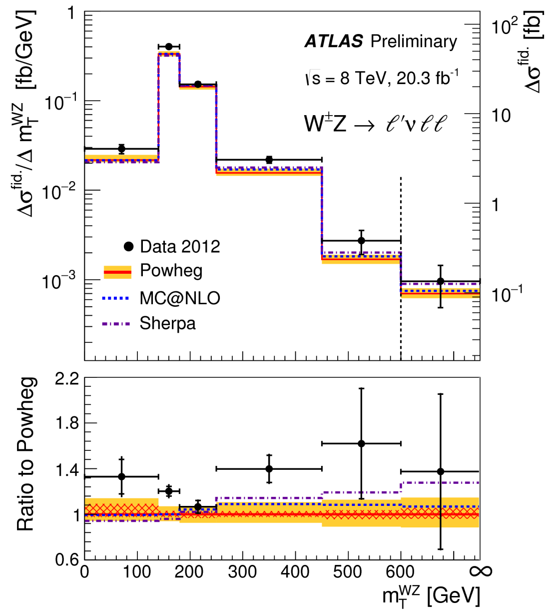
WZ – 8 TeV

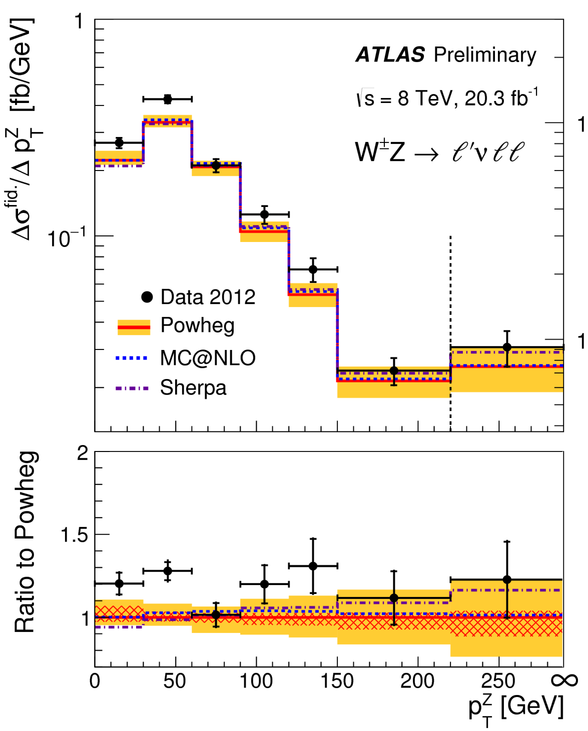
W+Z/W-Z cross-section ratio

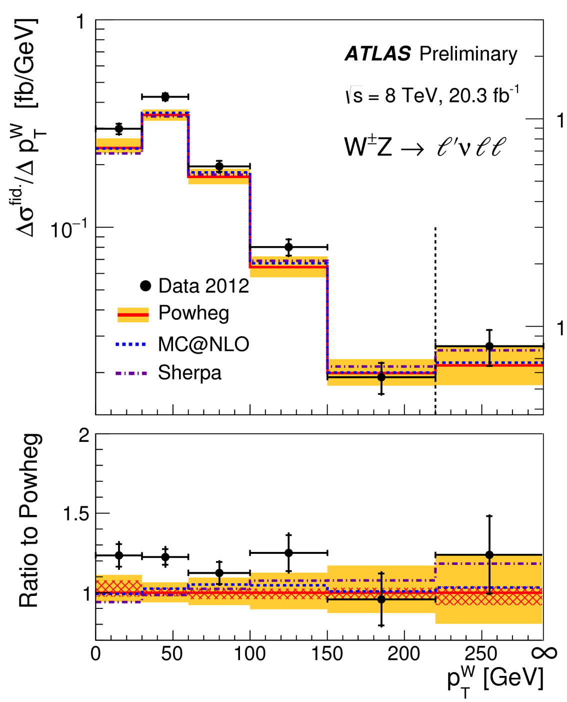


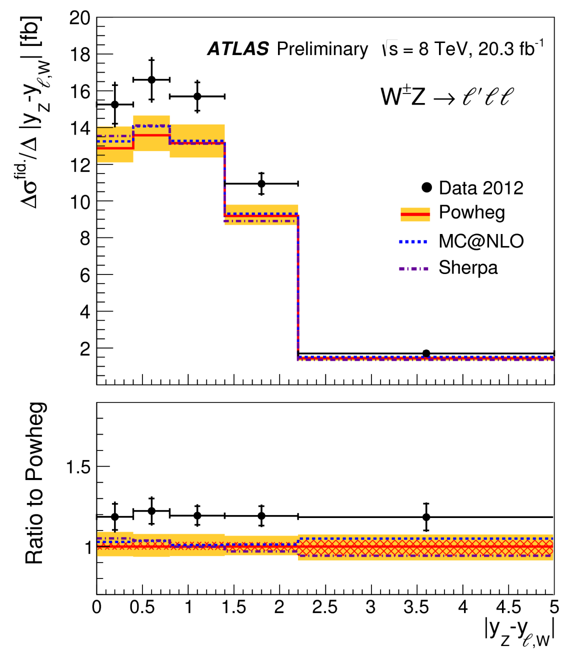
WZ - 8 TeV

Differential Cross-sections



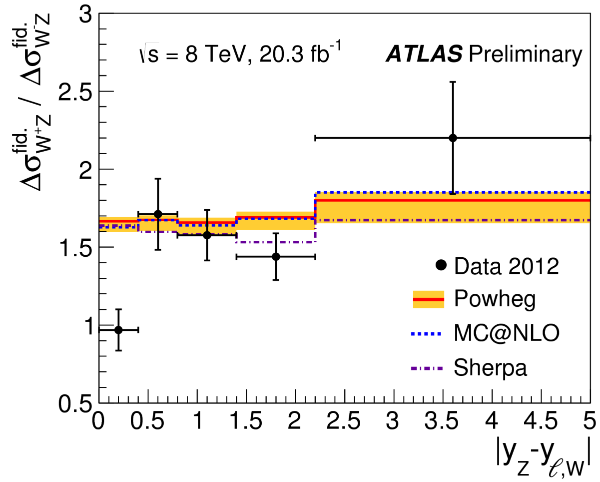


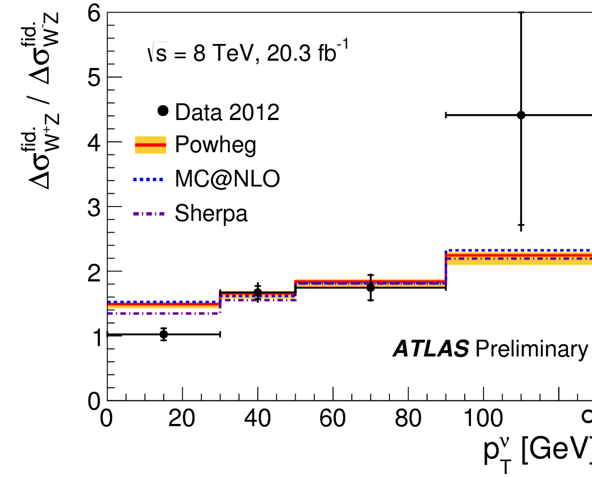


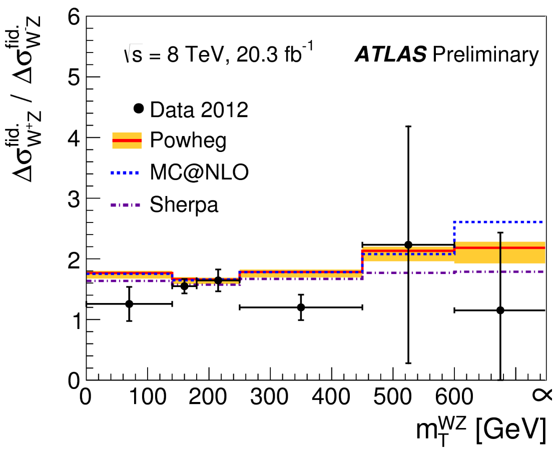


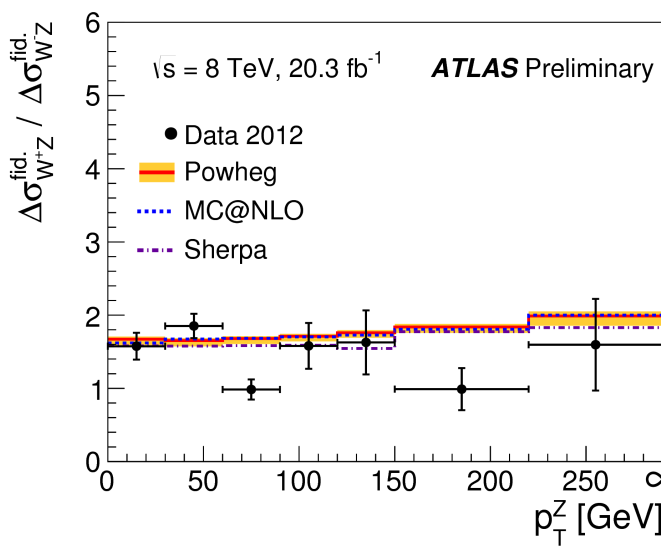
WZ - 8 TeV

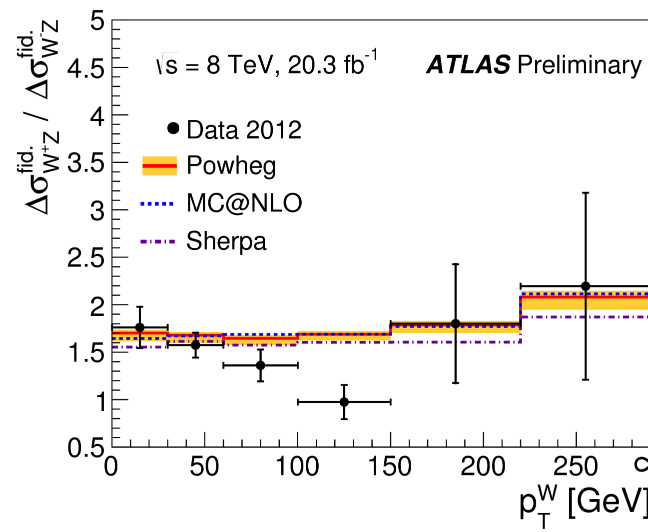
Differential Cross-sections Ratios











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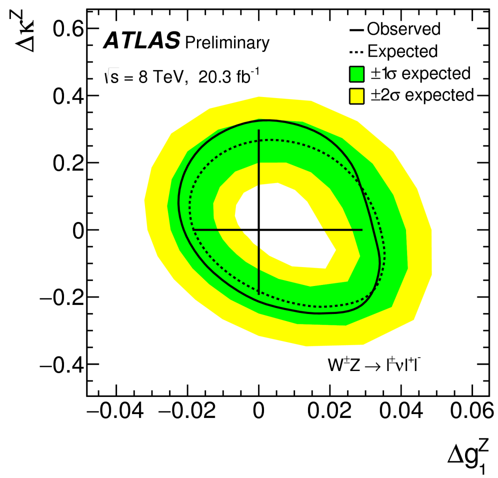
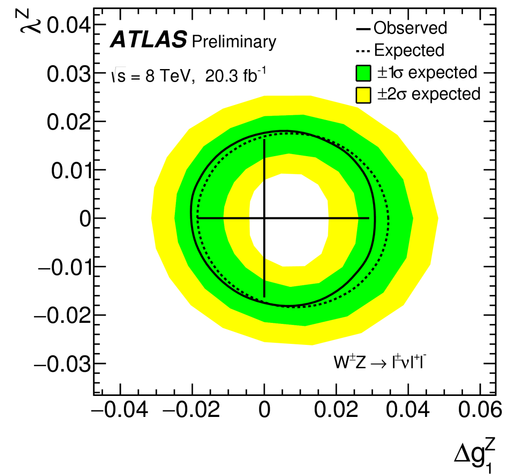
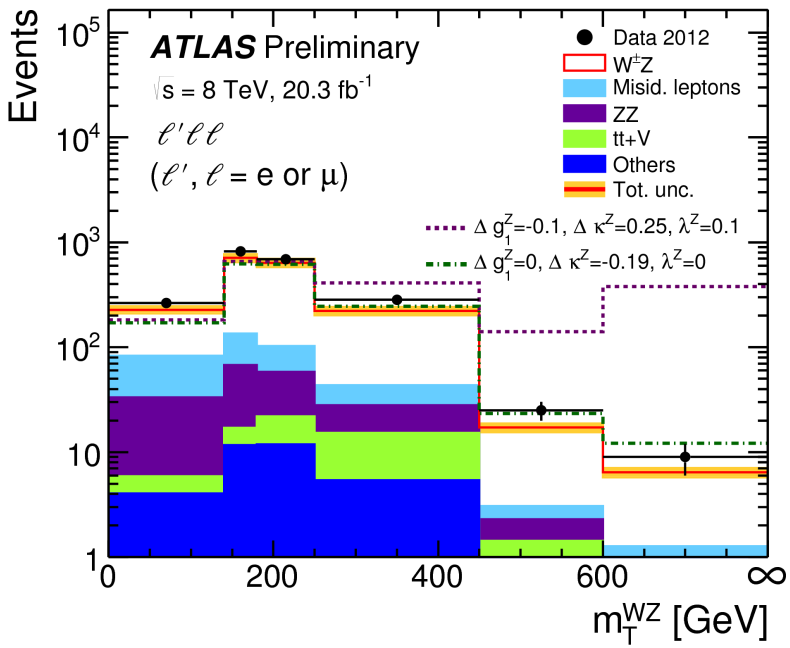
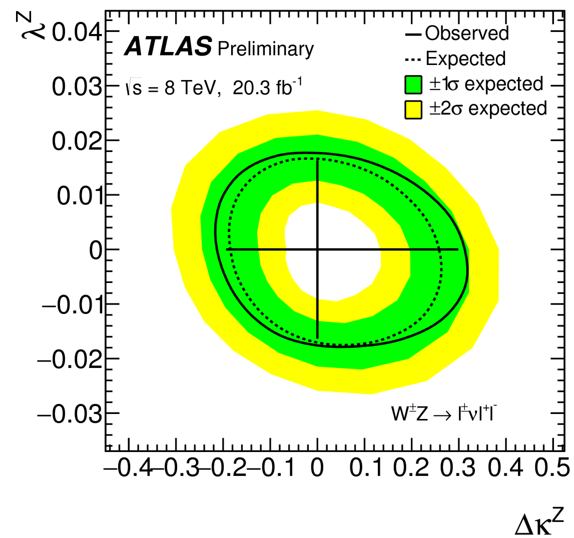
WZ - 8 TeV

aTGC


ATLAS Preliminary
√s = 8 TeV, 20.3 fb⁻¹
Observed
Expected
±1σ expected
±2σ expected
W±Z → l±νl+l−
Δκ^Z
Δg₁^Z

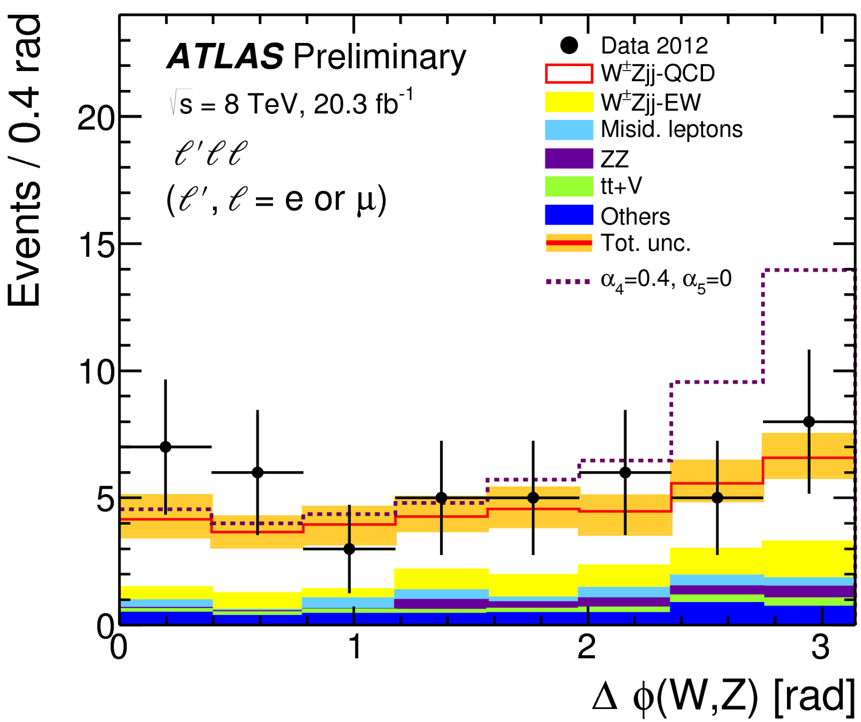

ATLAS Preliminary
√s = 8 TeV, 20.3 fb⁻¹
Observed
Expected
±1σ expected
±2σ expected
W±Z → l±νl+l−
λ^Z
Δg₁^Z

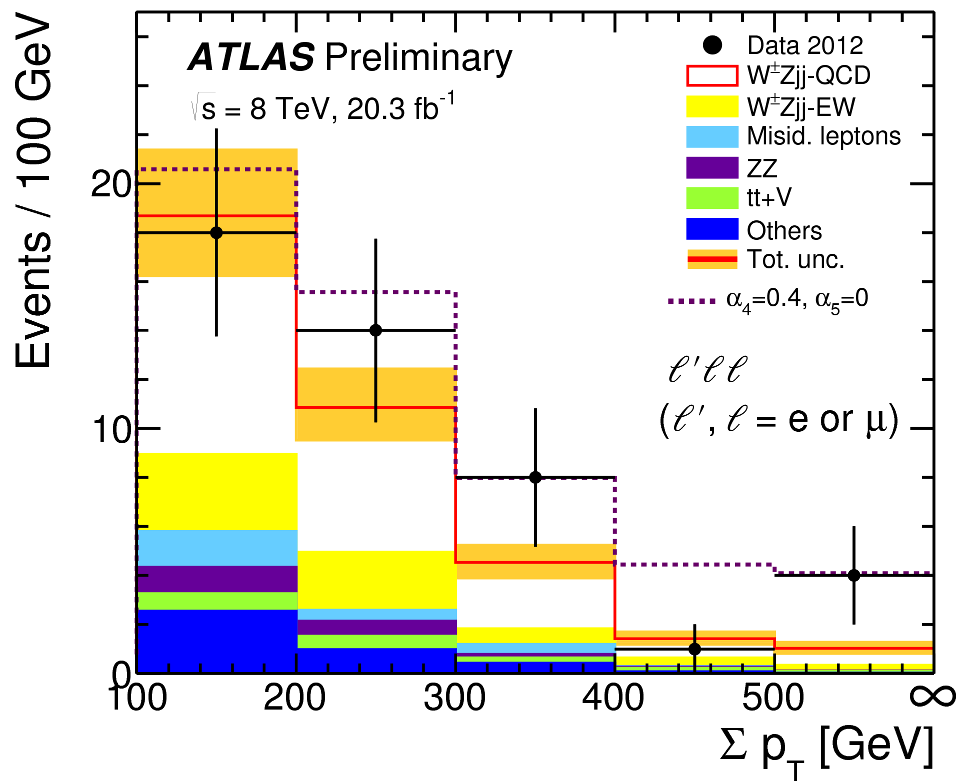

ATLAS Preliminary
√s = 8 TeV, 20.3 fb⁻¹
ℓ′ℓℓ
(ℓ′, ℓ = e or μ)
Data 2012
W±Z
Misid. leptons
ZZ
tt+V
Others
Tot. unc.
Δ g₁^Z=-0.1, Δ κ^Z=0.25, λ^Z=0.1
Δ g₁^Z=0, Δ κ^Z=-0.19, λ^Z=0
Events
m_T^WZ [GeV]


ATLAS Preliminary
√s = 8 TeV, 20.3 fb⁻¹
Observed
Expected
±1σ expected
±2σ expected
W±Z → l±νl+l−
λ^Z
Δκ^Z

WZ - 8 TeV

aQGC





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ATLAS EXPERIMENT

W/Z Cross-sections and Ratios – 13 TeV

W/Z Cross-sections and Ratios – 13 TeV

Selection

W+/W-	Z
Exactly one lepton	Exactly two leptons with same-flavor and opposite-sign
$p_T(l) > 25$ GeV	
$\lvert\eta(l)\rvert < 2.5$	
$p_T(\nu) > 25$ GeV	
$m_T > 50$ GeV	$66 < m(ll) < 116$ GeV

ZZ→4l - 13 TeV

ZZ→4l - 13 TeV

Selection

Exactly 4 leptons with p_T > 20 GeV and $\|\eta\|$<2.7
Leptons must form two separate same-flavor opposite-sign pairs. When ambiguous, choose combination that minimizs $\|m(ll)_a - m(Z)\| + \|m(ll)_b - m(Z)\|$
66< M(ll) < 116 GeV for both pairs

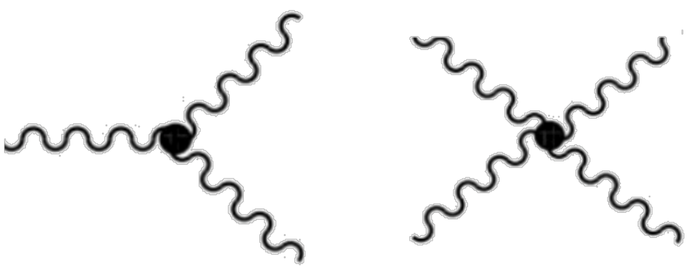
Anomalous Couplings

Anomalous Couplings

In addition to measuring cross-sections, we attempt to find new physics using an Effective Field Theory approach

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i + \sum_j \frac{f_j}{\Lambda^4}\mathcal{O}_j + \ldots$$

New physics suppressed by some cutoff scale, Λ



aTGC Operators

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	$Z\gamma$
$Z\gamma Z$	$f_{40}^\gamma, f_{50}^\gamma$	ZZ
ZZZ	f_{40}^Z, f_{50}^Z	ZZ

aQGC Operators

	WWWW	WWZZ	ZZZZ	WWAZ	WWAA	ZZZA	ZZAA	ZAAA	AAAA
$\mathcal{O}_{S,0}$, $\mathcal{O}_{S,1}$	X	X	X						
$\mathcal{O}_{M,0}$, $\mathcal{O}_{M,1}$,$\mathcal{O}_{M,6}$,$\mathcal{O}_{M,7}$	X	X	X	X	X	X	X		
$\mathcal{O}_{M,2}$,$\mathcal{O}_{M,3}$, $\mathcal{O}_{M,4}$,$\mathcal{O}_{M,5}$		X	X	X	X	X	X		
$\mathcal{O}_{T,0}$,$\mathcal{O}_{T,1}$,$\mathcal{O}_{T,2}$	X	X	X	X	X	X	X	X	X
$\mathcal{O}_{T,5}$,$\mathcal{O}_{T,6}$,$\mathcal{O}_{T,7}$		X	X	X	X	X	X	X	X
$\mathcal{O}_{T,8}$,$\mathcal{O}_{T,9}$			X			X	X	X	X

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arXiv:1310.6708

ATLAS EXPERIMENT

Dimension-6 EFT Operators

arXiv:1310.6708

Conserve CP:

$$\mathcal{O}_{WWW} = \mathrm{Tr}[W_{\mu\nu}W^{\nu\rho}W_{\rho}^{\mu}]$$

$$\mathcal{O}_{W} = (D_\mu\Phi)^\dagger W^{\mu\nu}(D_\nu\Phi)$$

$$\mathcal{O}_{B} = (D_\mu\Phi)^\dagger B^{\mu\nu}(D_\nu\Phi),$$

$$\mathcal{O}_{\Phi d} = \partial_\mu\left(\Phi^\dagger\Phi\right)\partial^\mu\left(\Phi^\dagger\Phi\right)$$

$$\mathcal{O}_{\Phi W} = \left(\Phi^\dagger\Phi\right)\mathrm{Tr}[W^{\mu\nu}W_{\mu\nu}]$$

$$\mathcal{O}_{\Phi B} = \left(\Phi^\dagger\Phi\right)B^{\mu\nu}B_{\mu\nu}$$

Violate CP:

$$\mathcal{O}_{\tilde{W}W} = \Phi^\dagger\tilde{W}_{\mu\nu}W^{\mu\nu}\Phi$$

$$\mathcal{O}_{\tilde{B}B} = \Phi^\dagger\tilde{B}_{\mu\nu}B^{\mu\nu}\Phi$$

$$\mathcal{O}_{\tilde{W}WW} = \mathrm{Tr}[\tilde{W}_{\mu\nu}W^{\nu\rho}W_{\rho}^{\mu}]$$

$$\mathcal{O}_{\tilde{W}} = (D_\mu\Phi)^\dagger\tilde{W}^{\mu\nu}(D_\nu\Phi),$$

	ZWW	AWW	HWW	HZZ	HZA	HAA	WWWW	ZZWW	ZAWW	AAWW
$\mathcal{O}_{WWW}$	X	X					X	X	X	X
$\mathcal{O}_{W}$	X	X	X	X	X		X	X	X	
$\mathcal{O}_{B}$	X	X		X	X					
$\mathcal{O}_{\Phi d}$			X	X						
$\mathcal{O}_{\Phi W}$			X	X	X	X				
$\mathcal{O}_{\Phi B}$				X	X	X				
$\mathcal{O}_{\tilde{W}WW}$	X	X					X	X	X	X
$\mathcal{O}_{\tilde{W}}$	X	X	X	X	X					
$\mathcal{O}_{\tilde{W}W}$			X	X	X	X				
$\mathcal{O}_{\tilde{B}B}$				X	X	X				

Dimension-8 EFT Operators

arXiv:1310.6708

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

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

$$\mathcal{O}_{M,0} = \mathrm{Tr}\left[W_{\mu\nu}W^{\mu\nu}\right] \times \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right],$$

$$\mathcal{O}_{M,1} = \mathrm{Tr}\left[W_{\mu\nu}W^{\nu\beta}\right] \times \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right],$$

$$\mathcal{O}_{M,2} = \left[B_{\mu\nu}B^{\mu\nu}\right] \times \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right],$$

$$\mathcal{O}_{M,3} = \left[B_{\mu\nu}B^{\nu\beta}\right] \times \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right],$$

$$\mathcal{O}_{M,4} = \left[(D_\mu\Phi)^\dagger W_{\beta\nu}D^\mu\Phi\right] \times B^{\beta\nu},$$

$$\mathcal{O}_{M,5} = \left[(D_\mu\Phi)^\dagger W_{\beta\nu}D^\nu\Phi\right] \times B^{\beta\mu},$$

$$\mathcal{O}_{M,6} = \left[(D_\mu\Phi)^\dagger W_{\beta\nu}W^{\beta\nu}D^\mu\Phi\right],$$

$$\mathcal{O}_{M,7} = \left[(D_\mu\Phi)^\dagger W_{\beta\nu}W^{\beta\mu}D^\nu\Phi\right],$$

$$\mathcal{O}_{T,0} = \mathrm{Tr}\left[W_{\mu\nu}W^{\mu\nu}\right] \times \mathrm{Tr}\left[W_{\alpha\beta}W^{\alpha\beta}\right],$$

$$\mathcal{O}_{T,1} = \mathrm{Tr}\left[W_{\alpha\nu}W^{\mu\beta}\right] \times \mathrm{Tr}\left[W_{\mu\beta}W^{\alpha\nu}\right],$$

$$\mathcal{O}_{T,2} = \mathrm{Tr}\left[W_{\alpha\mu}W^{\mu\beta}\right] \times \mathrm{Tr}\left[W_{\beta\nu}W^{\nu\alpha}\right],$$

$$\mathcal{O}_{T,5} = \mathrm{Tr}\left[W_{\mu\nu}W^{\mu\nu}\right] \times B_{\alpha\beta}B^{\alpha\beta},$$

$$\mathcal{O}_{T,6} = \mathrm{Tr}\left[W_{\alpha\nu}W^{\mu\beta}\right] \times B_{\mu\beta}B^{\alpha\nu},$$

$$\mathcal{O}_{T,7} = \mathrm{Tr}\left[W_{\alpha\mu}W^{\mu\beta}\right] \times B_{\beta\nu}B^{\nu\alpha},$$

$$\mathcal{O}_{T,8} = B_{\mu\nu}B^{\mu\nu}B_{\alpha\beta}B^{\alpha\beta}$$

$$\mathcal{O}_{T,9} = B_{\alpha\mu}B^{\mu\beta}B_{\beta\nu}B^{\nu\alpha}.$$

	WWWW	WWZZ	ZZZZ	WWAZ	WWAA	ZZZA	ZZAA	ZAAA	AAAA
$\mathcal{O}_{S,0}$, $\mathcal{O}_{S,1}$	X	X	X						
$\mathcal{O}_{M,0}$, $\mathcal{O}_{M,1}$, $\mathcal{O}_{M,6}$, $\mathcal{O}_{M,7}$	X	X	X	X	X	X	X		
$\mathcal{O}_{M,2}$, $\mathcal{O}_{M,3}$, $\mathcal{O}_{M,4}$, $\mathcal{O}_{M,5}$		X	X	X	X	X	X		
$\mathcal{O}_{T,0}$, $\mathcal{O}_{T,1}$, $\mathcal{O}_{T,2}$	X	X	X	X	X	X	X	X	X
$\mathcal{O}_{T,5}$, $\mathcal{O}_{T,6}$, $\mathcal{O}_{T,7}$		X	X	X	X	X	X	X	X
$\mathcal{O}_{T,8}$, $\mathcal{O}_{T,9}$			X			X	X	X	X

WV Semi-leptonic - 7 TeV

WV Semi-leptonic - 7 TeV

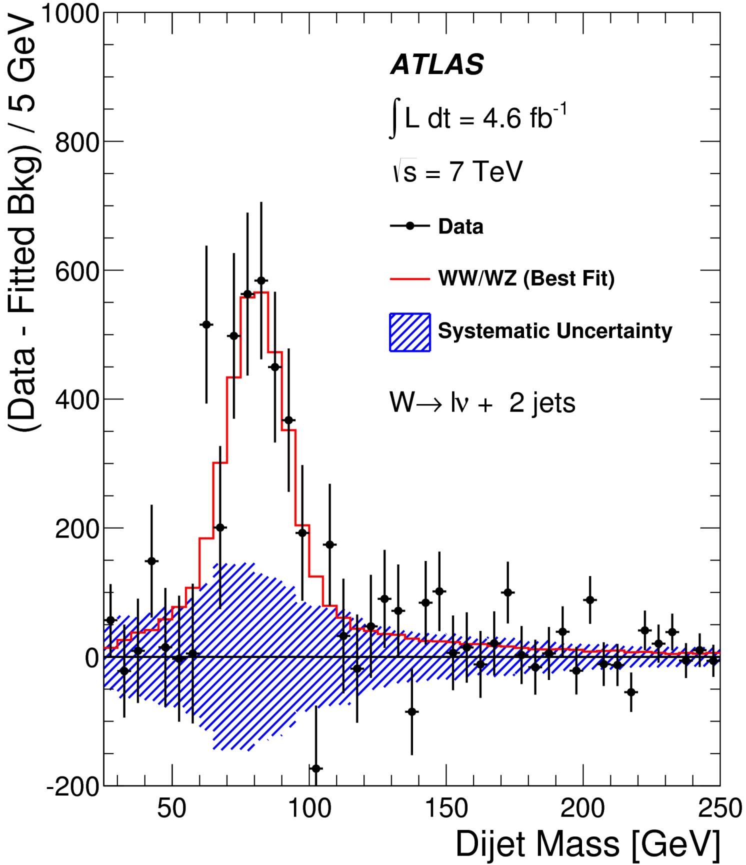
JHEP 01 (2015) 049
arXiv:1410.7238v2

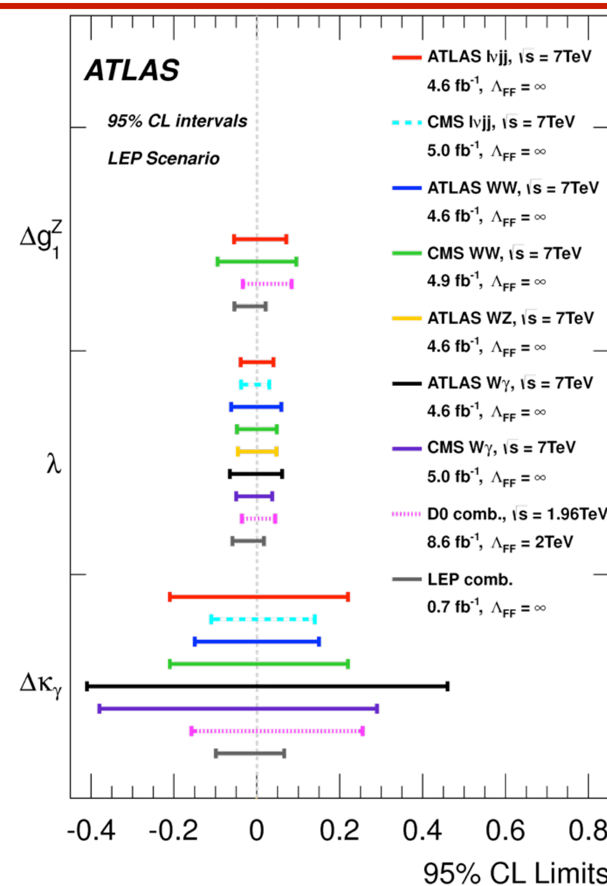
WW+WZ →lν jj cross-section measured with observed (expected) significance of 3.4σ (3.2σ)

σ(Total NLO Exp.) = 61.1 ± 2.2 pb

σ(Total Obs.) = 68 ± 7 (Stat.) ± 19 (Syst.) pb

Shape of dijet mass used to extract cross-section





Limits set on three aTGC parameters using LEP scenario

Fit performed on p_T(jj) spectrum with 75 < m(jj) < 95 GeV

No unitarization form factors are applied

WV Semi-leptonic - 7 TeV

Selection

Exactly 1 lepton with p_T > 25 GeV and exactly 2 jets with leading (subleading) p_T > 30 (25) GeV
MET > 30GeV
M_T > 40GeV
$\lvert\Delta\varphi(\mathrm{MET,Leading\ jet})\rvert > 0.8$
$\lvert\Delta\eta(j,j)\rvert < 1.5$
$\Delta R(j,j) > 0.7$ if $p_T(jj) < 250$ GeV
$p_T(jj) > 250$ GeV
$25 < m(jj) < 250$ GeV

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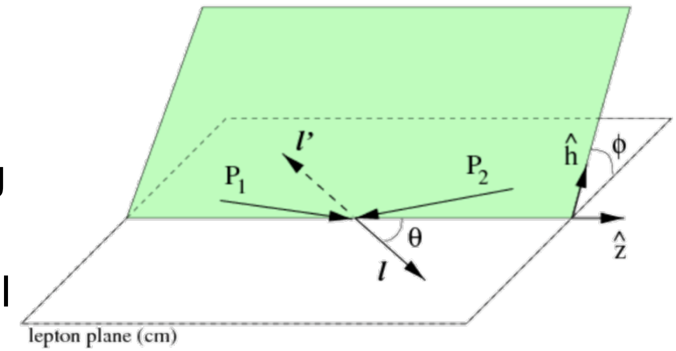
ATLAS EXPERIMENT

Z Forward-Backward Asymmetry - 7 TeV

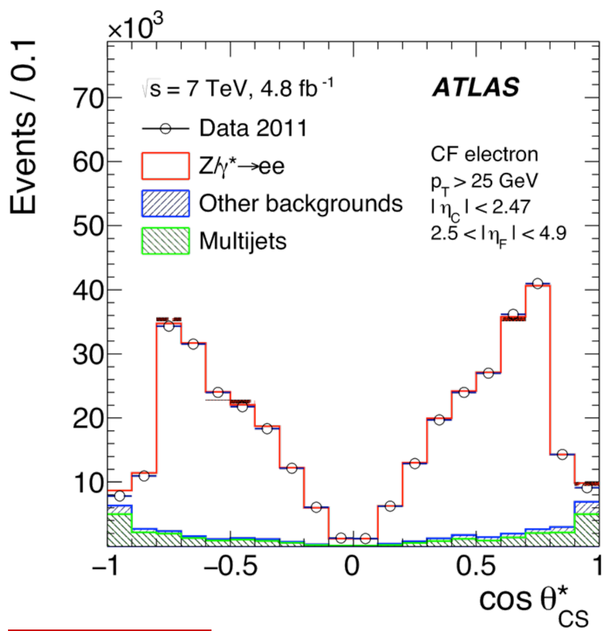
Z Forward-Backward Asymmetry - 7 TeV

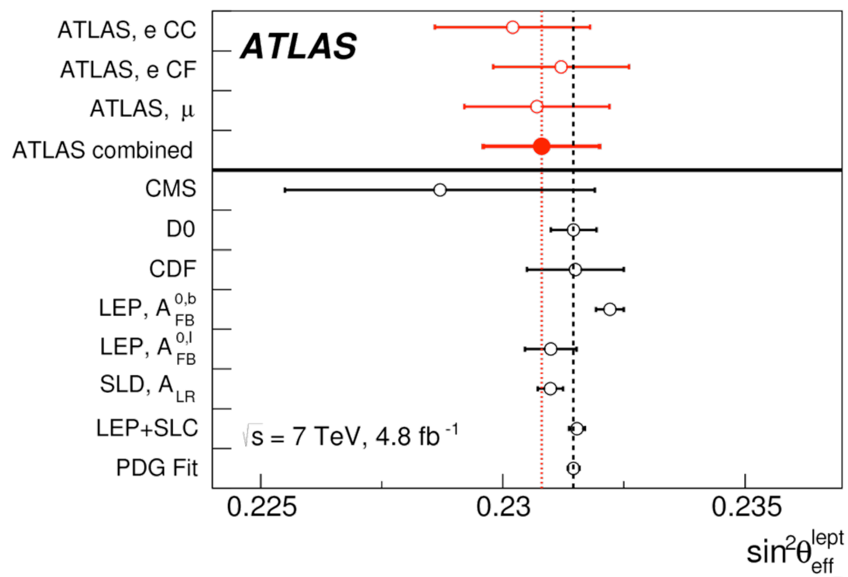
JHEP 09 (2015) 049
arXiv:1503.03709



- Extract $\sin^2(\theta^{lept}_{eff})$ from template fit of A_{FB} at the Z-pole
- Collins-Soper frame used to minimize ambiguity of incoming quark
- Combined measurement is found to be within 0.6 σ of global PDG fit:

$$\sin^2\theta^{\rm lept}_{\rm eff} = 0.2308 \pm 0.0005\ ({\rm Stat.}) \pm 0.0006\ ({\rm Syst.}) \pm 0.0009\ ({\rm PDF})$$





$$A_{\rm FB} = \frac{N_{\cos\theta^*_{\rm CS}\geq 0} - N_{\cos\theta^*_{\rm CS}<0}}{N_{\cos\theta^*_{\rm CS}\geq 0} + N_{\cos\theta^*_{\rm CS}<0}}$$

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ATLAS EXPERIMENT

Z Forward-Backward Asymmetry - 7 TeV

Selection

Object Selection

Electron Central	Electron Forward	Muon
Electron $|\eta| < 2.47$ except $1.37 < |\eta| < 1.52$	Electron $2.5 < |\eta| < 4.9$ except $3.16 < |\eta| < 3.35$	$|\eta| < 2.4$
$E_T > 25$ GeV	$E_T > 25$ GeV	$p_T > 20$ GeV

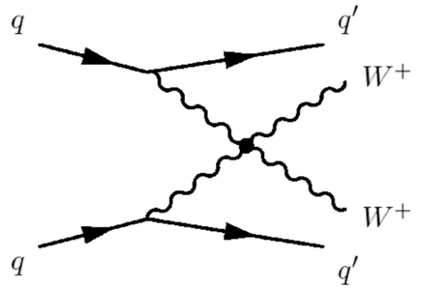
Event Selection

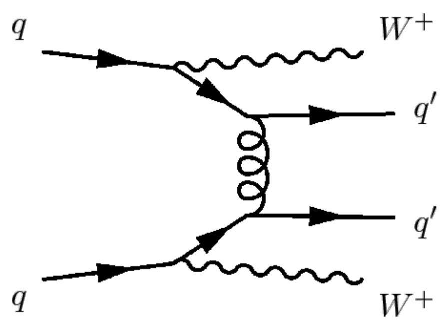
Electron Central-Central	Electron Central-Forward	Muon
Two opposite-sign medium quality central electron candidates	One tight quality central and one medium quality forward electron candidate. (No charge requirement)	Two combined muons
$E_T > 25$ GeV	$E_T > 25$ GeV	$p_T > 20$ GeV
M(ll) < 1 TeV	M(ll) < 250 GeV	M(ll) < 1 TeV

Same-Sign WW - 8 TeV

Same-Sign WW - 8 TeV

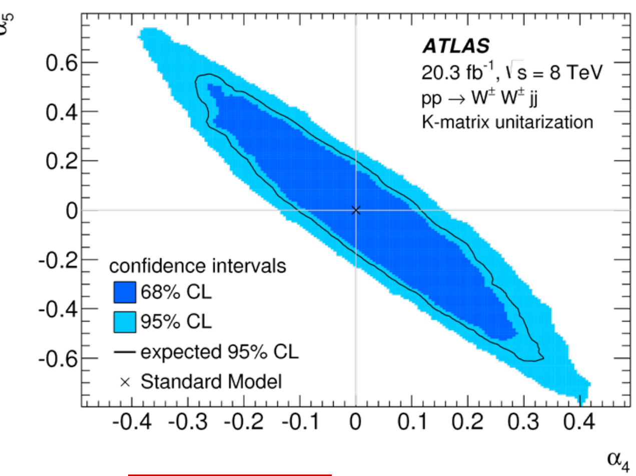
PRL. 113, (2014) 141803
arXiv:1405.6241v2

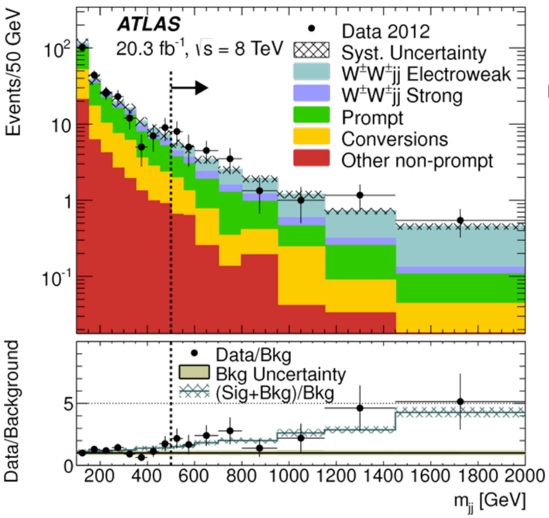


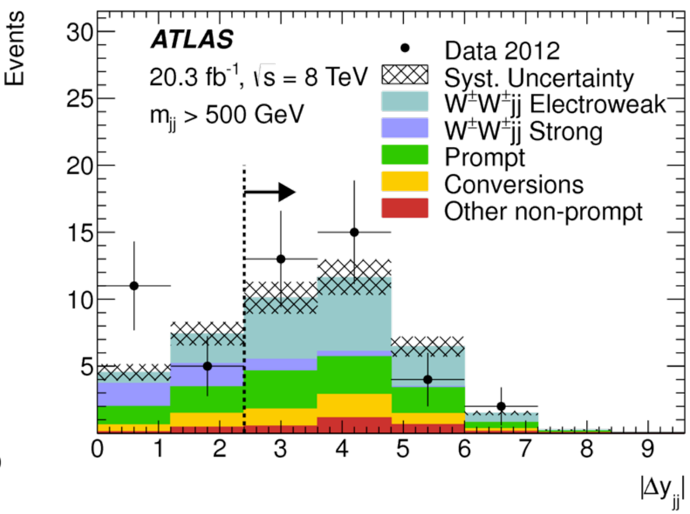


First evidence for W±W±jj VBS process at 4.5σ inclusive (3.6σ for EW only).

- σ(Fid. NLO EW) = 1.52 ± 0.11 fb
  σ(Obs. EW) = 2.1 ± 0.5 (Stat.) ± 0.3 (Syst.) fb
- σ(Fid. NLO EW+QCD) = 0.95 ± 0.06 fb
  σ(Obs. EW+QCD) = 1.3 ± 0.4 (Stat.) ± 0.2 (Syst.) fb







- Limits are set on aQGCS for dimension-8 operators α_4 vs α_5
- First limits on these parameters.
- aQGC predictions unitarized using k-matrix

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ATLAS EXPERIMENT

Same-Sign WW - 8 TeV

Selection

Inclusive Region (QCD + EW)	VBS Region (EW)
Exactly two leptons with same charge, p_T > 25 GeV, $\|\eta\|$ <2.5	
At least two jets with p_T > 30 GeV	
MET > 40 GeV	
M(ll) > 20 GeV	
ΔR(ll) > 0.3	
M(jj) > 500 GeV	
	$\|\Delta y(jj)\|$ > 2.4

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ATLAS EXPERIMENT

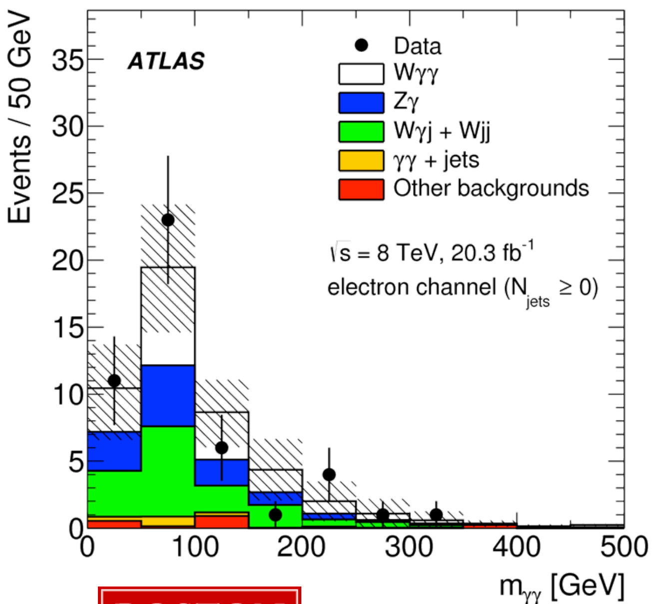
Wγγ - 8 TeV

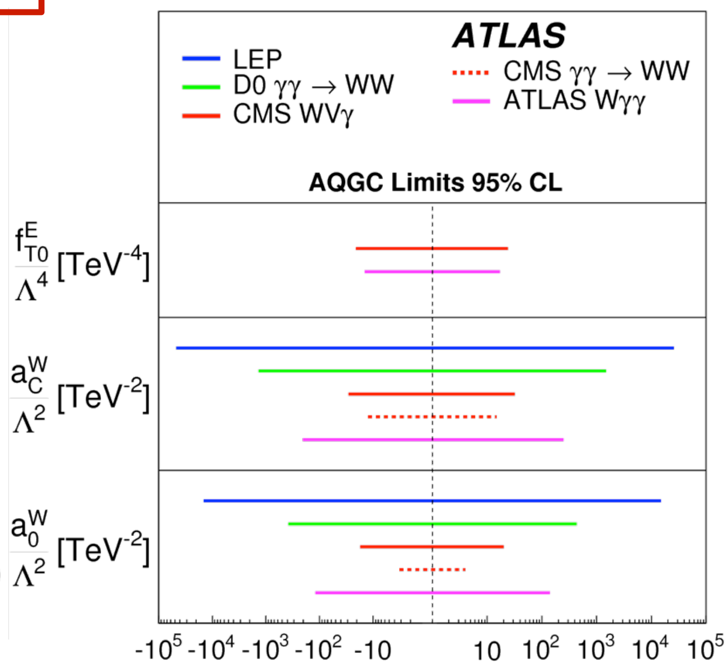
Wγγ - 8 TeV

PRL 115, 031802 (2015)
arXiv:1503.03243v2

- First ever measurement of a tri-boson process
- Process comes from ISR/FSR and TGC/QGC with W boson.
- Considering only leptonic decays.
- Significance of inclusive cross-section measurement is > 3 σ compared to NLO prediction

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





- Limits set on dimension-8 couplings: f_{T0}, f_{M2}, and f_{M3}
- Best sensitivity for f_{T0}
- f_{M2} and f_{M3} can be compared to dimension-6 operators studied at LEP, D0 and CMS

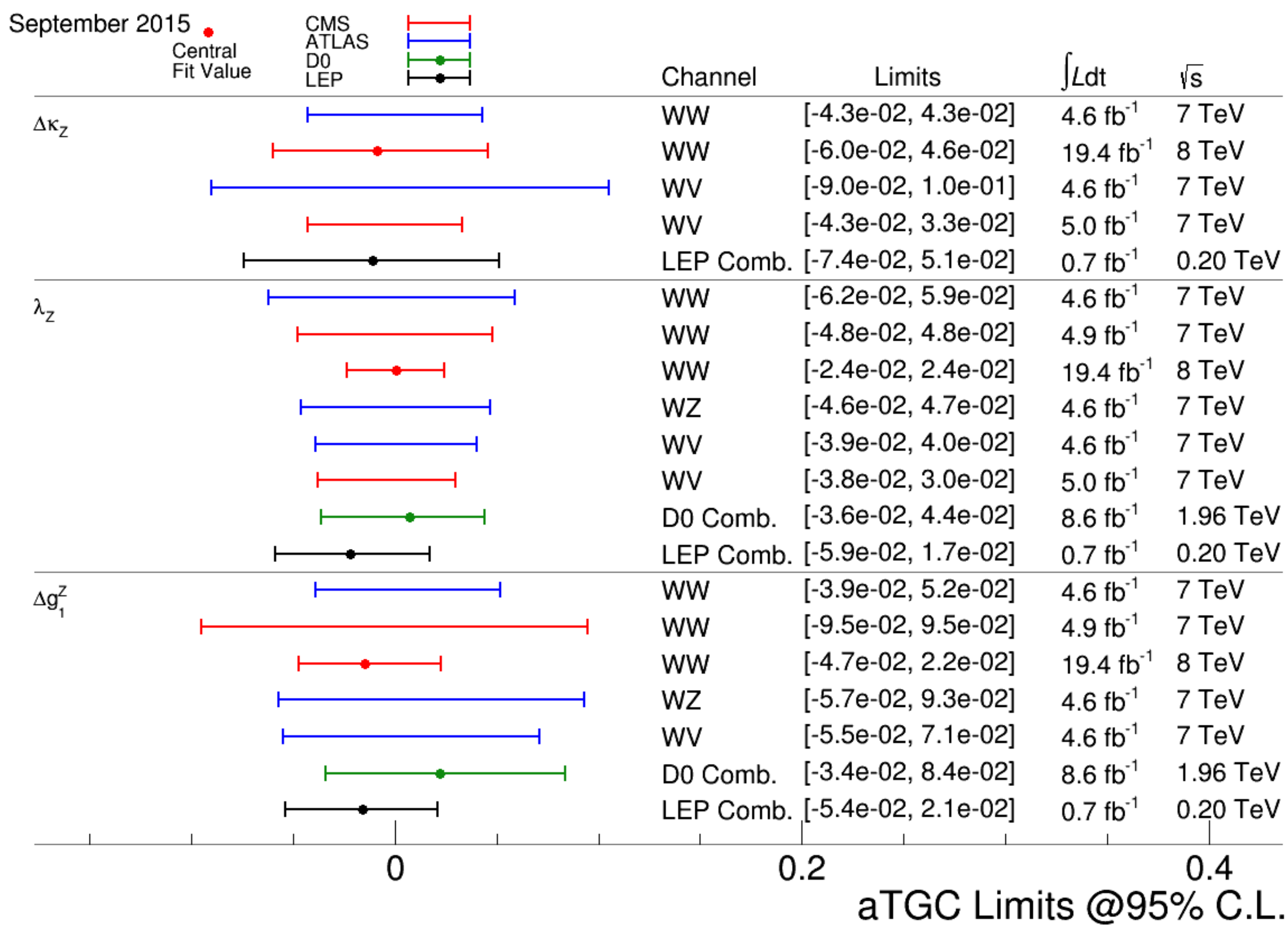
Wγγ - 8 TeV

Selection

Definition of the fiducial region
$p_{\mathrm{T}}^{\ell} > 20\,GeV$, $p_{\mathrm{T}}^{\nu} > 25\,GeV$, $\lvert\eta_{\ell}\rvert < 2.5$
$m_{\mathrm{T}} > 40\,GeV$
$E_{\mathrm{T}}^{\gamma} > 20\,GeV$, $\lvert\eta^{\gamma}\rvert < 2.37$, 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 $p_{\mathrm{T}}^{\mathrm{jet}} > 30\,GeV$, $\lvert\eta^{\mathrm{jet}}\rvert < 4.4$

CMS

CMS – WWZ aTGC limits

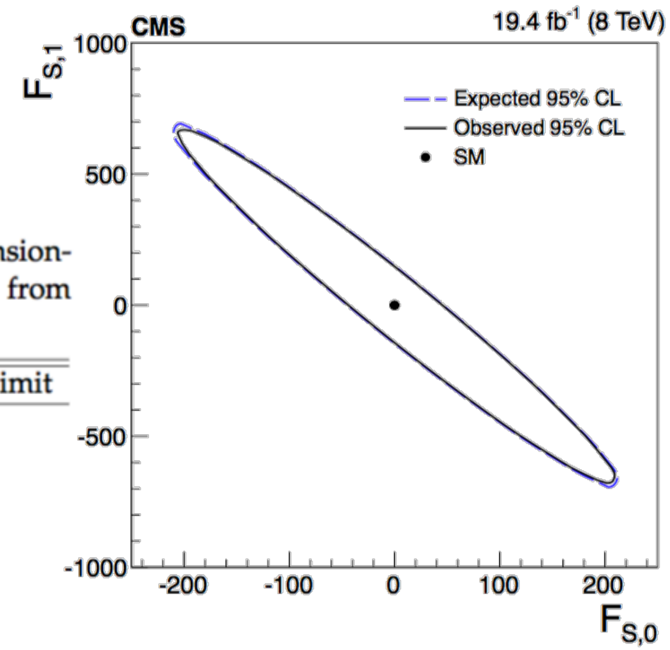


https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMPaTGC

CMS – ssWW aQGC limits

Table 2: Observed and expected upper and lower limits at 95% CL limits on the nine dimension-eight operators that effect quartic couplings between the weak gauge bosons. Limits from unitarity are reported. The units are TeV^{-4}.

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



arXiv:1410.6315v2