Diboson and Multiboson Results with ATLAS

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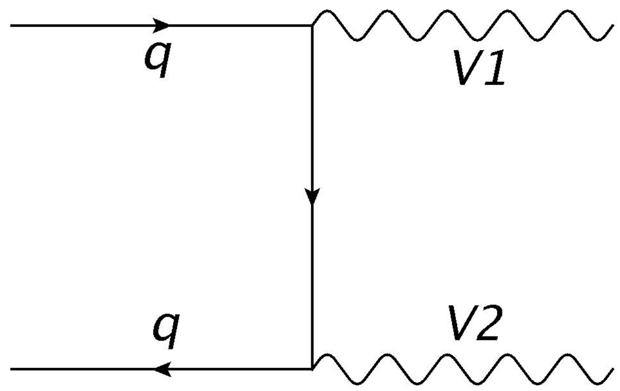
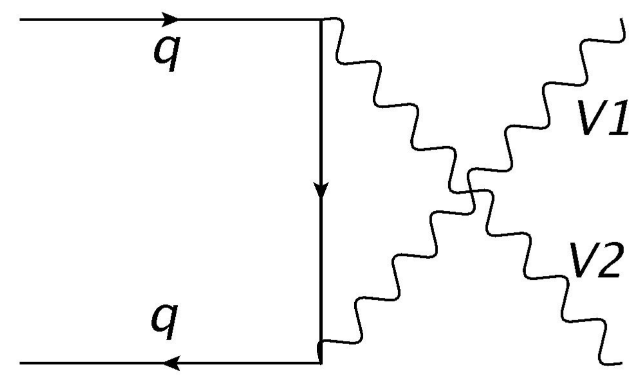
On behalf of the ATLAS collaboration

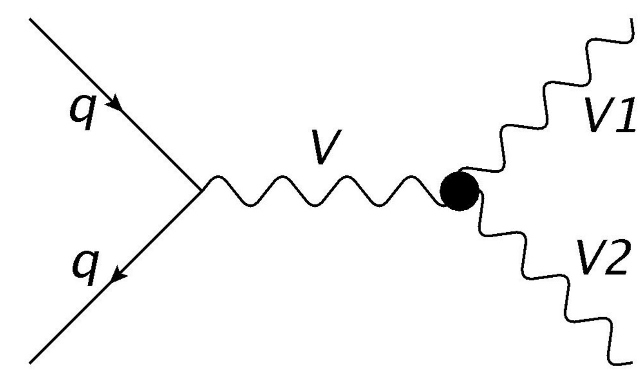
LHCP 2016 : Fourth Annual Large Hadron Collider Physics Conference
Lund, Sweden

13th - 18th June 2016

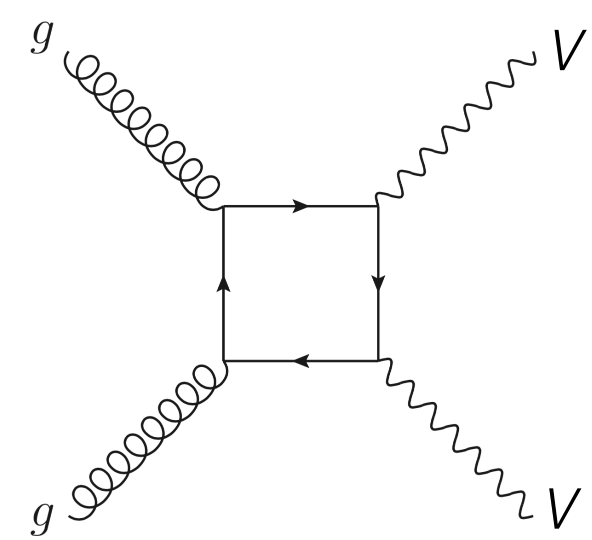
Diboson and Multiboson physics at the LHC

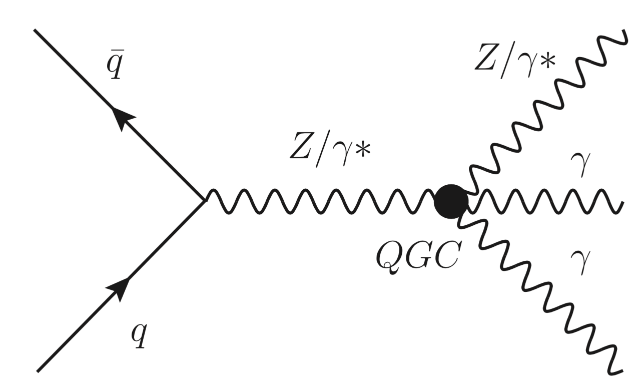






- ✦ Precision test of the standard model (SM) at the TeV scale.
- ✦ Understanding these processes is important for background estimations needed for many measurements.
- ✦ Allows constraints to be set on many exotic models through the study of cross-sections, triple and quartic gauge boson couplings (TGC and QGC) vertices.





Multiboson measurement strategy

✦ Measure cross sections within fiducial region :

$$\sigma_{\text{fid}} = \frac{N_{data} - N_{bg}}{\mathcal{L} C_{VV}}$$

✦ Extrapolate to the total cross section :

$$\sigma_{\text{tot}} = \sigma_{\text{fid}} \times \frac{1}{A_{VV}\mathcal{B}}$$

C_{VV} - ratio of # measured events to # events in fiducial region

A_{VV} - ratio of events in fiducial region to total region

$\mathcal{B}$ - Branching ratio

$\mathcal{L}$ - integrated luminosity

✦ Study unfolded differential distributions and probe high momentum events for anomalous TGC's and QGC's (aTGC's and aQGC's).

Charged couplings : γWW, ZWW, WWZZ, WWZγ, WWγγ - allowed within the SM.

Neutral couplings : ZZγ, γγZ, ZZZ, ZZγγ, Zγγγ - Not allowed within the SM.

Intro to aTGC/aQGCs and Parameterisation

- Effective Lagrangians can be used to probe for new physics at energy scale Λ in a model independent way.
- Assume Λ lies above energy range of experiments.

$$\mathcal{L}_{eff} = \sum_n \frac{1}{\Lambda^n} \sum_i \alpha_i^{(n)} \mathcal{O}_i^{(n)}$$

$\alpha_i^{(n)}$ - coupling coefficients

$\mathcal{O}_i^{(n)}$ - operators of dimension mass^{4+n}

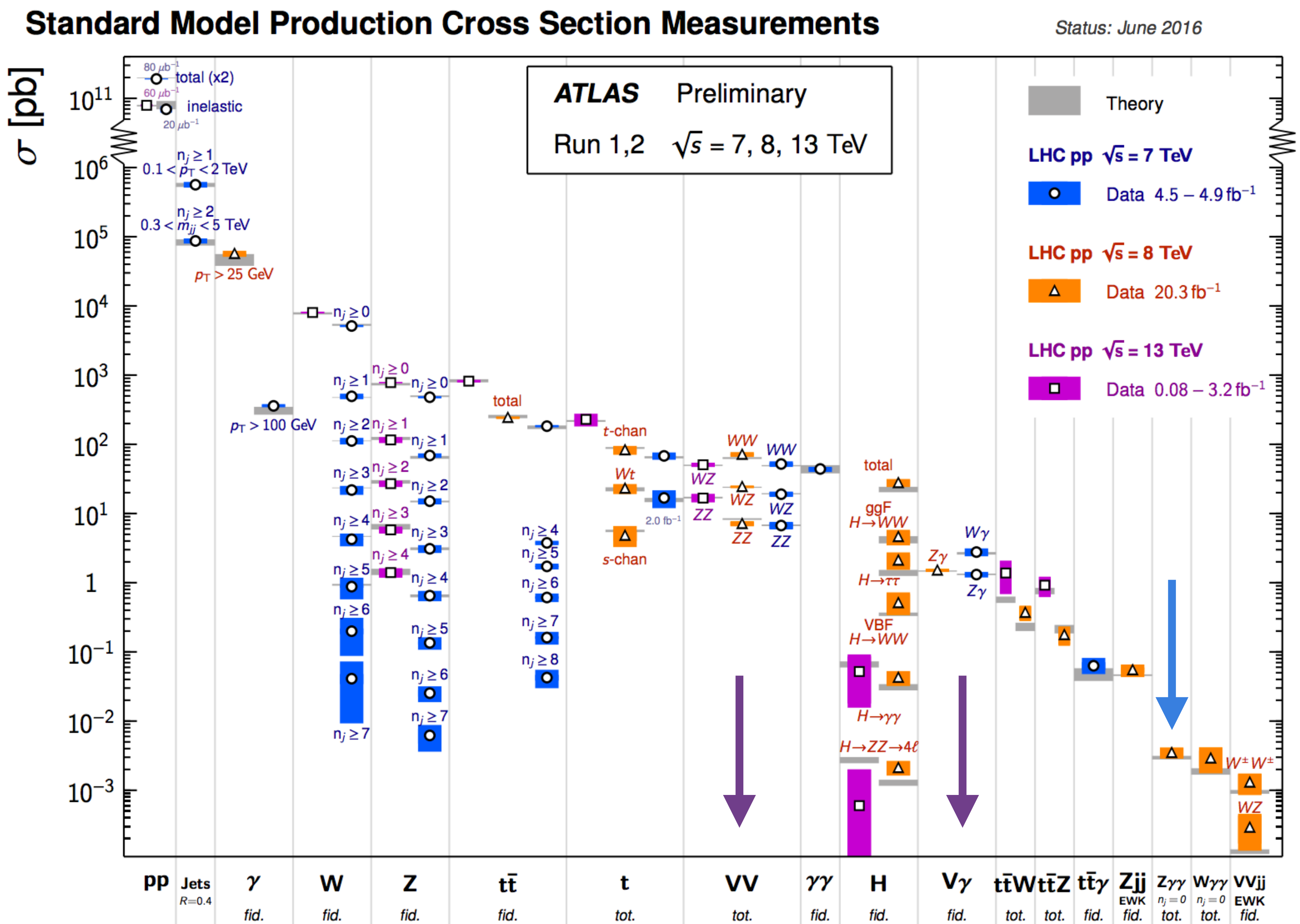
- Expanding up to dim.6 and including only CP conserving couplings - couplings for WWV vertex.

$$\mathcal{L} = -ig_{WWV}[g_1^V(W^\dagger_{\mu\nu}W^\mu - W^{\dagger\mu}W_{\mu\nu})V^\nu + \kappa^V W^\dagger_\mu W_\nu V^{\mu\nu} + \frac{\lambda^V}{m_W^2} W^\dagger_{\rho\mu} W^\mu_\nu V^{\nu\rho}]$$

$$\mathbf{SM : g_1^V = \kappa_V = 1; \lambda_V = 0}$$

- Additional couplings for QGC's and neutral couplings from dim.8 operators.

Multiboson measurements at ATLAS



New

8 TeV

✦ $W^+W^- \rightarrow l^+\nu l^-\nu$

✦ $W^\pm Z \rightarrow l^\pm\nu l^\pm l^\mp$

✦ $Z\gamma$, $Z\gamma\gamma$ ($Z \rightarrow l^\pm l^\mp$ or $\nu\nu$)

13 TeV

✦ $ZZ \rightarrow 4l$

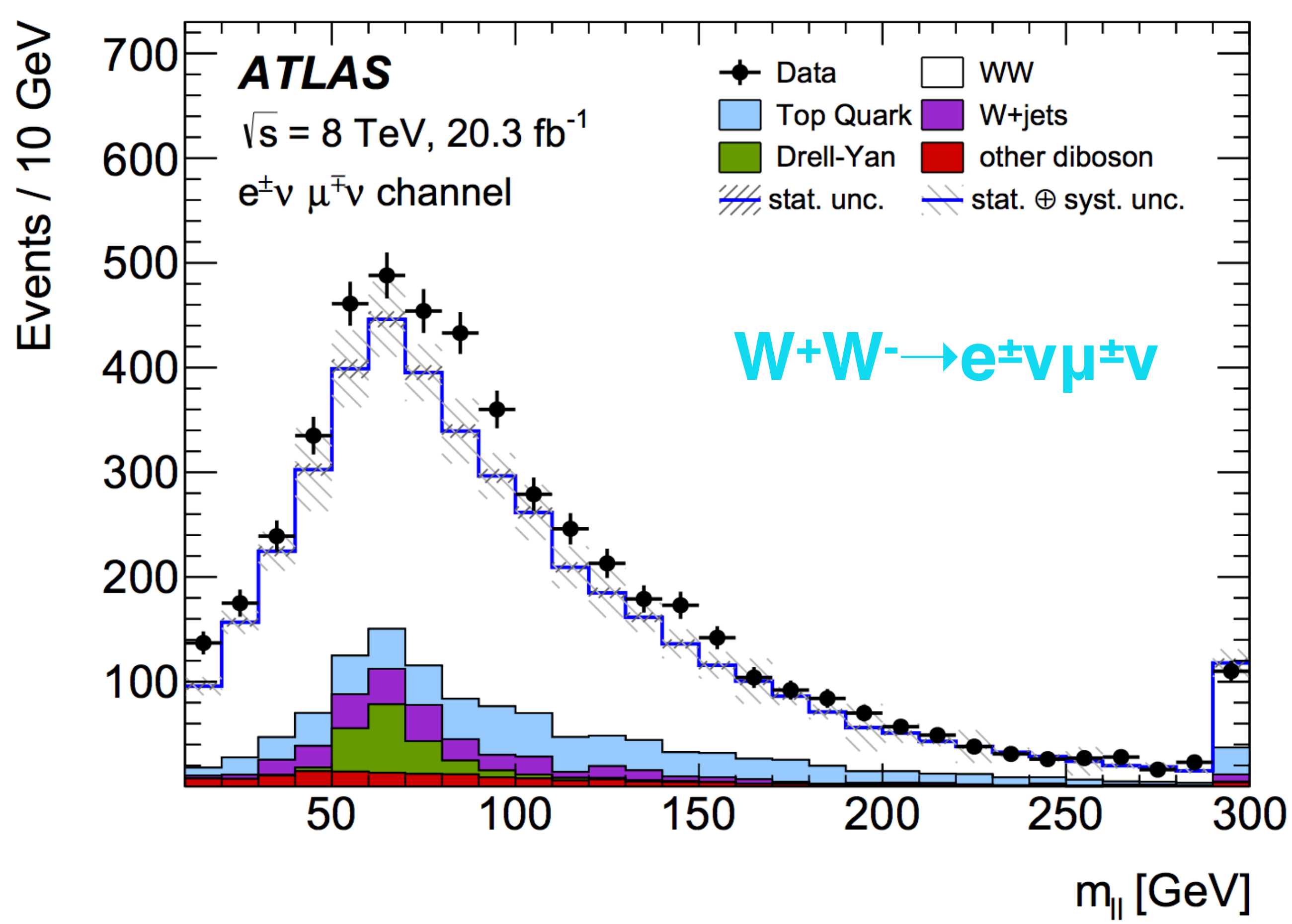
✦ $WZ \rightarrow l^\pm\nu l^\pm l^\mp$

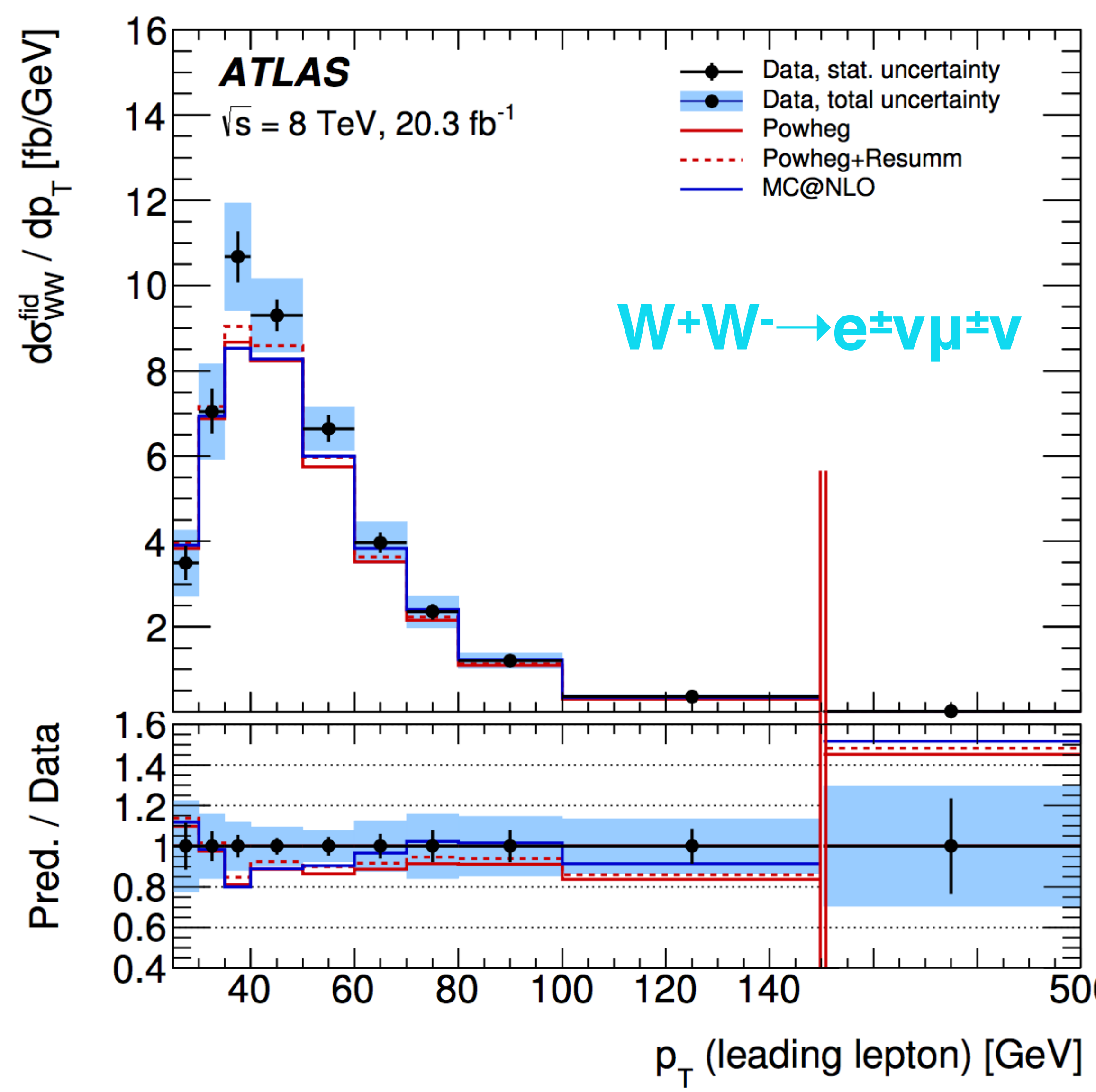
Diboson Triboson

- ✦ Preceding talks
  - Di-boson production at the LHC (Lara Iglesias)
  - Multi-boson production, vector boson fusion & scattering processes at the LHC (Emily Nurse)
- ✦ Succeeding talks
  - Diboson and multiboson results with CMS (Nate Woods)
  - Vector boson scattering and fusion results from ATLAS and CMS (Qiang Li)

$W^+W^- \rightarrow l^+ \nu l^- \nu$ measurements at 8 TeV

- ✦ $W^+W^- \rightarrow l^+ \nu l^- \nu$ (W decay to $e^\pm$ or $\mu^\pm + \nu$), jet veto applied to suppress top quark background.
- ✦ Measurements of σ_{fid}, σ_{tot}, differential distributions and limits set on aTGC's.
- ✦ Background ~20-30% dominated by top quark backgrounds (ttbar and single top)
- ✦ Prediction generally undershoots data but the shapes show agreement up to the level of ±15%.



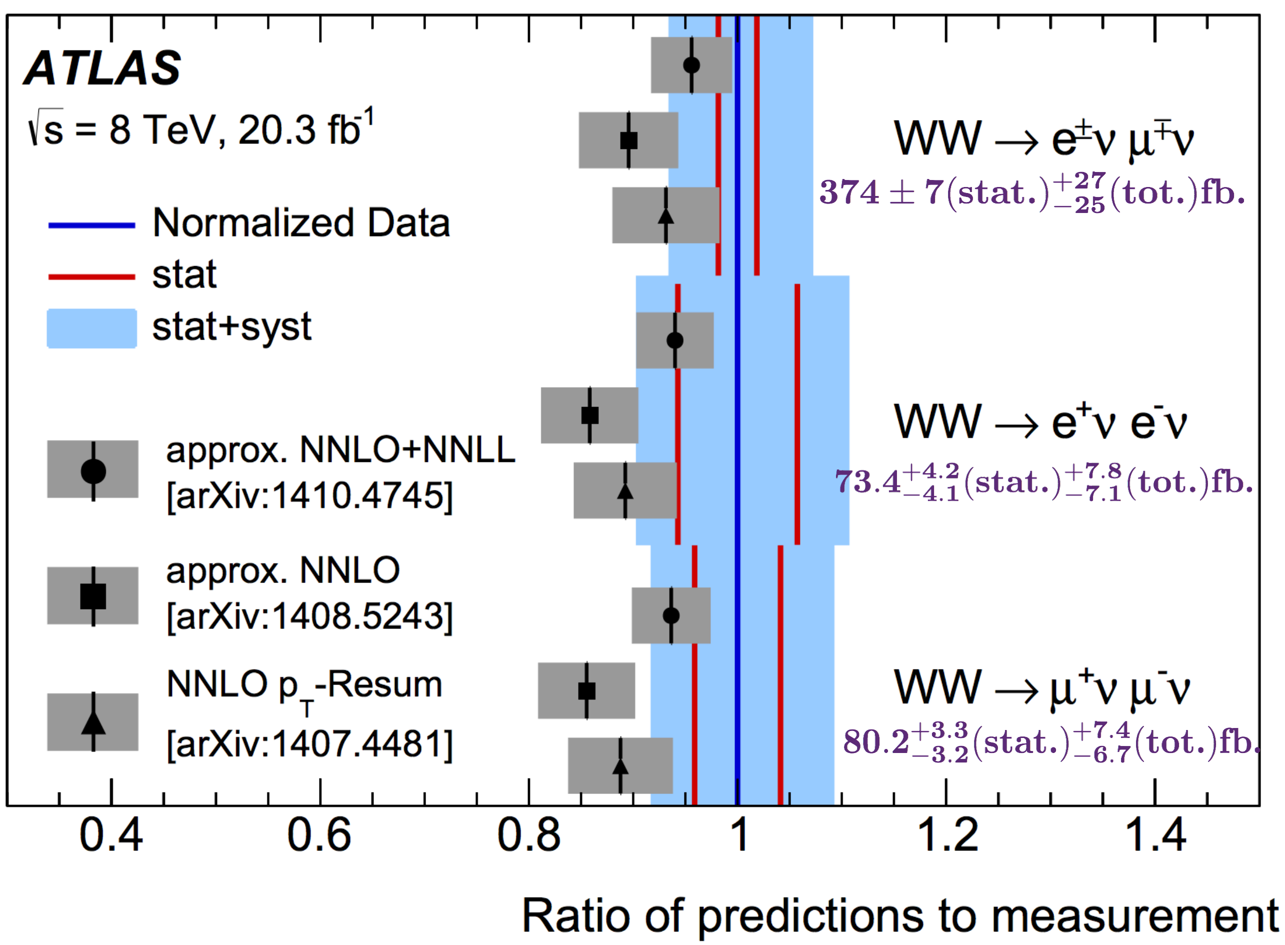


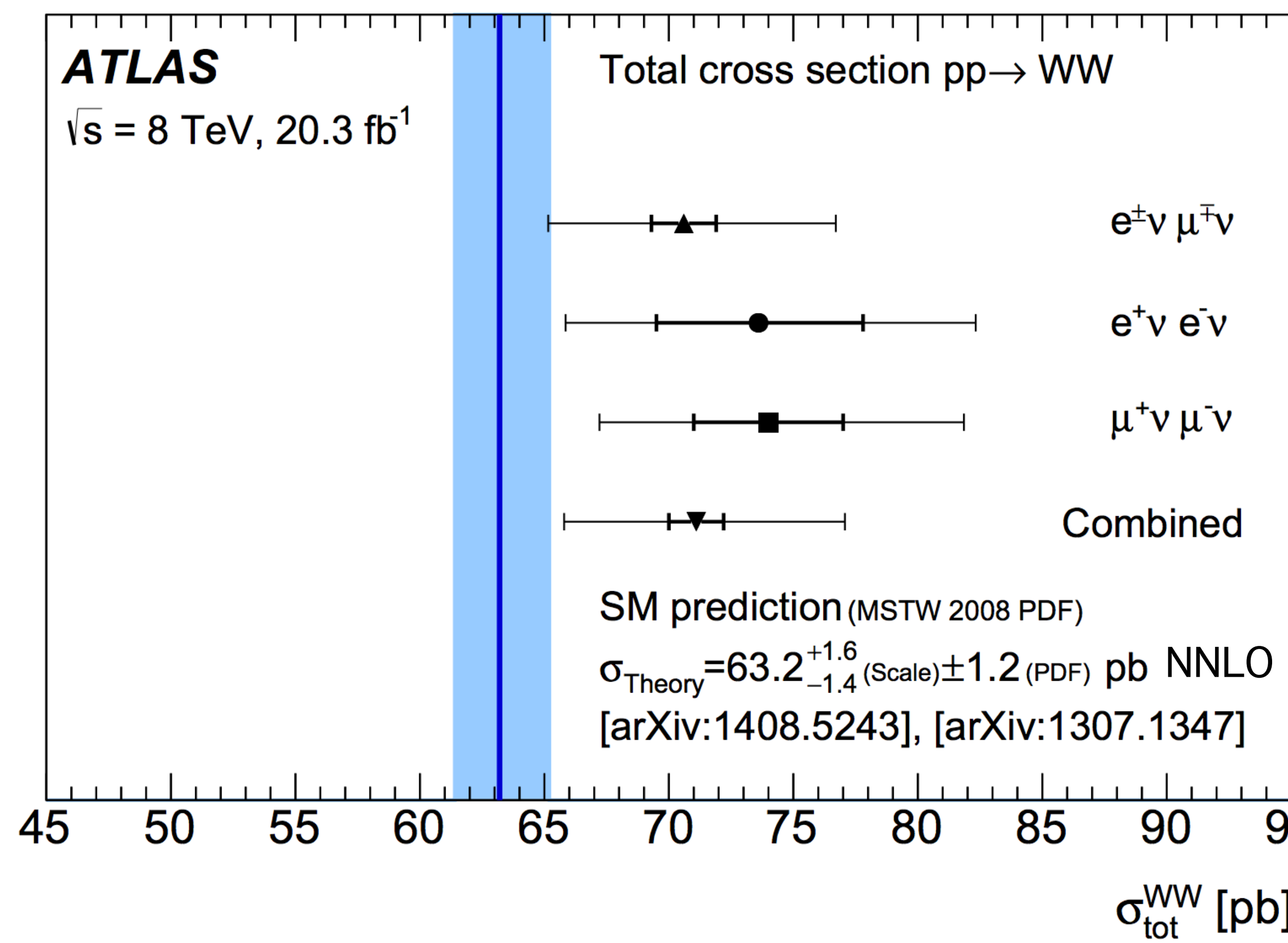
http://arxiv.org/abs/1603.01702

$W^+W^- \to l^+ \nu l^- \nu$ measurements at 8 TeV

- ✦ Systematically dominated measurement.
- ✦ Dominated by uncertainties due to jet energy scale (~4%) and knowledge of W+jets background (~3%)

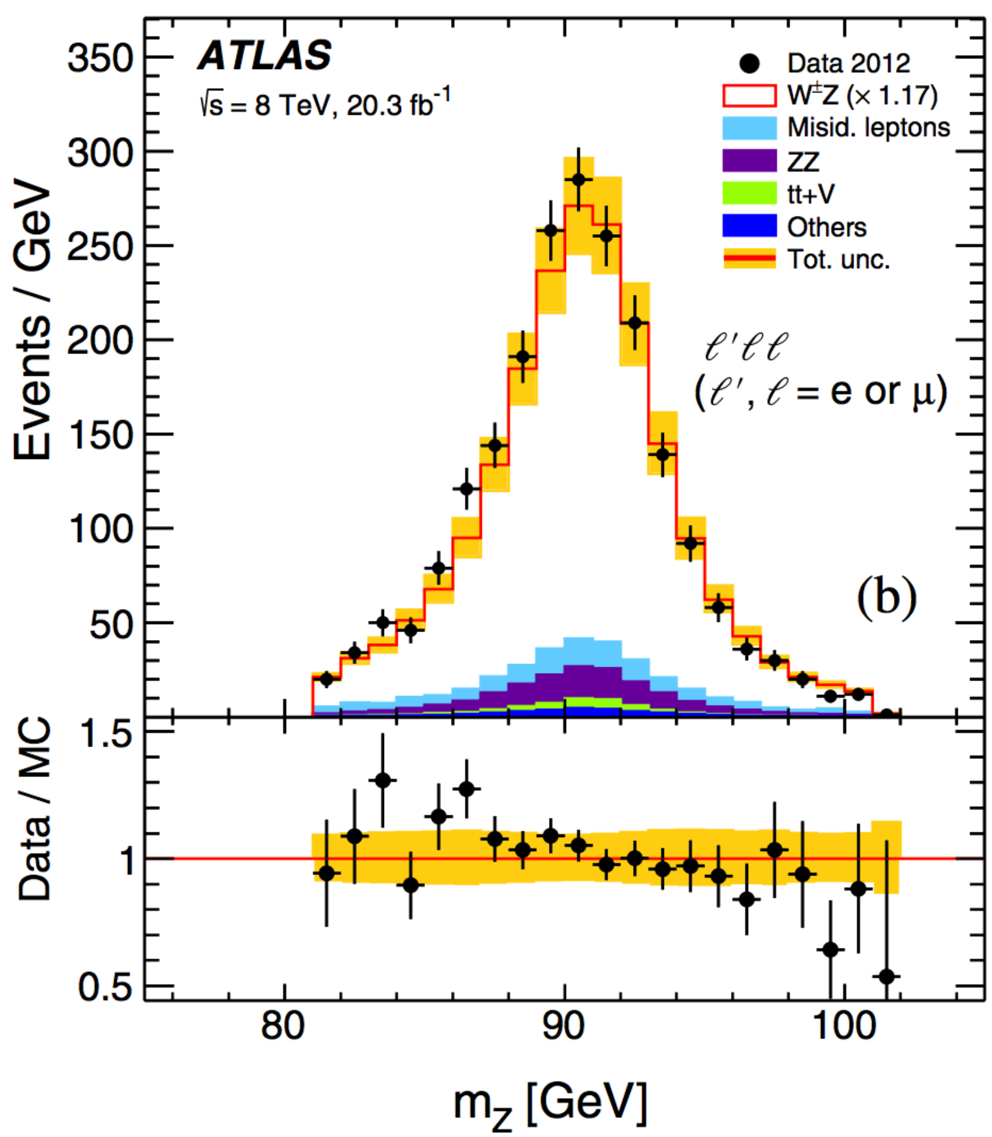
$$\sigma_{\mathbf{tot}}^{\mathbf{W^+W^-}} = \mathbf{71.1 \pm 1.1(stat.)^{+5.7}_{-5.0}(syst.) \pm 1.4(lumi.)pb.}$$

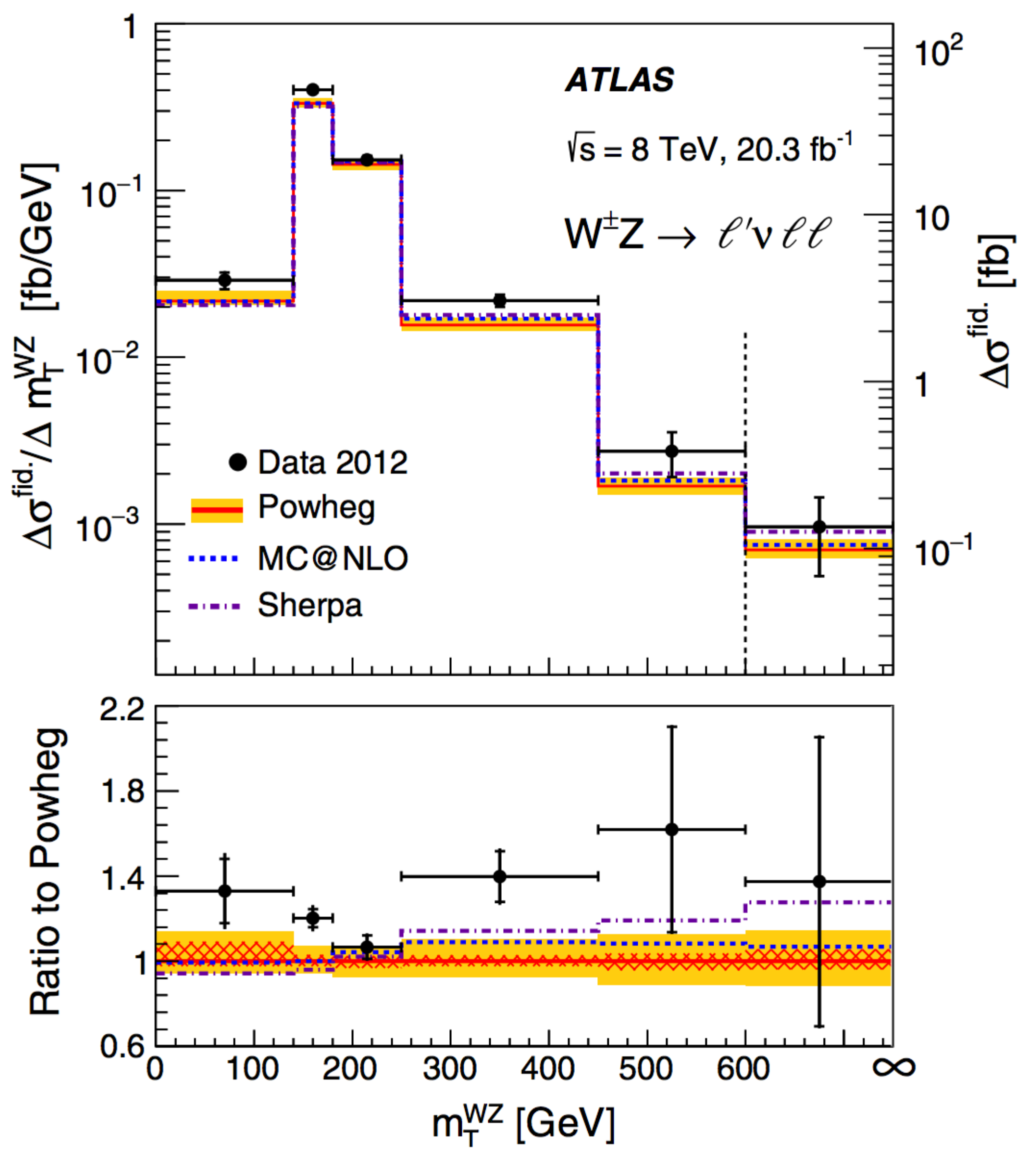




$W^{\pm}Z \rightarrow l^{\pm}\nu l^{\pm}l^{\mp}$ measurements at 8 TeV

- ✦ $W^{\pm}Z \rightarrow l^{\pm}\nu l^{\pm}l^{\mp}$ (decay to $e^{\pm}$ or $\mu^{\pm}$) - on shell Z boson, additional lepton and high m_T^W (>30 GeV).
- ✦ Measurements of σ_{fid}, σ_{tot}, $\sigma(W^+Z)/\sigma(W^-Z)$, differential distributions and limits set on aTGC's.
- ✦ (**) Search for VBS WZ and aQGC's limits set in VBS phase space.
- ✦ Background ~20% dominated by misidentified leptons and ZZ.





http://journals.aps.org/prd/abstract/10.1103/PhysRevD.93.092004

(**) **Details shown on slide 30, also see talk by Qiang Li.**

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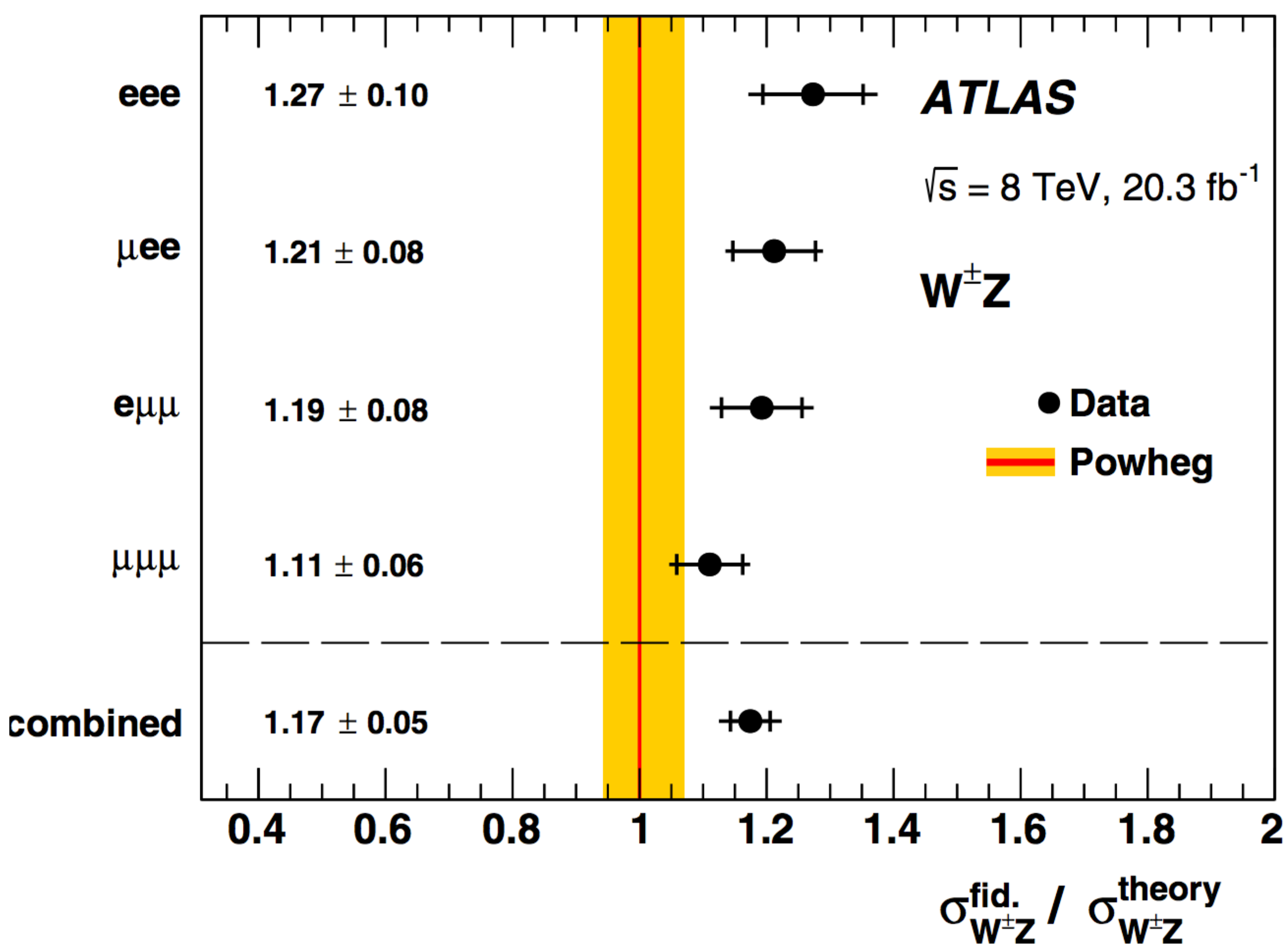
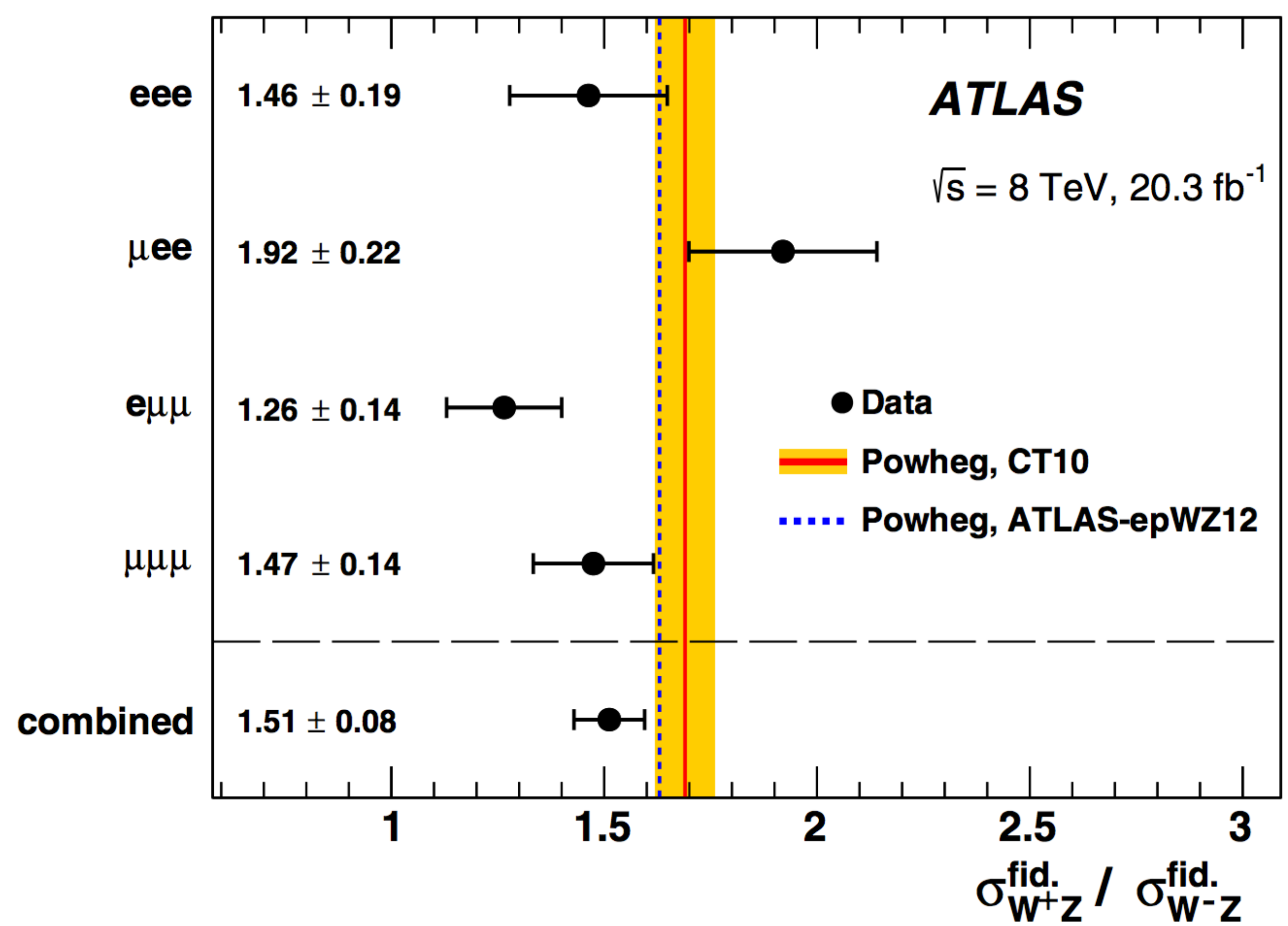
$W^{\pm}Z \rightarrow l^{\pm}\nu l^{\pm}l^{\mp}$ measurements at 8 TeV

- σ_{fid}, σ_{tot} - statistical and systematic uncertainties ~ equal. $\sigma(W^{+}Z)/\sigma(W^{-}Z)$ - stats dominated.
- Systematics dominated by electron Id. efficiency, muon reco. efficiency and knowledge of mis. Id background.
- Dominant theory uncertainty due to QCD scale uncertainty.

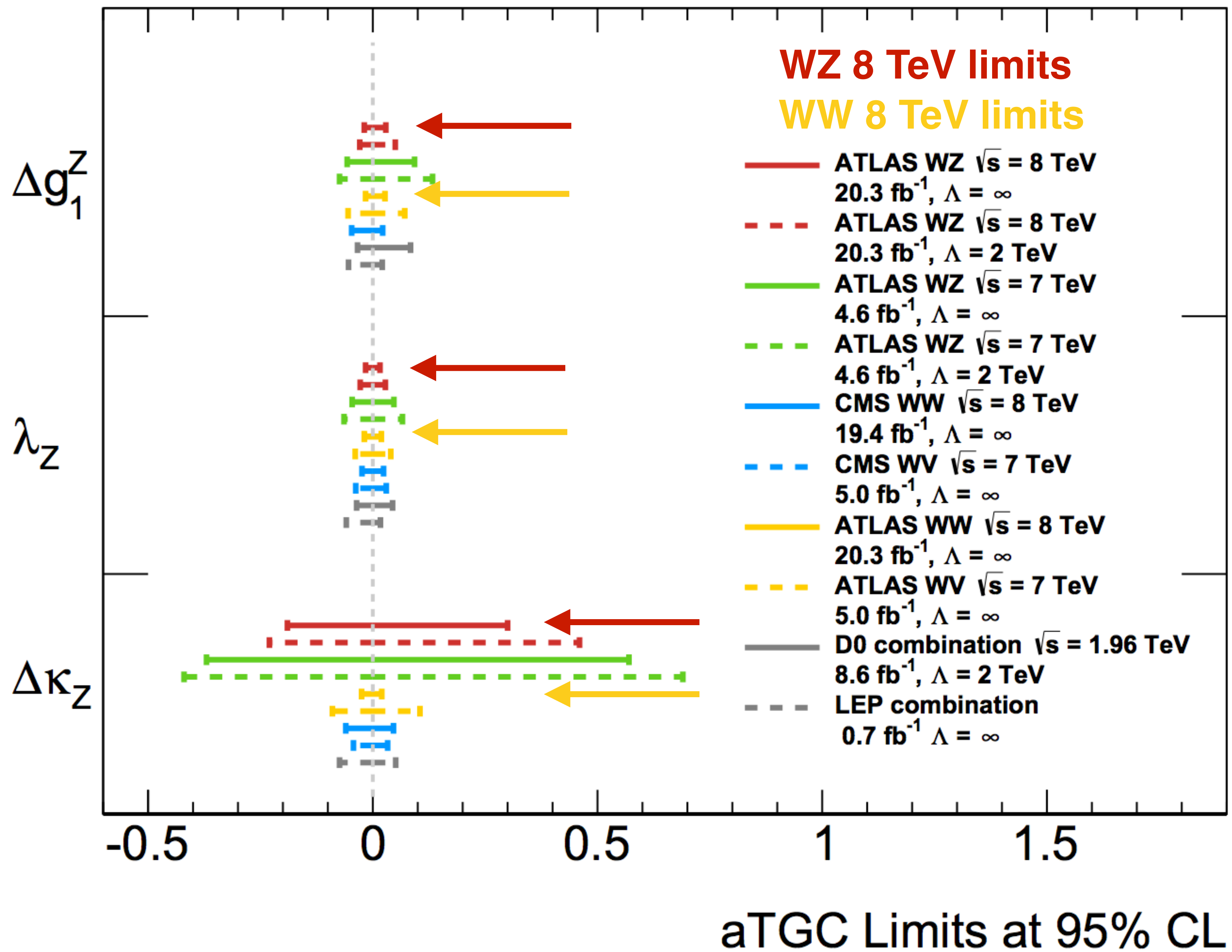
$$\sigma^{tot}_{W^{\pm}Z} = 24.3 \pm 0.6(\text{stat.}) \pm 0.6(\text{syst.}) \pm 0.4(\text{th.}) \pm 0.5(\text{lumi.})\text{pb}.$$





Limits on charged aTGC couplings at 8 TeV

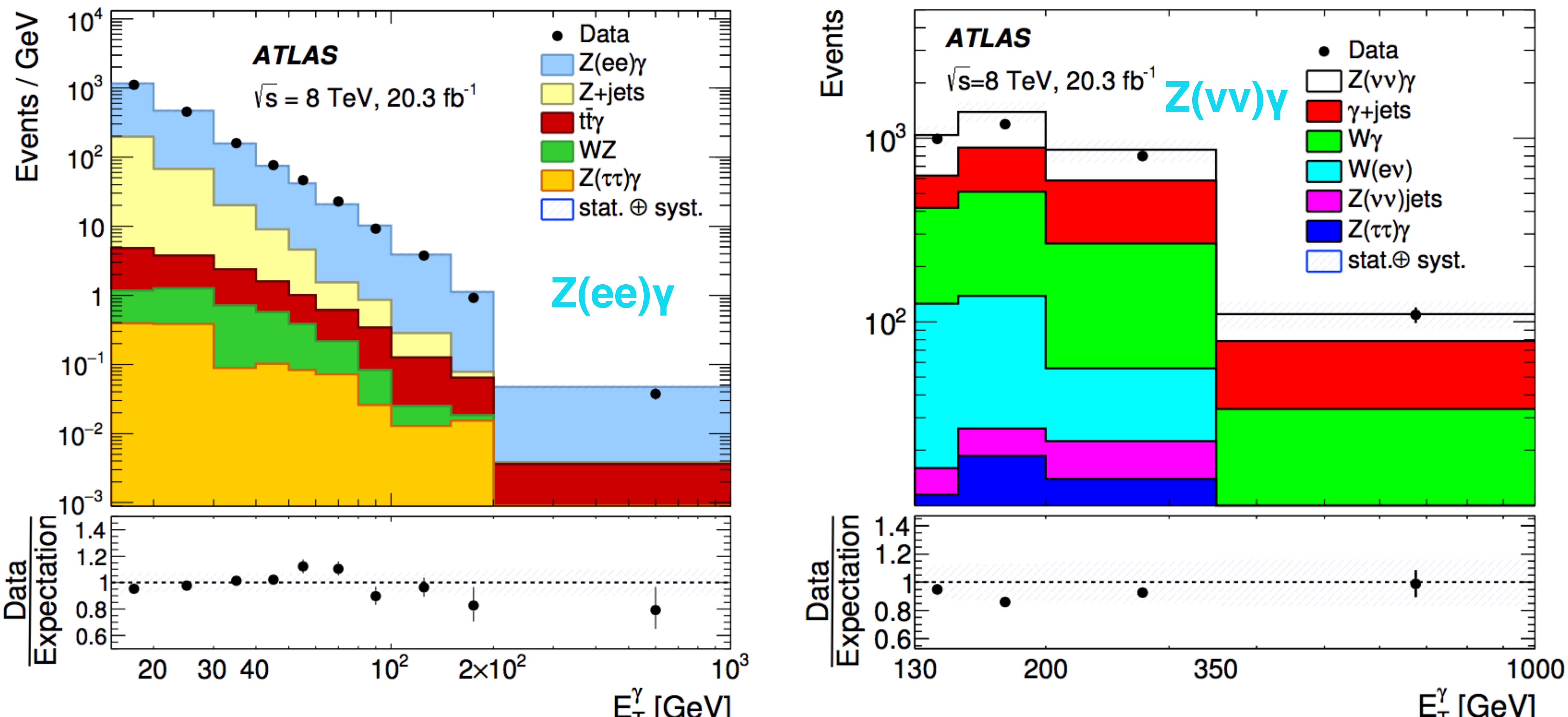
- ✦ aTGC limits on charged couplings shown for WZ and WW 8 TeV analysis.
- ✦ All limits consistent with the SM.
- ✦ ATLAS limits similar to or improving on LEP limits.



(**) **Full list of references for these results available on slide 32**

Zγ and Zγγ measurements at 8 TeV

- ✦Leptonic decay modes of the Z (to e^+e^-, $\mu^+\mu^-$, $\nu\bar{\nu}$) with associated γ + X or γγ + X.
- ✦Events selected with high $E_{T,\gamma}$. Inclusive and exclusive selection made on 'X'.
- ✦Measurements of σ_{fid} made in fiducial regions, limits set on aTGC's (Zγ) and aQGC's (Zγγ).
- ✦Backgrounds dominated by photon misidentification.

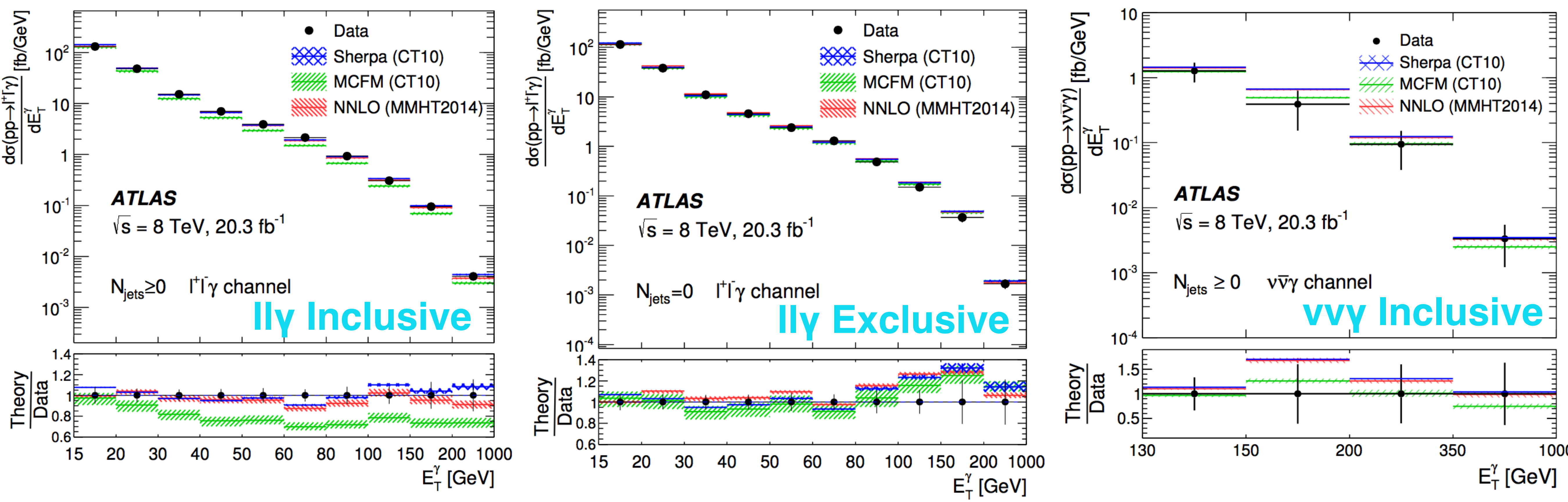


https://arxiv.org/abs/1604.05232v1

Zγ and Zγγ measurements at 8 TeV

- ✦ Generally syst. (stat.) dominated measurement in Zγ (Zγγ).
- ✦ Dominant systematics vary between channels - generally photon Id. , EM energy scale and lepton isolation and impact parameter selection efficiency.

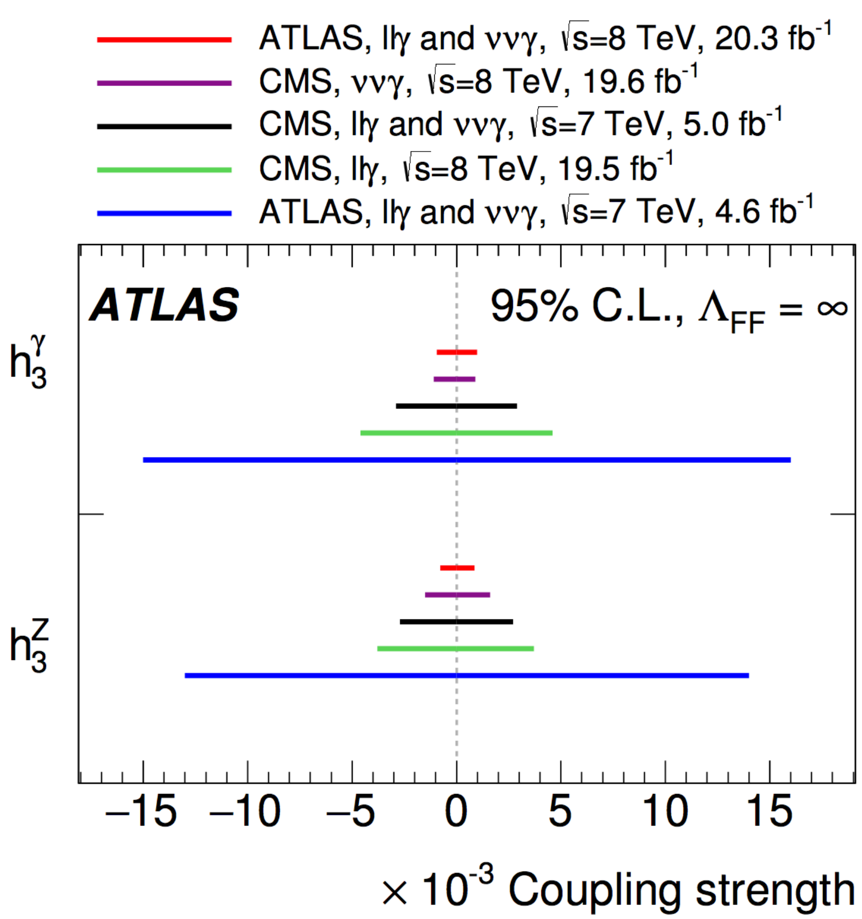
Channel (**)	$l^+l^-\gamma$ (excl)	$l^+l^-\gamma\gamma$ (excl.)	ννγ	ννγγ
σ_{fid} deviation from SM prediction	< +1σ (-1σ) (NNLO)	~ +1.7σ (+0.9σ) (NLO)	< -1σ (NNLO)	~ +1.2σ (NLO)

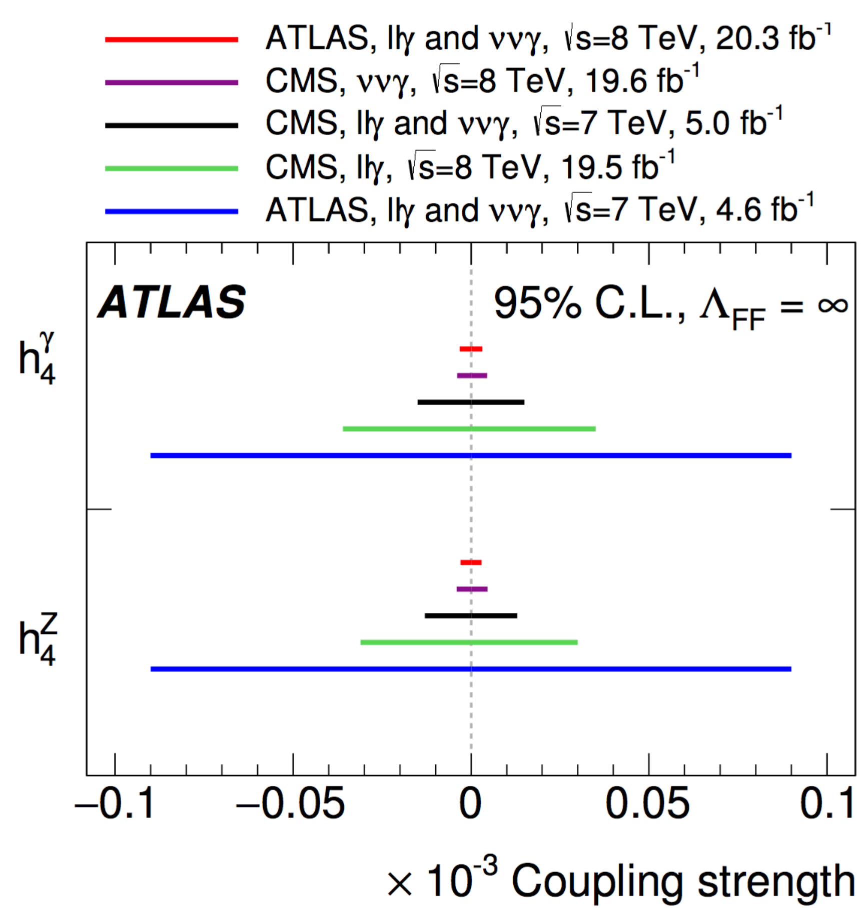


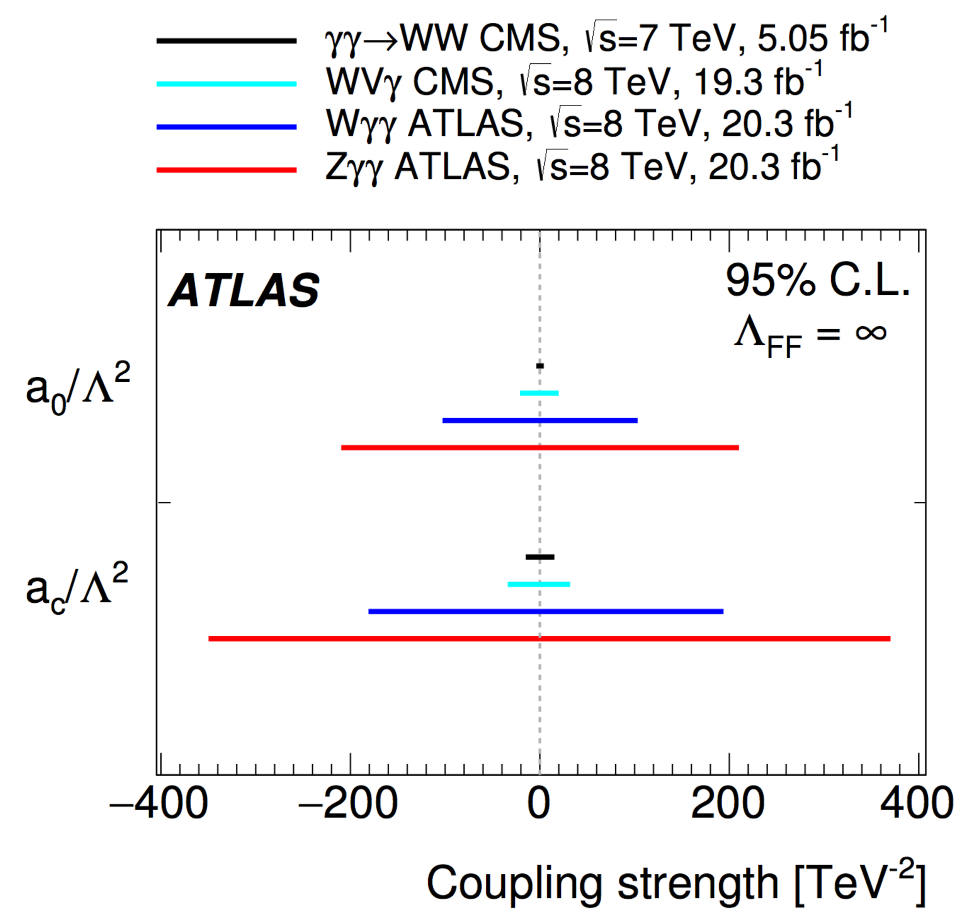
(**) Full list of fiducial measurements available on slide 38

Zγ and Zγγ measurements at 8 TeV

- ✦aTGC (Zγγ and ZZγ couplings) and aQGC limits (ZZγγ and Zγγγ couplings) set.
- ✦Limits set on CP conserving coefficients for dim.8 expansions of effective Lagrangian.



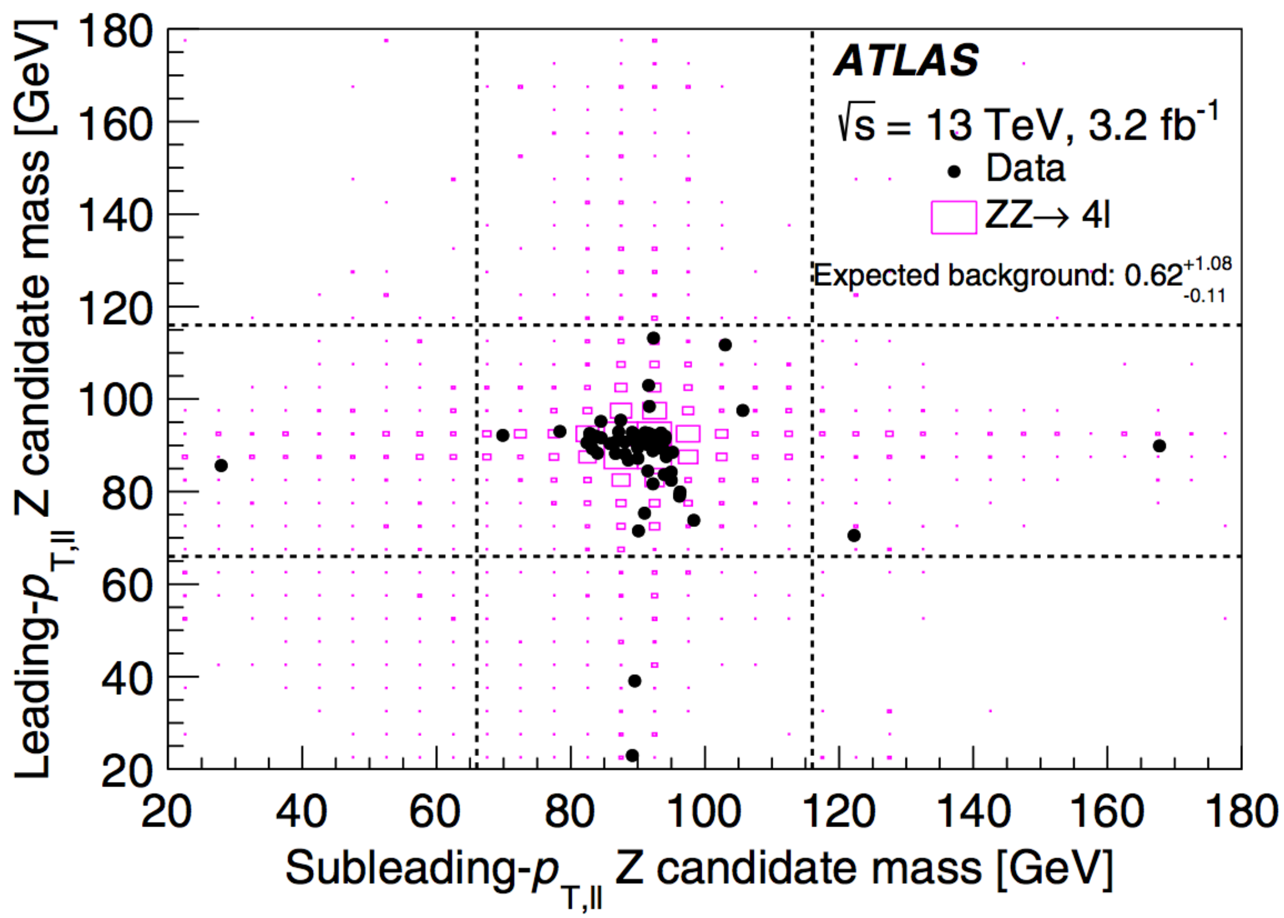


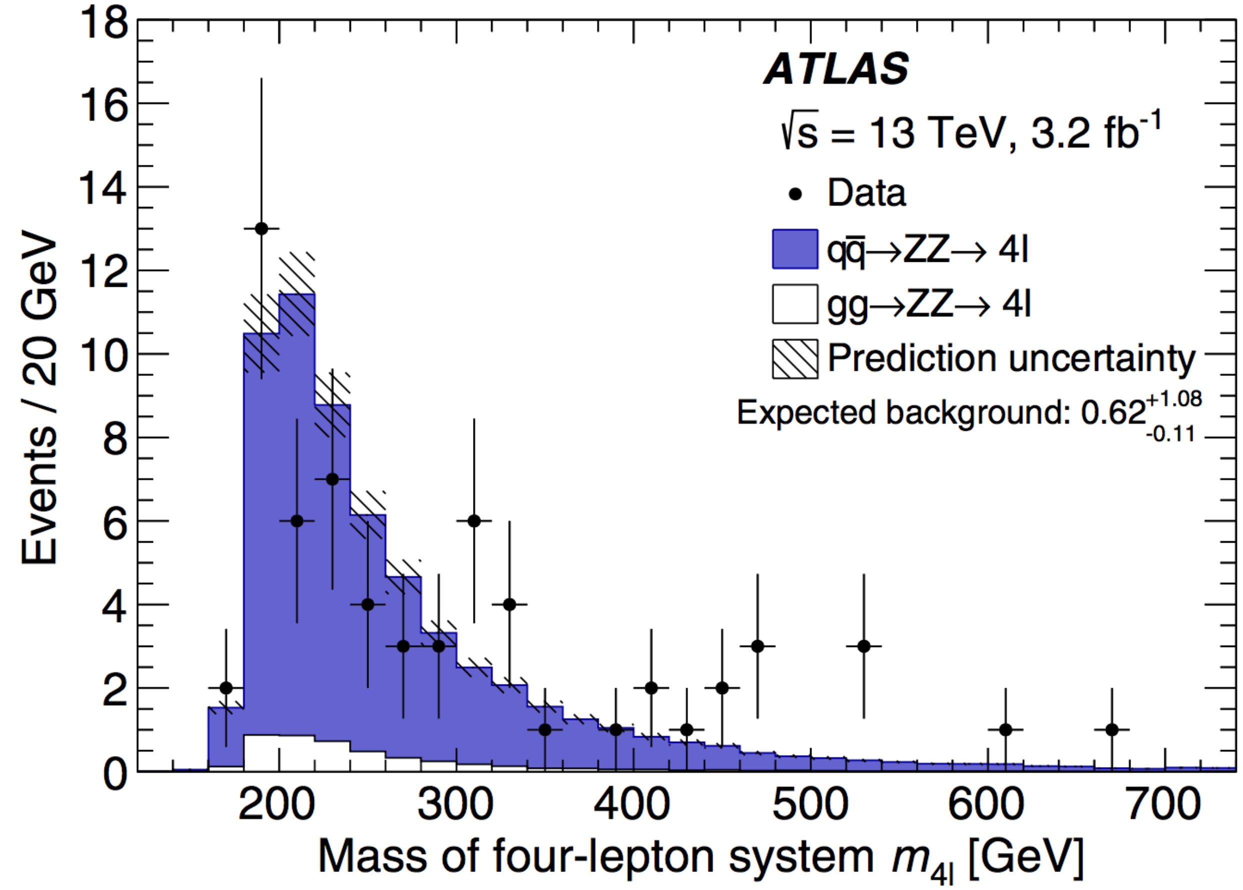


ZZ→4l Production at 13 TeV

- ZZ→4l (decay to $e^{\pm}$ or $\mu^{\pm}$ pairs) with 2 on-shell Z bosons (66 GeV<m_Z<116 GeV).
- Measurements of σ_{fid}, σ_{tot} .
- Small background ~1% - largest contributions from ttZ and misidentified leptons.
- Total of 63 events observed.

	4e	2e2μ	4μ
N.Events	15	30	18



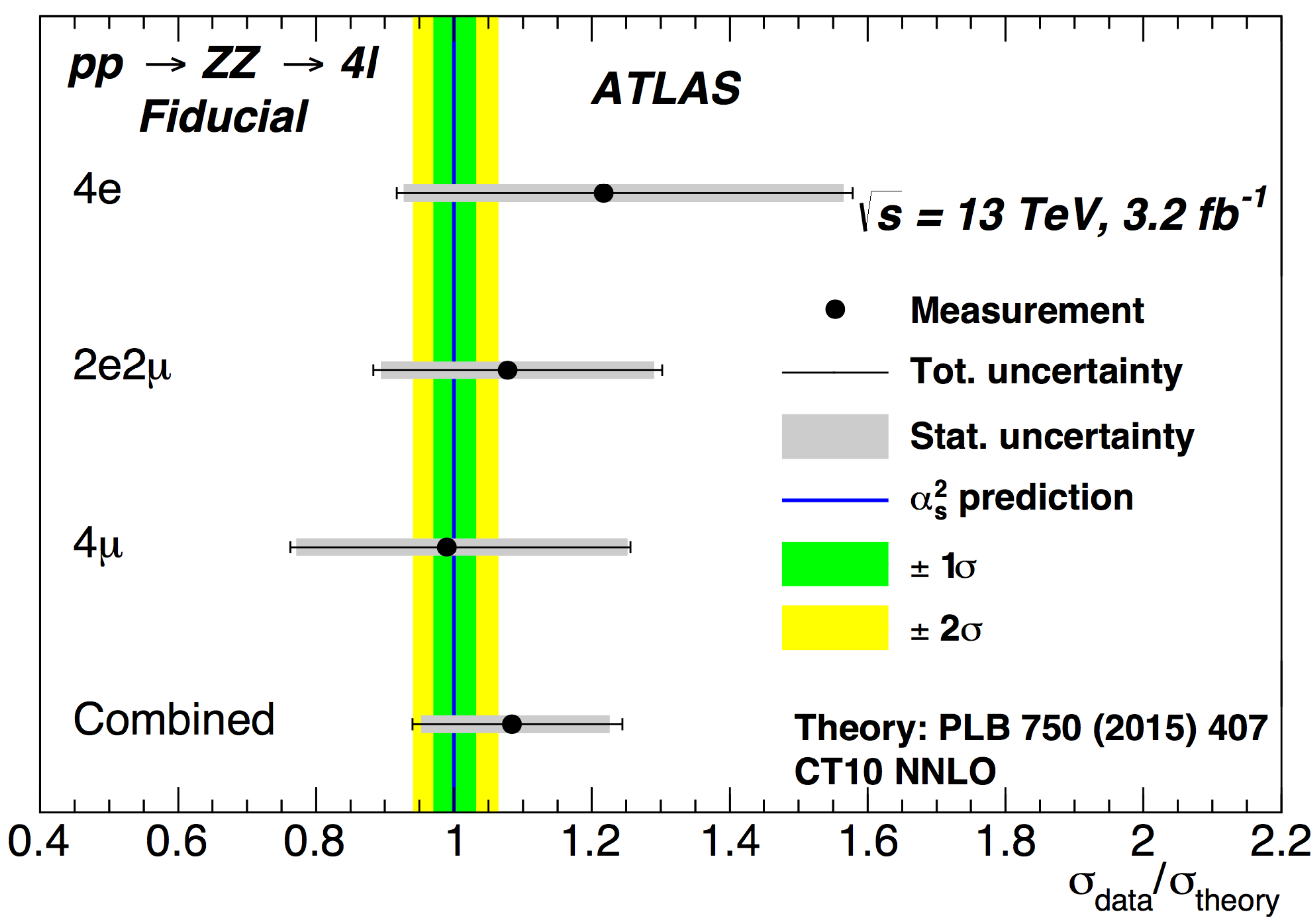


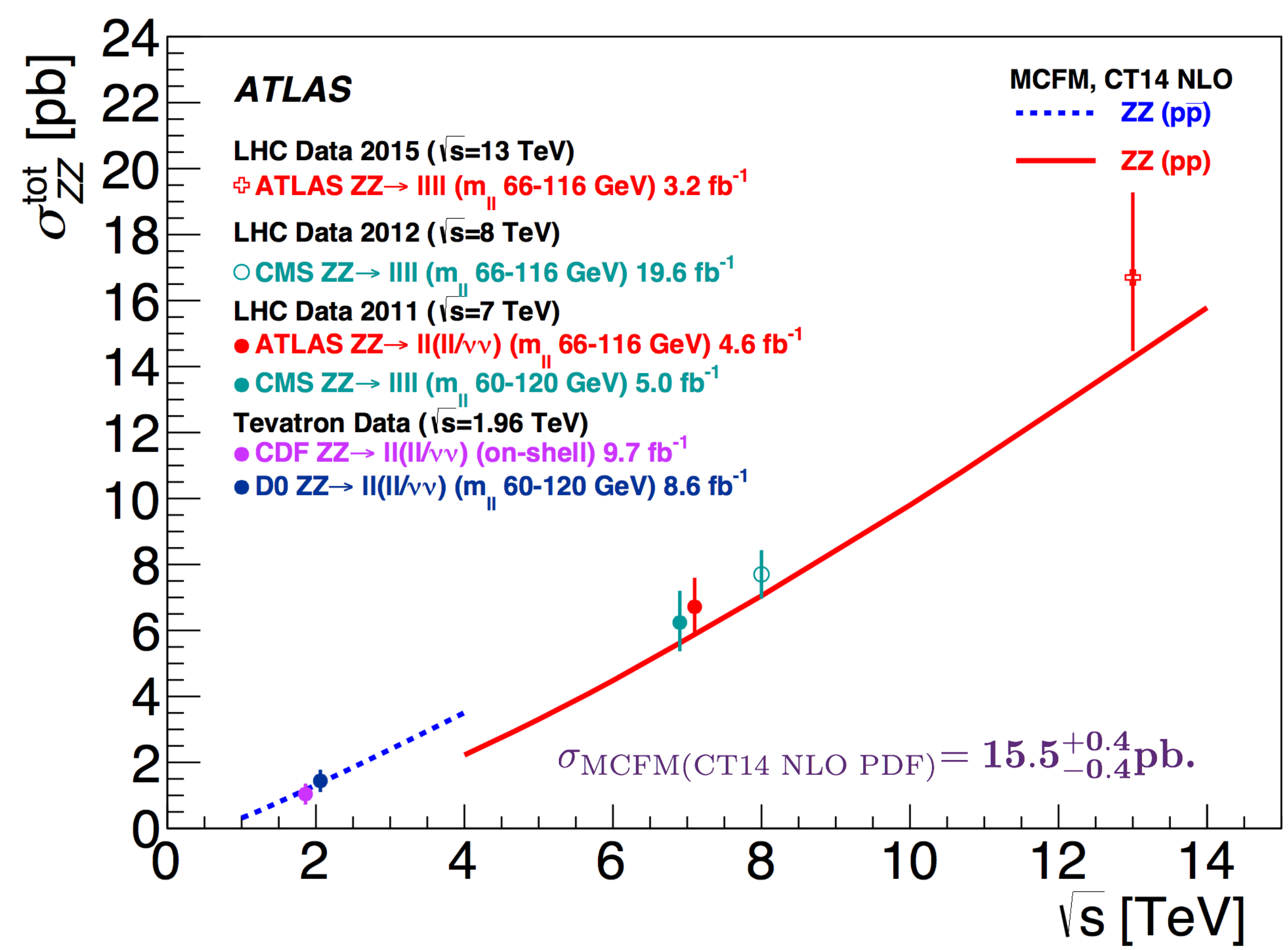
http://journals.aps.org/prl/abstract/10.1103/PhysRevLett.116.101801

ZZ→4l Production at 13 TeV

- ✦ Currently a statistically limited measurement.
- ✦ Systematics are dominated by uncertainties on scale factors used to correct lepton reco. and Id. efficiencies, and the difference between the MC generators used to model the signal processes.

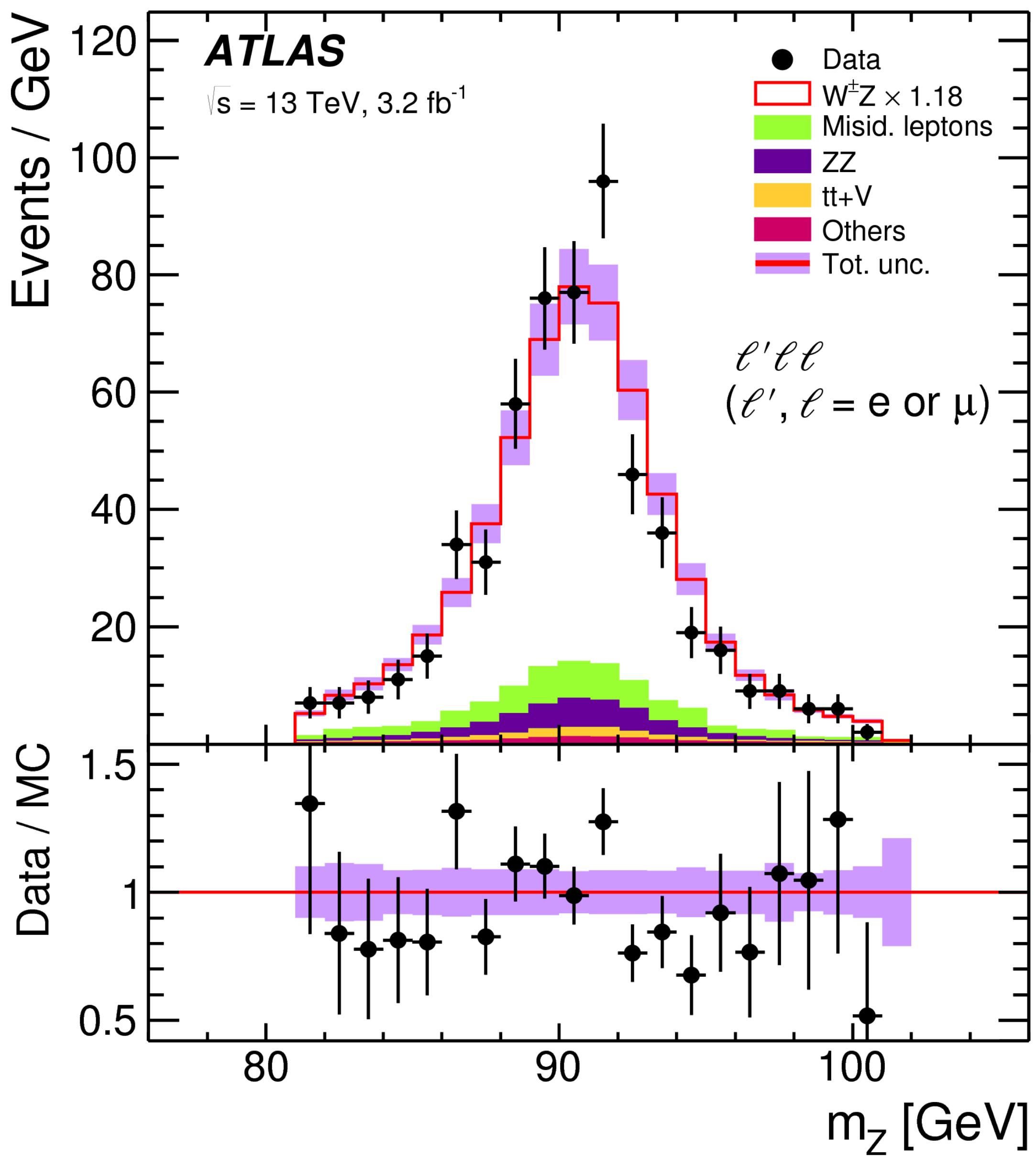
$$\sigma_{\mathbf{tot}} = \mathbf{16.7^{+2.2}_{-2.0}(stat.)^{+0.9}_{-0.7}(syst.)^{+1.0}_{-0.7}(lumi.)pb.}$$

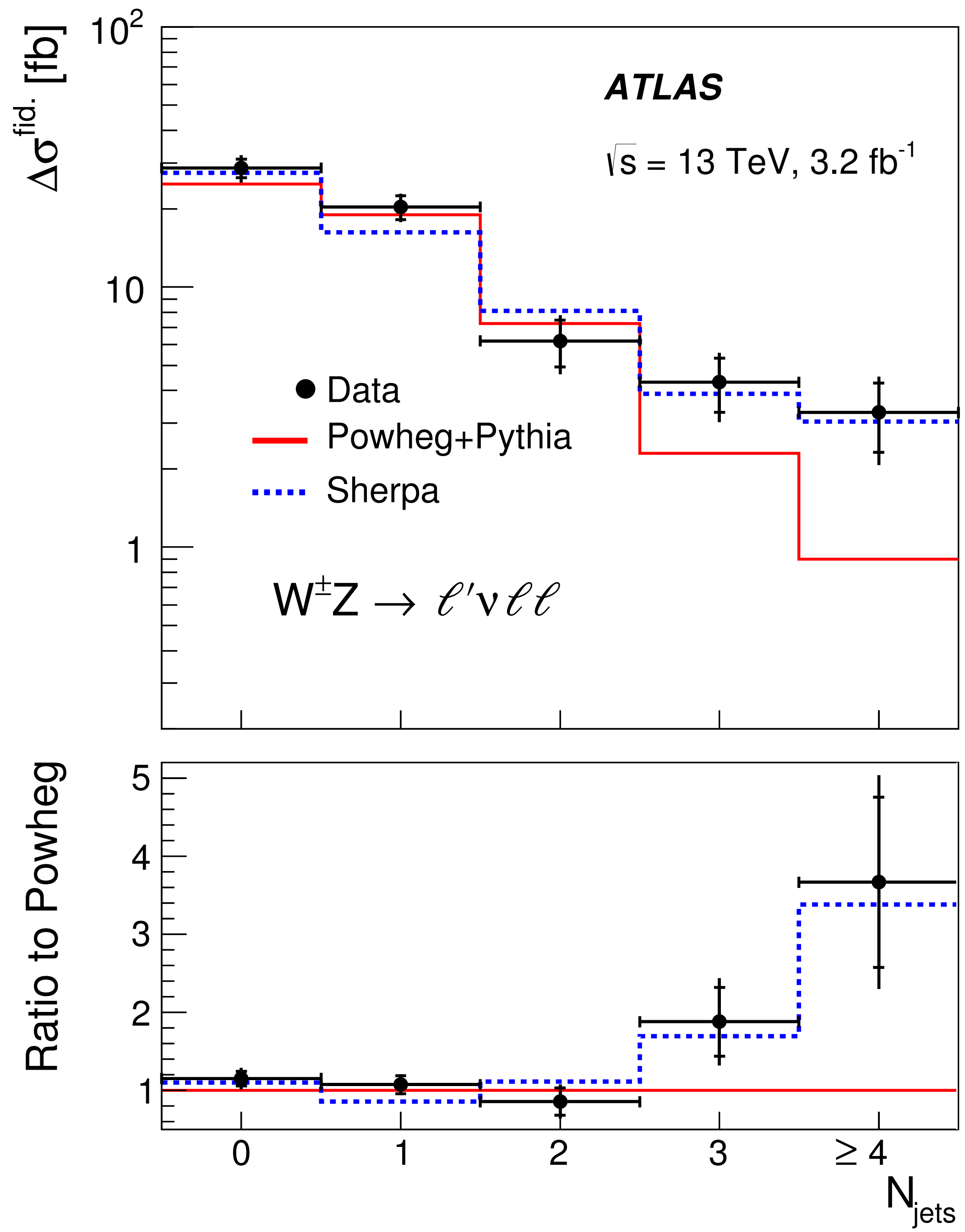




$W^{\pm}Z \rightarrow l^{\pm}\nu l^{\pm}l^{\mp}$ Production at 13 TeV

- ✦ Similar selection to the 8 TeV analysis.
- ✦ Measurements of σ_{fid}, σ_{tot}, $\sigma(W^+Z)/\sigma(W^-Z)$ and differential distributions.
- ✦ Background ~20% dominated by misidentified leptons and ZZ.

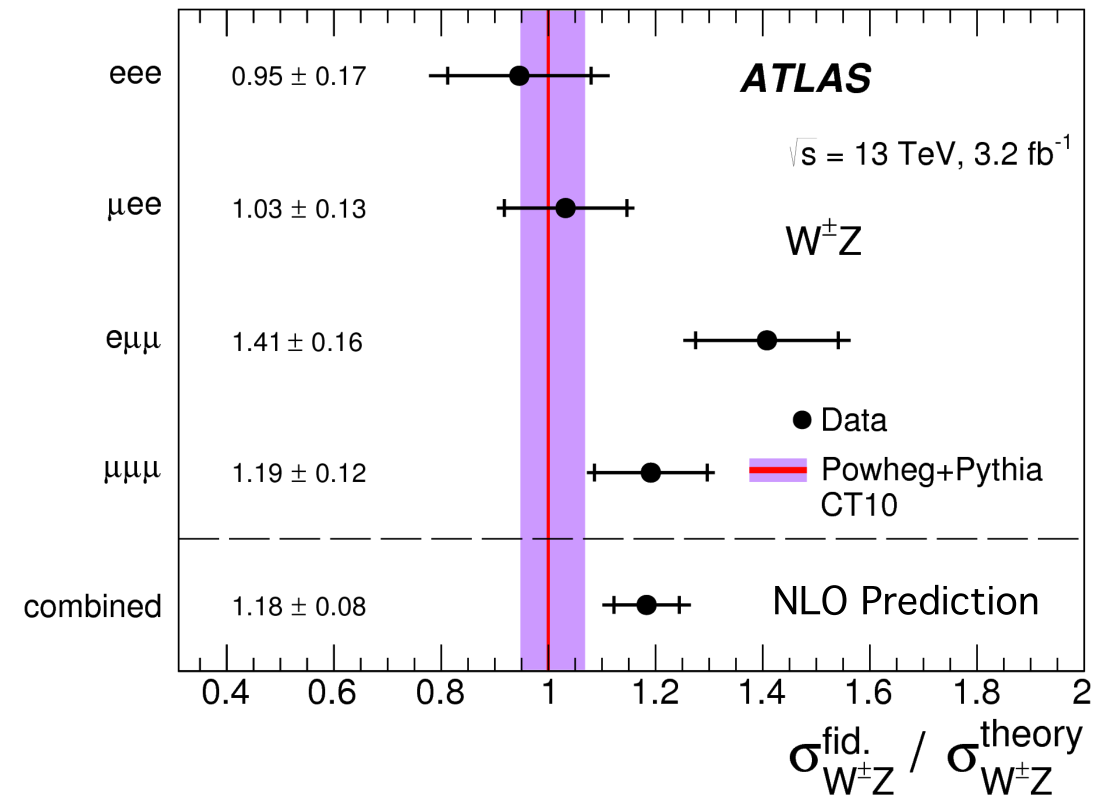


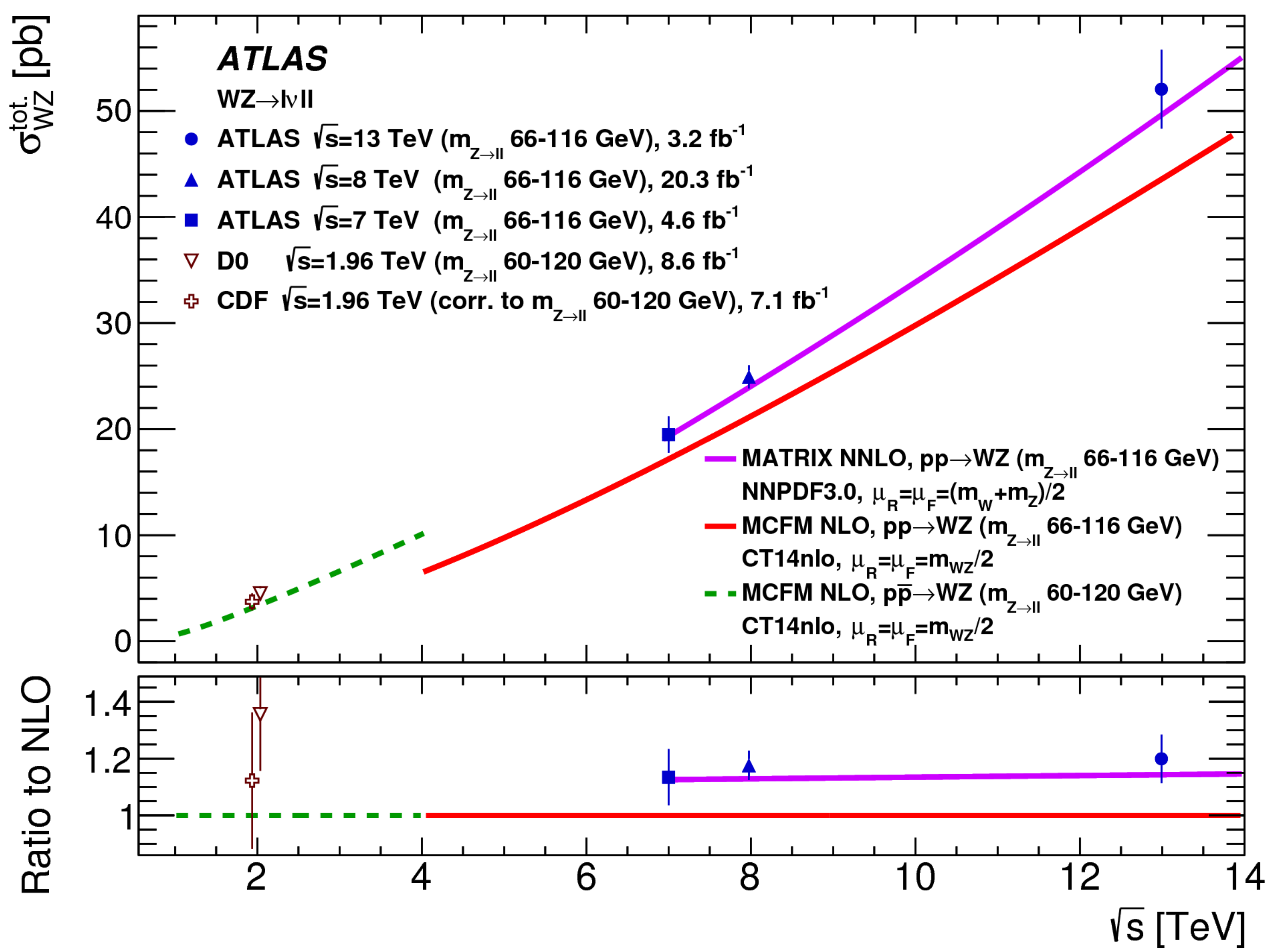


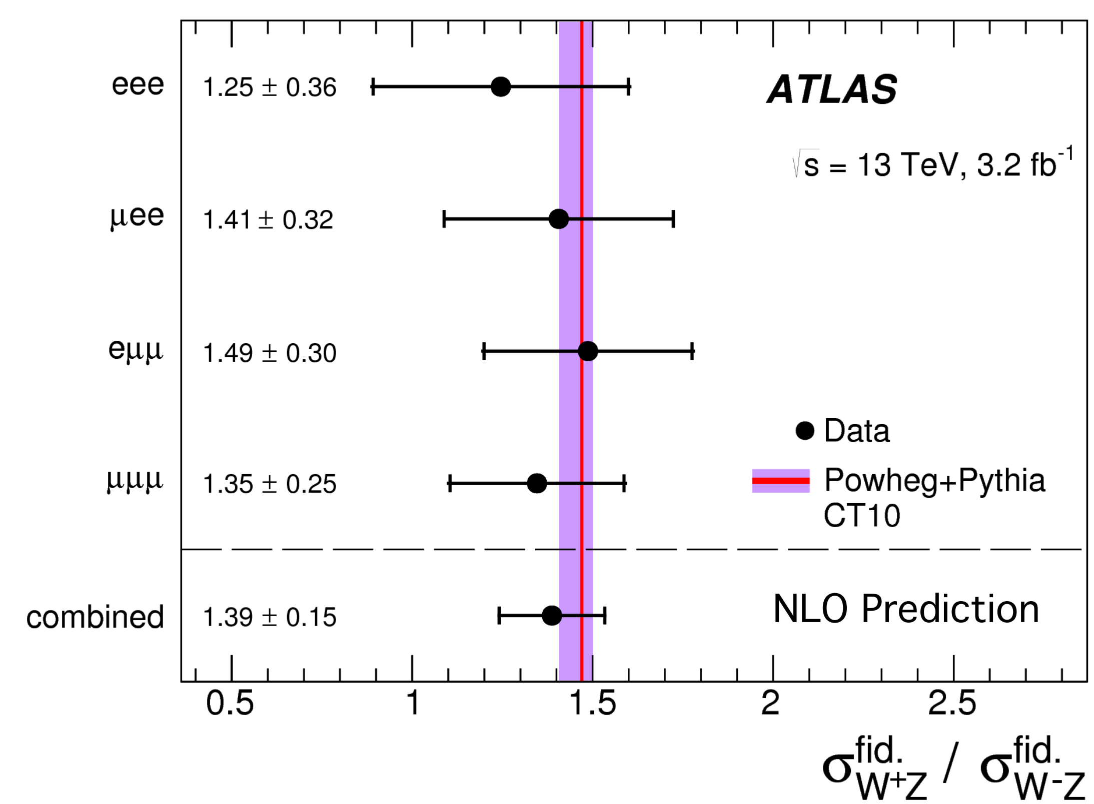
https://arxiv.org/abs/1606.04017

$W^{\pm}Z \rightarrow l^{\pm}\nu l^{\pm}l^{\mp}$ Production at 13 TeV

- Currently a statistically limited measurement.
- Dominant systematic from knowledge of lepton mis.Id background.
- Prediction compared to both NLO and NNLO predictions.







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Summary

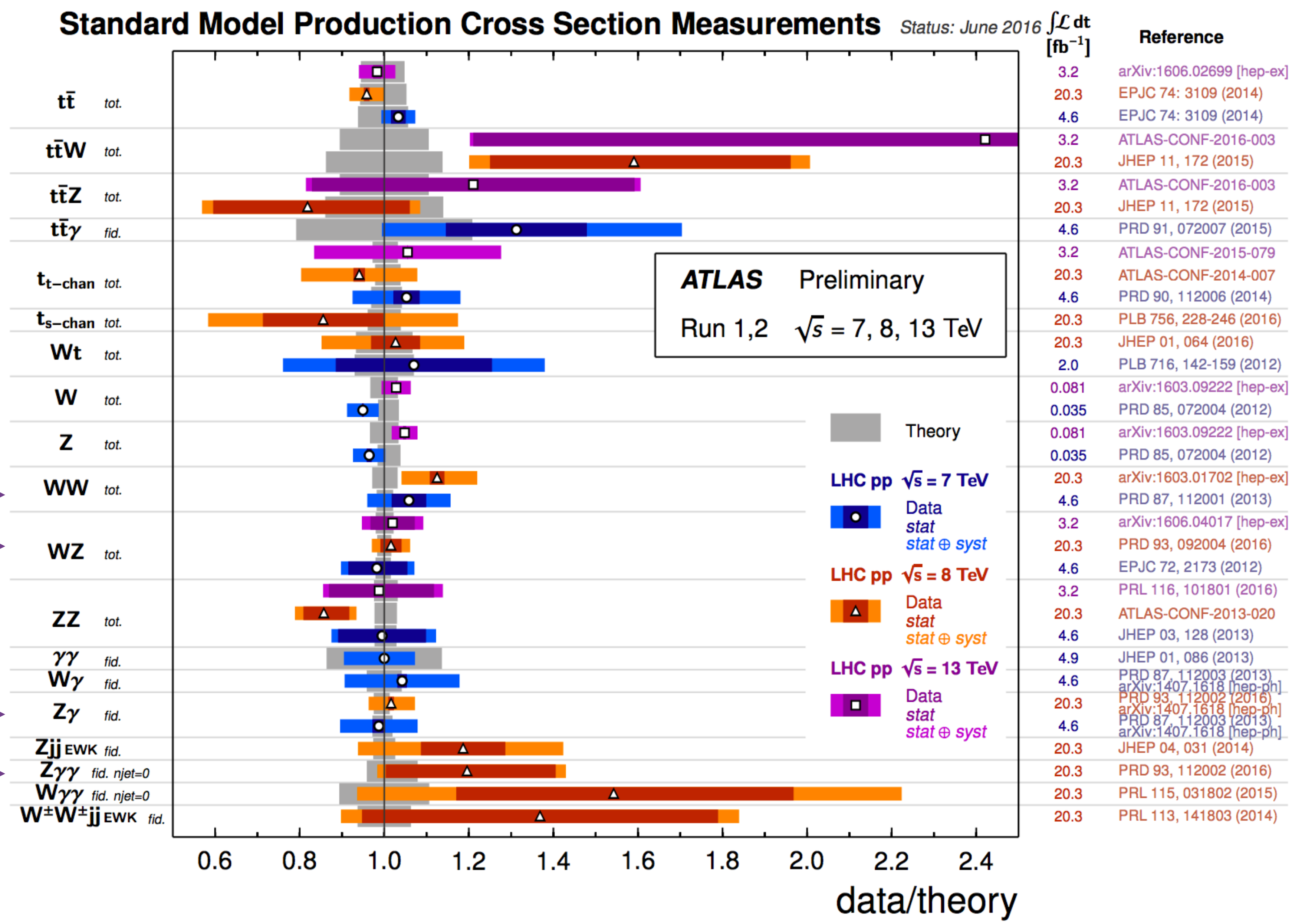
Many new interesting measurements have been made since last year!

- Many analysis stand to gain from the increased statistics in 2016

✦ Cross section measurements at both 8 and 13 TeV.

✦ Differential distributions studied at 8 TeV and 13 TeV with new theoretical precision!

✦ New aTGC and aQGC limits set at 8TeV.



Back-up Material

Intro to aTGC/aQGCs and Parameterisation

- ✦ The SM is a general theory where all operators are restricted to be of mass dimension 4 or less.
- ✦ It is possible to extend this theory by adding operators of higher dimension - this is an Effective Field Theory (EFT)

Λ - scale of new physics

$\mathcal{O}_i$ - dimension 6 operators

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i + \ldots$$

c_i - coefficients to parameterise the strength to which new physics couples to SM particles.

CP conserving dim.6 operators

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

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

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

Conversion to coefficients from effective Lagrangian formulation.

$$g_1^Z = 1 + c_W \frac{m_Z^2}{2\Lambda^2}$$

$$\kappa_\gamma = 1 + (c_W + c_B)\frac{m_W^2}{2\Lambda^2}$$

$$\kappa_Z = 1 + (c_W - c_B \tan^2\theta_W)\frac{m_W^2}{2\Lambda^2}$$

$$\lambda_\gamma = \lambda_Z = c_{WWW}\frac{3g^2 m_W^2}{2\Lambda^2}$$

Similarly with dim.8 operators give rise to aTQGC vertices.

https://arxiv.org/pdf/1205.4231v1.pdf

WW Production at 8 TeV

Pre Selection :

- Single electron/muon trigger (iso 24 GeV or 60 GeV/ 24 GeV loose or 36 GeV), el-μ, di-el, di-μ.
- $|\eta| < 2.47$ excluding crack (e), $|\eta| < 2.4$ (μ).
- Very tight electrons.
- Combined muons.
- Electron removed within $\Delta R < 0.1$ of selected muon.
- Muons removed if within $\Delta R < 0.3$ of selected jet.

- Jets : $p_T > 25$ GeV, $|\eta| < 4.5$, removed if within $\Delta R < 0.3$ of selected electron.
- Jets with pT < 50 GeV and $|\eta| < 2.4$; JVF > 0.5.

WW Selection :

- 2 oppositely charged leptons; $p_{T,lead} > 25$ GeV $p_{T,sublead} > 20$ GeV.
- reject events with more leptons $p_T > 7$ GeV
- $m_{l,l} > 10$ GeV (15 GeV) for eμ (ee/μμ)
- ee/μμ - reject events with invariant mass within 15 GeV of m_Z
- $E_{Tmiss,rel} > 15$ GeV (45 GeV) for eμ (ee/μμ)
- $P_{Tmiss} > 20$ GeV (45 GeV) for eμ (ee/μμ)
- $\Delta\phi(E_{Tmiss}, P_{Tmiss}) < 0.6$ (0.3) for eμ (ee/μμ)
- Events must contain no selected jets

$$E_{\mathrm{T,\,Rel}}^{\mathrm{miss}} = \begin{cases} E_{\mathrm{T}}^{\mathrm{miss}} \times \sin(\Delta\phi_\ell) & \text{if } \Delta\phi_\ell < \pi/2 \\ E_{\mathrm{T}}^{\mathrm{miss}} & \text{if } \Delta\phi_\ell \geq \pi/2, \end{cases}$$

WW Production at 8 TeV

Fiducial region :

	$e\mu$	$ee/\mu\mu$
p_T^ℓ (leading/sub-leading)	> 25 / 20 GeV	
$\lvert\eta^\ell\rvert$	$\lvert\eta^\mu\rvert < 2.4$ and $\lvert\eta^e\rvert < 2.47$, excluding $1.37 < \lvert\eta^e\rvert < 1.52$	
$m_{\ell\ell}$	> 10 GeV	> 15 GeV
$\lvert m_Z - m_{\ell\ell}\rvert$	—	> 15 GeV
Number of jets with $p_T > 25$ GeV, $\lvert\eta\rvert < 4.5$	0	0
$\lvert\Sigma \mathbf{p}_T^{\nu_i}\rvert$ if $\Delta\phi_\ell > \pi/2$ $\lvert\Sigma \mathbf{p}_T^{\nu_i}\rvert \times \sin(\Delta\phi_\ell)$ if $\Delta\phi_\ell < \pi/2$ ($E_{T,\,Rel}^{miss}$)	> 15 GeV	> 45 GeV
Transverse magnitude of the vectorial sum of all neutrinos, $\lvert\Sigma \mathbf{p}_T^{\nu_i}\rvert$ (p_T^{miss})	> 20 GeV	> 45 GeV

WW Production at 8 TeV

Backgrounds :

- ✦ Main background from ttbar and single top - estimated with data driven approach using control regions, Shape from MC normalisation using data.
- ✦ Drell-Yan - Shape from MC normalised using data.
- ✦ W+jets - Data drive approach, estimating the number of fakes leptons form jets.
- ✦ Diboson background has a small contribution - estimated with MC.

In eμ channel W+jets and Drell-Yan have similar contributions, in ee/μμ Drell-yan is much larger.

Final state	$e\mu$	ee	$\mu\mu$
Observed events	5067	594	975
Total expected events (Signal + background)	4420 ± 30 ± 320	507 ± 9 ± 39	820 ± 10 ± 65
WW signal (MC)	3240 ± 10 ± 280	346 ± 3 ± 33	613 ± 5 ± 60
Top quark (data-driven)	609 ± 18 ± 52	92 ± 7 ± 8	127 ± 9 ± 11
W+jets (data-driven)	250 ± 20 ± 140	14 ± 5 ± 14	6 ± 5 ± 12
Drell–Yan (data-driven)	175 ± 3 ± 18	28 ± 0 ± 13	33 ± 0 ± 17
Other dibosons (MC)	150 ± 4 ± 30	27 ± 1 ± 5	38 ± 1 ± 5
Total background	1180 ± 30 ± 150	161 ± 9 ± 21	205 ± 11 ± 24

WW Production at 8 TeV

Systematics :

Sources of uncertainty	$e\mu$	ee	$\mu\mu$	Combined
Experimental uncertainties in fiducial and total cross sections [%]				
Integrated luminosity	±2.0	±2.0	±2.0	±2.0
Pile-up	±1.35	±2.00	±2.03	±1.48
Trigger	±0.43	±2.8	±3.0	±0.75
Electron energy scale	±0.42	±1.45	—	±0.43
Electron energy resolution	±0.04	±0.23	—	±0.05
Electron identification and reconstruction	±0.99	±2.19	—	±0.91
Electron isolation	±0.22	±0.47	—	±0.21
Muon momentum scale	±0.10	—	±0.39	±0.14
Muon momentum resolution (ID)	±0.56	—	±1.67	±0.67
Muon momentum resolution (MS)	±0.09	—	±0.21	±0.11
Muon identification and reconstruction	±0.41	—	±0.82	±0.43
Muon isolation	±0.59	—	±1.20	±0.62
Jet vertex fraction (JVF)	±0.22	±0.26	±0.24	±0.23
Jet energy scale	±4.1	±3.9	±4.4	±4.1
Jet energy resolution	±1.35	±1.30	±1.47	±1.35
E_T^{miss} scale soft terms	±1.12	±2.07	±1.85	±1.28
E_T^{miss} resolultion soft terms	±0.31	±0.38	±0.53	±0.35
p_T^{miss} scale soft terms	±0.23	±0.38	±0.35	±0.25
p_T^{miss} resolution soft terms	±0.13	±0.19	±0.14	±0.13
Background uncertainties in fiducial and total cross sections [%]				
Top-quark background	±1.35	±1.82	±1.42	±1.39
W+jets & multijet background	±3.6	±3.1	±2.0	±2.8
Drell–Yan background	±0.46	±3.00	±2.26	±0.86
MC statistics (top-quark, W+jets, Drell–Yan)	±0.61	±2.03	±1.39	±0.53
Other diboson cross sections	±0.70	±1.01	±0.55	±0.69
MC statistics (other diboson)	±0.10	±0.32	±0.18	±0.09

$W^+W^- \to l^+ \nu l^- \nu$ measurements at 8 TeV

- Limits set on aTGC's in multiple scenarios :

Scenario	Parameter	Expected ($\Lambda = \infty$)	Observed ($\Lambda = \infty$)	Expected ($\Lambda = 7$ TeV)	Observed ($\Lambda = 7$ 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 [TeV^{-2}]	Observed [TeV^{-2}]
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]

WZ Production at 8 TeV

Pre Selection :

- ✦ Electron and Muon triggers (iso 24 GeV) or (60 GeV (e) and 36 GeV (μ)).
- ✦ Require primary vertex with at least 3 tracks with $p_T > 0.4$ GeV
- ✦ $P_T > 15$ GeV leptons
- ✦ $|\eta| < 2.5$ (2.47 excl. crack) muons (electrons).
- ✦ $Z_0 \sin\theta < 0.5$mm, d_0 significance $< 3\sigma$ (6σ) muons (electrons)
- ✦ All objects isolated
- ✦ Electron removed within $\Delta R < 0.1$ of selected muon.

- ✦ Jets with pT < 50 GeV and $|\eta| < 2.4$; JVF > 0.5.
- ✦ Removed if within $\Delta R < 0.3$ of selected electron or muon.

WZ Selection :

- ✦ Reject events with > 3 leptons with $P_T > 7$ GeV
- ✦ One lepton matched t triggered object with $P_T >$ 25 GeV.
- ✦ one SFOS pair of leptons with $|m_{l,l} - m_{Z,PDG}| < 10$ GeV, closest pair to $m_{Z,PDG}$ chosen.
- ✦ W lep : $P_T > 20$ GeV, tighter identification and isolation
- ✦ $m_{T,W} > 30$ GeV

VBS Selection : (WZ Selection +)

- ✦ 2 jets $p_T > 30$ GeV, $|\eta| < 4.5$.
- ✦ mjj > 500 GeV
- ✦ Removed if within $\Delta R < 0.3$ of selected electron or muon.

WZ Production at 8 TeV

Backgrounds :

✦ Reducible (non prompt leptons) and irreducible backgrounds (misidentified prompt leptons)

✦ Reducible : Z+jets, Zγ ttbar and WW. Background estimated using data driven approach (global matrix method.) - corresponds to about 50% of total background

✦ Irreducible : ZZ tt+V, VVV, tZ(j). Estimated with MC. Dominant contribution from ZZ which is ~70% of irreducible. ZZ validated using control regions in data.

✦ VBS : WZjj-QCD (~70%) and tZj

Channel	eee	μee	$e\mu\mu$	$\mu\mu\mu$	All
Data	406	483	539	663	2091
Total expected	336.7 ± 2.2	410.8 ± 2.4	469.1 ± 2.1	608.2 ± 3.5	1824.8 ± 7.0
WZ	255.7 ± 1.1	337.2 ± 1.0	367.0 ± 1.1	495.9 ± 2.3	1455.7 ± 5.5
Misid. leptons	43.7 ± 1.9	32.2 ± 2.1	50.2 ± 1.7	52.8 ± 2.6	178.9 ± 4.2
ZZ	25.9 ± 0.2	26.7 ± 0.3	36.1 ± 0.3	39.5 ± 0.3	128.2 ± 0.6
$t\bar{t} + V$	5.5 ± 0.2	6.7 ± 0.2	7.2 ± 0.3	9.1 ± 0.3	28.5 ± 0.5
tZ	4.2 ± 0.1	5.5 ± 0.2	6.0 ± 0.2	7.7 ± 0.2	23.3 ± 0.3
DPS	1.2 ± 0.1	1.9 ± 0.1	1.8 ± 0.1	2.3 ± 0.2	7.2 ± 0.3
VVV	0.5 ± 0.0	0.7 ± 0.0	0.8 ± 0.0	0.9 ± 0.0	3.0 ± 0.1

WZ Production at 8 TeV

Fiducial Selection:

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

WZ Production at 8 TeV

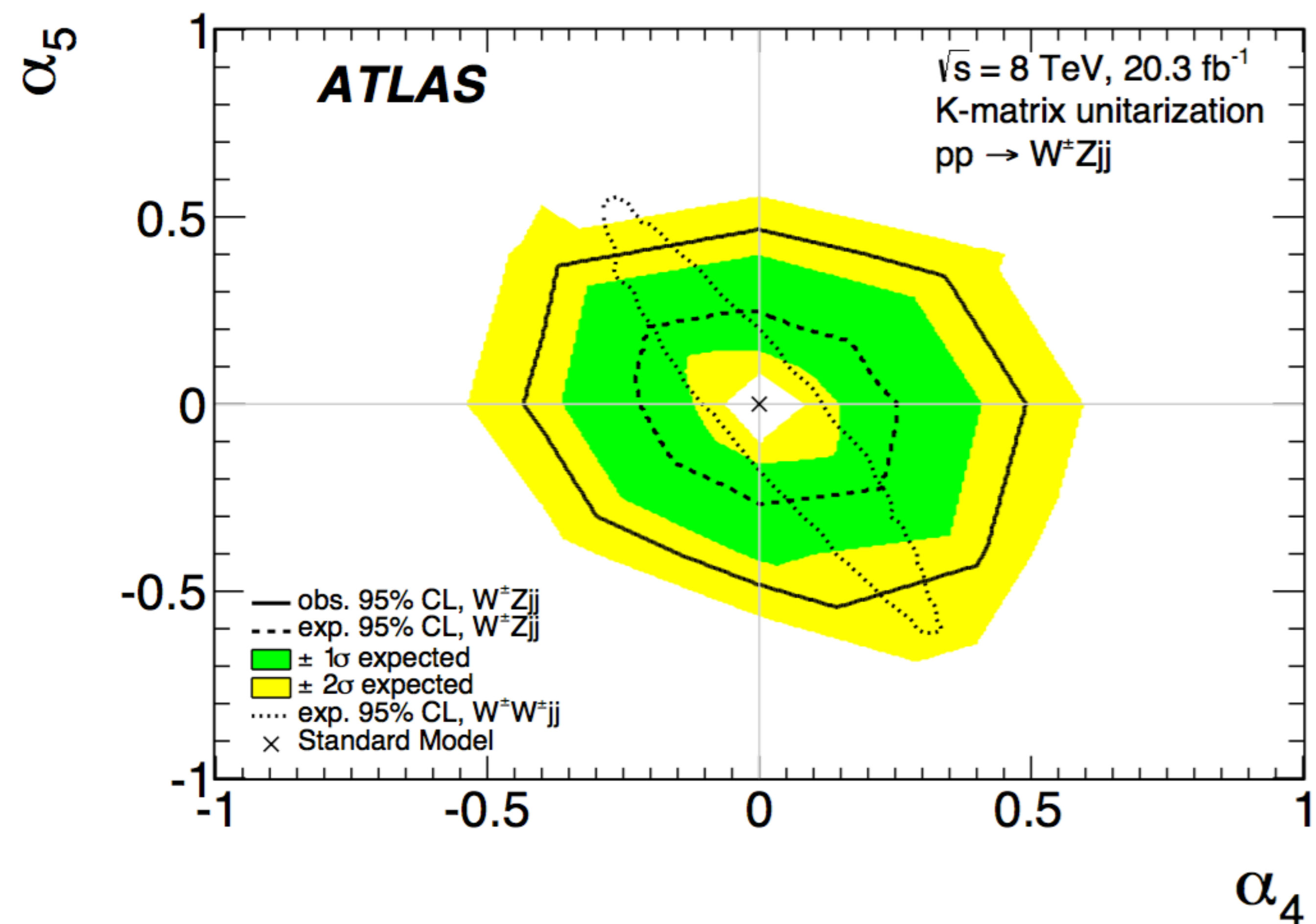
Systematics :

	eee	*μee*	*eμμ*	*μμμ*	combined
Source	Relative uncertainties [%]				
e energy scale	0.8	0.4	0.4	0.0	0.3
e id. efficiency	2.9	1.8	1.0	0.0	1.0
μ momentum scale	0.0	0.1	0.1	0.1	0.1
μ id. efficiency	0.0	0.7	1.3	2.0	1.4
$E_{\mathrm{T}}^{\mathrm{miss}}$ and jets	0.3	0.2	0.2	0.1	0.3
Trigger	0.1	0.1	0.2	0.3	0.2
Pileup	0.3	0.2	0.2	0.1	0.2
Misid. leptons background	2.9	0.9	3.1	0.9	1.3
ZZ background	0.6	0.5	0.6	0.5	0.5
Other backgrounds	0.7	0.7	0.7	0.7	0.7
Uncorrelated	0.7	0.6	0.5	0.5	0.3
Total systematics	4.5	2.6	3.7	2.5	2.4
Luminosity	2.2	2.2	2.2	2.2	2.2
Statistics	6.2	5.4	5.3	4.7	2.7
Total	8.0	6.3	6.8	5.7	4.2

WZ Production at 8 TeV

VBS and aQGC :

95% CL upper limit on $\sigma^{\text{fid.}}_{W^{\pm}Zjj\text{-EW}\rightarrow\ell'\nu\ell\ell}$ [fb]	VBS only	VBS + tZj
VBS phase space		
Observed	0.63	0.67
Expected	0.45	0.49
$\pm1\sigma$ Expected	[0.28 ; 0.62]	[0.33 ; 0.67]
$\pm2\sigma$ Expected	[0.08 ; 0.80]	[0.19 ; 0.84]
aQGC phase space		
Observed	0.25	0.25
Expected	0.13	0.13
$\pm1\sigma$ Expected	[0.08 ; 0.20]	[0.08 ; 0.20]
$\pm2\sigma$ Expected	[0.04 ; 0.28]	[0.06 ; 0.28]



Expectation : 0.13 ± 0.01 fb from VBFNLO.

Probe new phase space not available from WWjj analysis

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

WZ measurements at 8 TeV

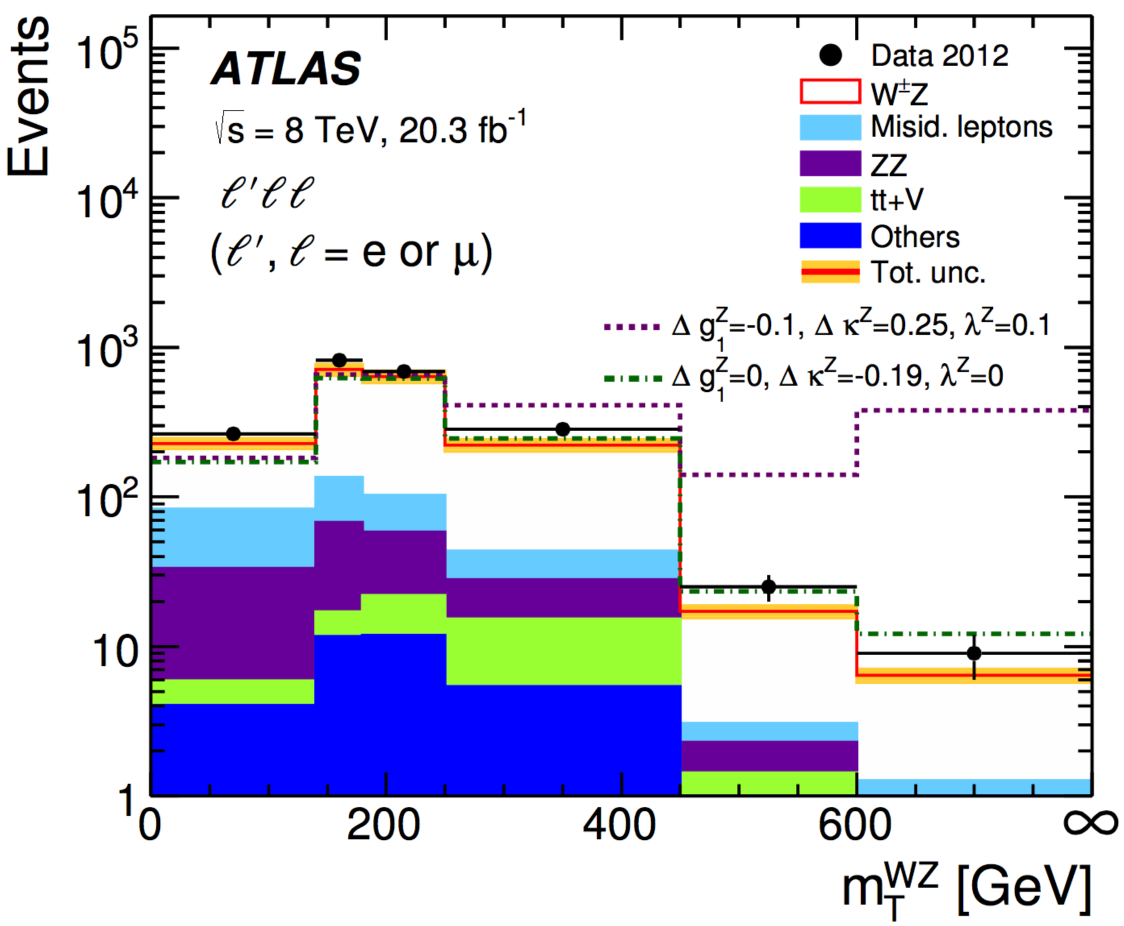


TABLE VIII. Expected and observed one-dimensional 95% C.L. intervals on the anomalous coupling parameters.

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_{WWW}/Λ^2	[-3.9 ; 3.8]	[-3.9 ; 4.0]

Table 69: Observed 1D 95% C.I. and expected 95% C.I. on the EFT parameters

Charged coupling references

ATLAS WZ 8 TeV

http://arxiv.org/abs/1603.02151

ATLAS WZ 7 TeV

http://arxiv.org/abs/1208.1390

ATLAS WW 8 TeV

http://arxiv.org/abs/1603.01702

ATLAS WV 7 TeV

http://link.springer.com/article/10.1007/JHEP01(2015)049

CMS WW 8 TeV

http://arxiv.org/abs/1507.03268

CMS WV 7 TeV

http://link.springer.com/article/10.1140%2Fepjc%2Fs10052-013-2283-3

D0 combination

http://journals.aps.org/prd/abstract/10.1103/PhysRevD.85.112005

LEP combination

http://arxiv.org/pdf/1302.3415v4.pdf

$Z\gamma$ and $Z\gamma\gamma$ measurements at 8 TeV

Selection :

$p_{T,miss}$ - vector of momentum inbalance in the transverse plane

- Require primary vertex with at least 3 tracks with $p_T > 0.4$ GeV
- $|\eta|<2.47$ (e), $|\eta|<2.37$ (γ) and $|\eta|<2.5$ (μ) - crack region excluded
- Both converted and unconverted γ used in analysis.
- $Z_0 \sin\theta < 0.5$mm, d_0 significance $< 3\sigma$ (6σ) muons (electrons)
- muon $p_T > 25$ GeV
- All objects isolated (for specific definitions see note)

- Jet pT > 30 GeV and $|\eta| < 4.5$
- Jets with pT < 50 GeV and $|\eta| < 2.4$; JVF > 0.5.
- Jets removed if within $\Delta R > 0.4$ of lepton/γ

Selection	$l^+l^-\gamma$+X	$l^+l^-\gamma\gamma$+X	$\nu\nu\gamma$+X	$\nu\nu\gamma\gamma$+X
$E_{T,\gamma}$ (GeV)	15	15	130	22

Lepton channels

- One SFOS pair
- $m_{ll} > 40$ GeV
- Overlap removal for e within $\Delta R > 0.1$ of selected muon.
- γ removed if within $\Delta R > 0.7(0.4)$ of selected lepton for $ll\gamma$ ($ll\gamma\gamma$).
- $\Delta R(\gamma\gamma) > 0.4$ for $ll\gamma\gamma$

Neutrino channels

$\nu\nu\gamma$

- $E_{T,miss} > 100$ GeV
- $\Delta\phi(p_{T,miss}, \gamma) > \pi/2$

$\nu\nu\gamma\gamma$

- $E_{T,miss} > 110$ GeV
- $\Delta R(\gamma\gamma) > 0.4$
- $\Delta\phi(p_{T,miss}, \gamma) > 5\pi/6$

both

- Reject events with leptons

Zγ and Zγγ measurements at 8 TeV

Backgrounds :

- llγ/llγγ - Dominated by events with hadronic jets containing γ from π^0 and η decays being misidentified as prompt γ (Z+jets/Zγ+jets) - estimated with data driven sideband approach.

  - Other backgrounds ttγ, WZ, ττγ/ττγγ (<1.5%)

- ννγ/ννγγ - Many sources ; events with prompt γ and mis-measured jet momenta misidentified causing missing transverse momentum (dominant in inclusive measurement), no signal EWK processes with partial detection (eg W(lν)γ), events with $E_{T,miss}$ and misidentified photons (Zνν or W(eν)). - estimated mainly with data driven approaches

  - Other backgrounds ττγ/ττγγ (<1.5%)

Zγ and Zγγ measurements at 8 TeV

Event yields Z(ll)γ + X :

	$e^+e^-\gamma$	$\mu^+\mu^-\gamma$	$e^+e^-\gamma$	$\mu^+\mu^-\gamma$
	$N_{\text{jets}} \geq 0$		$N_{\text{jets}} = 0$	
$N_{Z\gamma}^{\text{obs}}$	13807	17054	10268	12738
$N_{Z\gamma}^{j\to\gamma}$	1840 ± 90 ± 480	2120 ± 90 ± 560	1260 ± 80 ± 330	1510 ± 80 ± 400
$N_{Z\gamma}^{\text{Other BKG}}$	143 ± 3 ± 28	146 ± 2 ± 29	30.8 ± 1.6 ± 6.7	26.9 ± 1.5 ± 5.8
$N_{Z\gamma}^{\text{sig}}$ (SHERPA)	12040 ± 40 ± 820	15070 ± 40 ± 960	9160 ± 30 ± 750	11570 ± 40 ± 910

Event yields Z(ll)γγ + X :

	$e^+e^-\gamma\gamma$	$\mu^+\mu^-\gamma\gamma$	$e^+e^-\gamma\gamma$	$\mu^+\mu^-\gamma\gamma$
	$N_{\text{jets}} \geq 0$		$N_{\text{jets}} = 0$	
$N_{Z\gamma\gamma}^{\text{obs}}$	43	37	29	22
$N_{Z\gamma\gamma}^{j\to\gamma}$	5.8 ± 1.0 ± 1.4	10.9 ± 1.1 ± 2.8	3.08 ± 0.73 ± 0.75	6.4 ± 0.9 ± 1.8
$N_{Z\gamma\gamma}^{\text{Other BKG}}$	0.42 ± 0.08 ± 0.18	0.194 ± 0.047 ± 0.097	0.24 ± 0.05 ± 0.11	0.105 ± 0.028 ± 0.055
$N_{Z\gamma\gamma}^{\text{sig}}$ (SHERPA)	25.7 ± 0.5 ± 1.6	29.5 ± 0.6 ± 1.7	18.9 ± 0.5 ± 1.5	21.8 ± 0.5 ± 1.7

Zγ and Zγγ measurements at 8 TeV

Extended fiducial regions :

Cuts	$\ell^+\ell^-\gamma$	$\ell^+\ell^-\gamma\gamma$	$\nu\bar{\nu}\gamma$	$\nu\bar{\nu}\gamma\gamma$
Lepton	$p_T^\ell > 25$ GeV	$p_T^\ell > 25$ GeV	-	-
	$\|\eta^\ell\| < 2.47$	$\|\eta^\ell\| < 2.47$	-	-
Boson	$m_{\ell^+\ell^-} > 40$ GeV	$m_{\ell^+\ell^-} > 40$ GeV	$p_T^{\nu\bar{\nu}} > 100$ GeV	$p_T^{\nu\bar{\nu}} > 110$ GeV
Photon	$E_T^\gamma > 15$ GeV	$E_T^\gamma > 15$ GeV	$E_T^\gamma > 130$ GeV	$E_T^\gamma > 22$ GeV
	$\|\eta^\gamma\| < 2.37$			
	$\Delta R(\ell,\gamma) > 0.7$	$\Delta R(\ell,\gamma) > 0.4$	-	-
	-	$\Delta R(\gamma,\gamma) > 0.4$	-	$\Delta R(\gamma,\gamma) > 0.4$
	$\epsilon_h^p < 0.5$			
Jet	$p_T^{\text{jet}} > 30$ GeV, $\|\eta^{\text{jet}}\| < 4.5$			
	$\Delta R(\text{jet},\ell/\gamma) > 0.3$	$\Delta R(\text{jet},\ell/\gamma) > 0.3$	$\Delta R(\text{jet},\gamma) > 0.3$	$\Delta R(\text{jet},\gamma) > 0.3$
	Inclusive : $N_{\text{jet}} \geq 0$, Exclusive : $N_{\text{jet}} = 0$			

Zγ and Zγγ measurements at 8 TeV

Event yields Z(νν)γ + X :

	$N_{\text{jets}} \geq 0$	$N_{\text{jets}} = 0$
$N^{\text{obs}}_{Z\gamma}$	3085	1039
$N^{\gamma+\text{jets}}_{Z\gamma}$	$950 \pm 30 \pm 300$	$9.2 \pm 3.5 \pm 0.7$
$N^{W(\ell\nu)\gamma}_{Z\gamma}$	$900 \pm 50 \pm 300$	$272 \pm 14 \pm 92$
$N^{W(e\nu)}_{Z\gamma}$	$258 \pm 38 \pm 18$	$147 \pm 21 \pm 10$
$N^{Z(\nu\bar{\nu})+\text{jets}}_{Z\gamma}$	$22.9 \pm 0.5 \pm 6.1$	$11.1 \pm 0.4 \pm 3.4$
$N^{Z(\tau^+\tau^-)\gamma}_{Z\gamma}$	$46.2 \pm 0.9 \pm 3.2$	$10.23 \pm 0.43 \pm 0.72$
$N^{\text{bkg}}_{Z\gamma}$	$2180 \pm 70 \pm 420$	$450 \pm 25 \pm 93$
$N^{\text{sig}}_{Z\gamma}$ (SHERPA)	$1221 \pm 2 \pm 65$	$742 \pm 2 \pm 44$

Event yields Z(νν)γγ + X :

	$N_{\text{jets}} \geq 0$	$N_{\text{jets}} = 0$
$N^{\text{obs}}_{Z\gamma\gamma}$	46	19
$N^{\text{jets}+\gamma(\gamma)}_{Z\gamma\gamma}$	$12.2 \pm 6.7 \pm 1.8$	$2.9 \pm 4.0 \pm 0.4$
$N^{W(\ell\nu)\gamma\gamma}_{Z\gamma\gamma}$	$3.6 \pm 0.1 \pm 3.6$	$1.0 \pm 0.1 \pm 1.0$
$N^{W(e\nu)\gamma}_{Z\gamma\gamma}$	$10.4 \pm 0.5 \pm 2.1$	$3.47 \pm 0.28 \pm 0.69$
$N^{Z(\nu\bar{\nu})\gamma+\text{jets}}_{Z\gamma\gamma}$	$0.71 \pm 0.71 \pm 0.90$	$0.71 \pm 0.71 \pm 0.75$
$N^{Z(\tau^+\tau^-)\gamma\gamma}_{Z\gamma\gamma}$	$0.381 \pm 0.055 \pm 0.027$	$0.141 \pm 0.036 \pm 0.010$
$N^{\text{bkg}}_{Z\gamma\gamma}$	$27.2 \pm 6.8 \pm 4.6$	$8.3 \pm 4.1 \pm 1.5$
$N^{\text{sig}}_{Z\gamma\gamma}$ (SHERPA)	$7.54 \pm 0.07 \pm 0.34$	$4.80 \pm 0.06 \pm 0.29$

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Zγ and Zγγ measurements at 8 TeV

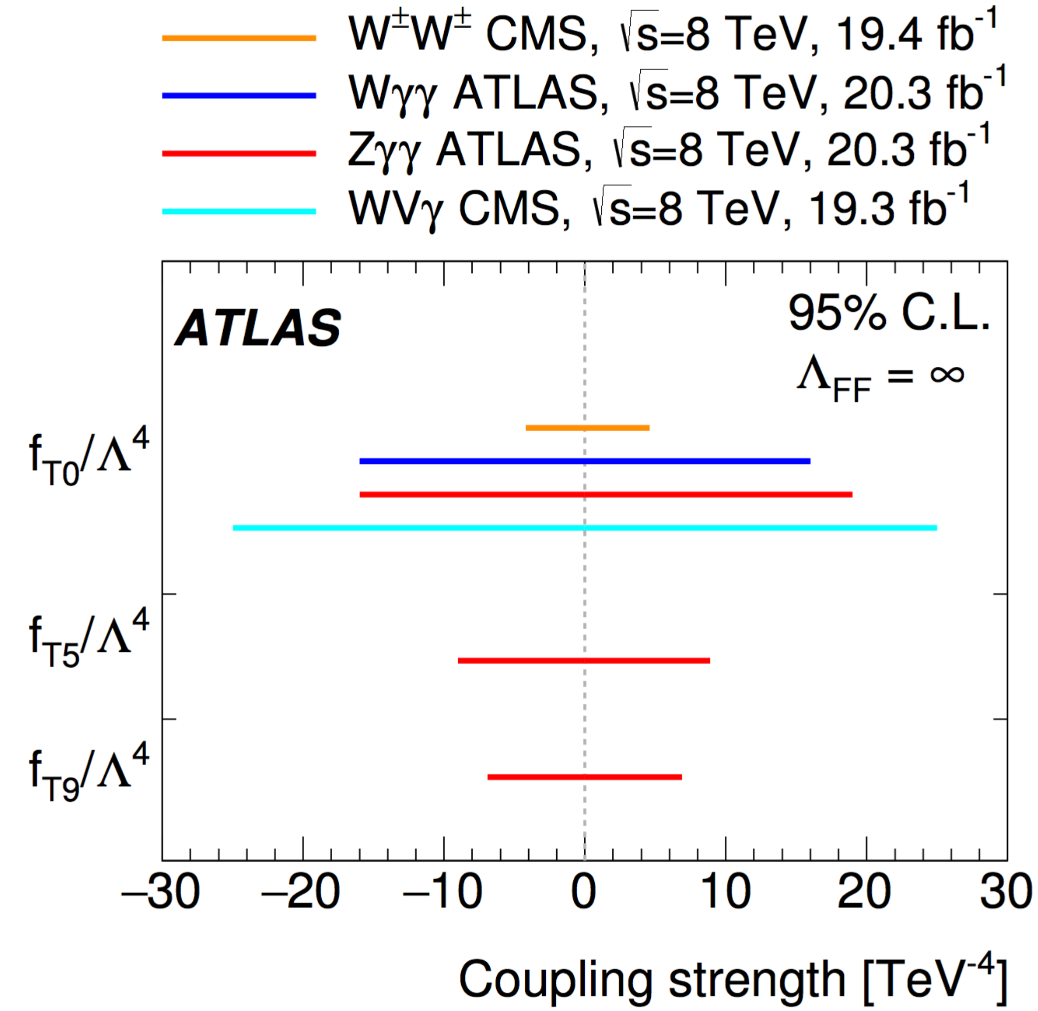
Cross sections :

Channel	Measurement [fb]	MCFM Prediction [fb]	NNLO Prediction [fb]
$N_{jets} \geq 0$			
$e^+e^-\gamma$	$1510 \pm 15(\text{stat.})^{+91}_{-84}(\text{syst.})^{+30}_{-28}(\text{lumi.})$	1345^{+66}_{-82}	1483^{+19}_{-37}
$\mu^+\mu^-\gamma$	$1507 \pm 13(\text{stat.})^{+78}_{-73}(\text{syst.})^{+29}_{-28}(\text{lumi.})$		
$\ell^+\ell^-\gamma$	$1507 \pm 10(\text{stat.})^{+78}_{-73}(\text{syst.})^{+29}_{-28}(\text{lumi.})$		
$\nu\bar{\nu}\gamma$	$68 \pm 4(\text{stat.})^{+33}_{-32}(\text{syst.}) \pm 1(\text{lumi.})$	68.2 ± 2.2	$81.4^{+2.4}_{-2.2}$
$N_{jets} = 0$			
$e^+e^-\gamma$	$1205 \pm 14(\text{stat.})^{+84}_{-75}(\text{syst.}) \pm 23(\text{lumi.})$	1191^{+71}_{-89}	1230^{+10}_{-18}
$\mu^+\mu^-\gamma$	$1188 \pm 12(\text{stat.})^{+68}_{-63}(\text{syst.})^{+23}_{-22}(\text{lumi.})$		
$\ell^+\ell^-\gamma$	$1189 \pm 9(\text{stat.})^{+69}_{-63}(\text{syst.})^{+23}_{-22}(\text{lumi.})$		
$\nu\bar{\nu}\gamma$	$43 \pm 2(\text{stat.}) \pm 10(\text{syst.}) \pm 1(\text{lumi.})$	$51.0^{+2.1}_{-2.3}$	$49.21^{+0.61}_{-0.52}$

$N_{jets} \geq 0$			
$e^+e^-\gamma\gamma$	$6.2\ ^{+1.2}_{-1.1}(\text{stat.}) \pm 0.4(\text{syst.}) \pm 0.1(\text{lumi.})$	$3.70^{+0.21}_{-0.11}$	
$\mu^+\mu^-\gamma\gamma$	$3.83\ ^{+0.95}_{-0.85}(\text{stat.})^{+0.48}_{-0.47}(\text{syst.}) \pm 0.07(\text{lumi.})$		
$\ell^+\ell^-\gamma\gamma$	$5.07\ ^{+0.73}_{-0.68}(\text{stat.})^{+0.41}_{-0.38}(\text{syst.}) \pm 0.10(\text{lumi.})$		
$\nu\bar{\nu}\gamma\gamma$	$2.5\ ^{+1.0}_{-0.9}(\text{stat.}) \pm 1.1(\text{syst.}) \pm 0.1(\text{lumi.})$	$0.737^{+0.039}_{-0.032}$	
$N_{jets} = 0$			
$e^+e^-\gamma\gamma$	$4.6\ ^{+1.0}_{-0.9}(\text{stat.})^{+0.4}_{-0.3}(\text{syst.}) \pm 0.1(\text{lumi.})$	$2.91^{+0.23}_{-0.12}$	
$\mu^+\mu^-\gamma\gamma$	$2.38\ ^{+0.77}_{-0.67}(\text{stat.})^{+0.33}_{-0.32}(\text{syst.})^{+0.05}_{-0.04}(\text{lumi.})$		
$\ell^+\ell^-\gamma\gamma$	$3.48\ ^{+0.61}_{-0.56}(\text{stat.})^{+0.29}_{-0.25}(\text{syst.}) \pm 0.07(\text{lumi.})$		
$\nu\bar{\nu}\gamma\gamma$	$1.18\ ^{+0.52}_{-0.44}(\text{stat.})^{+0.48}_{-0.49}(\text{syst.}) \pm 0.02(\text{lumi.})$	$0.395^{+0.049}_{-0.037}$	

Zγ and Zγγ measurements at 8 TeV

aQGC Limits :



aTGC Limits :

Process	$pp \to \ell^+\ell^-\gamma$ and $pp \to \nu\bar{\nu}\gamma$	
$\Lambda_{\rm FF}$	∞	
	Observed 95% C.L.	Expected 95% C.L.
h_3^γ	$[-9.5, 9.9] \times 10^{-4}$	$[-1.8, 1.8] \times 10^{-3}$
h_3^Z	$[-7.8, 8.6] \times 10^{-4}$	$[-1.5, 1.5] \times 10^{-3}$
h_4^γ	$[-3.2, 3.2] \times 10^{-6}$	$[-6.0, 5.9] \times 10^{-6}$
h_4^Z	$[-3.0, 2.9] \times 10^{-6}$	$[-5.5, 5.4] \times 10^{-6}$
$\Lambda_{\rm FF}$	4 TeV	
	Observed 95% C.L.	Expected 95% C.L.
h_3^γ	$[-1.6, 1.7] \times 10^{-3}$	$[-3.0, 3.1] \times 10^{-3}$
h_3^Z	$[-1.3, 1.4] \times 10^{-3}$	$[-2.5, 2.6] \times 10^{-3}$
h_4^γ	$[-1.2, 1.1] \times 10^{-5}$	$[-2.2, 2.1] \times 10^{-5}$
h_4^Z	$[-1.0, 1.0] \times 10^{-5}$	$[-1.9, 1.9] \times 10^{-5}$

n	$\Lambda_{\rm FF}$ [TeV]	Limits 95% C.L.	Observed [TeV^{-4}]	Expected [TeV^{-4}]
0	∞	f_{M2}/Λ^4	$[-1.6, 1.6] \times 10^4$	$[-1.2, 1.2] \times 10^4$
		f_{M3}/Λ^4	$[-2.9, 2.7] \times 10^4$	$[-2.2, 2.2] \times 10^4$
		f_{T0}/Λ^4	$[-0.86, 1.03] \times 10^2$	$[-0.65, 0.82] \times 10^2$
		f_{T5}/Λ^4	$[-0.69, 0.68] \times 10^3$	$[-0.52, 0.52] \times 10^3$
		f_{T9}/Λ^4	$[-0.74, 0.74] \times 10^4$	$[-0.58, 0.59] \times 10^4$
2	5.5	f_{M2}/Λ^4	$[-1.8, 1.9] \times 10^4$	$[-1.4, 1.5] \times 10^4$
	5.0	f_{M3}/Λ^4	$[-3.4, 3.3] \times 10^4$	$[-2.6, 2.6] \times 10^4$
	0.7	f_{T0}/Λ^4	$[-2.3, 2.1] \times 10^3$	$[-1.9, 1.6] \times 10^3$
	0.6	f_{T5}/Λ^4	$[-2.3, 2.2] \times 10^4$	$[-1.8, 1.8] \times 10^4$
	0.4	f_{T9}/Λ^4	$[-0.89, 0.86] \times 10^6$	$[-0.71, 0.68] \times 10^6$

$ZZ \rightarrow 4l$ Production at 13 TeV

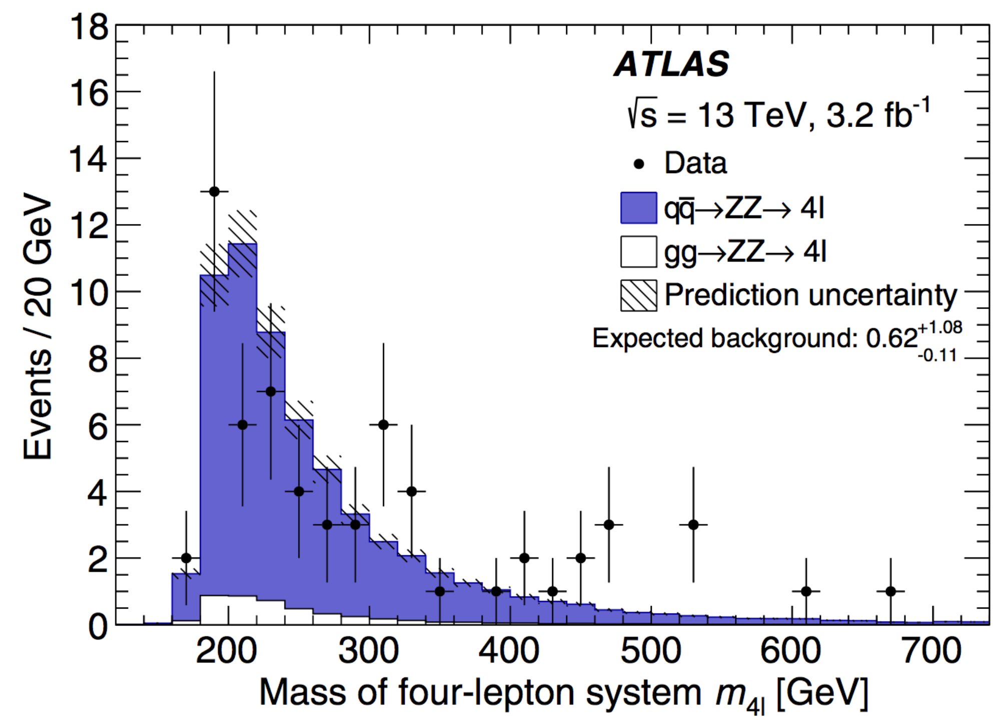
Fiducial Selection :

- ✦Prompt leptons used, dressed with prompt photons within $\Delta R < 0.1$
- ✦Leptons must be well separated $\Delta R > 0.2$
- ✦Lepton $p_T > 20$ GeV, $|\eta| < 2.7$
- ✦Exactly 4 leptons in event, with 2 SFOS pairs, allows 4 channels : 4e, 4μ, 2e2μ.
- ✦In 4e and 4μ, pairing that minimises $|m_{ll,a} - m_Z| + |m_{ll,b} - m_Z|$ chosen

Candidate Events - Same as above with small changes :

- ✦$Z_0 \sin\theta < 0.5$mm, d_0 significance < 3σ (5σ) muons (electrons)
- ✦Events pass single muon or dielectron trigger
- ✦Electrons - $|\eta| < 2.47$
- ✦Muons - one muon with $|\eta| < 2.4$ (for triggering), rest $|\eta| < 2.7$
- ✦Ignore event if >1 muon is calo-tagged or standalone.

ZZ→4l Production at 13 TeV



Background Contributions (small) :

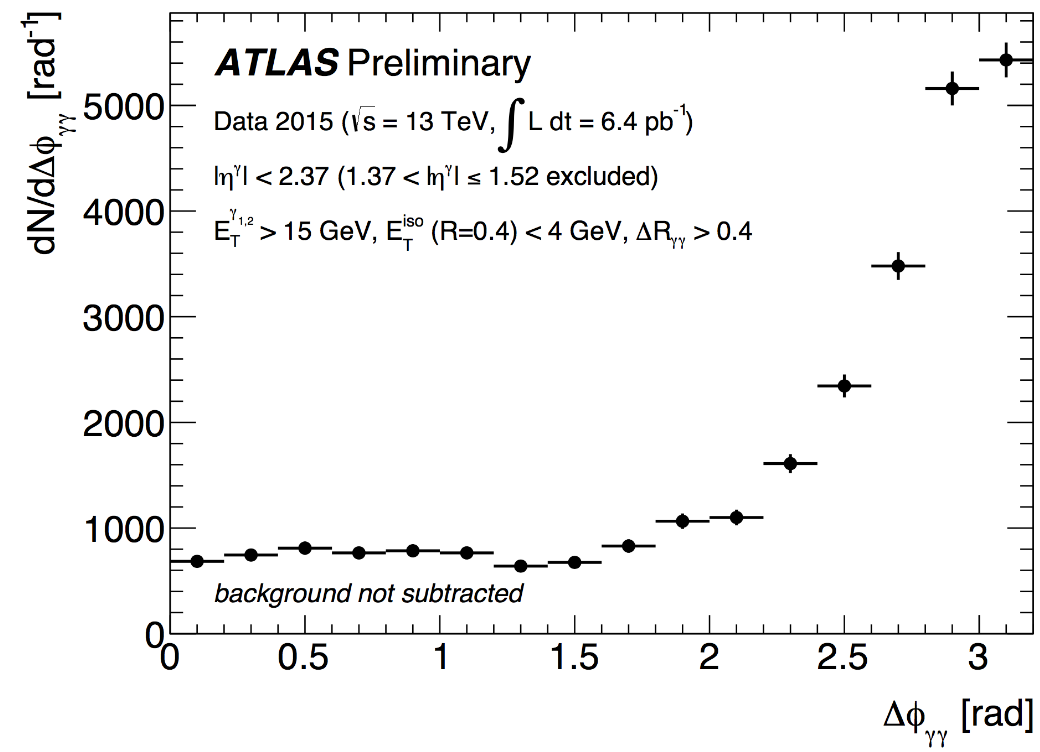
- ✦ZZ with one Z→ττ - 0.07 ± 0.02
- ✦Non-hadronic triboson processes - 0.17 ± 0.05
- ✦ttZ - 0.3 ± 0.09
- ✦Z, WW, WZ, ttbar, ZZ, qqbar where jet/γ fakes lepton (Data driven - CR) - 0.09 +(-) 1.08(-0.04)
- ✦Total : 0.62 +(-) 1.08(-0.04)

Dominant Systematics :

- ✦Uncertainties on SF' to correct for lepton identification and reconstruction efficiencies in MC.
- ✦Choice of MC generator.

Source	$4e$	$2e2\mu$	4μ
Statistical (signal samples)	0.7	0.5	0.5
Theoretical (generator, PDFs)	2.5	2.5	2.5
Experimental efficiencies	2.3	2.2	2.0
Momentum scales and resolutions	0.4	0.2	0.1
Total	3.5	3.3	3.2

Diphoton spectra 13 TeV



- ✦ Isolated diphoton pairs,
- ✦ Inclusive $m_{\gamma\gamma}$, $p_{T,\gamma\gamma}$ and $\Delta\phi_{\gamma\gamma}$ spectra measured with first 6.4 pb^{-1} of data.