Discussion of QCD aspects of multi-boson production measured with the ATLAS detector

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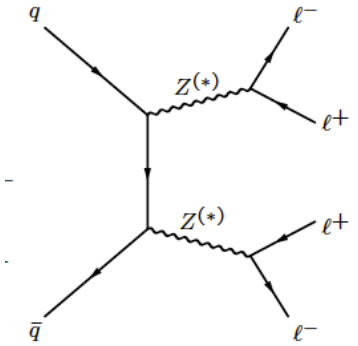
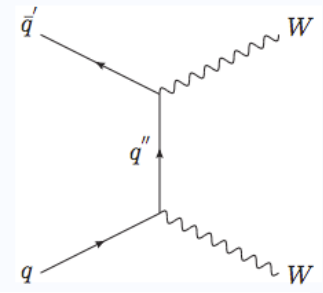
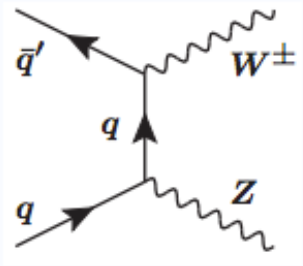
Introduction

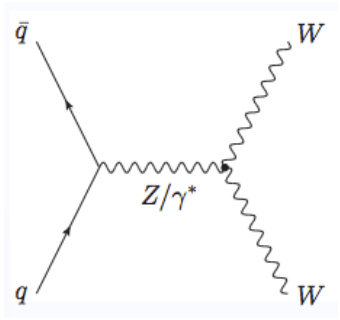
Multi-boson production measurements :

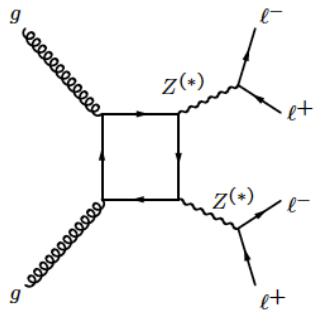
- Diboson *(ZZ, WZ, WW, Wγ, Zγ)*
- Triboson *(Wγγ, Zγγ)*











Physics Motivations:

- important test of Standard Model (SM) predictions at TeV scale
  - EWK precision measurements with higher order corrections
- understand background for many (Higgs, BSM, …) analyses
- explore new heavy particles decaying to diboson
- probe new physics through deviations of measured cross sections from predictions (anomalous couplings)

Production Cross section Estimation

$$N_{sigal} = N_{data} - N_{bkg} = L \cdot \sigma^{tot} \cdot BR \cdot A \cdot C$$

$$A = \frac{N^{fid}_{MC,gen}}{N^{tot}_{MC,gen}}$$

$$C = \frac{N^{Selected}_{Reco}}{N^{fid}_{MC,gen}}$$

Acceptance correction for the geometrical & kinematic criteria

Efficiency correction for detector ability to reconstruct these objects

N_{signal}	Number of signal events
N_{data}	Number of data events
N_{bkg}	Number of background events
L	Luminosity
BR	Branching Ratio
C	Efficiency corrections
A	Acceptance

$$\sigma^{fiducial} = \frac{N_{obs} - N_{bkg}}{L \cdot C}$$

We measure a "fiducial cross section" corresponding to the reduced phase-space of the actual measurement

$$\sigma^{tot} = \frac{N_{obs} - N_{bkg}}{L \cdot BR \cdot A \cdot C}$$

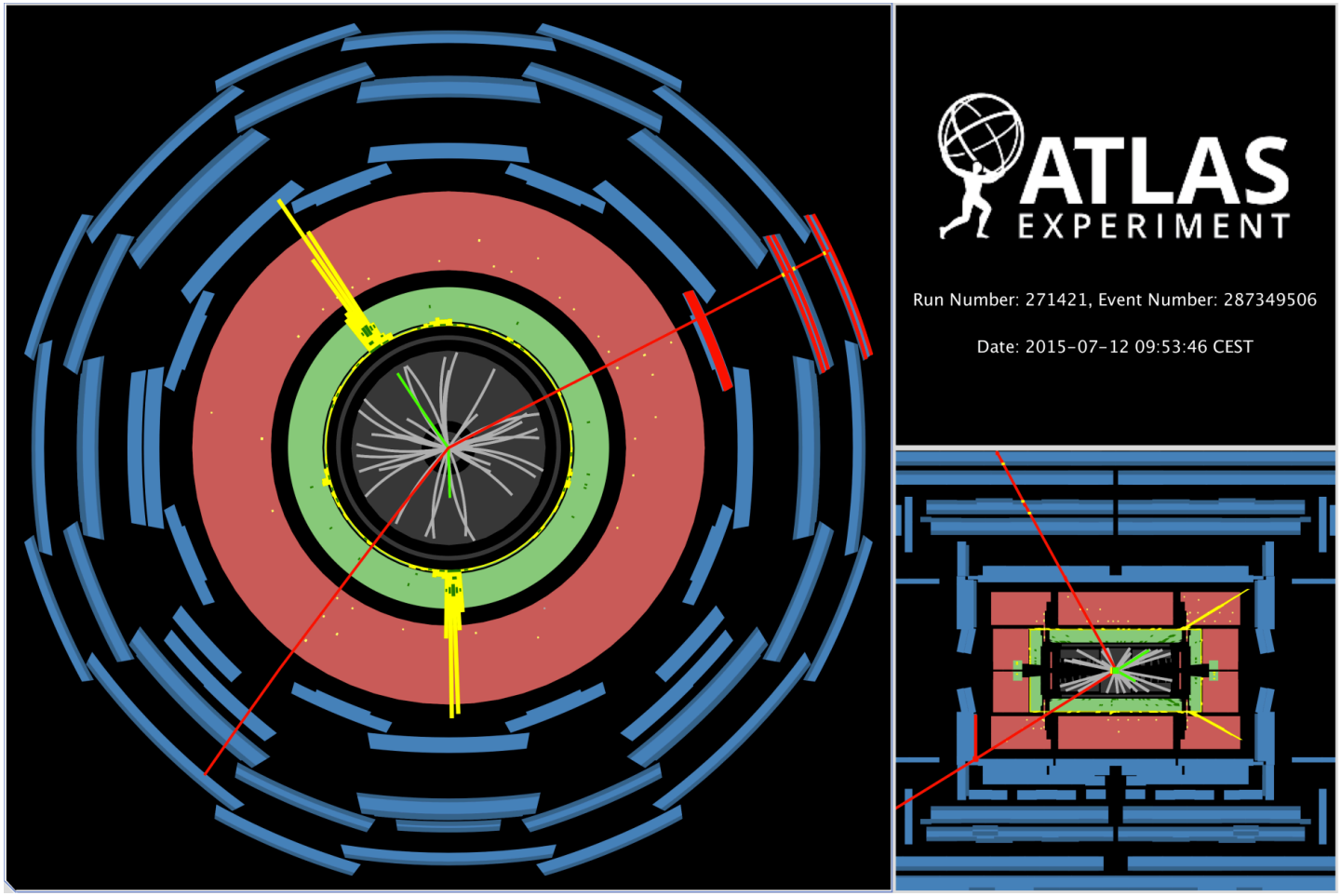
We then extrapolate to the "total cross section"

- Background estimation from Data or/and MC
- Differential distributions in key kinematical variables
- Systematic Uncertainties from Data/MC

Dibosons

ZZ @ 13 TeV

13 TeV ATLAS event display
Event display for the ZZ→ ee + μμ candidate event



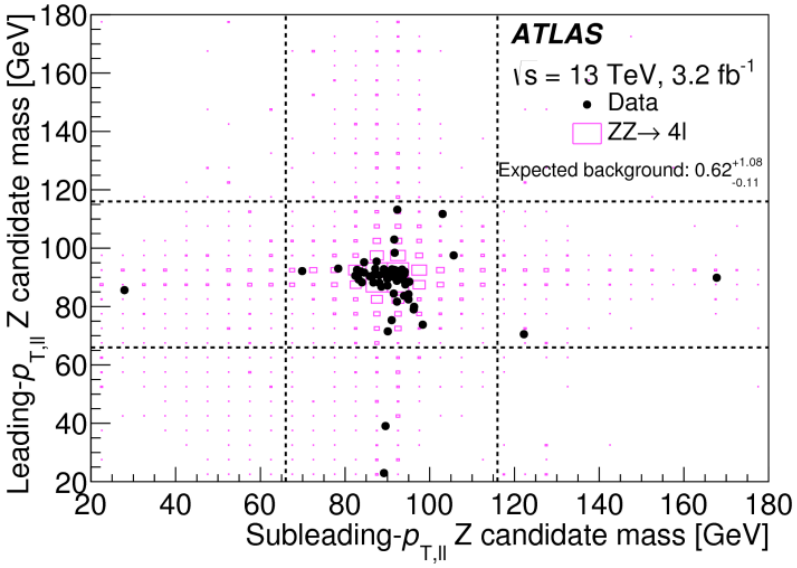
ZZ @13TeV

$ZZ \rightarrow llll$ channel (eeee, eeμμ, μμμμ)

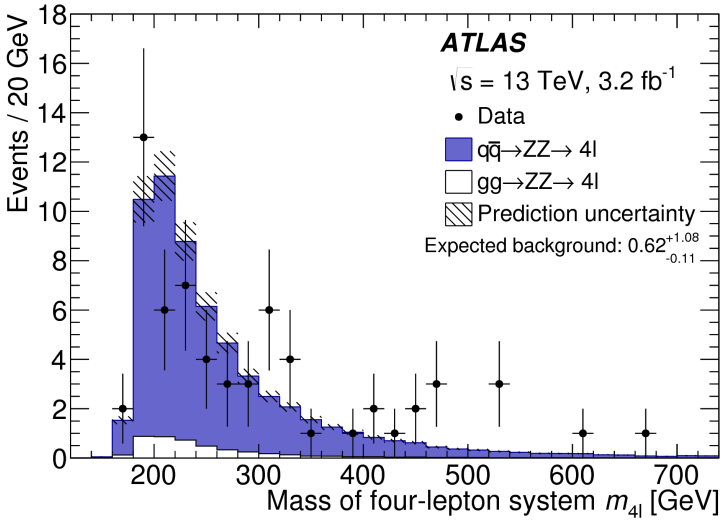
ArXiv:1512.05314 Phys. Rev. Lett. 116, 101801 (2016)

Event selection

- Exactly four isolated, $\Delta R(l,l) > 0.2$,
- prompt final state leptons (e or μ only)
- All four leptons $p_T > 20$ GeV & $|\eta|<2.7$
- Opposite Charge (OC), Same Flavor (SF) pairing
- On-shell mass selection
  66 GeV < $|m_{ll}|$ < 116 GeV
- When 4 leptons SF: select the pairings minimizing $|m_{1,2} - m_Z| + |m_{3,4} - m_Z|$



The precision on the measurement is dominated by statistics



- NNLO: qqbar →ZZ →4l
- NLO: gg →ZZ →4l
- interference with Higgs production and off-shell Higgs ->ZZ production is taken into account

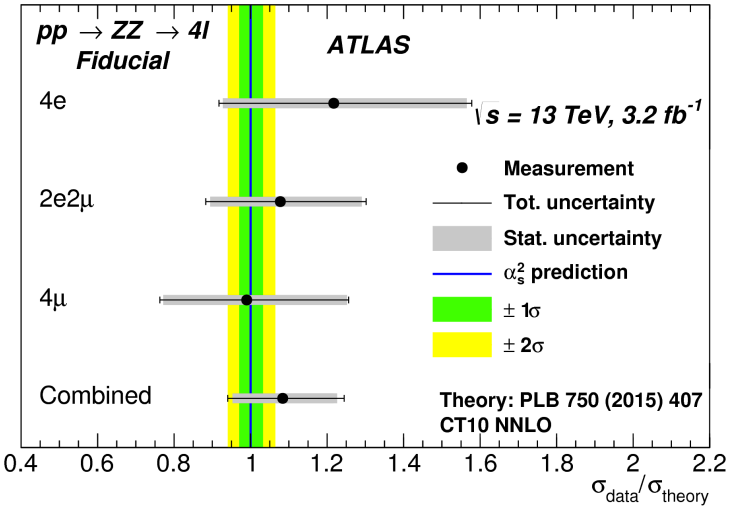
- Maximum-likelihood fit.
- Signal and background yields treated as Poisson variables.
- Systematic uncertainties treated as Gaussian nuisance parameters

ZZ @13TeV

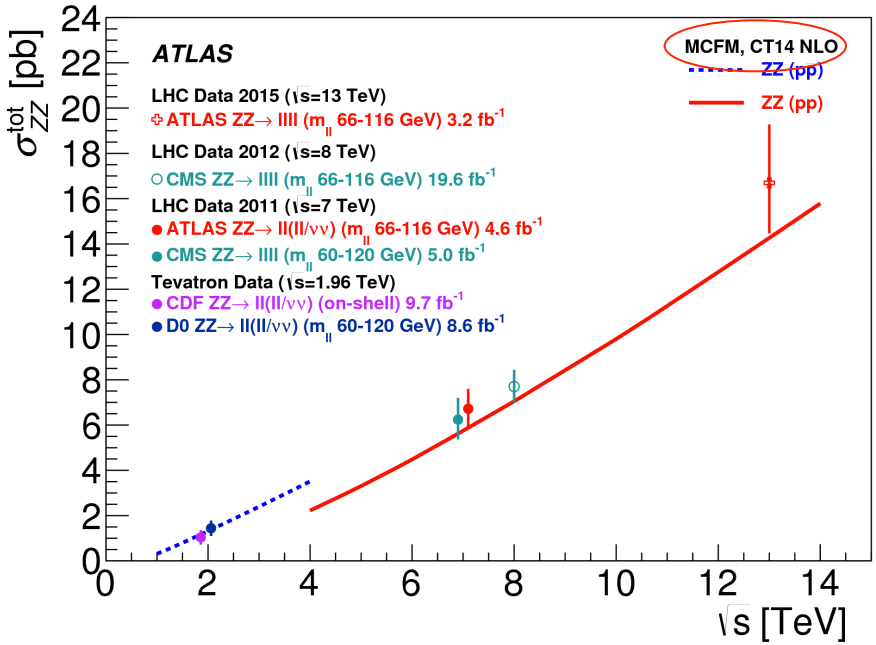
Phys. Rev. Lett. 116, 101801 (2016)

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

NNLO calc.



Measured fiducial cross-section vs $O(\alpha_s^2)$ Prediction

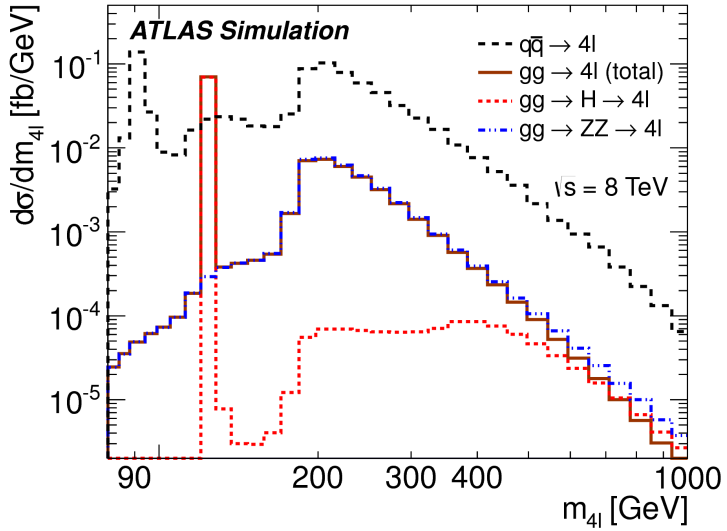


Up to NLO:
No additional order in this plot

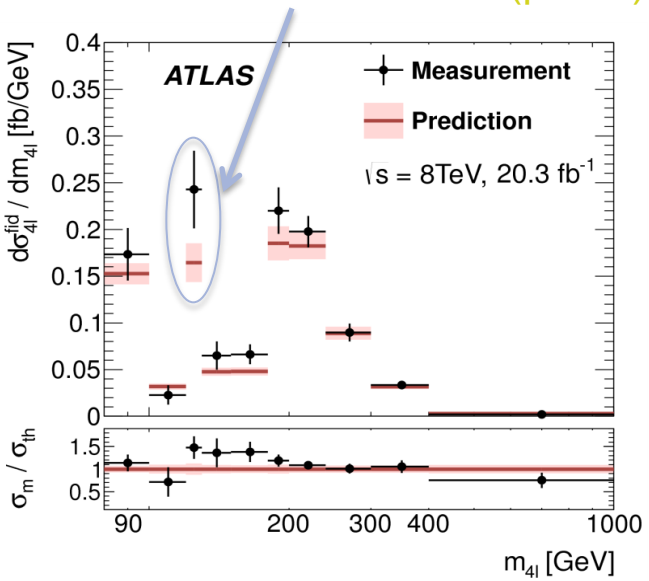
Total cross section NLO prediction compared to measurements for different center of mass energies at p-pbar and pp collisions

$pp \rightarrow 4l$ @ 8TeV

arXiv:1509.06734, Physics Letter B753 (2016) 552-527



Consistent with H→4ℓ (μ~1.4)

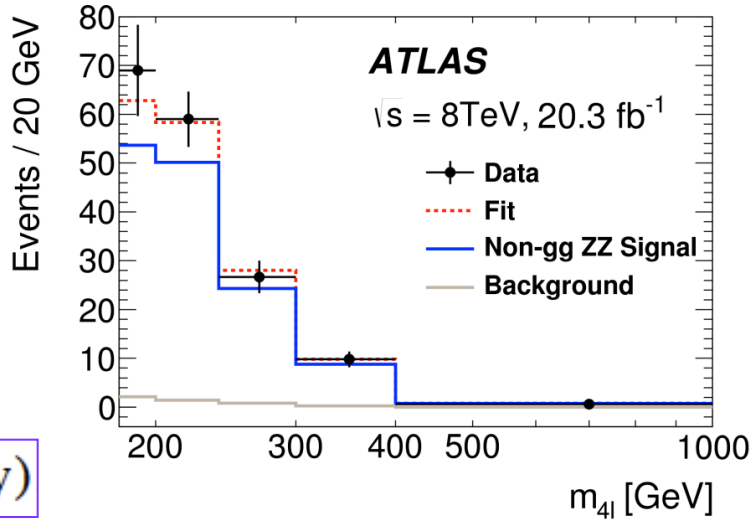


Contributions to the $m_{4\ell}$:

- LO: non resonant gg→4ℓ.
- NLO QCD: qq→4ℓ.
- NNLO QCD+NLO EW: H→4ℓ

  on-shell qq→Z→4ℓ

Extract gg component σ(LO) in $m_{4\ell}$>180 GeV region.



$$\sigma_{\mathrm{LO}}^{gg\to ZZ} = 0.97^{+0.3}_{-0.2}\ \mathrm{fb}, \qquad \sigma_{\mathrm{NLO}}^{gg\to ZZ} = 1.8^{+0.2}_{-0.2}\ \mathrm{fb}$$

$$\mu_{gg} = \sigma(\mathrm{data})/\sigma(\mathrm{LO})$$

$$\mu_{gg} = 2.4 \pm 1.0\ (\mathrm{stat.}) \pm 0.5\ (\mathrm{syst.}) \pm 0.8\ (\mathrm{theory})$$

$W^{\pm}Z$ @ 8TeV

arXiv:1603.02151 Phys. Rev. D 93, 092004 (2016)

$WZ \rightarrow l\nu\, ll$ channel (eee, eeμ, μμe, μμμ)

Event selection

- Three isolated charged leptons
- Lepton p_T>15 GeV

Z selection

- 2 OC SF leptons
- $| m_{2l} - m_Z | < 10$ GeV

W selection

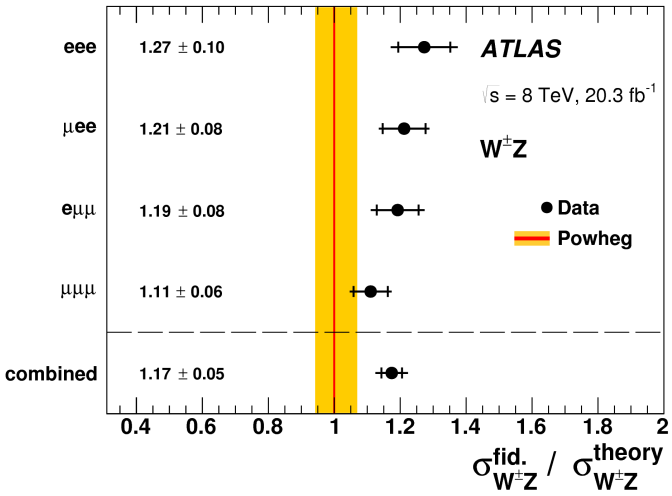
- Lepton p_T> 20 GeV,
- $m_T(W)$ >30 GeV

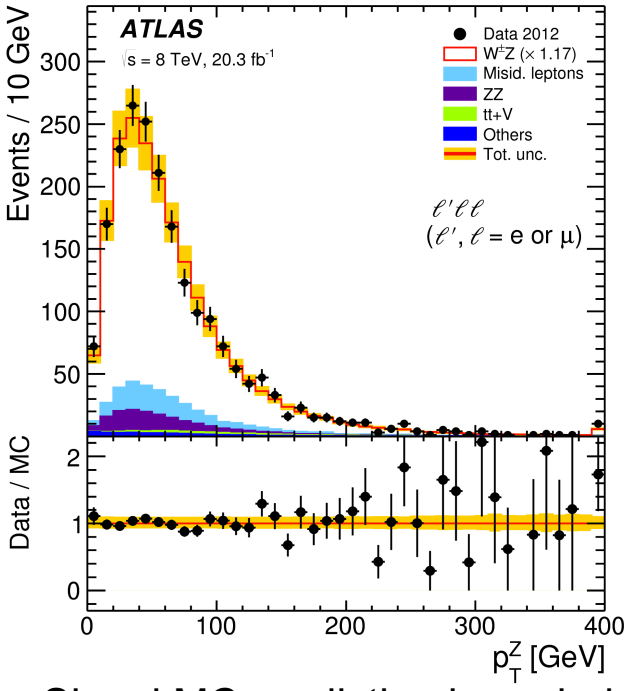
Background

Reducible: 1fake lepton (Z+j, Zγ, tt, and WW)

Irreducible: all prompt leptons (ZZ, tt+V, VVV, tZ(j))

Main systematic is the background estimation method (data driven)





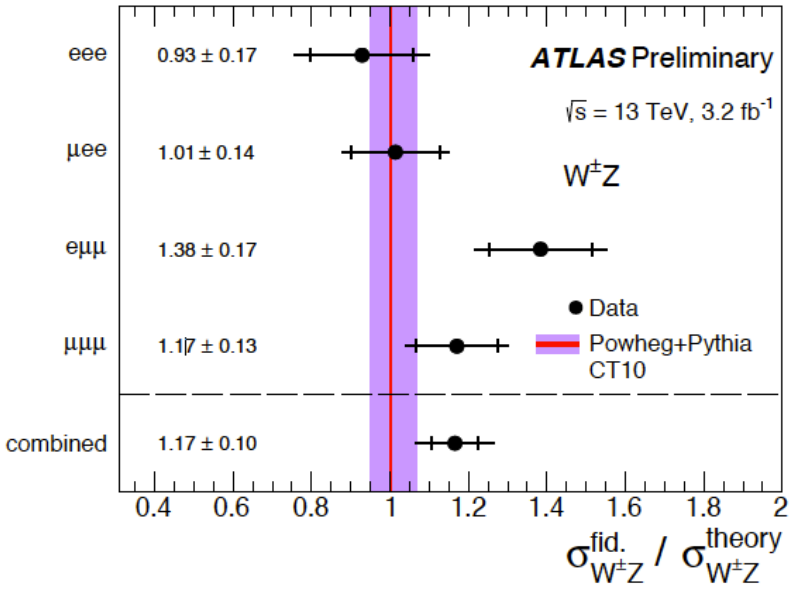
Signal MC prediction is scaled by a global factor of 1.17 to match the measured data

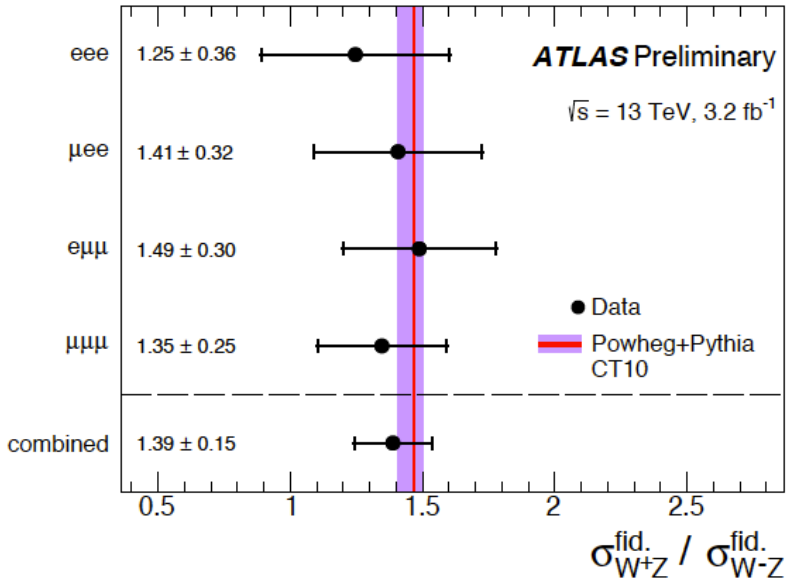
$$\sigma^{\text{fid.}}_{W^{\pm}Z\rightarrow \ell'\nu\ell\ell} = 35.1 \pm 0.9\,(\text{stat.}) \pm 0.8\,(\text{sys.}) \pm 0.8\,(\text{lumi.})\ \text{fb}$$

NLO MC σ = 30.0 ± 2.1fb

WZ production rate is higher than MC NLO calculation

$W^{\pm}Z$ @13TeV



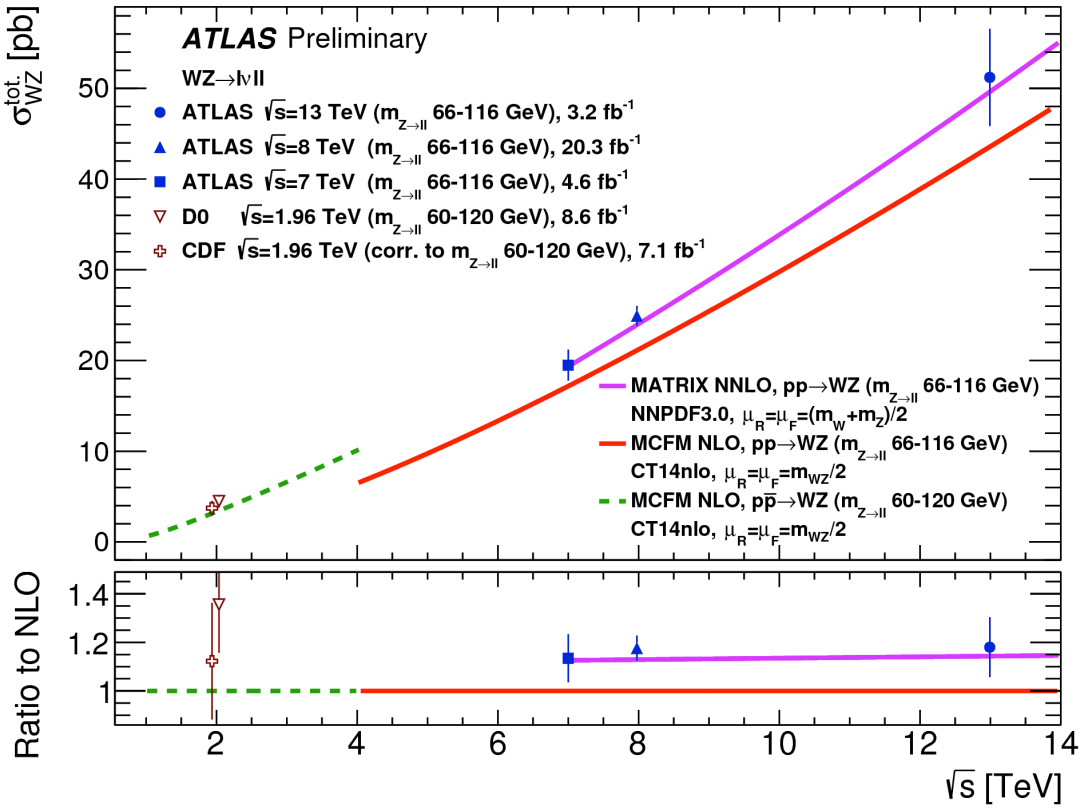


- NLO SM prediction from POWHEG+PYTHIA with $\mu_R = 0.5 \cdot m_{WZ}$ and CT10 PDF
- Same deviation (~1.3σ) from NLO prediction as observed in RunI

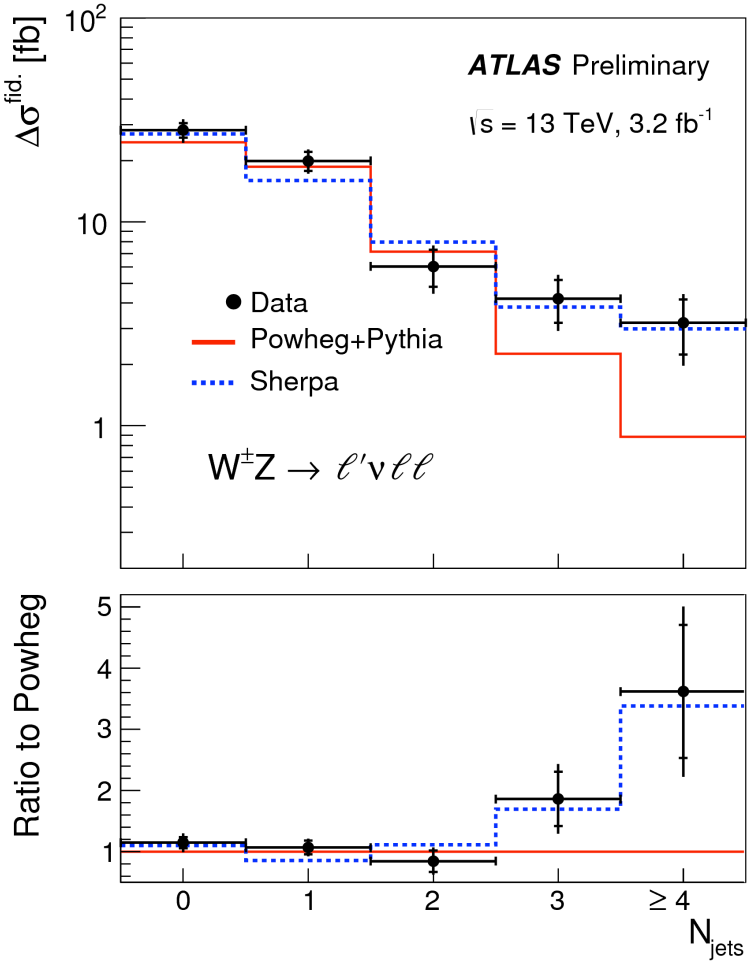
NNLO 14% higher than NLO → compatible to measurements

$W^{\pm}Z$ @13TeV

- Comparison of previous results vs √s to MCFM(NLO) predictions
- ATLAS results in excellent agreement with NNLO predictions



Differential $W^{\pm}Z$ @13TeV



Differential cross-section vs N_{jets}

- All 4 channels added together
- Jets with $p_T > 25$ GeV, $|\eta|<4.5$
- Unfolded distribution (Bayesian iterative)

Data in good agreement with Sherpa

$W^+W^- \rightarrow lvlv$ @ 8 TeV

arXiv:1603.01702 submitted to JHEP

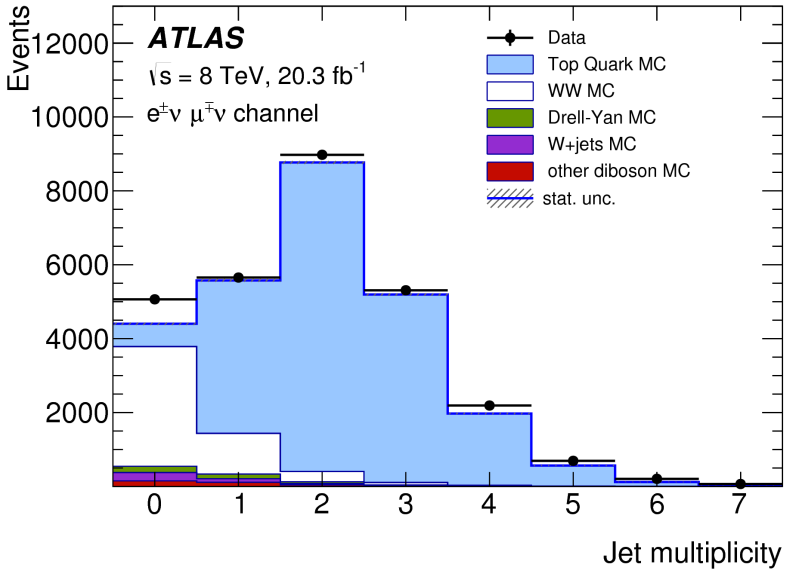
$W^+W^- \rightarrow lv\,lv$ channel (ee, eμ, μμ)+E_T^{miss}

Event Selection:

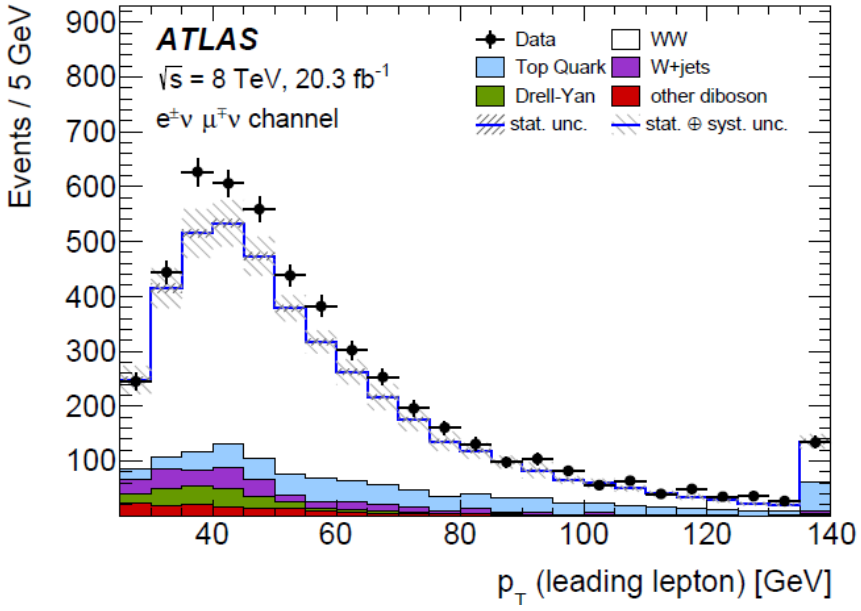
- 2 opposite sign high p_T leptons
- High E_t^{miss}
- Additional lepton veto, top veto, Jet veto, Z veto, etc
- incl. Higgs → WW as signal

Backgrounds:

- top, drell-yan. W+jets (data driven) other dibosons (MC based)



Dominant systematic from modeling of signal efficiency (Jets)

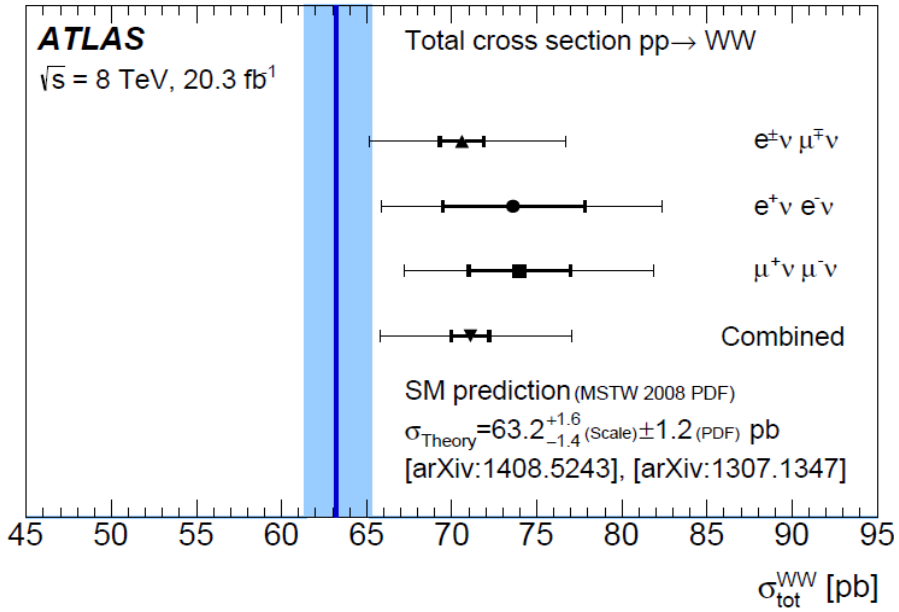


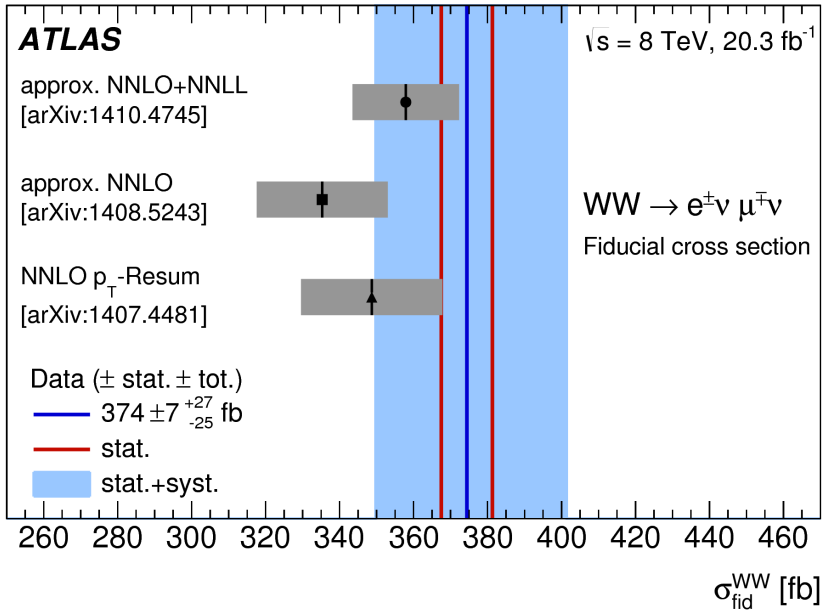
The dominant top-quark background is suppressed by requiring 0-jets

$W^+W^- \rightarrow l\nu l\nu$ @ 8 TeV

arXiv:1603.01702 submitted to JHEP

	σ(total) (pb)
Data	$71.1^{+1.1}_{-1.1}(\text{stat})\ ^{+5.7}_{-5.0}(\text{syst})\ ^{+1.4}_{-1.4}(\text{lumi})$
NNLO	$63.2^{+1.6}_{-1.4}(\text{scale}) \pm 1.2(\text{PDF})$





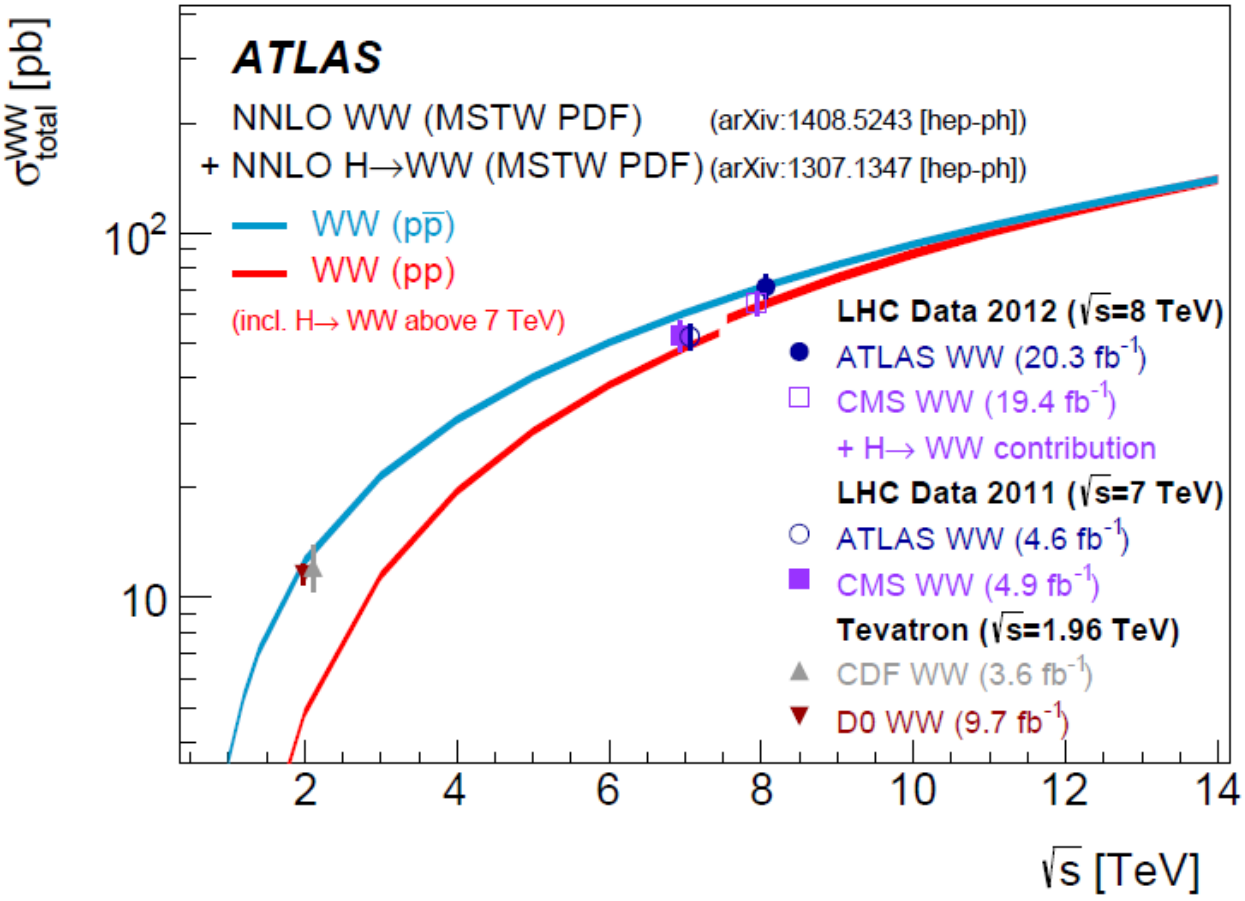
The WW cross sections measured at √s=8 TeV compared to the NNLO prediction

Consistent within 1.4 standard deviations

Comparison of the measured fiducial cross sections with various theoretical predictions

$W^+W^- \rightarrow l\nu l\nu$ @ 8 TeV

arXiv:1603.01702 submitted to JHEP



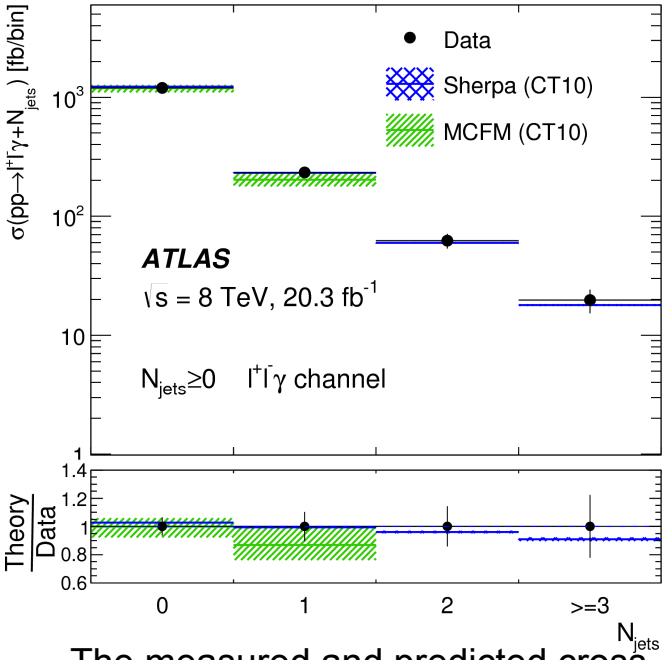
Zγ @ 8TeV

arXiv:1604.05232, accepted by PRD

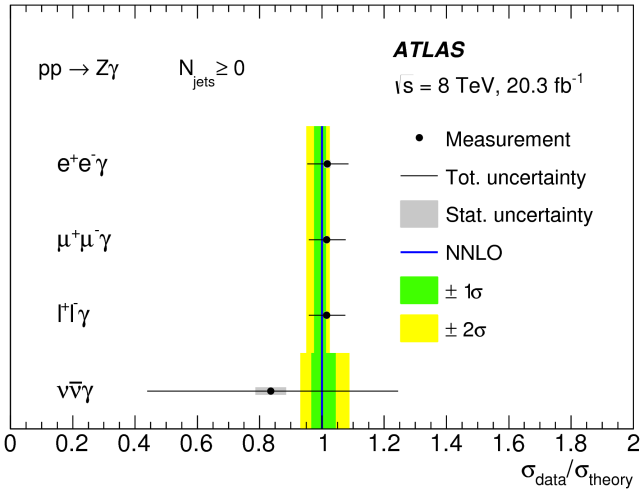
$Z\gamma \rightarrow ee, e\mu, \mu\mu + \gamma$

OC SF lepton pair
γ E_T > 15 GeV

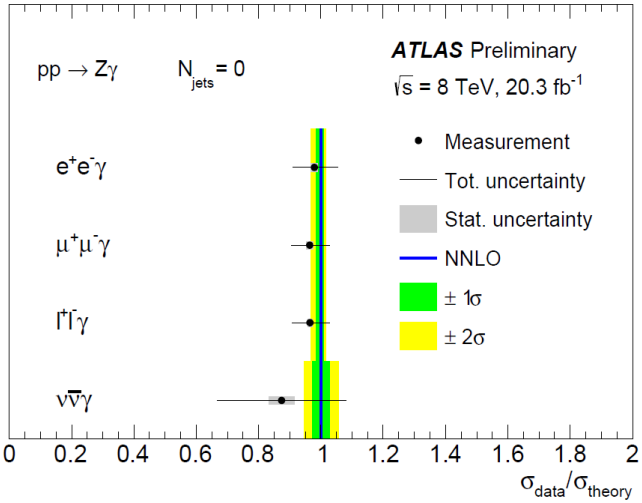
for the aTGC search
γ p_T > 250 GeV [llγ channel]
γ p_T > 400 GeV [vvγ channel]



The measured and predicted cross sections as a function of N_{jets} in the extended fiducial region.

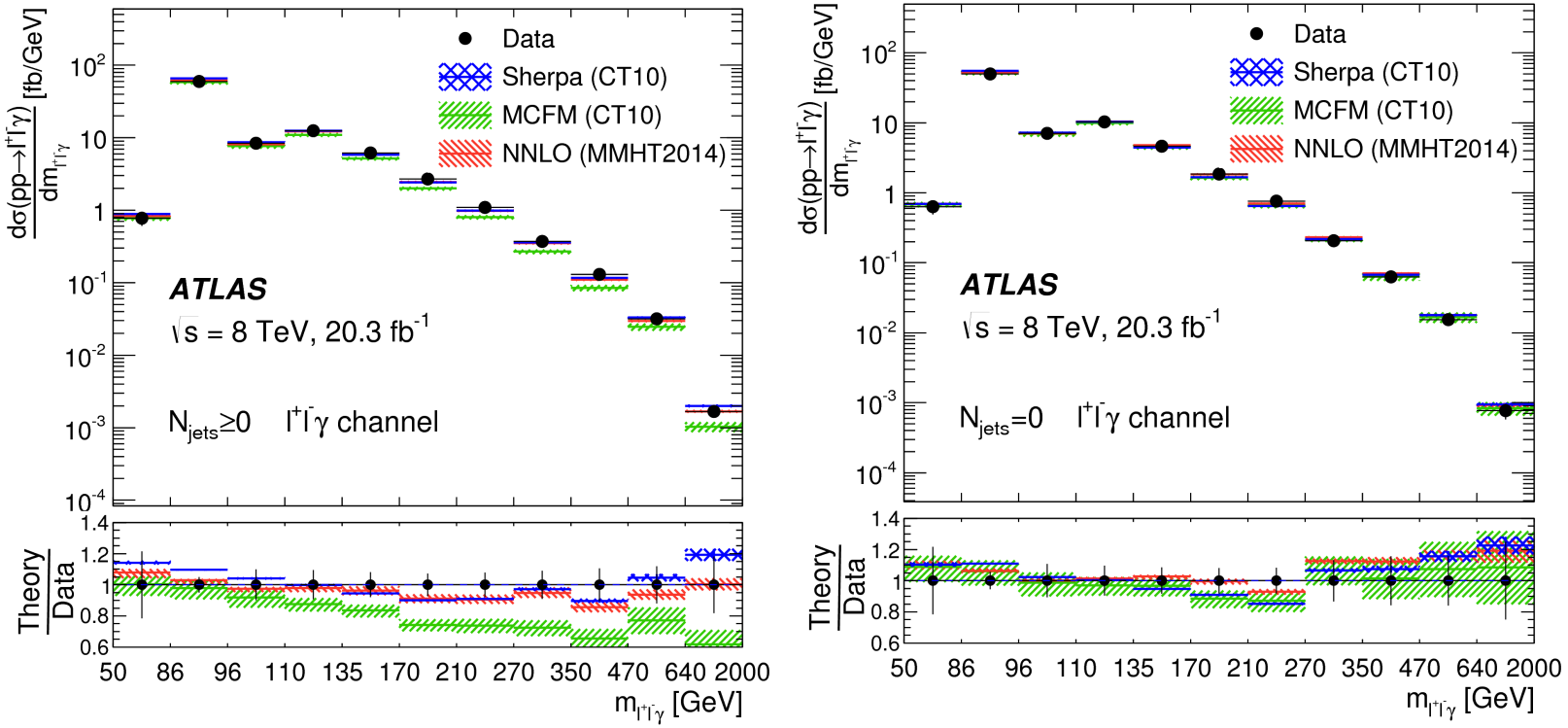


measured cross sections and the theory predictions in the inclusive Njets ≥ 0 and exclusive Njets = 0 extended fiducial regions.



Zγ @ 8TeV

arXiv:1604.05232, accepted by PRD



The measured and predicted differential cross sections as a function of $m_{ll\gamma}$ in the inclusive Njets ≥ 0 and exclusive Njets = 0 extended fiducial regions

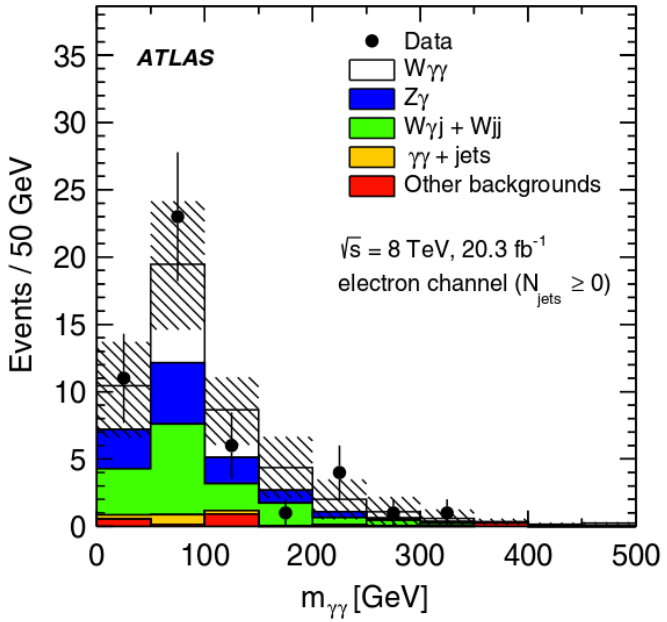
Tri-boson Production

Wγγ @ 8 TeV

Final state:
Isolated lepton p_T>20GeV + E_{tmiss} + two photons
$N_j \geq 0$: inclusive
$N_j = 0$: exclusive

Backgrounds:
- multijet (data driven)
- prompt leptons (MC)

	σ^{fid} [fb]	σ^{MCFM} [fb]
Inclusive ($N_{jet} \geq 0$)		
$\mu\nu\gamma\gamma$	$7.1\ ^{+1.3}_{-1.2}$ (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 ($N_{jet} = 0$)		
$\mu\nu\gamma\gamma$	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.)	



- Combined significance over background : 3.6σ
- Consistent with SM, within 2σ for inclusive (less than 1σ exclusive)
- May have better agreement with NNLO
- Exclusive cross section, m(γγ)>300GeV used for aQGC limits

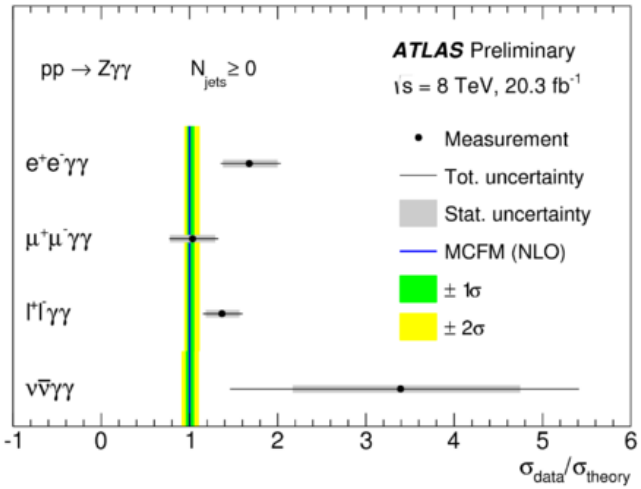
Zγγ @ 8 TeV

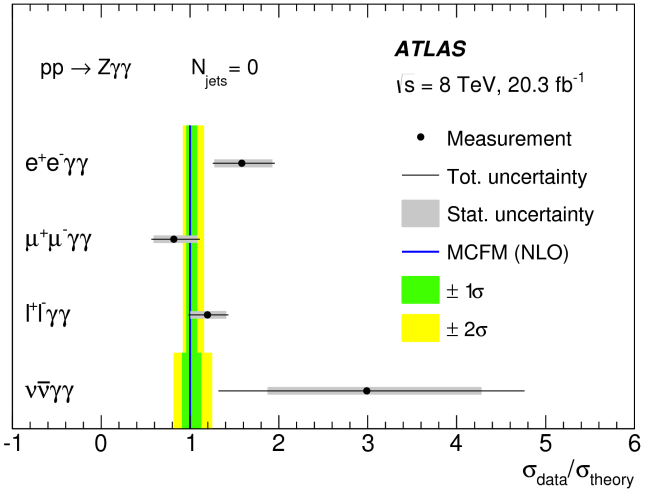
arXiv:1604.05232, accepted by PRD

Final state:
Isolated leptons m_{ll}>40GeV
two isolated photons E_T>15 GeV
E_T^{miss}>100GeV (for the vvγγ)
$N_j \geq 0$: inclusive
$N_j = 0$: exclusive

Statistically limited

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





- Exclusive cross section, m(γγ)>300 (200) GeV used for aQGC limits for the *vvγγ (llγγ)* channel.

Anomalous Couplings

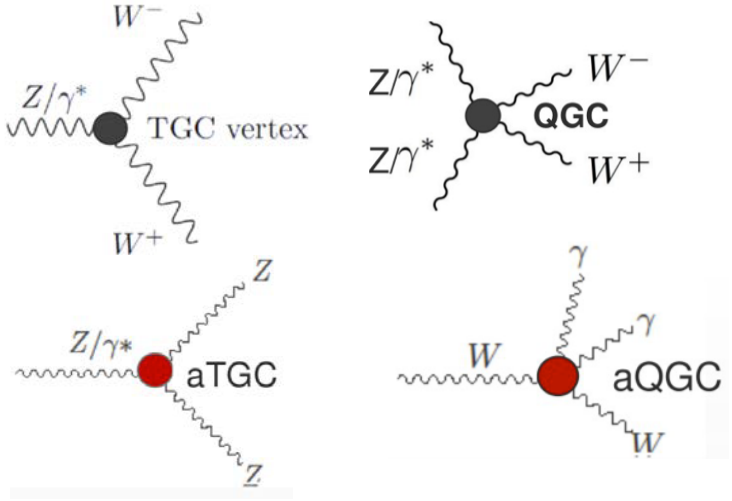
- The non-abelian nature of the EWK sector of the SM predicts the self-interaction of gauge bosons in the form of triple and quartic couplings
- Deviations from SM are parametrized, in terms of anomalous couplings using effective Lagrangian (SM+higher dimension operators)

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

Λ: scale of New Physics

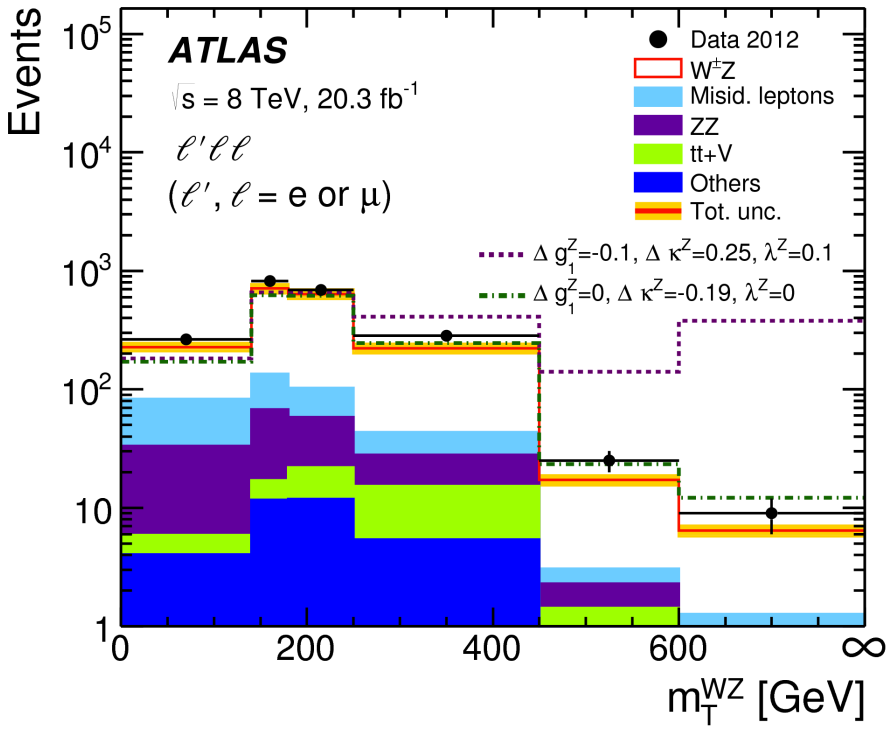
coupling	parameters	channel
$WW\gamma$	$\lambda_\gamma, \Delta k_\gamma$	$WW, W\gamma$
WWZ	$\lambda_Z, \Delta k_Z, \Delta g_1^Z$	WW, WZ
$ZZ\gamma$	h_3^Z, h_4^Z	$Z\gamma$
$Z\gamma\gamma$	h_3^γ, h_4^γ	$Z\gamma$
$Z\gamma Z$	f_{40}^Z, f_{50}^Z	ZZ
ZZZ	$f_{40}^\gamma, f_{50}^\gamma$	ZZ

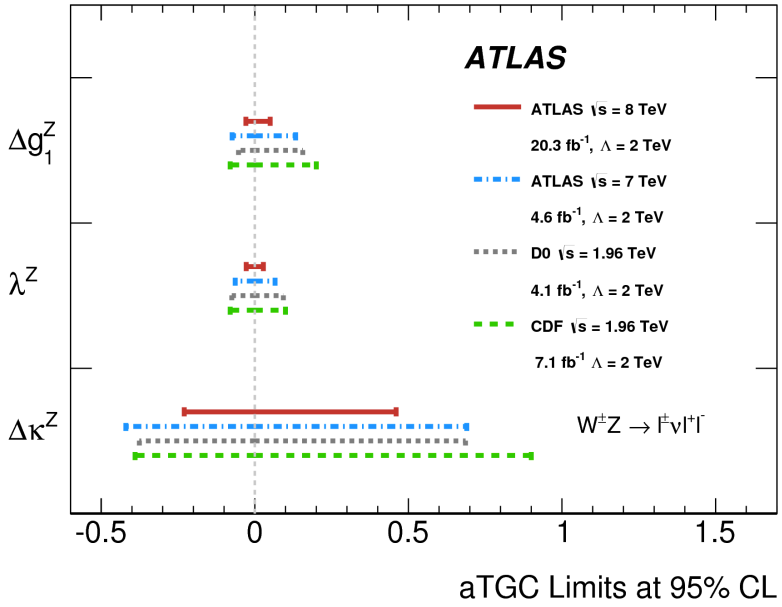
Triple Gage Coupling / Quartic Gage Coupling



- Anomalous couplings can manifest as increase cross sections and modification of kinematic distributions compared with SM predictions
- The SM predictions should be known to high precision.

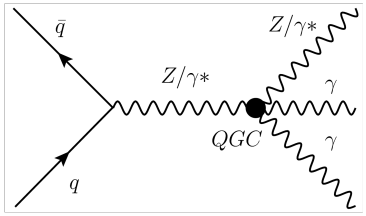
Limits on aTGC $W^{\pm}Z$ @ 8TeV

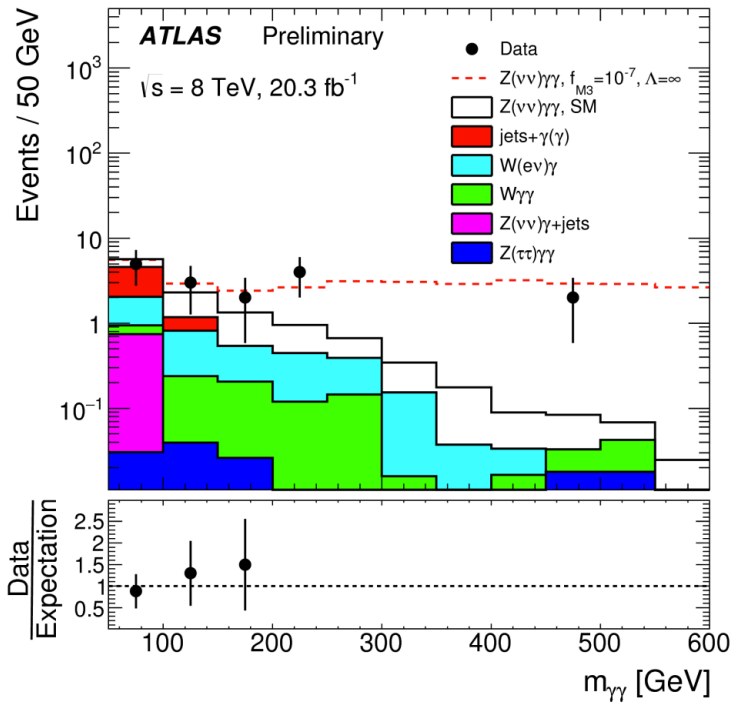


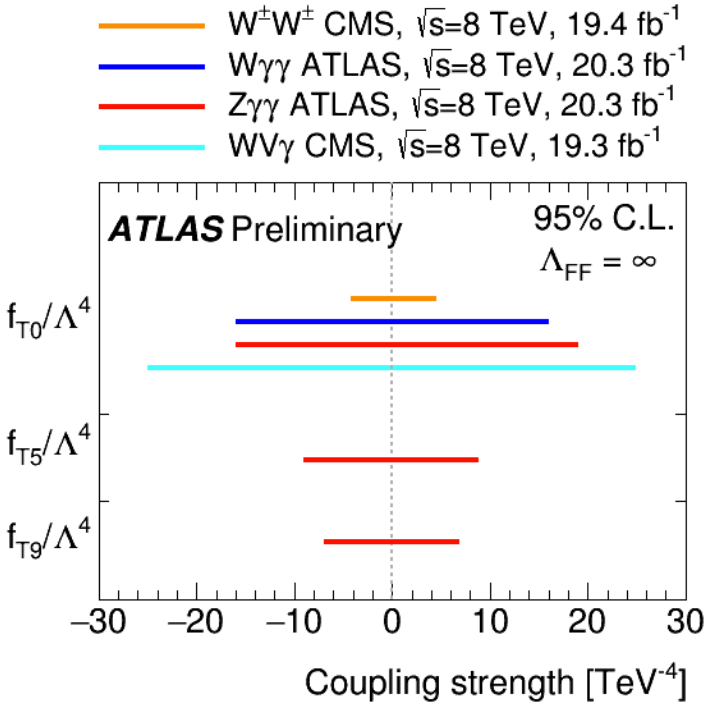


The Powheg+Pythia MC prediction for the SM W±Z signal contribution.
Predictions with nonzero values of some of the anomalous coupling parameters by the dashed and dotted-dashed lines, respectively.

Limits on aQGC $Z\gamma\gamma$ @ 8TeV



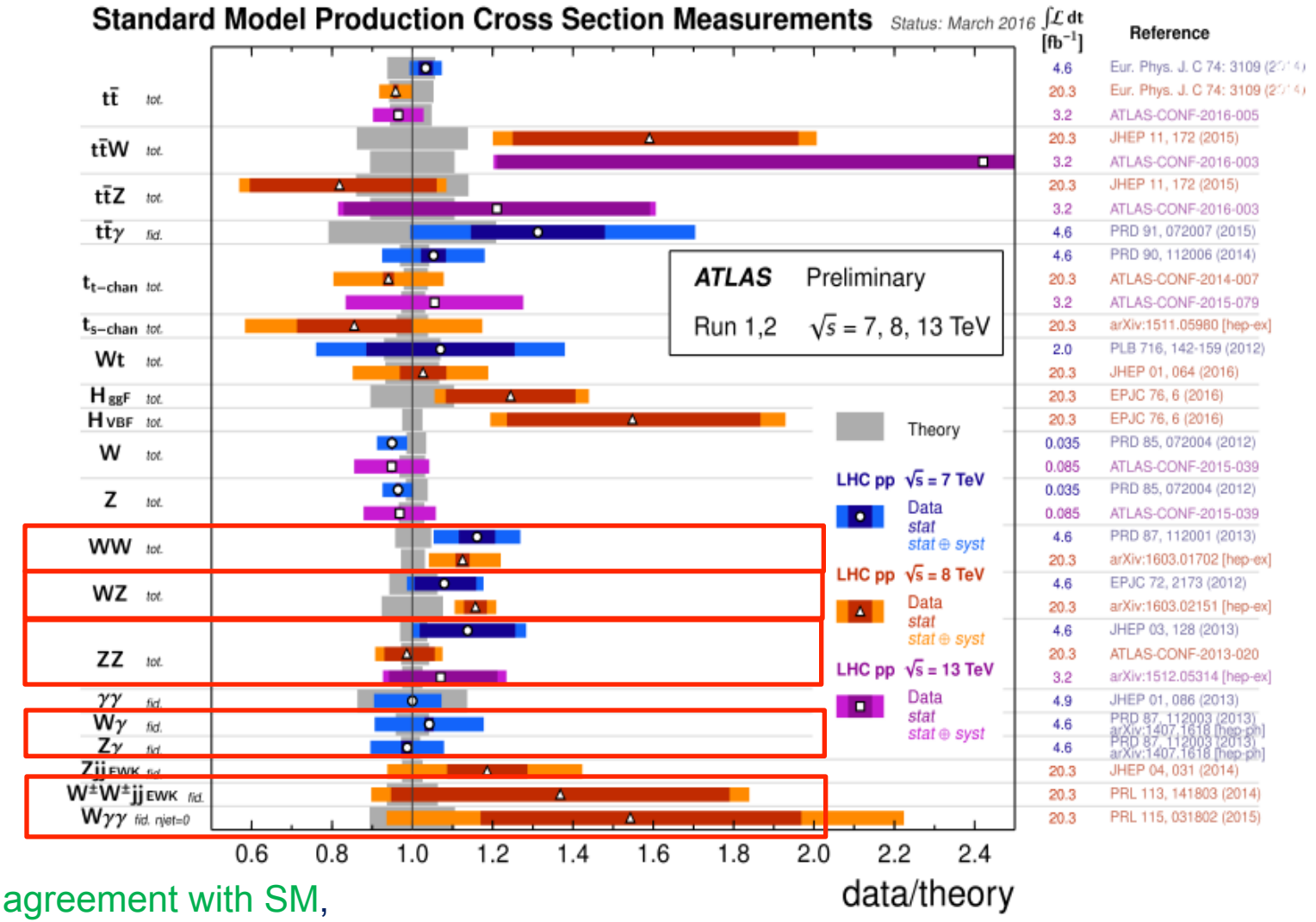




Limits for ft5 and ft9 were obtained in ATLAS and CMS

- Exclusive cross section, m(γγ)>300 (200) GeV used for aQGC limits for the *vvγγ (llγγ)* channel.

Summary table ATLAS



Good agreement with SM,

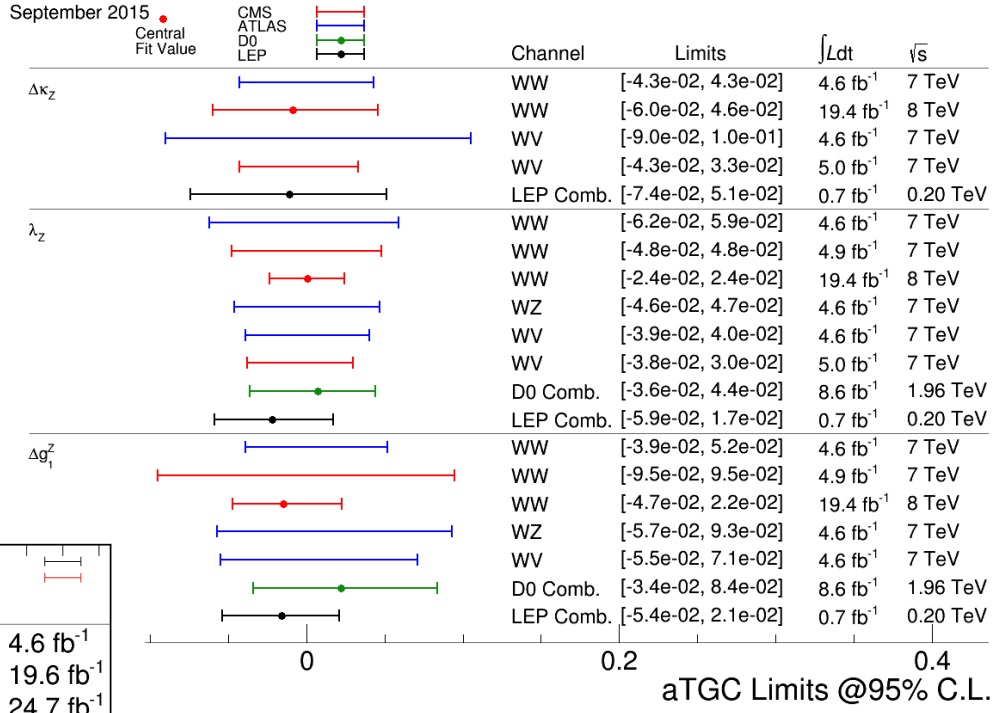
WZ cross-section higher than NLO prediction (8 TeV) → in 13 TeV NNLO nessecery !!!

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/StandardModelPublicResults

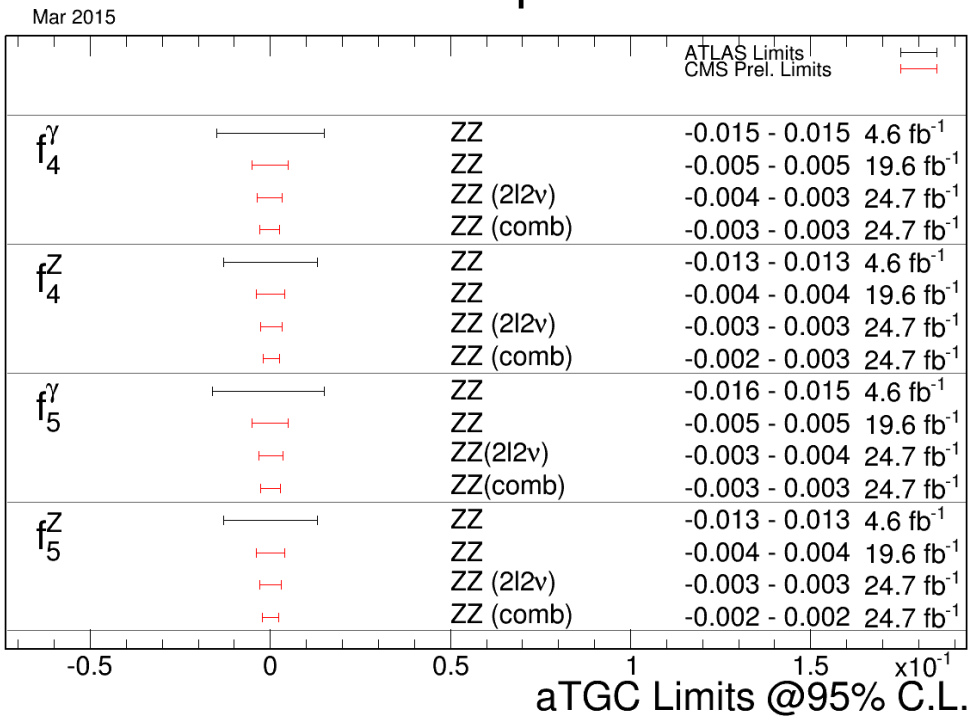
Summary of aTGC Limits

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

Charged aTGC for WWZ vertex



Neutral aTGC ZZγ and ZZZ



- Stringent 95% CL Limits, and agree with SM prediction
- Limits similar or (way) better than previous experiments at Tevatron (D0) and at LEP.

Summary

Large set of ATLAS results from the analysis of multi boson final states have been presented.

- Diboson
  - Most measured cross-sections agree with SM predictions (compared to calculations with NNLO QCD corrections)
  - NNLO calculations agree much better with the measurements
  - NNLO QCD calculations are needed
  - Differential measurements consistent with SM prediction
  - Explored aTGC with good sensitivities
- Triboson
  - Starting probe triple boson physics including aQGC
  - NNLO QCD calculations may also needed

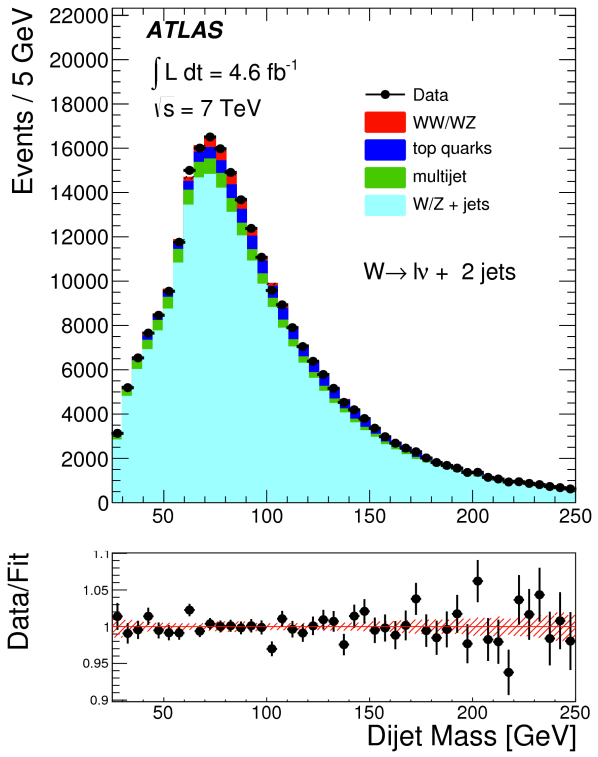
Looking forward on LHC Run 2

- Thank you!

Backup Slides

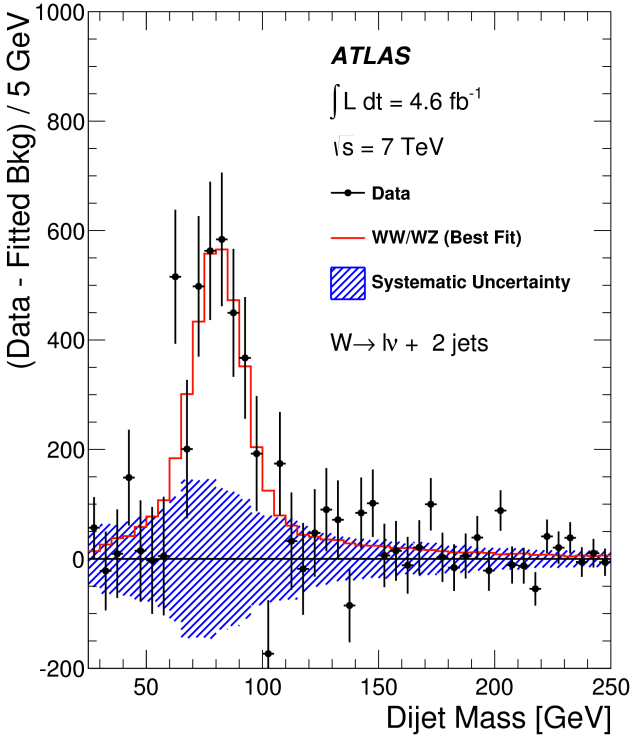
WW / WZ → lνjj (semileptonic)

Event Selection
one high P_T, isolated lepton
E_T^{miss} >30 GeV, M_T>40 GeV



Backgrounds:
- W/Z+jets: ~89% (data driven)
- multi-jets: ~5% (data driven)
- top: ~4% (MC)

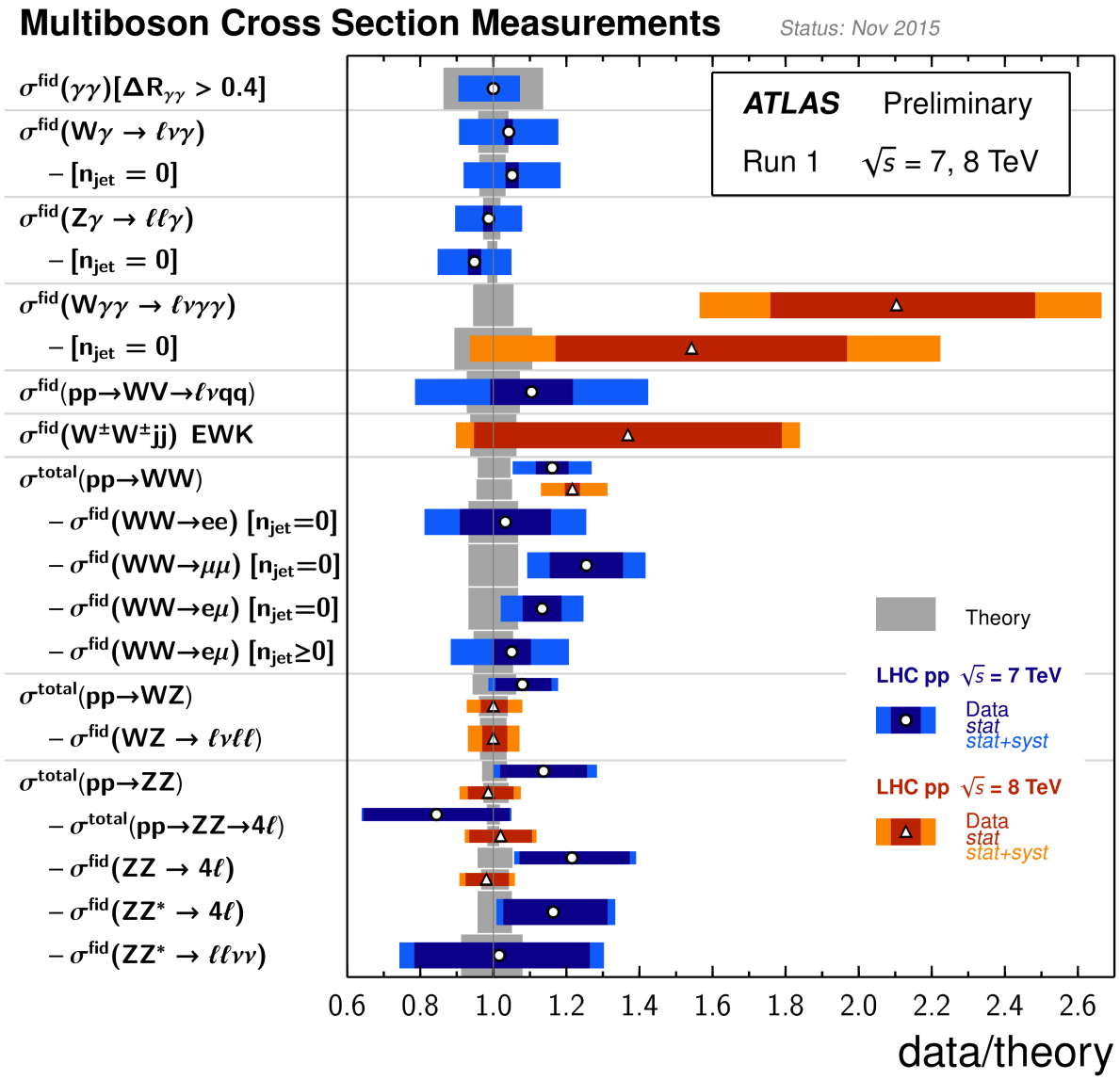
Total bkg modeled w/ combined LH fit



Measured (tot. comb.) [pb]	**68 ±7(stat.)±19(sys.)**
Theory pred. [pb]	**61.1±2.2**

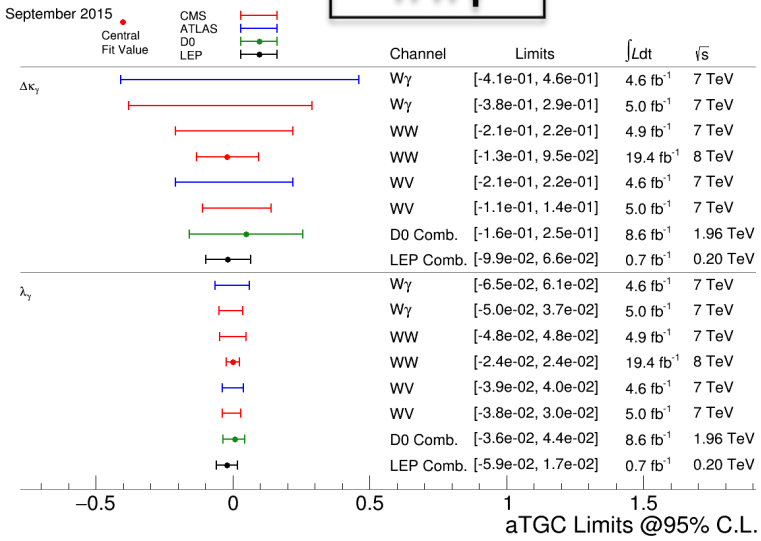
agreement w/ SM → limits on aTGC couplings

Multiboson cross section

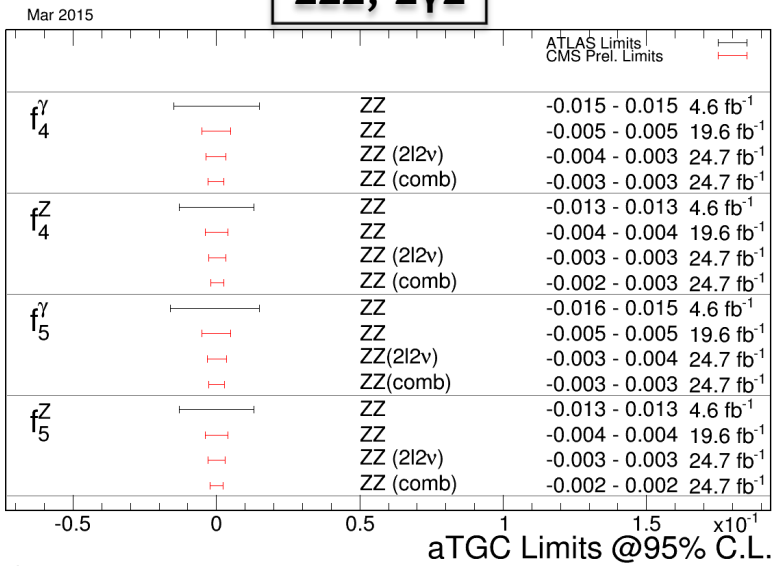


Summary of aTGC limits

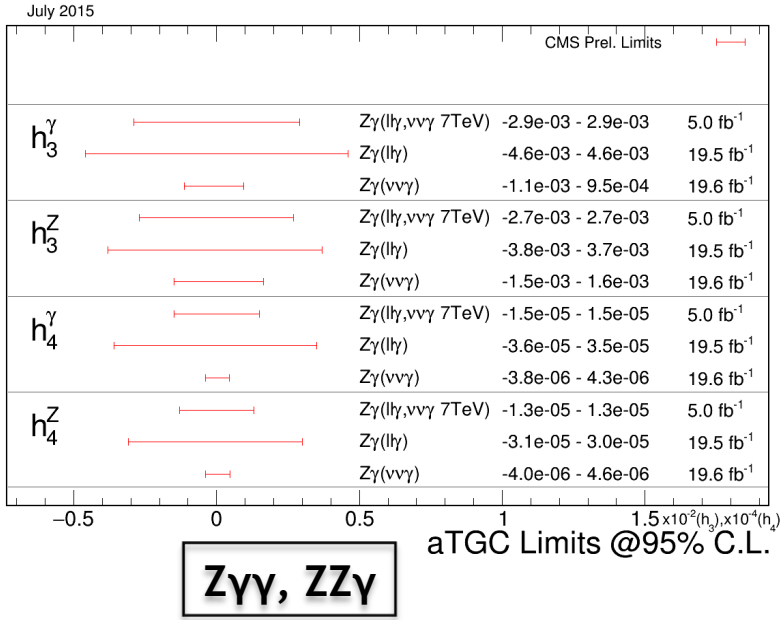
WWγ



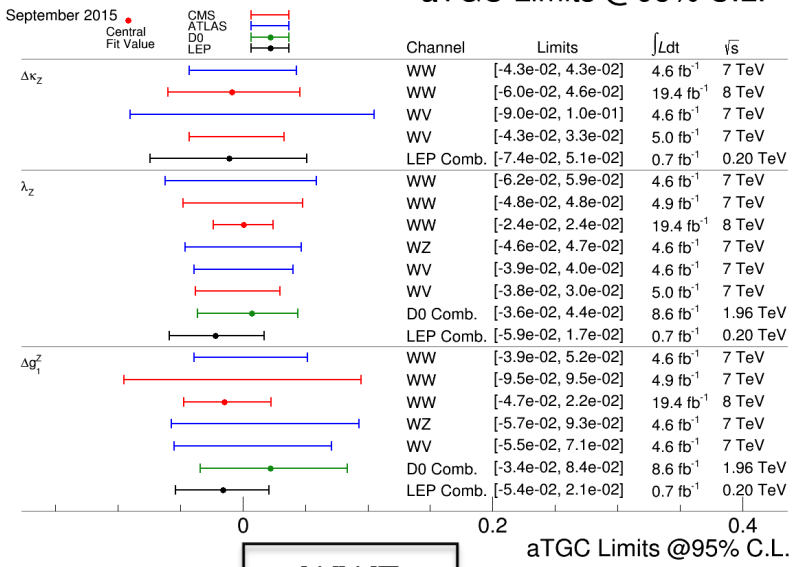
ZZZ, ZγZ



Zγγ, ZZγ



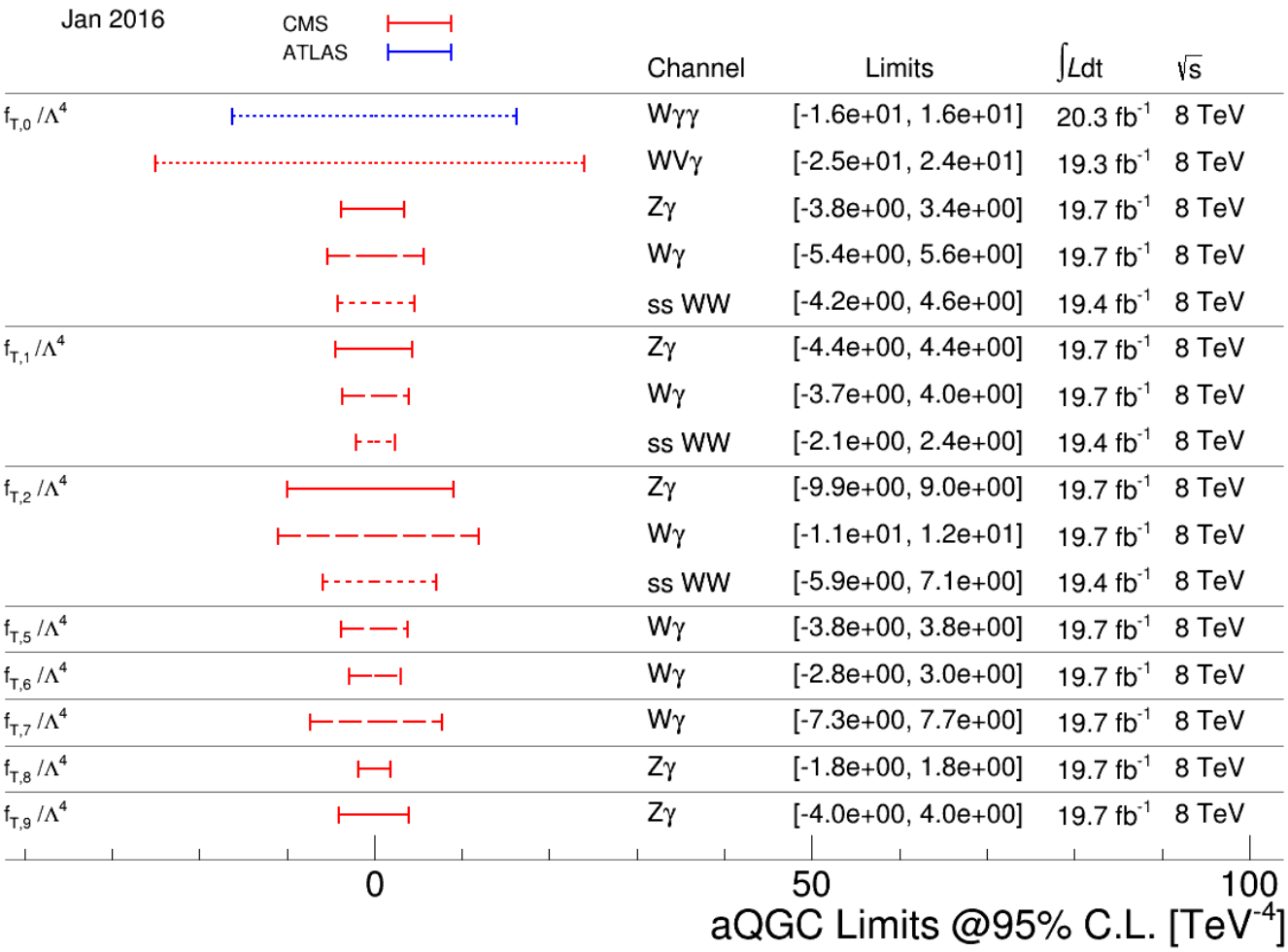
WWZ



Summary of aQGCs at LHC

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

Limits on 8-D Transverse Parameters



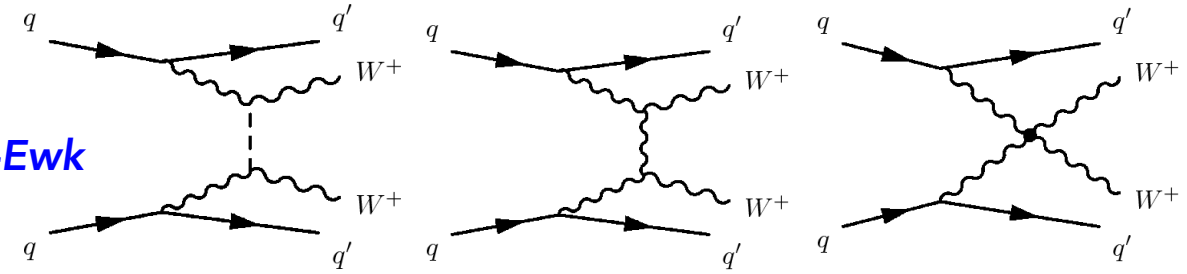
- No deviation from SM so far

VBS Production

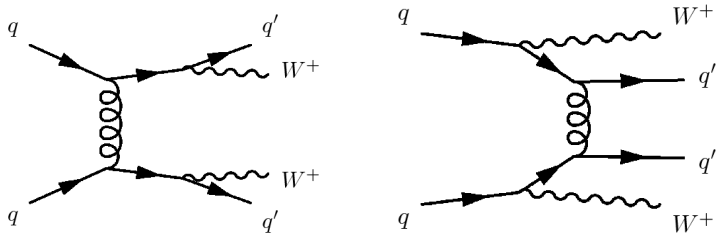
VBS $W^{\pm}W^{\pm}jj$ @8TeV

Phys. Rev. Lett. 113, 141803 (2014)

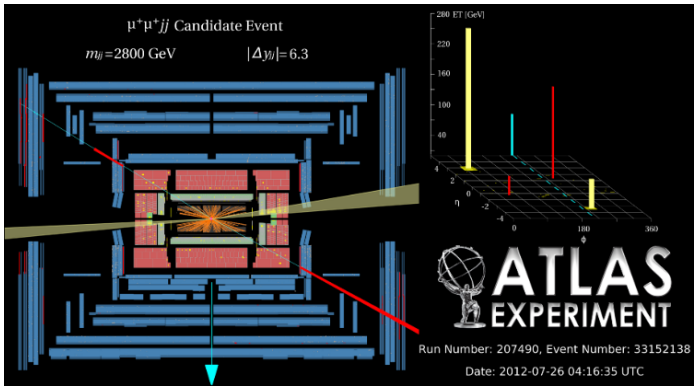
WWjj-Ewk



WWjj-strong



VBS pp → $W^{\pm}W^{\pm}jj$
(1st evidence of VBS diboson production)



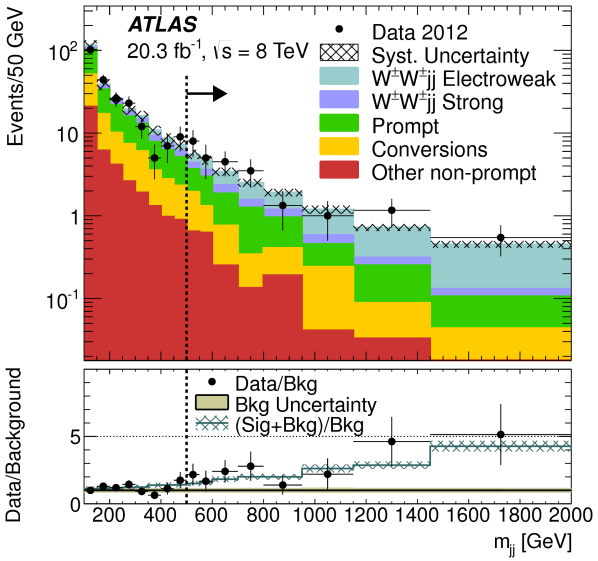
VBS topology :
2 bosons with two high momentum, forward jets
Jets well separated in rapiity

- Same charge WWjj scattering (VBS) is a key process to experimentally probe the SM nature of EWSB
- WWjj production process classification
  - Pure EWK WWjj production (VBS contribution)
  - Strong + Ewk WWjj production (inclusive)
- W±W± has the best ratio of σ(VVjj-Ewk)/σ(VVjj-strong)

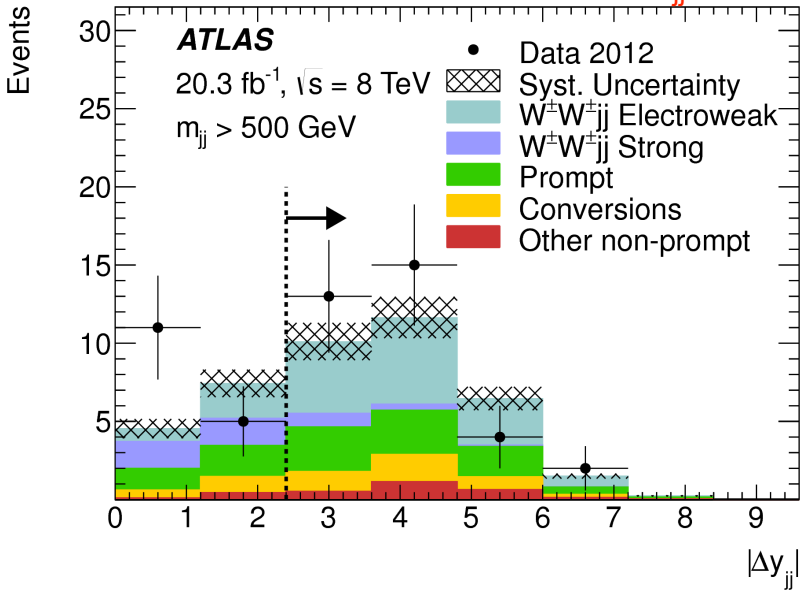
VBS $W^{\pm}W^{\pm}jj$ @8TeV

- Final states: ℓ±νℓ±ν + jj (ℓ=e,μ)
- Main backgrounds:
  - WZ+2jets , Wγ+2jets: estimated from MC
  - tt(bar) and single Z production through charge misidentification : estimated from data
- Systematics dominated by jet energy scale and WZ+2jets normalization

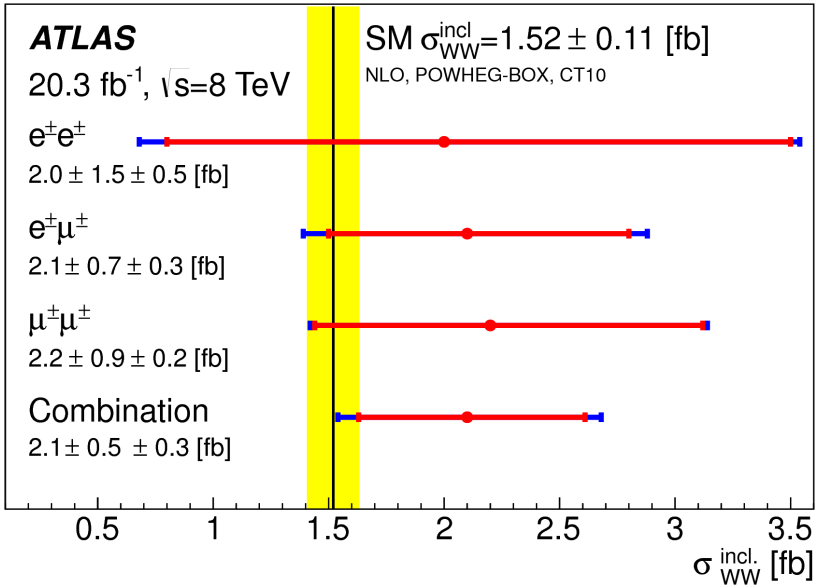
measurement of EW + strong production
selected with high di-jet mass

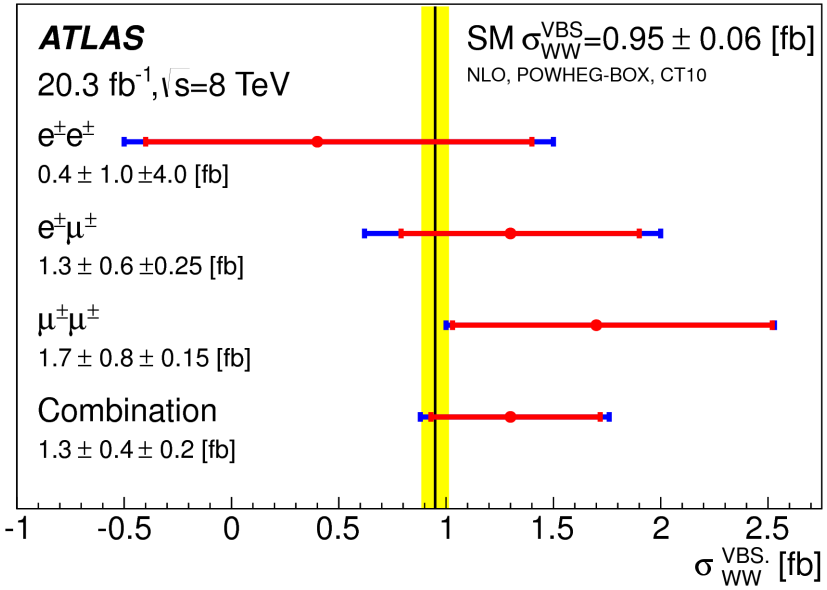


measurement of EW only
selection enhanced by ΔY_{jj} cut



VBS $W^{\pm}W^{\pm}jj$ @8TeV





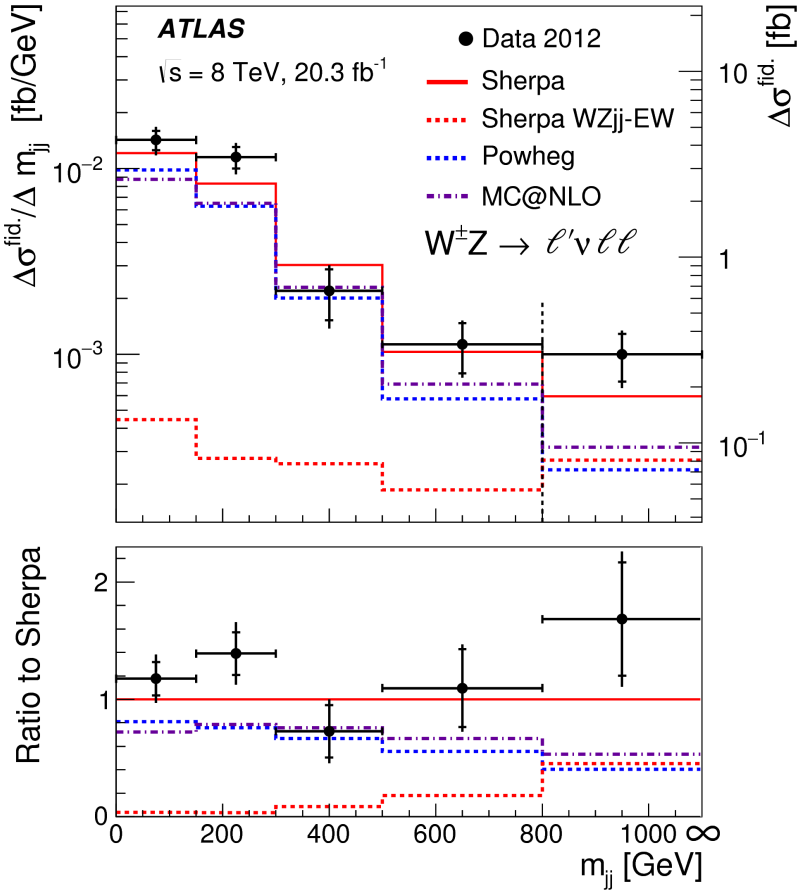
	Measurement [fb]	**Theory [fb]** (PowhegPythia8)	measurement significance
Inclusive	2.1 ± 0.5(stat) ± 0.3(syst)	1.5 ± 0.11	4,5
Ewk-only	1.3 ± 0.4(stat) ± 0.2(syst)	0.95 ± 0.06	3,6

First evidence for EWK VV → VV scattering !

Measurements consistent with prediction

VBS: WZjj @ 8 TeV

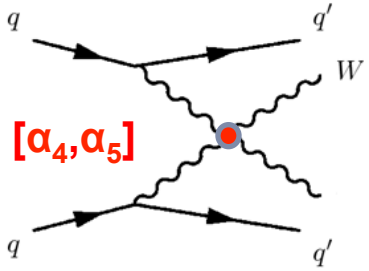
arXiv:1603.02151, submitted to Phys. Rev. D.



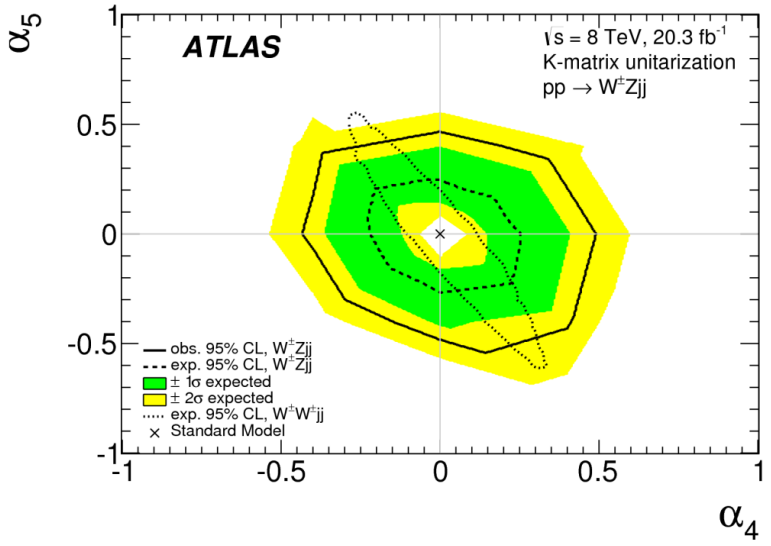
SHERPA is used for the SM WZjj-QCD and WZjj-EW predictions

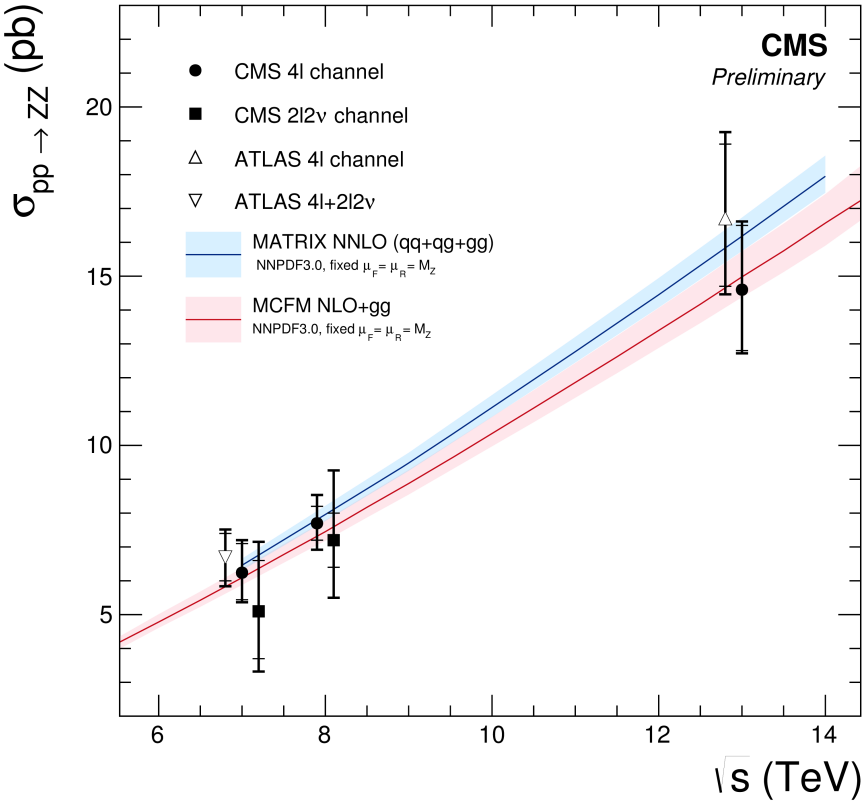
$$\sigma^{\text{fid.}}_{W^\pm Zjj\text{-EW}\to\ell'\nu\ell\ell} = 0.29\,^{+0.14}_{-0.12}\,(\text{stat.})\,^{+0.09}_{-0.1}\,(\text{sys.})\ \text{fb}$$

VBFNLO MC Prediction: 0.13 ± 0.01 fb



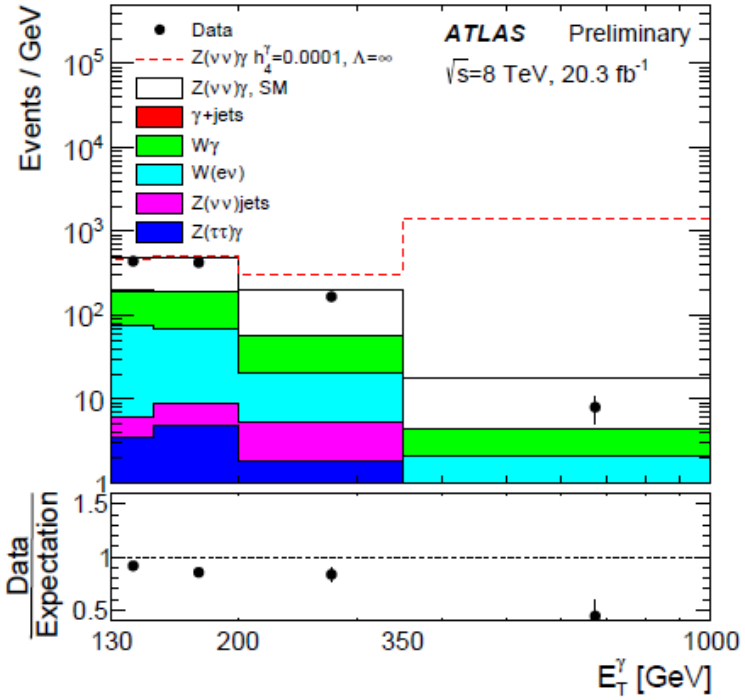
WIZARD MC for aQTGC cross-section contribution used in the fit

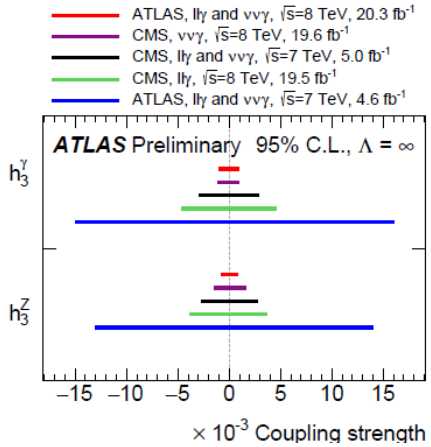


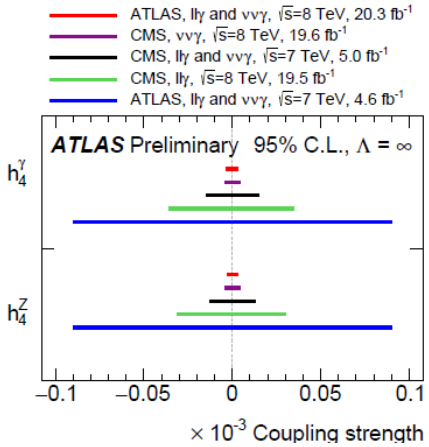

CMS
Preliminary
CMS 4l channel
CMS 2l2ν channel
ATLAS 4l channel
ATLAS 4l+2l2ν
MATRIX NNLO (qq+qg+gg)
NNPDF3.0, fixed μF = μR = MZ
MCFM NLO+gg
NNPDF3.0, fixed μF = μR = MZ
σpp → ZZ (pb)
√s (TeV)
5
10
15
20
6
8
10
12
14

Zγ @ 8TeV

arXiv:1604.05232, accepted by PRD







$E_T(\gamma)$ distributions are used for aTGC limit setting

aTGCs ZZ @7 TeV, 4.6 fb^{-1}

- aTGC contribution not the same across phase-space
- Use event yield as function of single kinematical variables.
  full 7 TeV result, 4.6 fb^{-}
- $p_T(Z)$
- m(ZZ) system

Effect of aTGCs most significant
in high pT / mass values