Precision measurements and searches with single and multiple gauge bosons with the ATLAS detector

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On behalf of the ATLAS Collaboration

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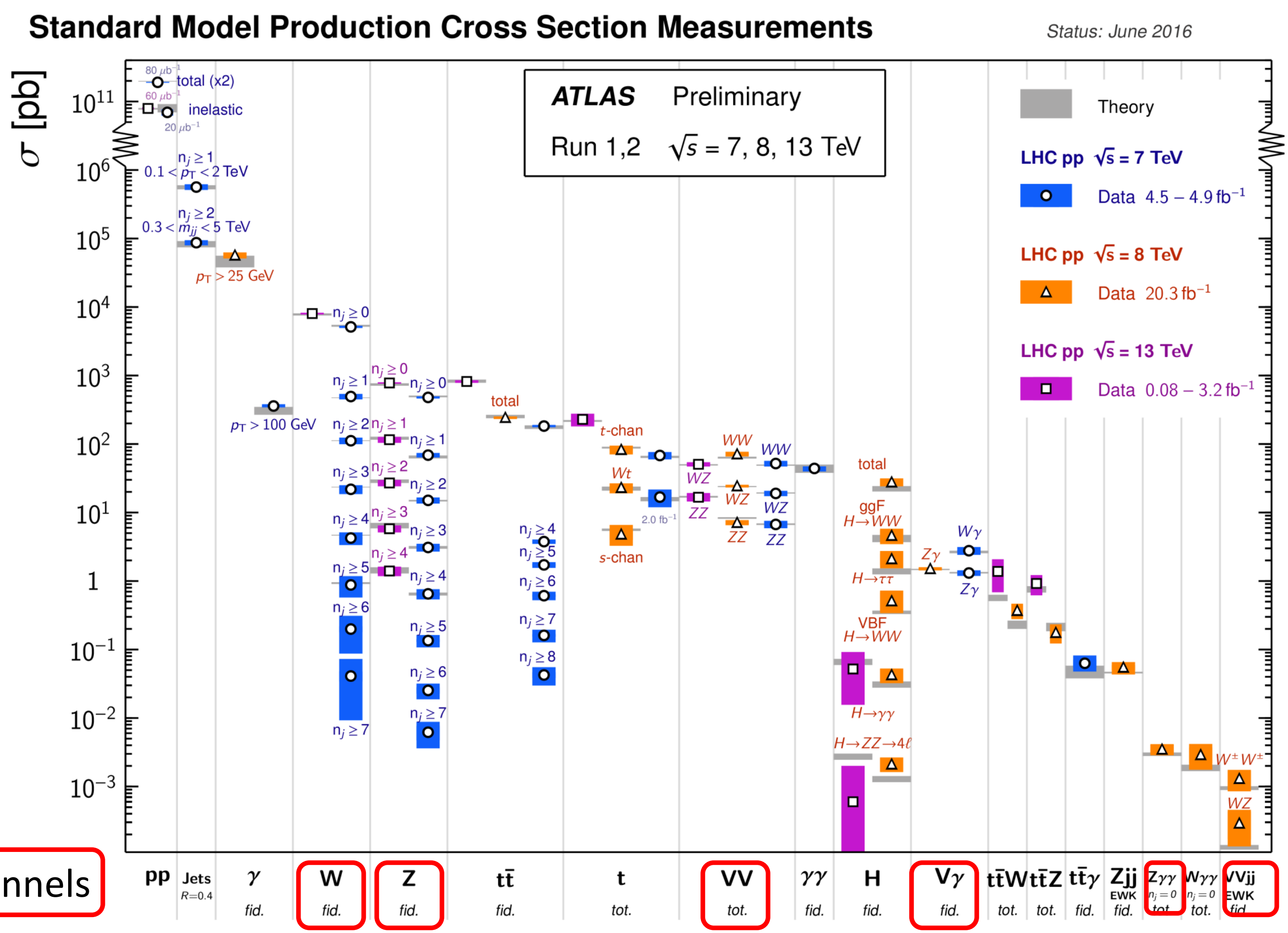
Introduction

- A lot of nice ATLAS SM results using Run1/Run2 data were currently produced.



Covered channels

- Precision increased up to comparisons with NNLO theory predictions.

Motivation

➢ **Two main goals of Standard Model (SM) measurements in ATLAS are: to test theory with high precision and to find signs of new physics.**

More details:

Measurement of integrated, differential cross sections and different angular distributions

- to prove validity of Standard Model at the TeV scale;

- to compare with theory predictions of higher order QCD and QED effects;

- to probe the proton structure;

- to understand irreducible diboson backgrounds into Higgs and exotic analyses.

Extrapolation of self-coupling structure of gauge bosons

- will improve our understanding of electroweak symmetry breaking and unitarity;

- intersect with determination of Higgs couplings;

- indicate "new physics" if anomalous triple/quartic gauge couplings are present.

Cross-section measurement in a nutshell

Number of observed events in fiducial region

Number of background (MC simulation / data-driven)

$$\sigma \times BR = \frac{N_{obs} - N_{bkg}}{A \times C \times \int L dt}$$

Signal acceptance on generator level in fiducial region

$$A = \frac{N_{fid}}{N_{gen}}$$

Signal efficiency on detector level

$$C = \frac{N_{sel}}{N_{fid}}$$

Differential cross section: Study of unfolded differential distributions and probe high momentum events for anomalous TGC's and QGC's

Single gauge boson measurements

Inclusive W and Z @ 13 TeV

arXiv:1603.09222

Starting point:

Data: L=81 pb^{-1} ± 2.1% (50 ns)

MC signal: Powheg+Pythia8; Main bkgs: jet-jet, Z/W inc.

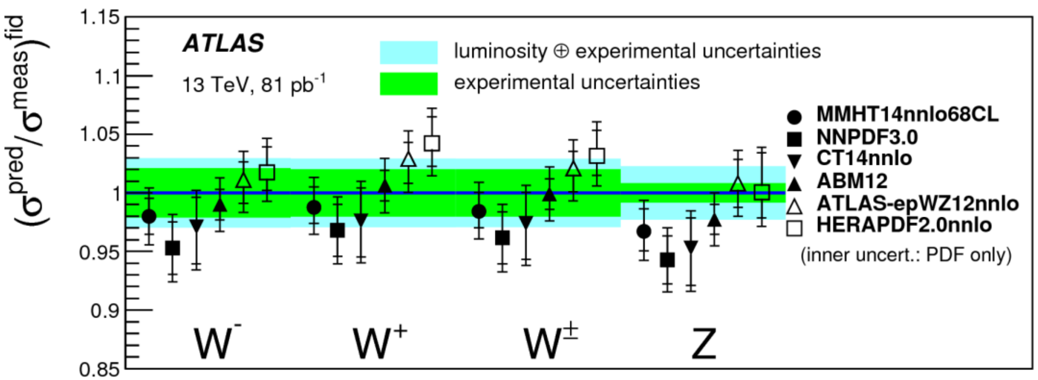
Selection for fiducial region:

$W \to e\nu/\mu\nu$ $m_T(W) > 50$ GeV

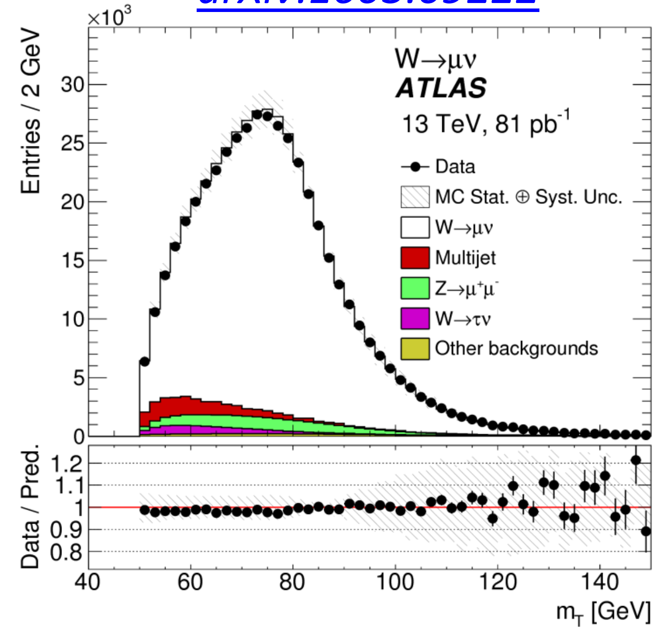
$Z \to ee/\mu\mu$ 66 GeV < m_{ll} < 116 GeV

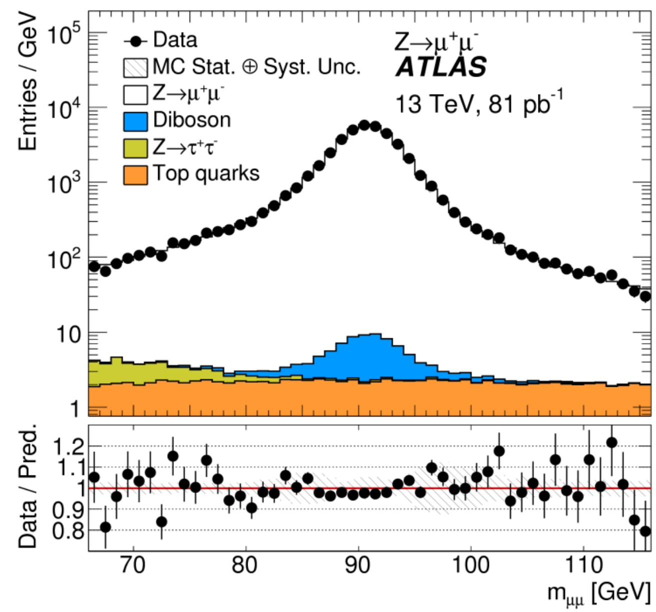
$p_T(l,\nu) > 25$ GeV $|\eta_l|<2.5$

Cross section measurement results:



- **Good agreement with NNLO QCD and NLO EW prediction (several different PDF sets were considered)**
- **Dominant uncertainties are from Luminosity, JES and multijet bkg.**





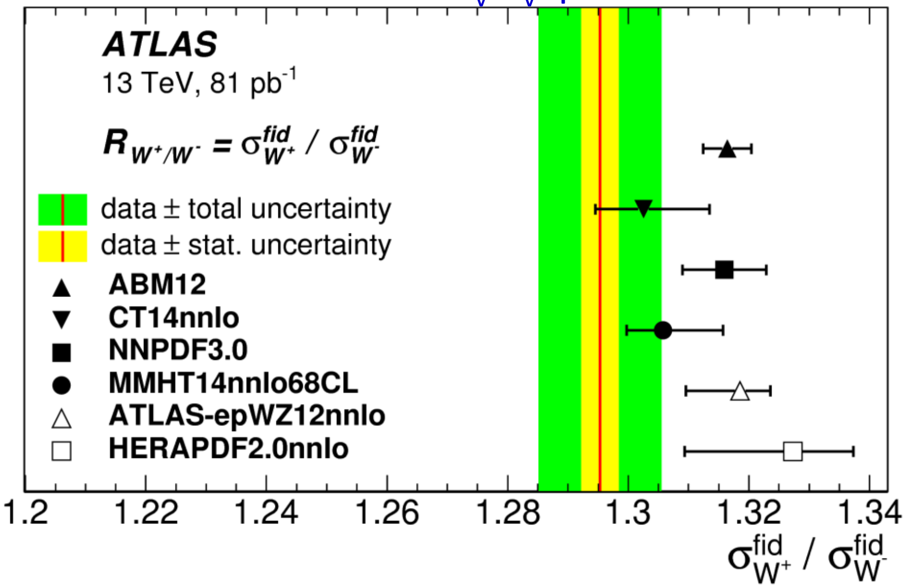
Inclusive W and Z @ 13 TeV

arXiv:1603.09222

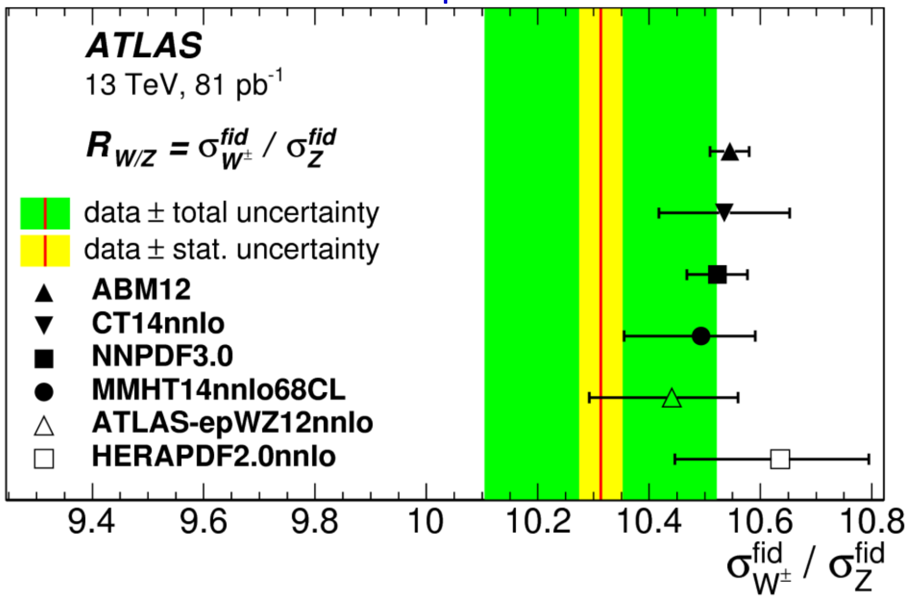
Cross section ratios:

	Measured ratio	Predicted ratio
W^+/W^-	$1.295 \pm 0.003 \pm 0.010$	1.30 ± 0.01
$W^\pm/Z$	$10.31 \pm 0.04 \pm 0.20$	10.54 ± 0.12

Sensitive to low-x u_v-d_v quark PDFs



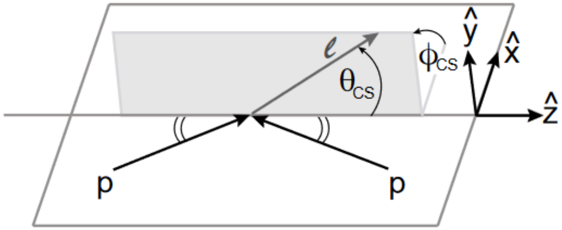
Sensitive to s-quark PDFs



- Some uncertainties are partially cancelled in ratios (lumi, lepton ID and trigger)
- W^+/W^-: better agreement with CT14nnlo and MMHT14nnlo (precision: ~1%: just uncorrelated part of multijet bkg uncertainty)
- W/Z: good agreement for all PDF sets (precision: ~2%: multijet bkg, JES, JER error).
  - To improve PDFs – it needs higher precision.

Angular coefficients in Z boson events @ 8 TeV

arXiv:1606.00689



Motivation:

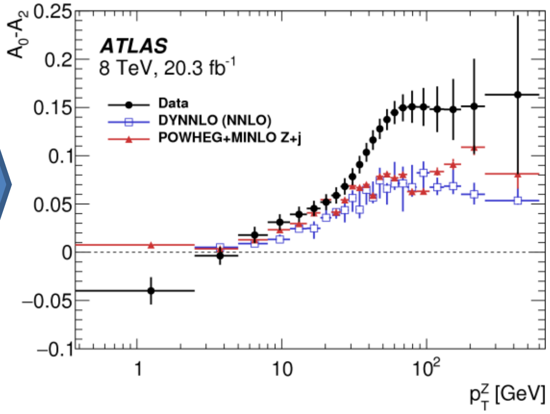
- Measurement of production dynamics through a spin 1 Z via spin correlation between initial and final state partons.
- Use Collins-Soper (CS) reference frame: it defines lepton θ and ϕ. Coefficients can be expressed as a function of θ and ϕ:

$$\langle \frac{1}{2}(1-3\cos^2\theta)\rangle = \frac{3}{20}(A_0-\frac{2}{3}); \quad \langle \sin 2\theta \cos\phi\rangle = \frac{1}{5}A_1; \quad \langle \sin^2\theta\cos 2\phi\rangle = \frac{1}{10}A_2;$$

$$\langle \sin\theta\cos\phi\rangle = \frac{1}{4}A_3; \quad \langle\cos\theta\rangle = \frac{1}{4}A_4; \quad \langle \sin^2\theta \sin 2\phi\rangle = \frac{1}{5}A_5;$$

$$\langle \sin 2\theta \sin\phi\rangle = \frac{1}{5}A_6; \quad \langle \sin\theta\sin\phi\rangle = \frac{1}{4}A_7.$$

Deviations are due to higher-order QCD effects

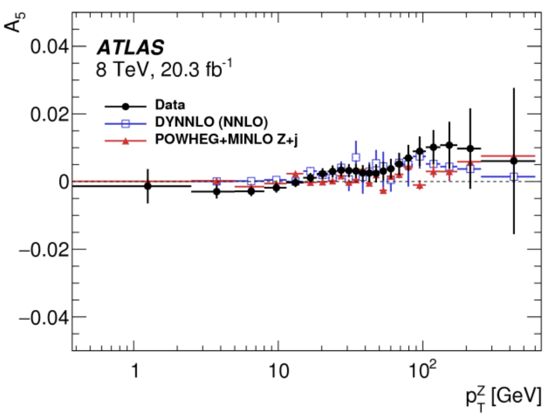


Selection for fiducial region:

Z → ee/μμ 80 GeV < m_{ll} < 100 GeV

Central-central channel: $p_T(l)$ > 25 GeV $|\eta_l|$<2.4 **OR**

Central-forward channel: $p_T(e)$ > 20 GeV 2.5<$|\eta_e|$<4.9



Result:

Coefficients $A_{0\text{-}7}$ and comparison with theory:

- In general comparison with Powheg+MINLO and DYNNLO show good agreement with data.
- A_0-A_2 confirms Lam-Tung breaking @ higher orders than NLO → very sensitive probe of higher order QCD corrections!

Multiple gauge boson measurements

WZ @ 8 TeV

[Phys. Rev. D 93, 092004](#)

Starting point:

Data: L=20.3 fb^{-1} ± 1.9%

MC signal: Powheg+Pythia8; Main bkgs: misID leptons, ZZ (~20% total).

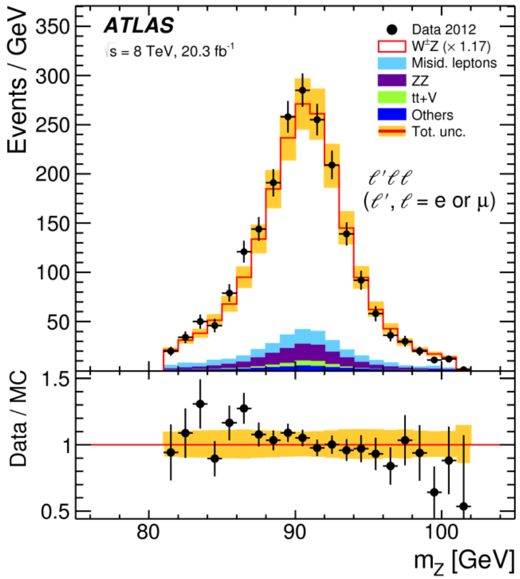
Selection for fiducial region:

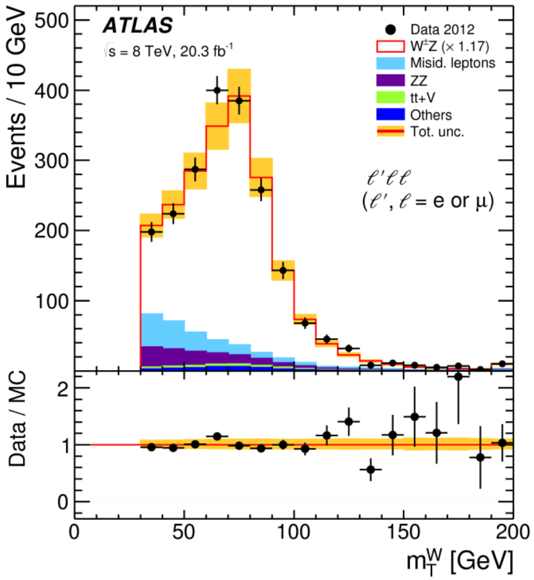
$W^{\pm}Z \rightarrow l^{\pm}\nu l^{\pm}l^{\pm}$ (l=e/μ): On shell Z – ll invariant mass within 10 GeV near Z peak;

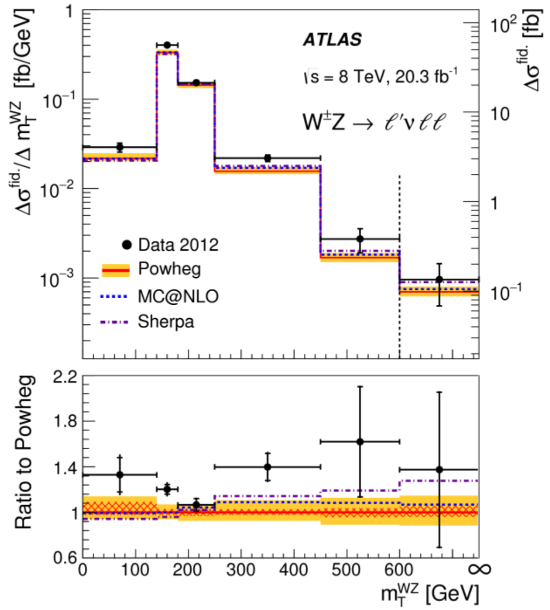
$p_T(l)$ > 15(20) GeV for lepton from Z(W), lepton |η|<2.5; $m_T(l\nu)$ > 30 GeV

Measurements of:

- Integrated σ, differential σ distributions, $\sigma(W^+Z)/\sigma(W^-Z)$ and limits set on aTGC's.
- Search for VBS WZ and limits set on aQGC's in VBS phase space.







Good overall agreement between data and predictions.

Fair agreement, NNLO can help

WZ @ 8 TeV

Systematics:

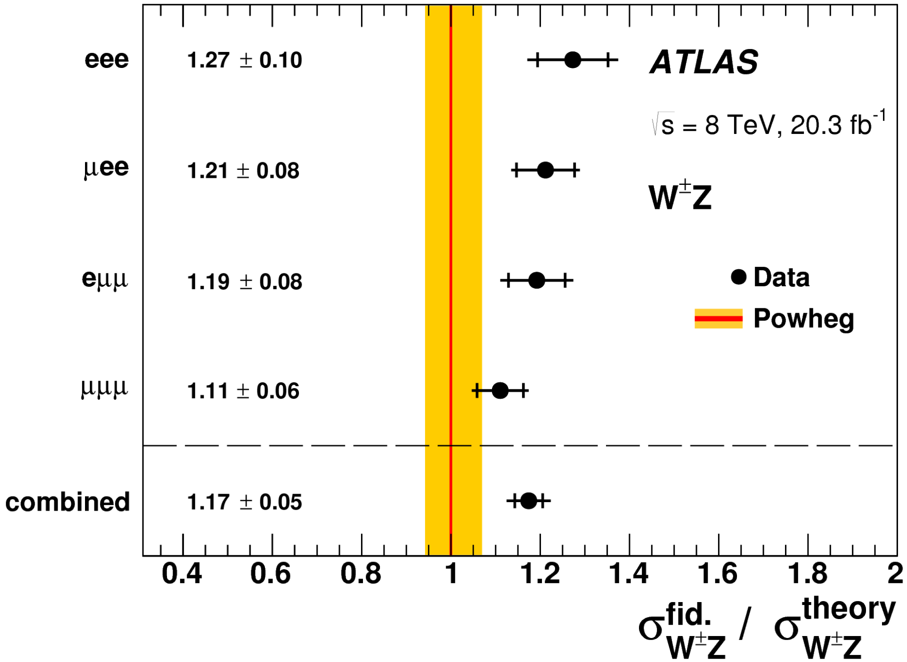
Phys. Rev. D 93, 092004

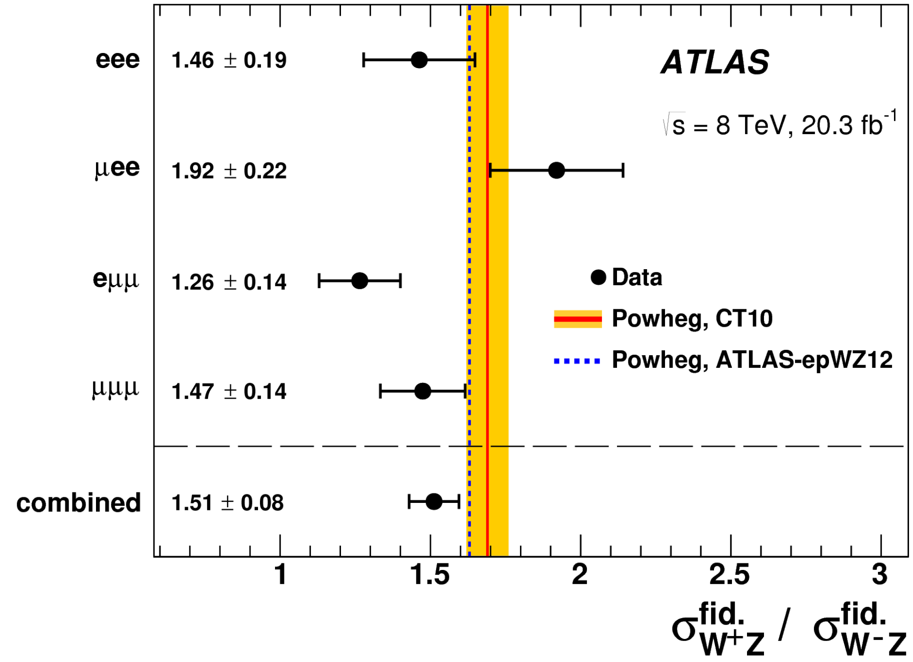
- Statistical and systematic uncertainties for the ratio $\sigma(W^+Z)/\sigma(W^-Z)$ is roughly on the same order as for integrated σ
- Uncertainty dominated by electron Id. efficiency, luminosity, muon reco. efficiency and knowledge of mis-id background.
- Dominant theory uncertainty due to QCD scale uncertainty.

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

NLO:

$$\sigma^{theory}_{W^\pm Z} = 21.0 \pm 1.6\ \mathrm{pb}$$





NNLO predictions can make agreement better.

WZ @ 13 TeV

arXiv:1606.04017

Starting point:

Data: L=3.2 fb^{-1} ± 2.1%

MC signal: Powheg+Pythia8; Main bkgs: misID leptons, ZZ (~20% total).

Selection for fiducial region:

$W^{\pm}Z \rightarrow l^{\pm}\nu l^{\pm}l^{\pm}$ ($l=e/\mu$): On shell Z – ll invariant mass within 10 GeV near Z peak;

$p_T(l)$ > 15(20) GeV for lepton from Z(W), lepton $|\eta|<2.5$; $m_T(l\nu)$ > 30 GeV

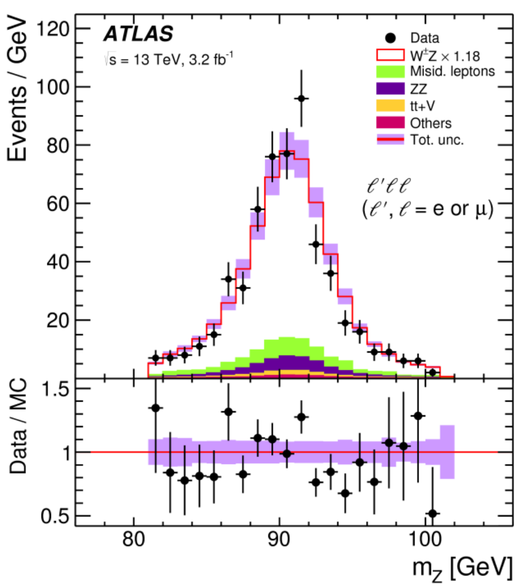
Measurements of:

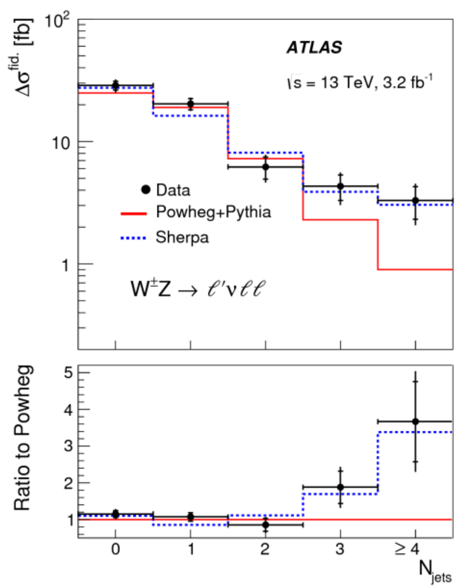
- Integrated σ, differential σ vs jet multiplicity and $\sigma(W^+Z)/\sigma(W^-Z)$.

$$\sigma^{\text{tot.}}_{W^{\pm}Z} = 50.6 \pm 2.6\,(\text{stat.}) \pm 2.0\,(\text{sys.}) \pm 0.9\,(\text{th.}) \pm 1.2\,(\text{lumi.})\ \text{pb}$$

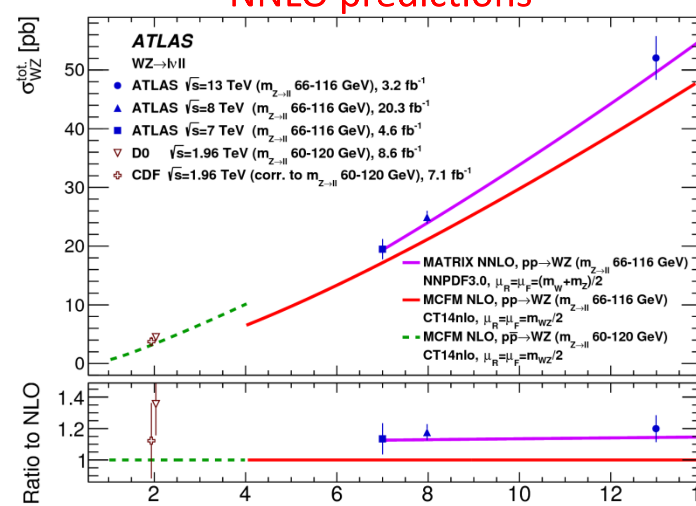
NNLO:

$$\sigma^{\text{theory}}_{W^{\pm}Z} = 48.2^{+1.1}_{-1.0}\,(\text{scale})\ \text{pb}$$





Comparison of data, NLO and NNLO predictions



Good overall agreement between data and predictions.

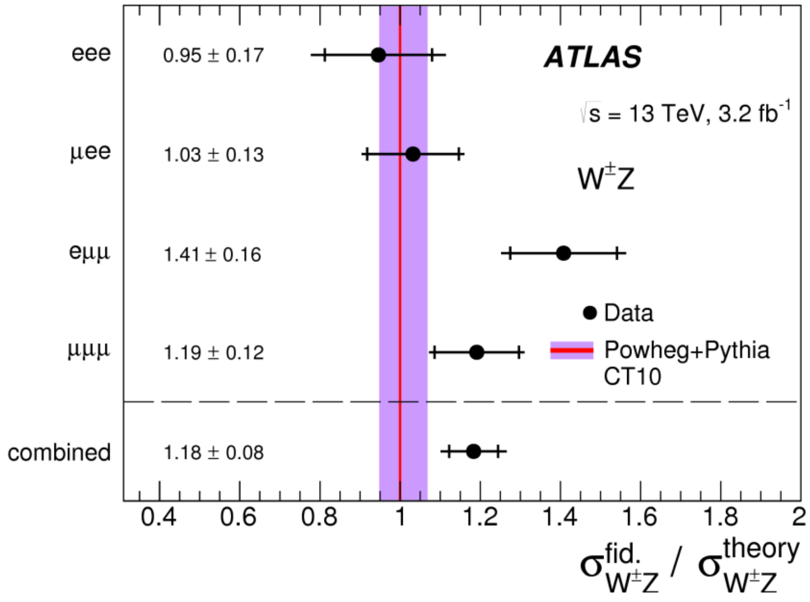
NLO and NNLO are quite different

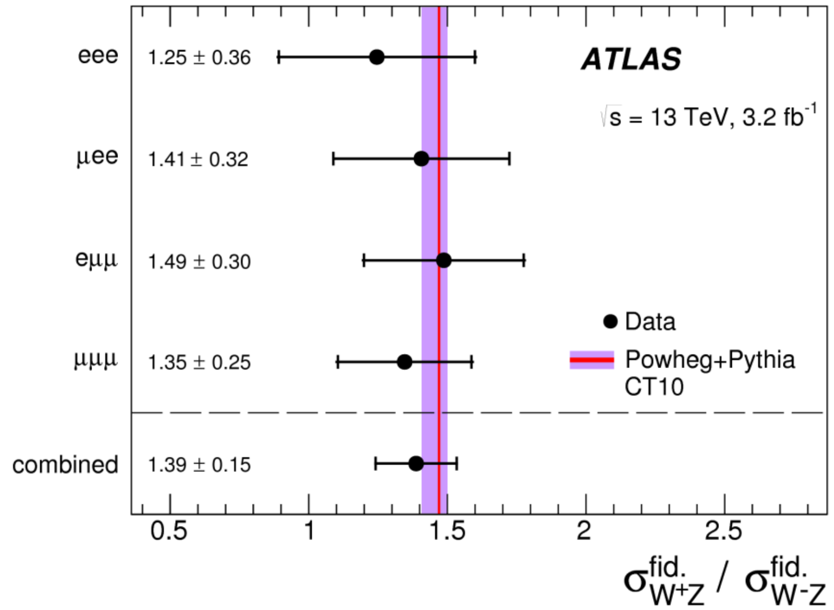
WZ @ 13 TeV

Systematics: arXiv:1606.04017

- Statistical and systematic uncertainties for the $\sigma(W^+Z)/\sigma(W^-Z)$ is roughly on the same order as for integrated σ
- Uncertainty dominated by electron Id. efficiency, luminosity, muon reco. efficiency and knowledge of mis-id background.
- Dominant theory uncertainty due to QCD scale uncertainty.

$$\frac{\sigma^{\text{fid.}}_{W^+Z\to\ell'\nu\ell\ell}}{\sigma^{\text{fid.}}_{W^-Z\to\ell'\nu\ell\ell}} = 1.39 \pm 0.14\,(\text{stat.}) \pm 0.03\,(\text{sys.})$$





$$\frac{\sigma^{\text{fid.,13 TeV}}_{W^\pm Z}}{\sigma^{\text{fid.,8 TeV}}_{W^\pm Z}} = 1.80 \pm 0.10\,(\text{stat.}) \pm 0.08\,(\text{sys.}) \pm 0.06\,(\text{lumi.})$$

ZZ @ 13 TeV

Phys. Rev. Lett. 116, 101801

Starting point:

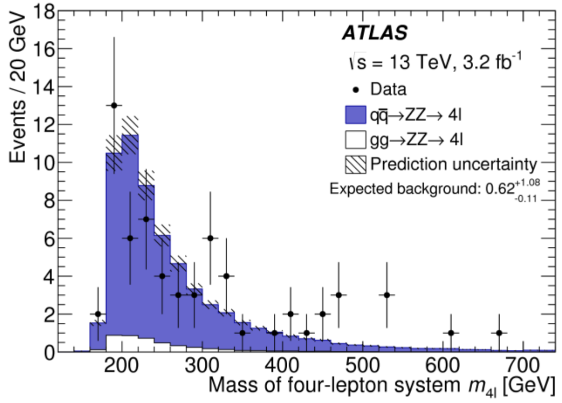
Data: L=3.2 fb^{-1} ± 2.1%

MC signal: Powheg+Pythia8; Main bkgs: $t\bar{t}Z$, non-hadronic triboson(~1% total).

Selection for fiducial region:

ZZ→4l(4l=4e/4μ/2e2μ): for each Z - 66 GeV < m_{ll} < 116 GeV;

$p_T(l)$ > 20 GeV, lepton |η|<2.7



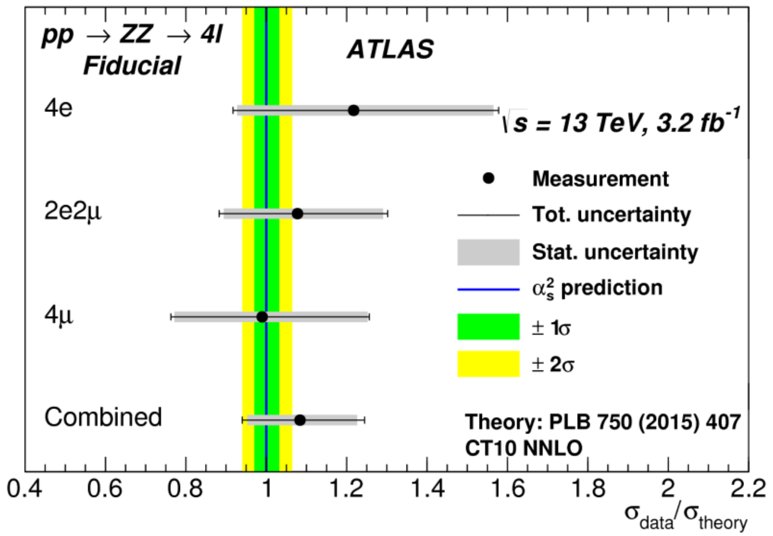
Measurements of:

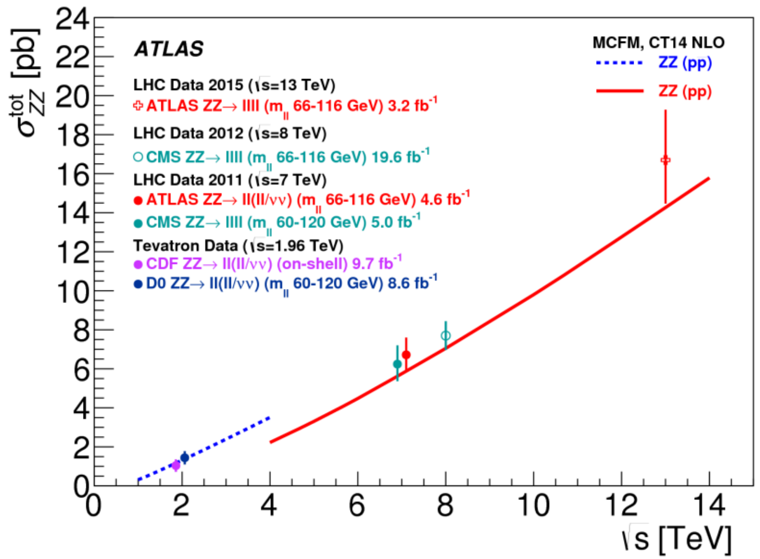
- Integrated σ

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

NNLO prediction:

$$\sigma_{ZZ}^{th} = 15.6^{+0.4}_{-0.4}\ \mathrm{pb}$$





Measurement is statistically dominated.

WW @ 8 TeV

arXiv:1603.01702

Starting point:

Data: L=20.3 fb^{-1} ± 1.9%

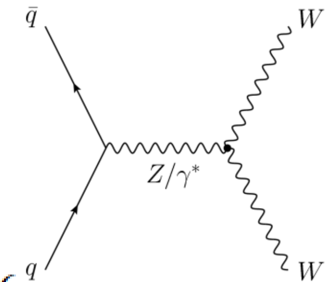
MC signal: Powheg+Pythia8; Main bkgs: top quark, W+jets, DY (~25% total).

Selection for fiducial region:

$W^+W^- \to ll\nu\nu (l=e/\mu)$: $p_T(\nu\nu)$>20(45) GeV for eμ(ee/μμ); $|m_Z - m_{ll}|$>15 GeV for ee/μμ events.

p_T(l) > 25(20) GeV for (sub)leading lepton, lepton |η|<2.4(2.47) for μ(e).

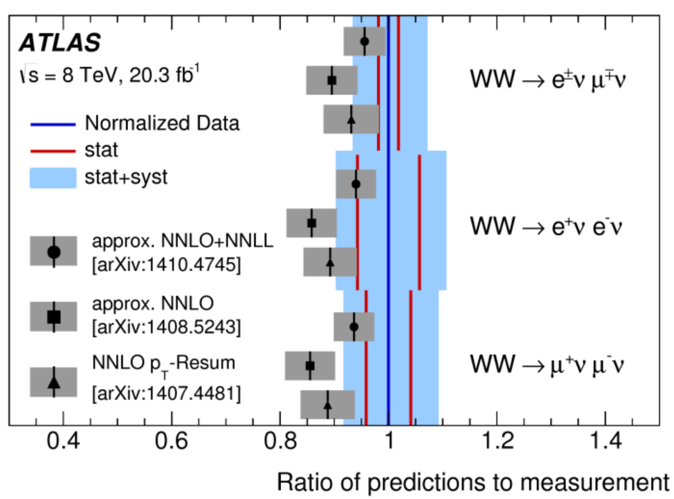
Jet veto applied.

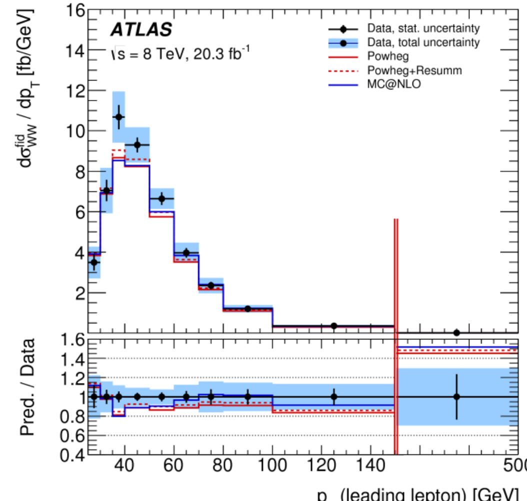


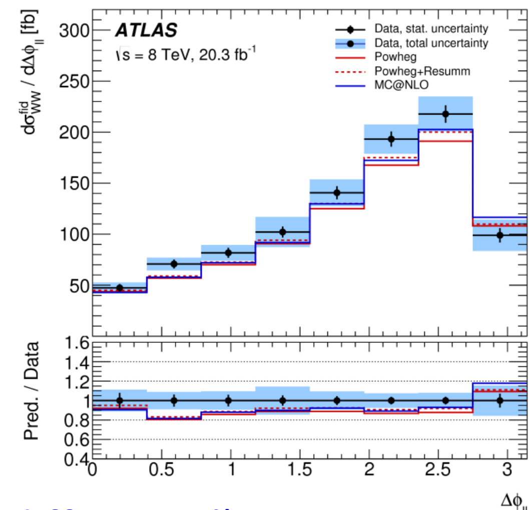
Measurements of:

- Integrated σ, differential σ distributions and limits set on aTGC's.

$\sigma_{tot}(pp \to WW) = 71.1 \pm 1.1(\text{stat}) ^{+5.7}_{-5.0}(\text{syst}) \pm 1.4(\text{lumi})$ pb $\sigma(\text{NNLO}_{tot})_{th} = 63.2^{+1.6}_{-1.4}(\text{scale}) \pm 1.2(\text{PDF})$





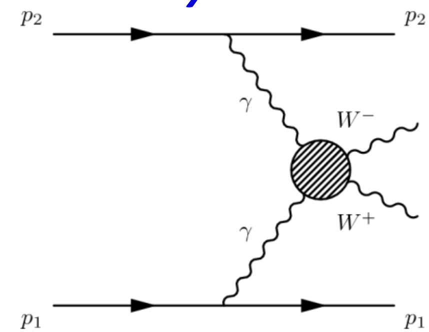


Measurement is in agreement with NNLO theory (integrated and differential).

Main systematics from JES, multijet bkg, jet veto, soft QCD.

$\gamma\gamma \to WW$ @ 8 TeV

Preliminary!



Starting point:

Data: L=20.3 $fb^{-1} \pm 1.9\%$

MC signal: Herwig++/FPMC; Main bkgs: $Z/\gamma^* \to \tau\tau$, VV

Event selection:

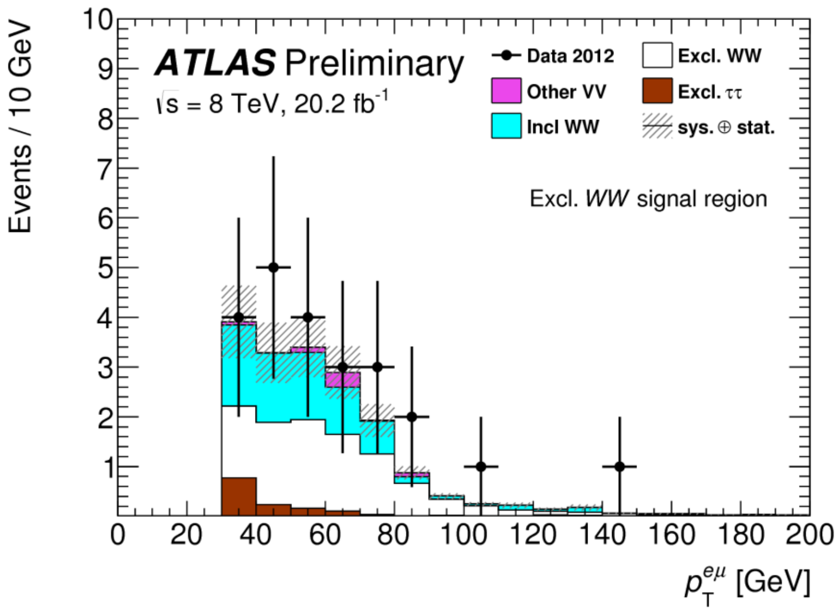
$\gamma\gamma \to W^+W^- \to e\mu\nu\nu$: $p_T(e\mu) > 30$ GeV; $m_{ll} > 20$ GeV;

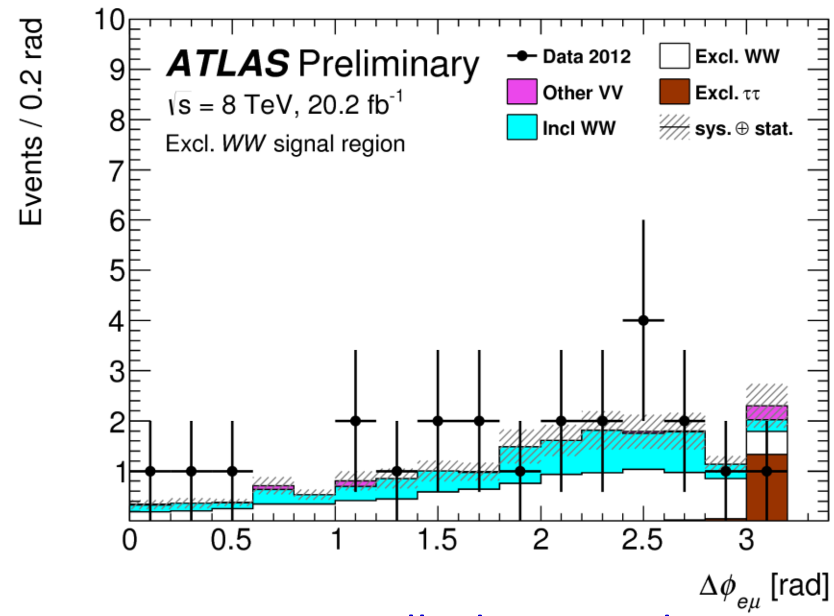
$p_T(l) > 25(20)$ GeV for leading(subleading) lepton, $|\eta_l| < 2.5(2.47)$ for μ(e);

Exclusivity selection: no extra tracks within Δz=1 mm from z average of 2 selected leptons.

Measurements of:

- Integrated σ and limits set on aQGC's.





Measurement is in agreement with theory, uncertainty is statistically dominated.

Zγ @ 8 TeV

Phys. Rev. D 93, 112002

Starting point:

Data: $L=20.3\ fb^{-1} \pm 1.9\%$

MC signal: Sherpa; Main bkgs: Z+jets - for llγ(~15%), γ+jets, Wγ, W(eν) – for ννγ(~40-60%).

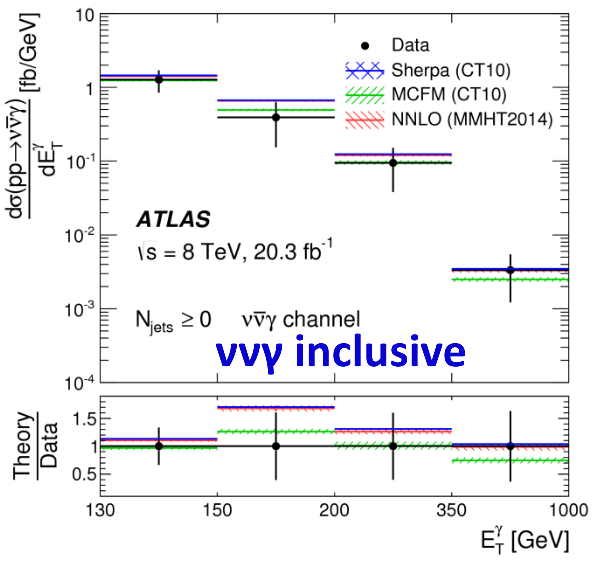
Selection for fiducial region:

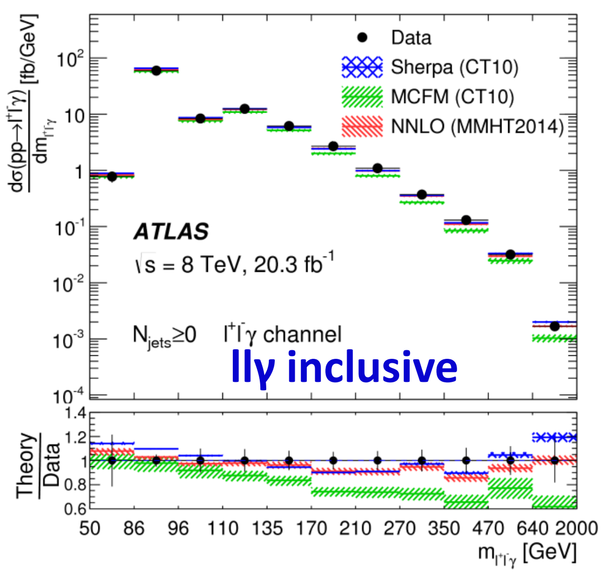
Zγ→llγ(l=e/μ): $p_T(l)>25$ GeV, $|\eta_l|<2.47$; $m_{ll}>40$ GeV; $E_T(\gamma)>15$ GeV, $|\eta_\gamma|<2.37$.

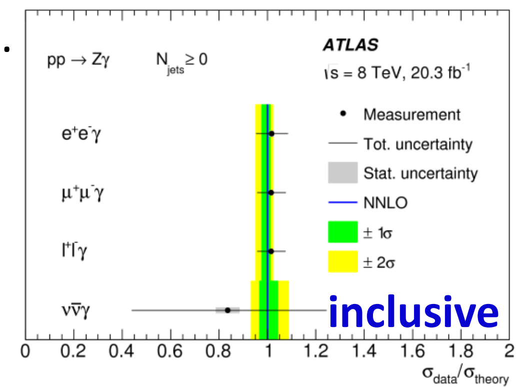
Zγ→ννγ: $E_T(\gamma)>130$ GeV, $|\eta_\gamma|<2.37$; $p_T(\nu\nu)>100$ GeV; $\Delta\varphi[\gamma, p_T(\nu\nu)]>\pi/2$

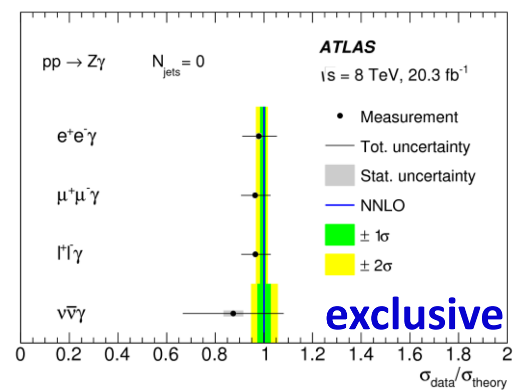
Measurements of:

- Integrated σ, differential σ distributions and limits set on aTGC's.









- Measured cross section agrees well with SM within uncertainties
- Main uncertainty on: lepton ISO (llγ), JES, lumi, γ-ISO (ννγ)

Zγγ @ 8 TeV

[Phys. Rev. D 93, 112002](#)

Starting point:

Data: $L=20.3\ fb^{-1} \pm 1.9\%$

MC signal: Sherpa; Main bkgs: Zjets - for llγγ(~15-30%), γ+jets, W(eν)γ – for ννγγ(~50-60%).

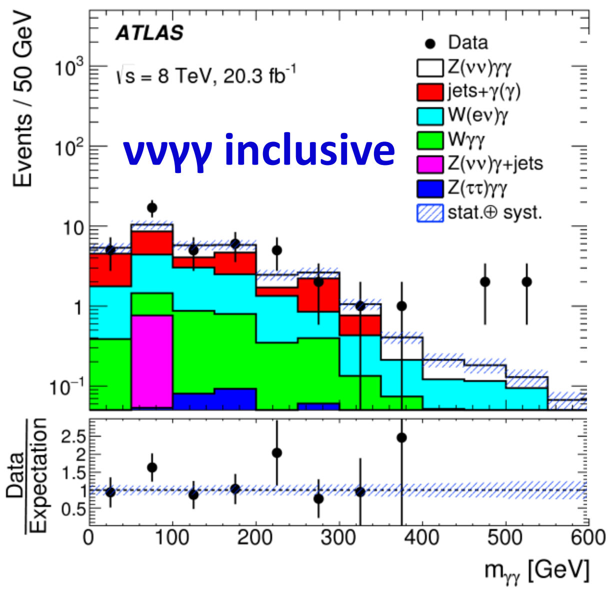
Selection for fiducial region:

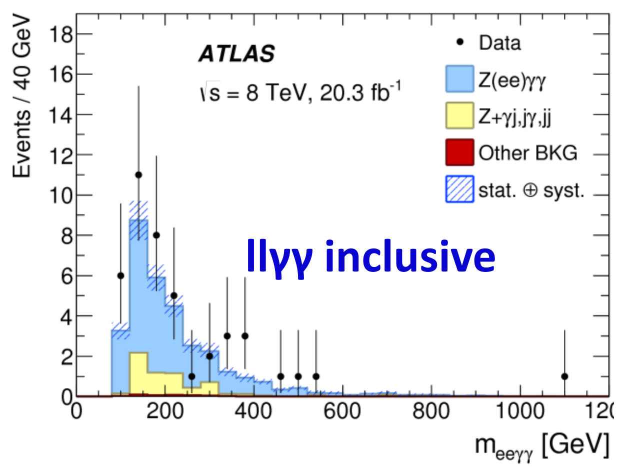
Zγγ→llγγ(l=e/μ): $p_T(l)>25$ GeV, $|\eta_l|<2.47$; $m_{ll}>40$ GeV; $E_T(\gamma)>15$ GeV, $|\eta_\gamma|<2.37$.

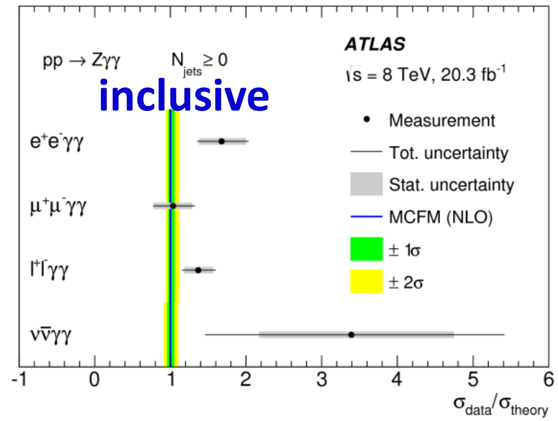
Zγγ→ννγγ: $E_T(\gamma)>22$ GeV, $|\eta_\gamma|<2.37$; $p_T(\nu\nu)>110$ GeV; $\Delta\varphi[\gamma\gamma, p_T(\nu\nu)]>5\pi/6$

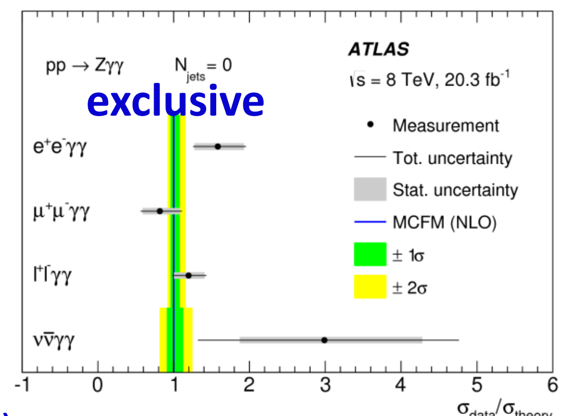
Measurements of:

- Integrated σ and limits set on aQGC's.









- Measured cross section agrees with SM within uncertainties
- Main uncertainty on: lepton ISO (llγ), γ-ID, JES, lumi, γ-ISO (ννγ)

6σ combined llγγ significance

Multiple gauge boson measurements: aGC

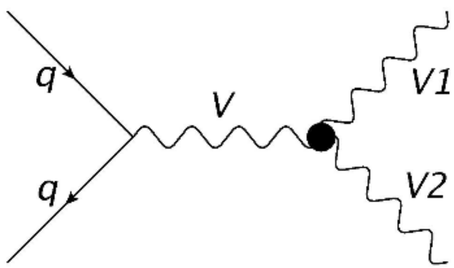
Coupling combinations

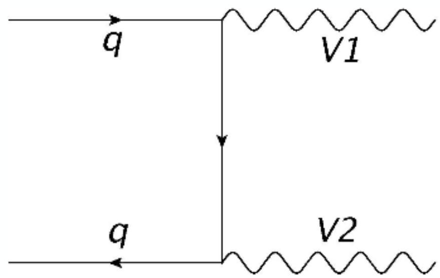
Charged couplings :

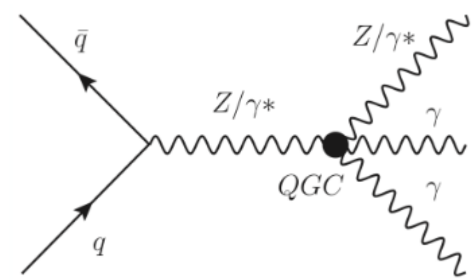
γWW, ZWW, WWZZ, WWZγ, WWγγ - allowed within the SM.

Neutral couplings :

ZZγ, γγZ, ZZZ, ZZγγ, Zγγγ - not allowed within the SM.







Anomalous coupling approaches

aTGC: **effective Lagrangian**

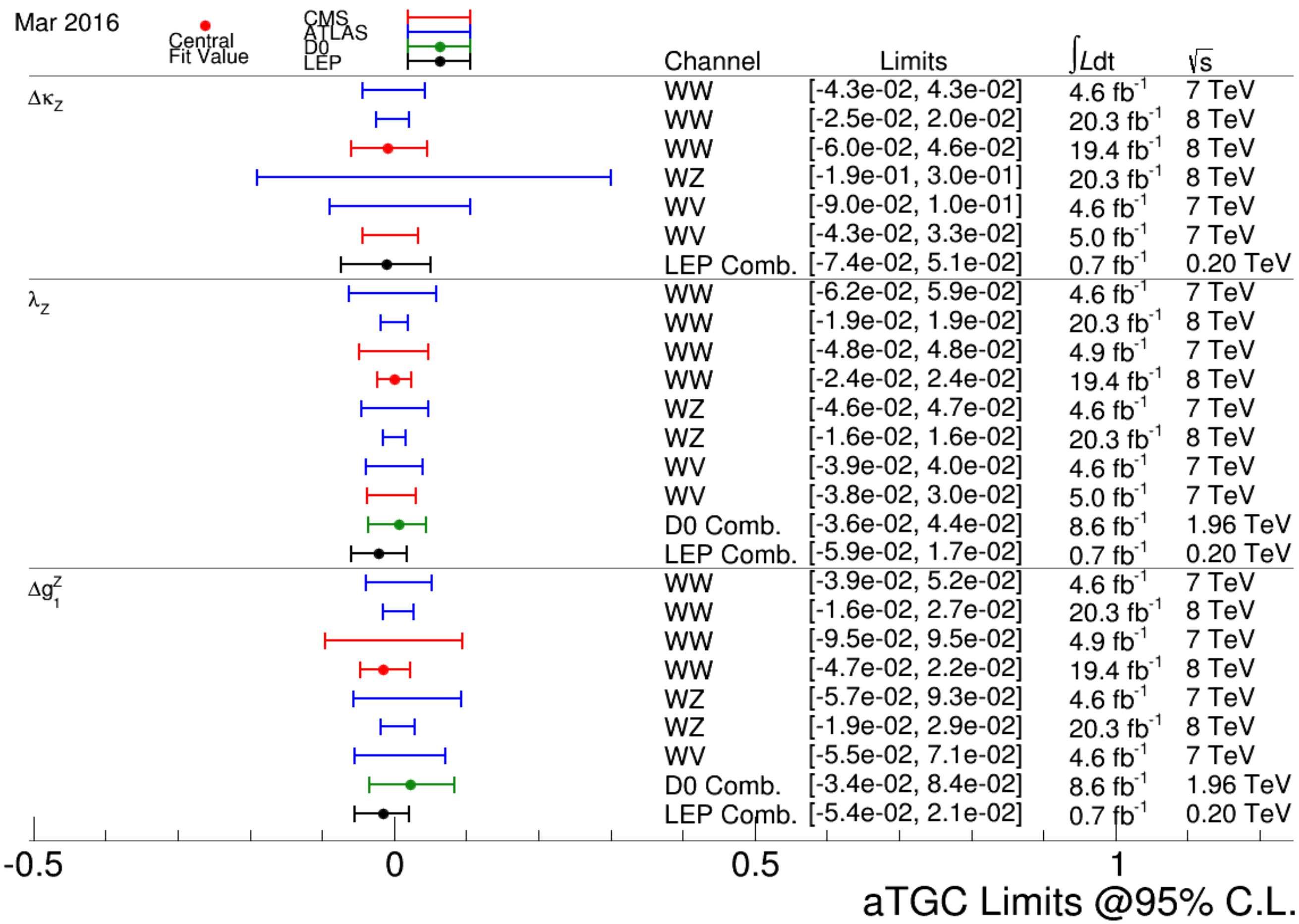
aQGC: **effective field theory**

Parameters of the couplings:

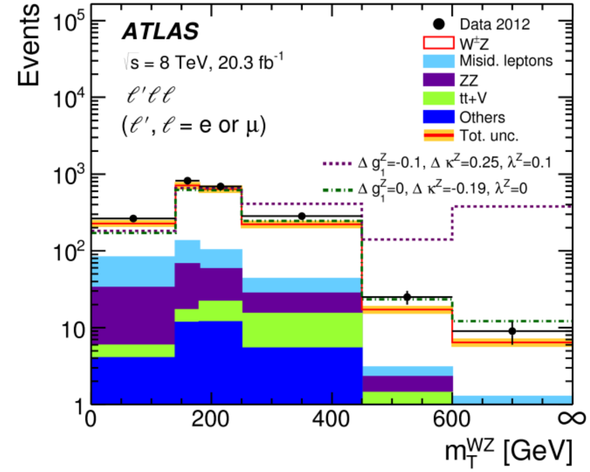
Coupling	Parameters	Channel
WWγ	$\lambda\gamma$, $\Delta k\gamma$	WW, Wγ
WWZ	λZ, ΔkZ, Δg_1^Z	WW, WZ
ZZγ	h_3^Z, h_4^Z	Zγ
Zγγ	h_3^γ, h_4^γ	Zγ
ZγZ	f_{40}^γ, f_{50}^γ	ZZ
ZZZ	f_{40}^Z, f_{50}^Z	ZZ

	$WWWW$	$WWZZ$	$ZZZZ$	$WW\gamma Z$	$WW\gamma\gamma$	$ZZZ\gamma$	$ZZ\gamma\gamma$	$Z\gamma\gamma\gamma$	$\gamma\gamma\gamma\gamma$
$\mathcal{L}_{S,0}$, $\mathcal{L}_{S,1}$	X	X	X	O	O	O	O	O	O
$\mathcal{L}_{M,0}$, $\mathcal{L}_{M,1}$, $\mathcal{L}_{M,6}$, $\mathcal{L}_{M,7}$	X	X	X	X	X	X	X	O	O
$\mathcal{L}_{M,2}$, $\mathcal{L}_{M,3}$, $\mathcal{L}_{M,4}$, $\mathcal{L}_{M,5}$	O	X	X	X	X	X	X	O	O
$\mathcal{L}_{T,0}$, $\mathcal{L}_{T,1}$, $\mathcal{L}_{T,2}$	X	X	X	X	X	X	X	X	X
$\mathcal{L}_{T,5}$, $\mathcal{L}_{T,6}$, $\mathcal{L}_{T,7}$	O	X	X	X	X	X	X	X	X
$\mathcal{L}_{T,8}$, $\mathcal{L}_{T,9}$	O	O	X	O	O	X	X	X	X

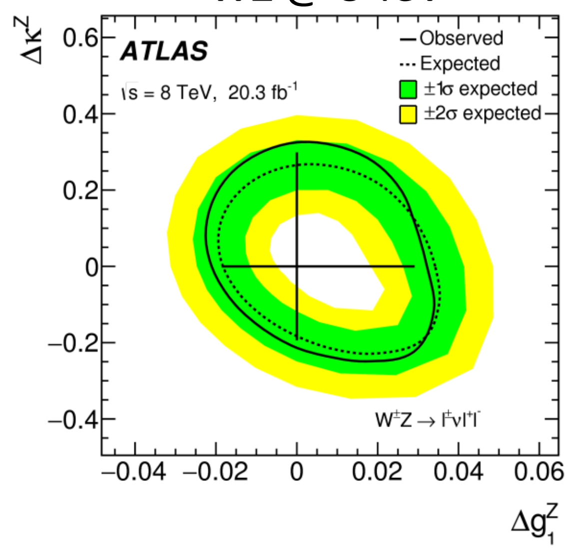
Latest aTGC results: charged couplings



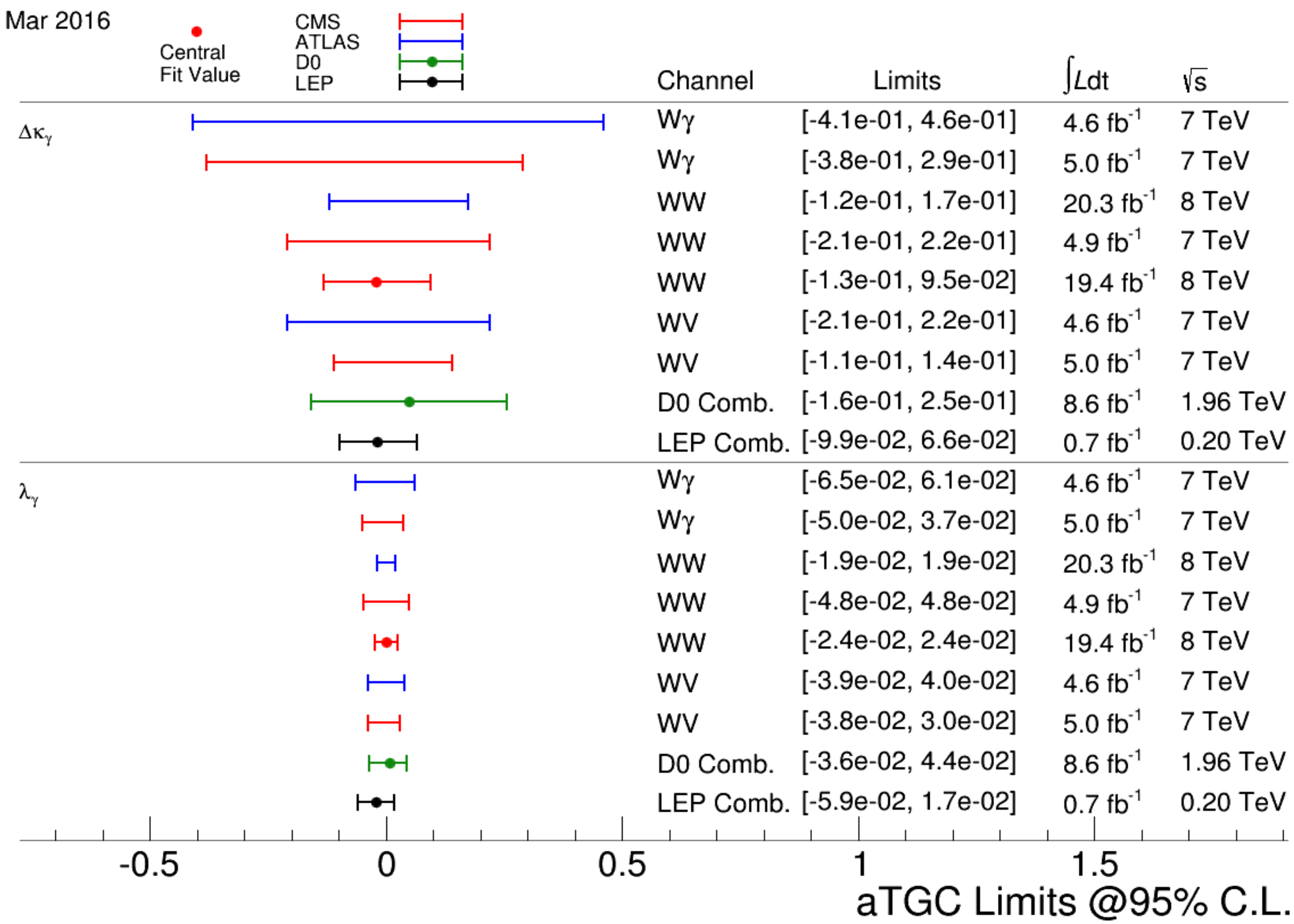
Effect of aTGC on kinematic distributions:



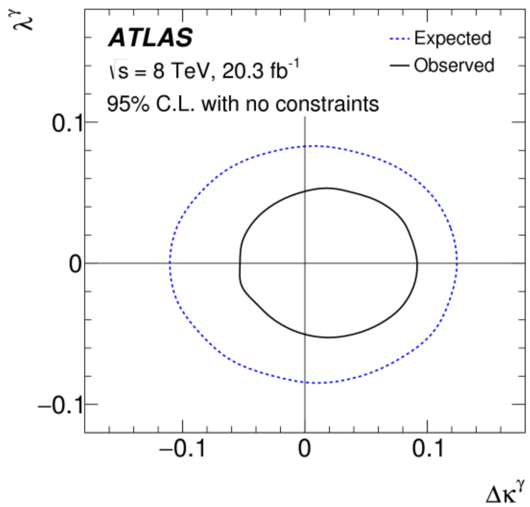
WZ @ 8 TeV



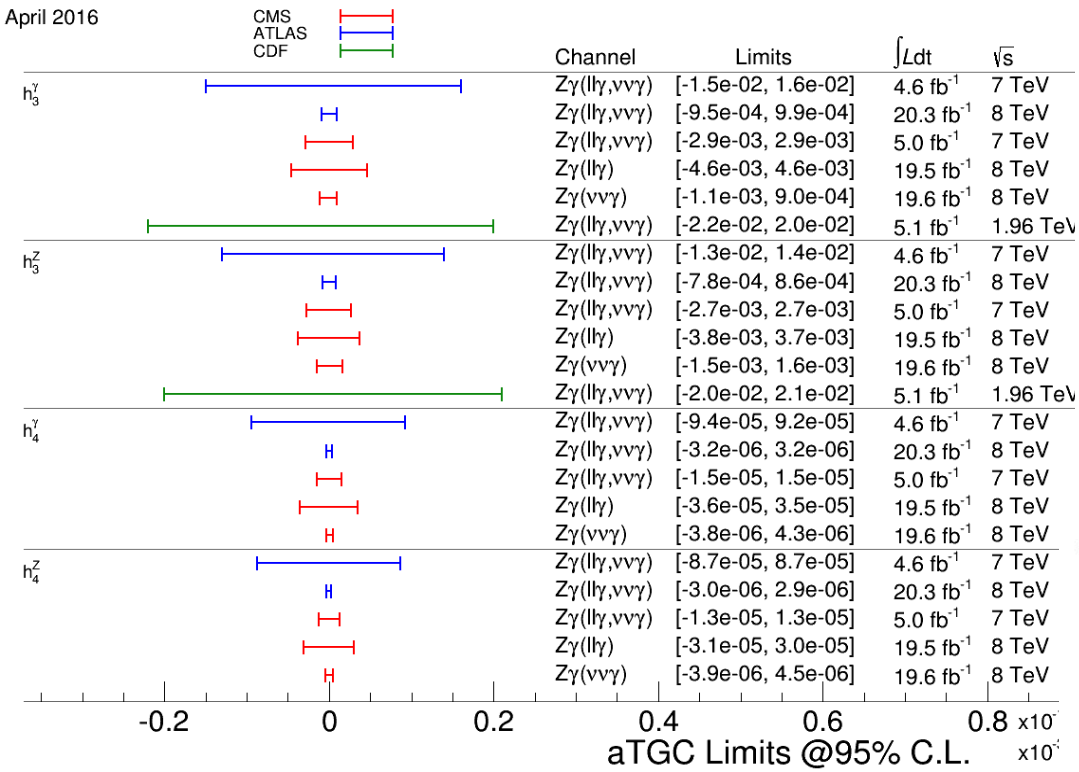
Latest aTGC results: charged couplings II



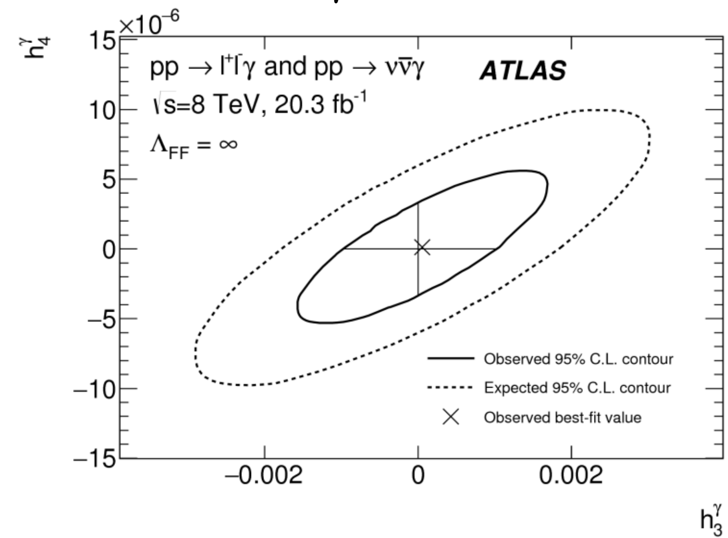
WW @ 8 TeV

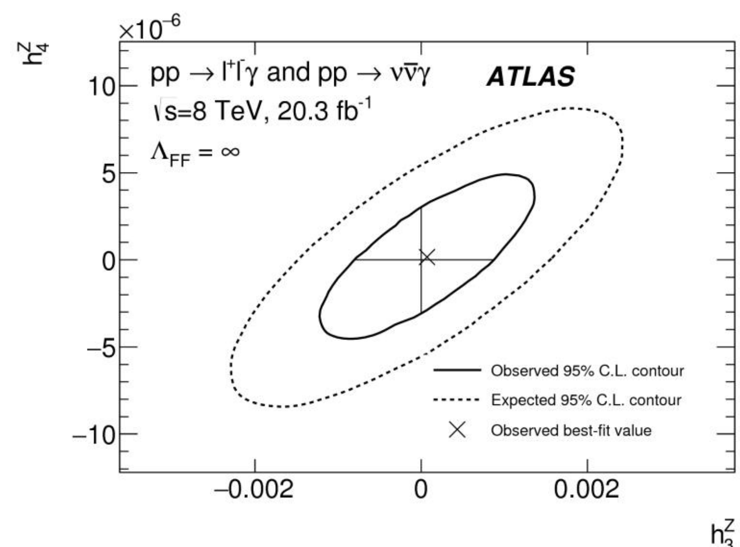


Latest aTGC results: neutral couplings

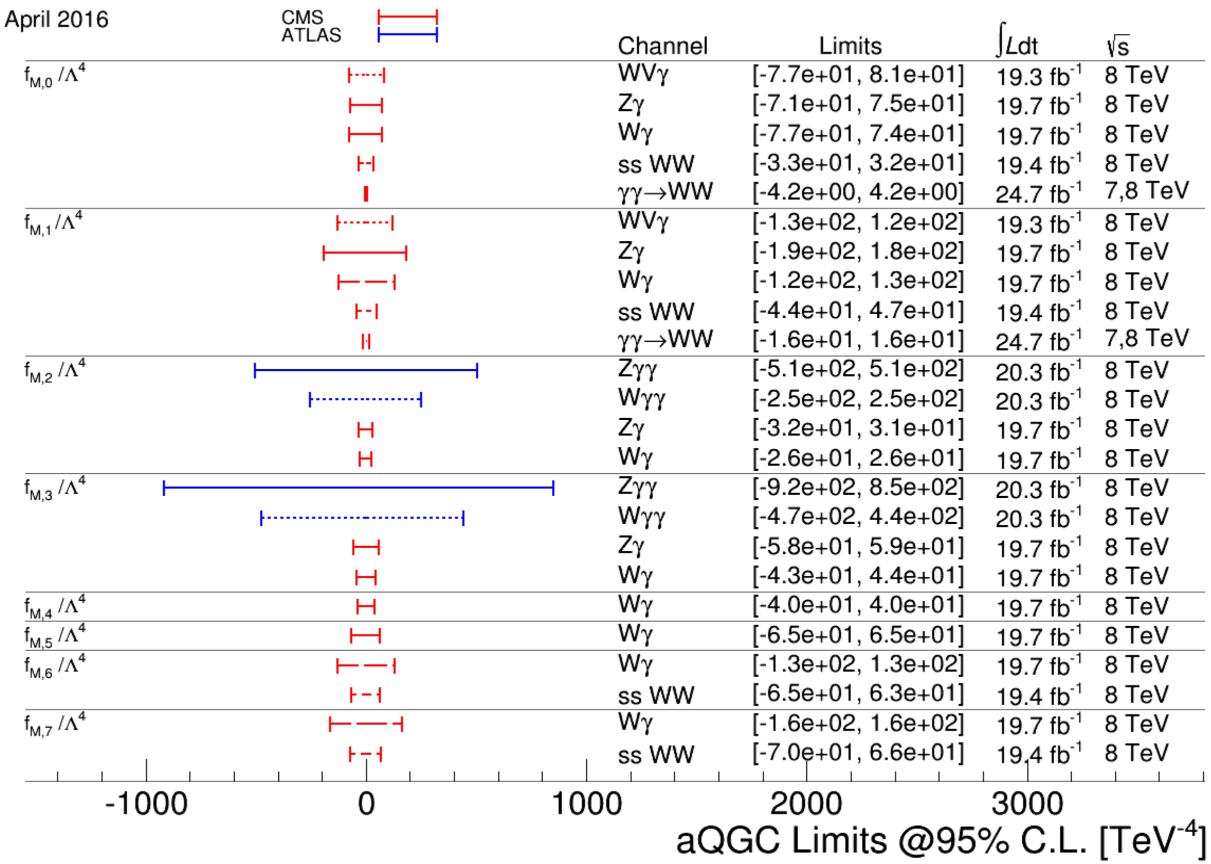


Zγ @ 8 TeV

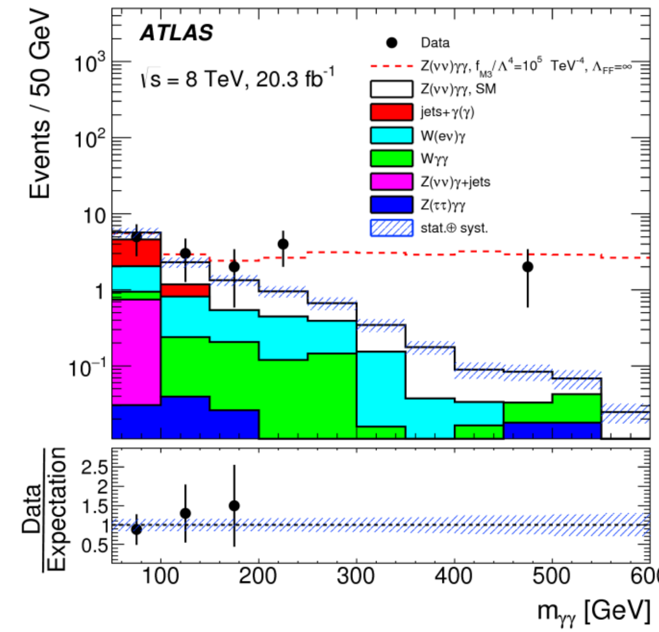




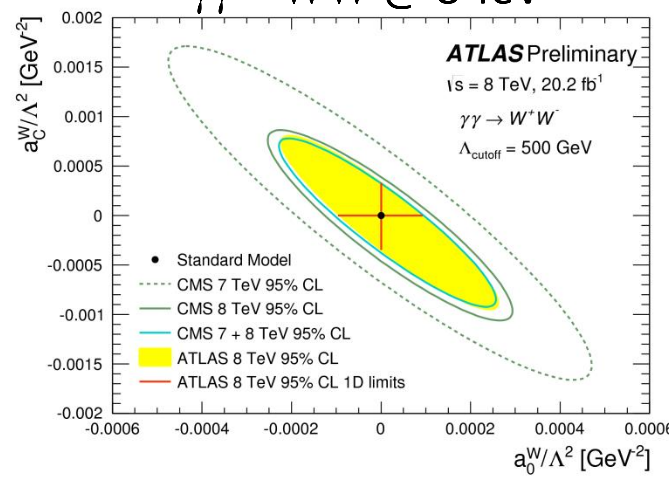
Latest aQGC results



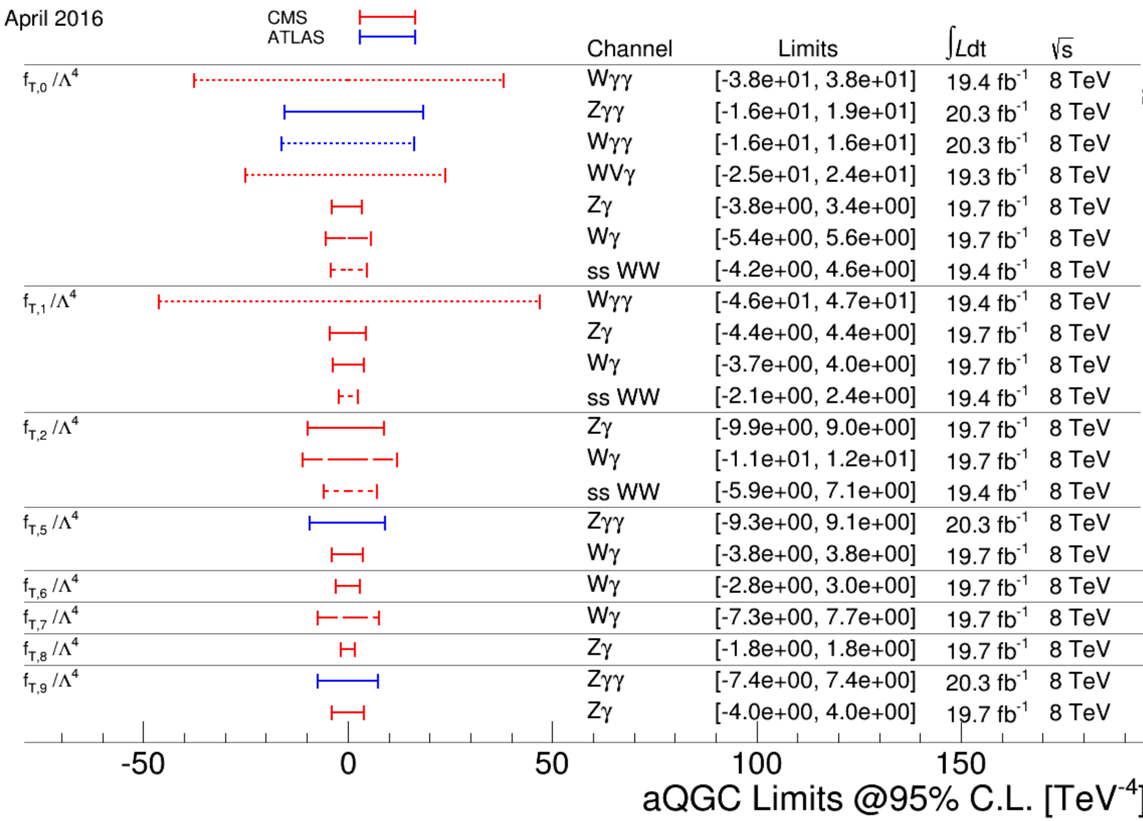
Effect of aQGC on kinematic distributions:



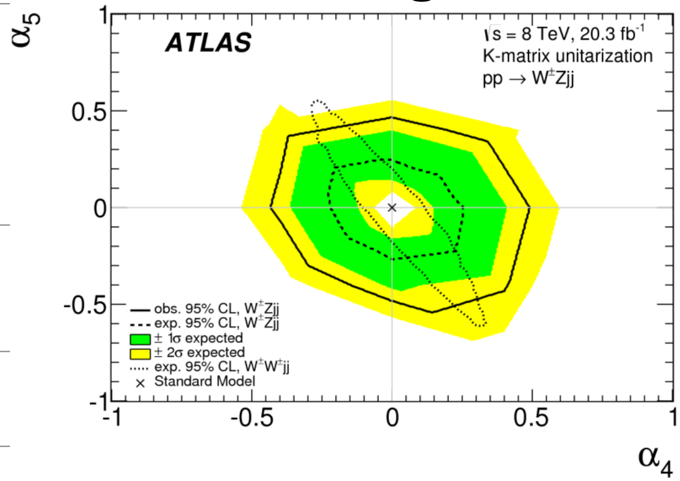
γγ→WW @ 8 TeV



Latest aQGC results II



EWK WZ @ 8 TeV



Conclusions

- A lot of new results from ATLAS experiment were shown.

- **Latest single and multiboson measurements using run1 and run2 datasets are compatible with SM expectations (NLO/NNLO).**

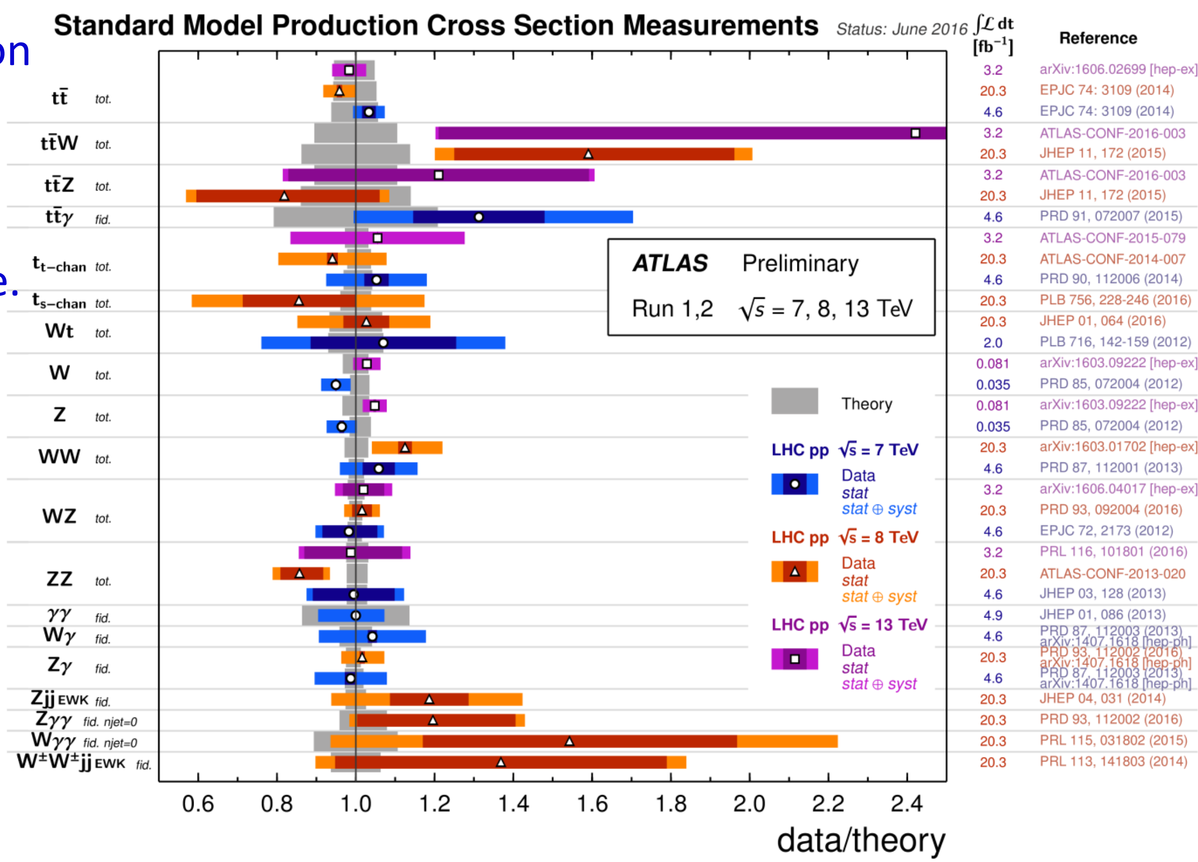
- Many differential cross-section distributions published.

- Ratios of the cross sections allow to probe proton structure.

- Z boson decay angular coefficients allow to probe its production dynamics.

- Very strong aTGC and aQGC limits set. **No deviations from SM observed.**

- Looking forward to the new run2 results!



Back-up slides

Drell-Yan lepton pairs transverse momentum and ϕ^* @ 8 TeV

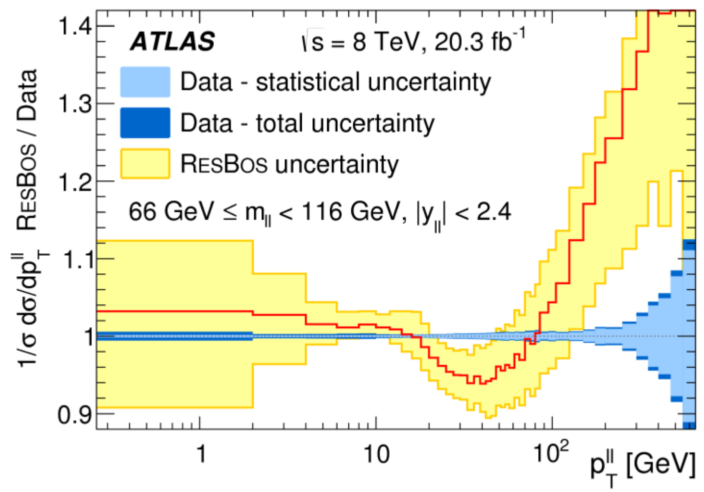
Motivation:

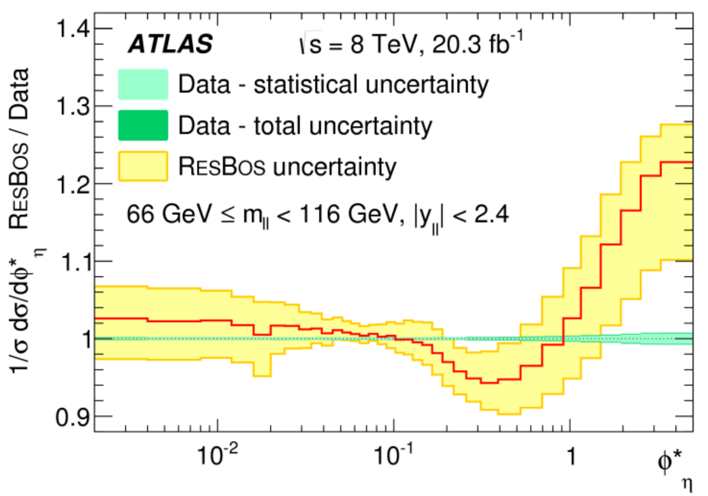
Eur. Phys. J. C 76(5), 1-61 (2016)

Testing different aspects of QCD:

- soft gluon resummation
- fixed-order perturbative QCD predictions
- parton shower models

Study $d\sigma/dp_T^{ll}$ and $d\sigma/d\phi^*_\eta$ in bins of m_{ll} and $|y_{ll}|$





Selection for fiducial region:

$Z \rightarrow ee/\mu\mu$ 66 GeV < m_{ll} < 116 GeV

$p_T(l)$ > 20 GeV $|\eta_l|$<2.4

Result:

QCD predictions comparison with RESBOS

- Low ϕ^*_η and dp_T^{ll}: dominated by soft-gluon-resummation effects → RESBOS predictions consistent with the data
- High ϕ^*_η and dp_T^{ll}: sensitive to hard parton emissions → RESBOS differs from data

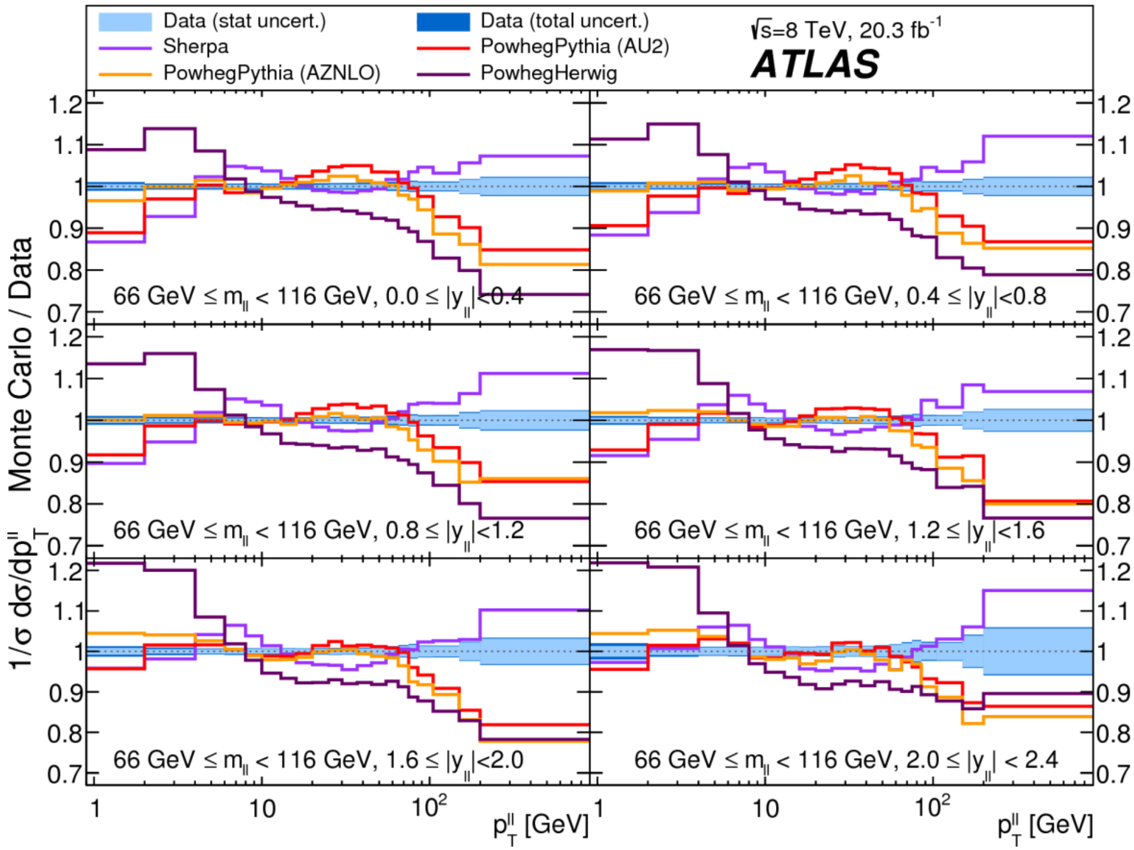
Comparison to PS approach and to fixed order QCD done also. Theoretical predictions describe data well.

Drell-Yan lepton pairs transverse momentum and ϕ* @ 8 TeV

Eur. Phys. J. C 76(5), 1-61 (2016)

Comparison to PS approach:

- For $5 < p_T(ll) < 100$ GeV description of MC is compatible with data at 10% level
- Powheg-Pythia – better agreement with data.
- Same study was performed for $d\sigma/d\phi^*_\eta$, which shows same behavior
- PS MC's describe well (maximal descrepancies – 5%)

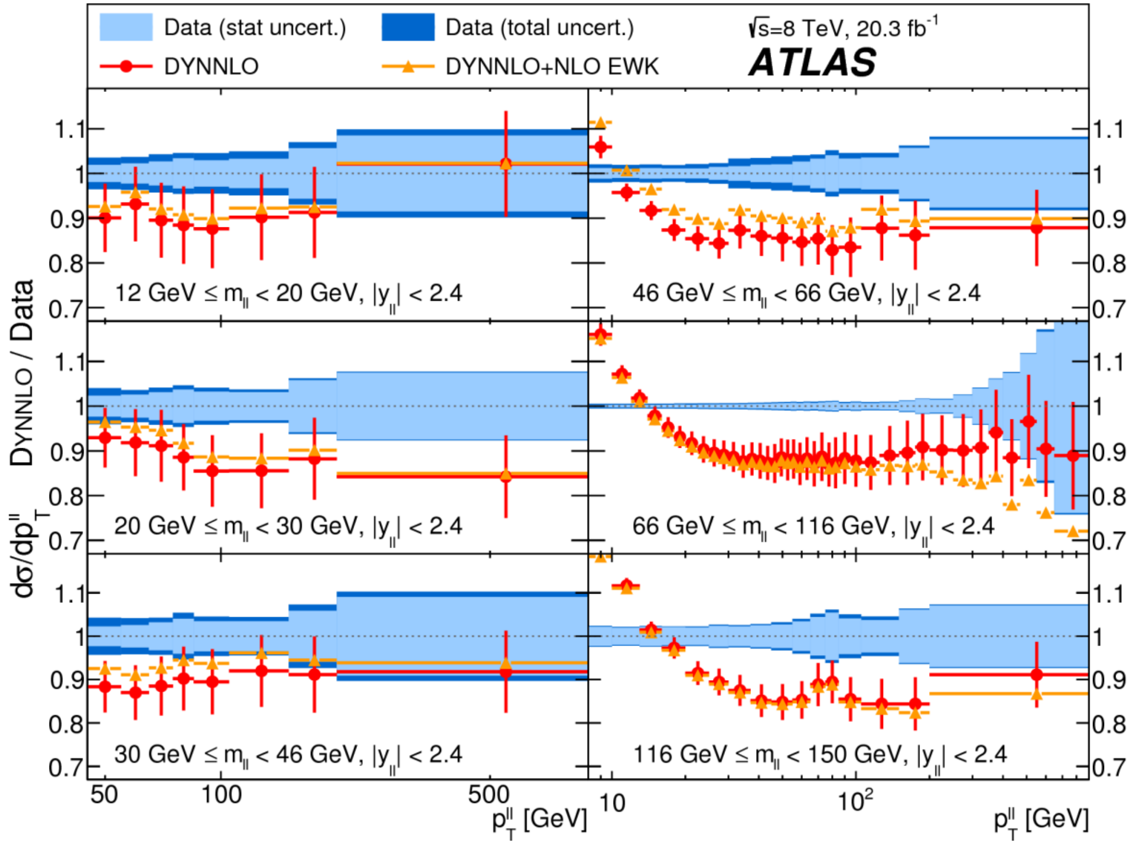


Drell-Yan lepton pairs transverse momentum and φ* @ 8 TeV

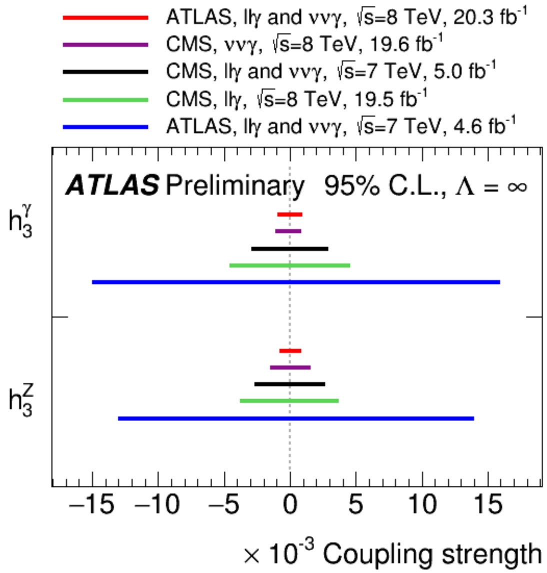
Eur. Phys. J. C 76(5), 1-61 (2016)

Comparison to fixed-order QCD:

- Low p_T^{ll} discrepancies expected because soft gluon emissions dominant
- Good shape description for p_T^{ll} >30 GeV, but normalization systematically 15% lower than d
- data
- Recent NNLO calculations show improved agreement with data

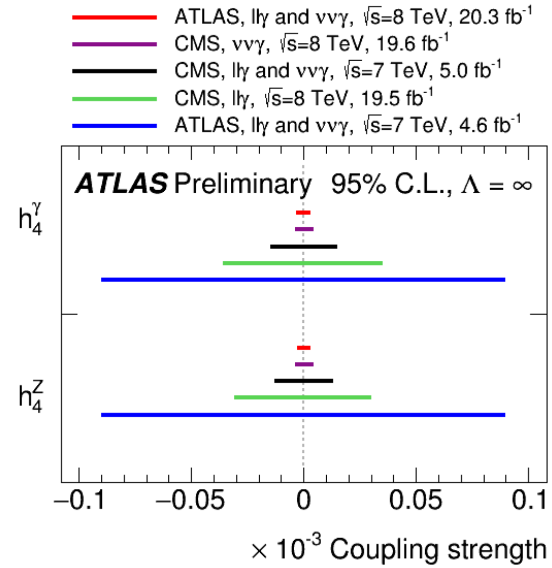


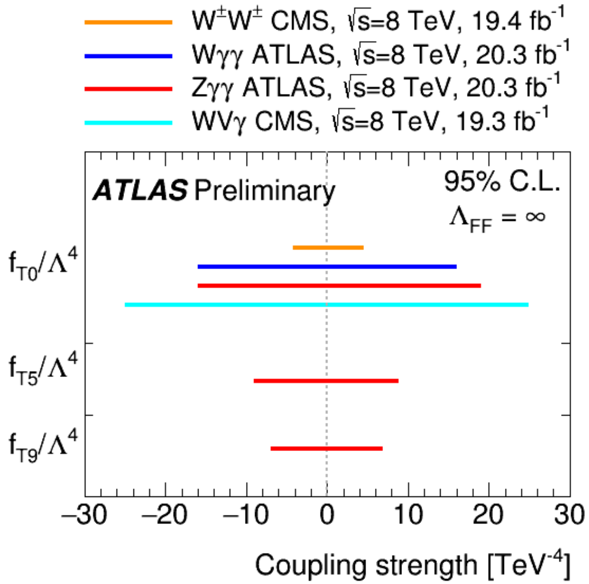
Limits on Anomalous Gauge Couplings: Zγ/Zγγ



aTGC

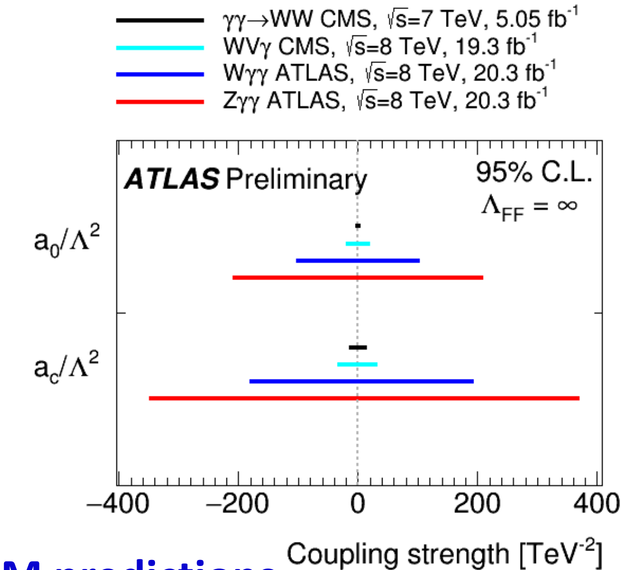
Vertex function approach





aQGC

EFT approach



No sign of deviation from SM predictions

Events signatures