Recent multi-boson and vector-boson scattering measurements from ATLAS

ICPPA - 2016

10th of October 2016

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ATLAS EXPERIMENT
http://atlas.ch

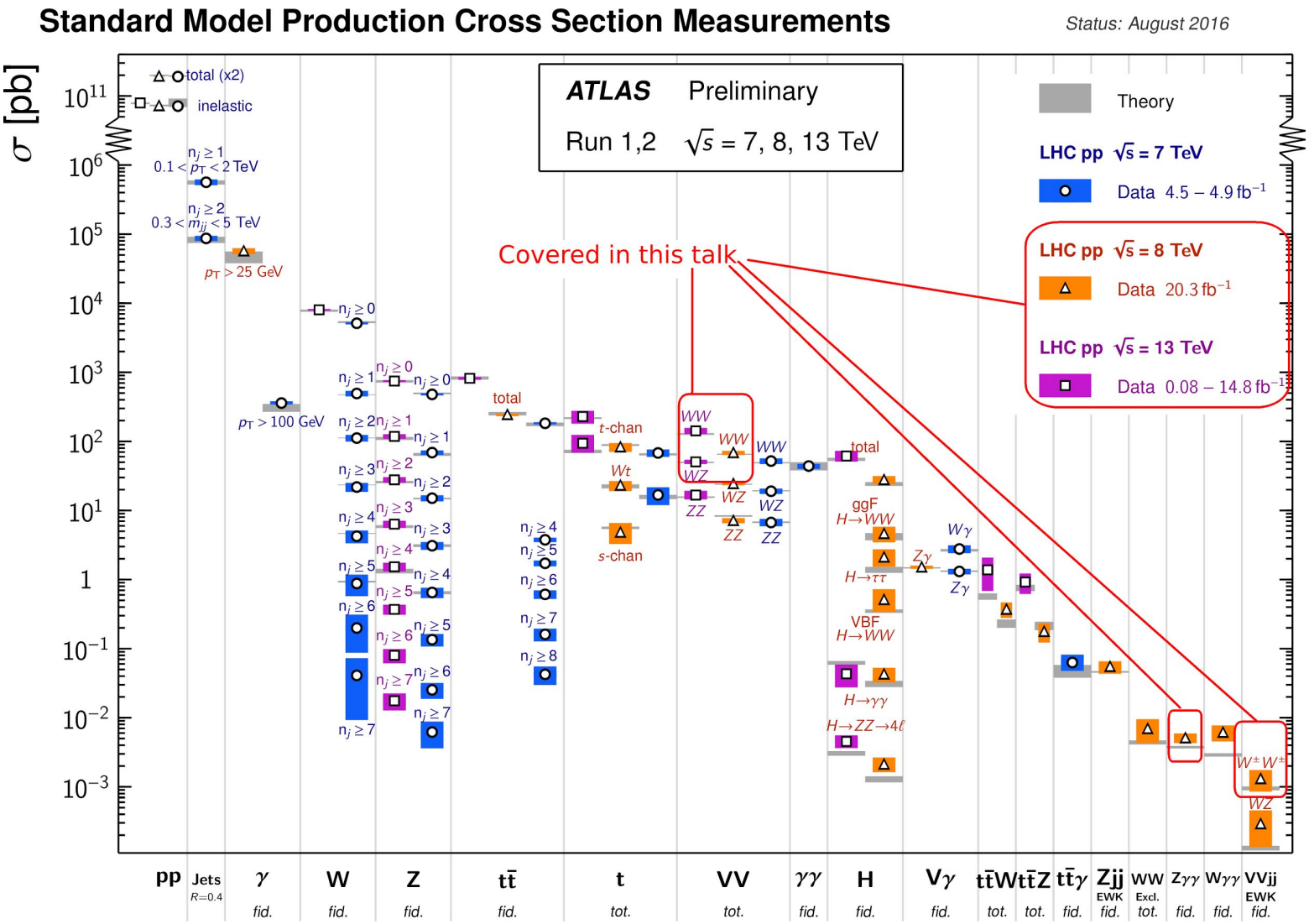
Outline and Motivation

- The production and scattering of vector bosons are sensitive to **physics beyond the Standard Model** (SM) via triple and quartic gauge boson vertices
  - ➢ Couplings could deviate from SM → **anomalous triple (quartic) gauge couplings (aTGCs, aQGCs)**
  - ➢ Search for new physics at the TeV scale
- Amplitudes of longitudinally polarized vector boson scattering (VBS) would violate unitarity at the TeV scale if no SM Higgs existed
  - ➢ Experimental verification that **cross section is precisely regulated**
- WW* processes are an irreducible **background to Higgs searches**
  - ➢ Validation of Monte Carlo modeling
- Test of **electroweak NLO corrections** and of **QCD calculations**

Analyses covered in this talk:

1. $Z(\rightarrow ee/\mu\mu/\nu\nu)\gamma$ and $Z(\rightarrow ee/\mu\mu/\nu\nu)\gamma\gamma$ @ 8 TeV
2. Same sign $WW(\rightarrow \ell\nu\ell\nu)jj$ @ 8 TeV
3. $WZ\rightarrow \ell\nu\ell\ell$ @ 13 TeV
4. $WW \rightarrow \ell\nu\ell\nu$+1 jet @ 8 TeV
5. $WW \rightarrow \ell\nu\ell\nu$ @ 13 TeV
6. $WWW\rightarrow(\ell\nu\ell\nu\ell\nu)$ or $(\ell\nu\ell\nu jj)$ @ 8 TeV

Outline and Motivation



Anomalous Gauge Couplings

Non-abelian nature of electroweak theory allows interactions among gauge bosons:

- **Effective Lagrangian formalism (aTGCs in this talk):**
  - Gauge invariant C and P conserving terms are added to the Lagrangian
  - Anomalous TGCs δ_i:
    - Charged (WWZ, WWγ): $\delta_i = g_1\text{-}1, \kappa^V\text{-}1, \lambda^V$, with V = Z/γ
    - Neutral (ZZZ, Z$\gamma\gamma$, ZZγ): $\delta_i = h^V_3, h^V_4, f^V_4, f^V_5$, all δ_i vanish in the SM
  - Formfactor has to be introduced in order to prevent unitarity violation at high energies:

$$\delta_i \rightarrow \frac{\delta_i}{(1+\hat{s}/\Lambda_{FF})^n}$$

- **Effective Field Theory (aQGCs in this talk):**
  - SM is an effective theory valid for energies $E << \Lambda_{co}$
  - Beyond SM couplings are introduced via higher mass dimension operators:

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_{d=5}^{\infty} \frac{1}{\Lambda^{d-4}} \sum_i c_i \mathcal{O}_i^{(d)}$$

  - In the SM, all c_i are 0

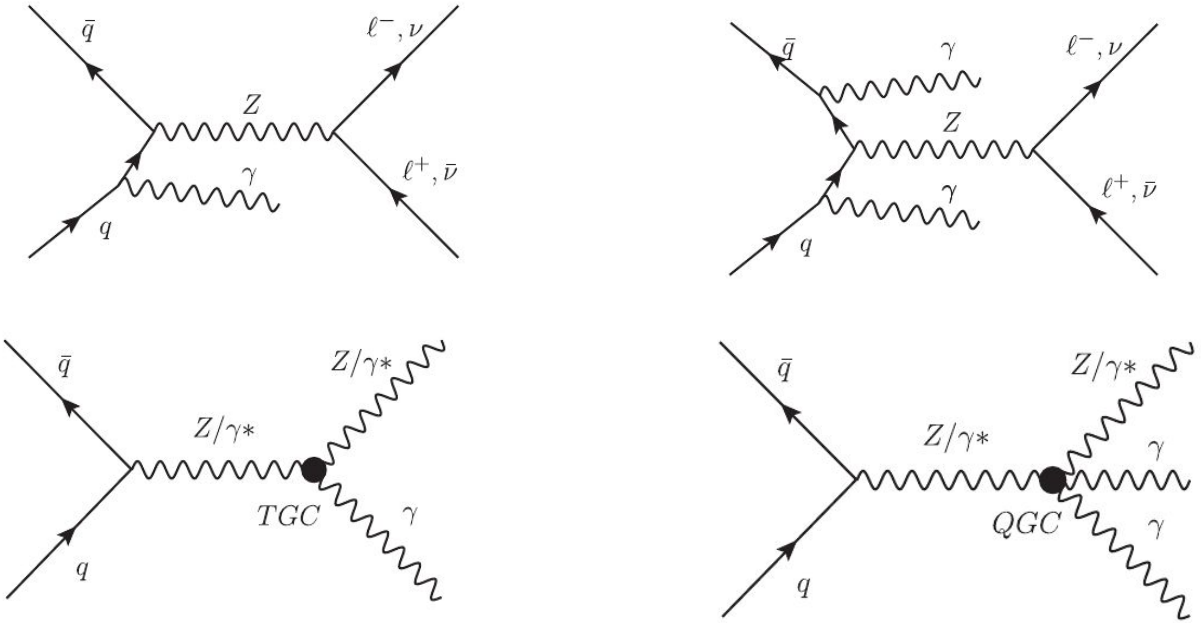
Dimension 4	Dimension 6	Dimension 8
WWWW, WWWZ	WWZγ, WW$\gamma\gamma$	all VVVV
α_4, α_5	a_0/Λ^2, a_c/Λ^2	$f_{S,i}/\Lambda^4$ $f_{M,i}/\Lambda^4$, $f_{T,i}/\Lambda^4$

arXiv:hep-ph/0606118v2

$Z\gamma$- and $Z\gamma\gamma$ Production

Phys. Rev. D 93, 112002

- Measurement of Z production in association with one or two photons
- **Goals:**
  - Measure production **cross section** in **inclusive** ($N_{jets}\geq 0$) and **exclusive** ($N_{jets}=0$)
  - Set limits on:
    - **aTGCs** ($ZZ\gamma$ and $Z\gamma\gamma$) from $Z\gamma$ cross section ($N_{jets}=0$)
    - **aQGCS** ($ZZ\gamma\gamma$ and $Z\gamma\gamma\gamma$) from $Z\gamma\gamma$ cross section



- **$Z\rightarrow\ell\ell\gamma(\gamma)$:**
  - Two opposite sign leptons and at least one (two) isolated photons, E_T>15 GeV
- **$Z\rightarrow\nu\nu\gamma(\gamma)$:**
  - $E_{\mathrm{T}}^{\mathrm{miss}} > 100(110)\,\mathrm{GeV}$ and at least one (two) photons with E_T>130 (22) GeV
- **Backgrounds:**
  - Most important backgrounds are Z+jets and Z+γj(j), estimated from data

$Z\gamma$- and $Z\gamma\gamma$ Production

Phys. Rev. D 93, 112002

- Measurement of Z production in association with one or two photons
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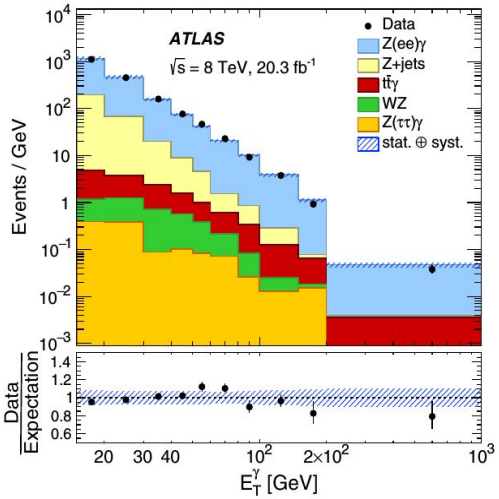
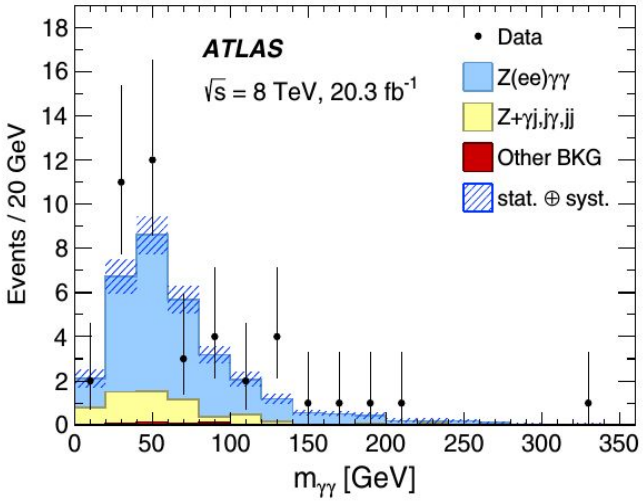
    - **aQGCS** ($ZZ\gamma\gamma$ and $Z\gamma\gamma\gamma$) from $Z\gamma\gamma$ cross section

$Z\gamma$:



Photon transverse energy from inclusive $e^+e^-\gamma$ events

$Z\gamma\gamma$:



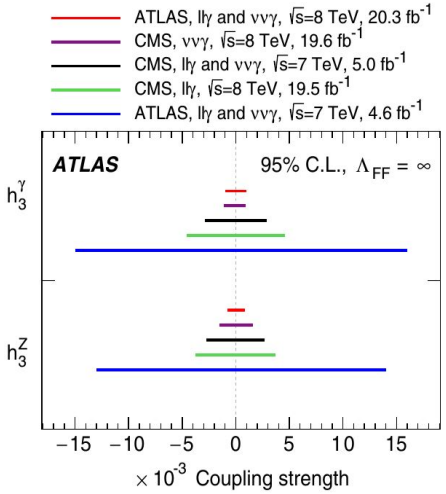
Diphoton invariant mass from inclusive $e^+e^-\gamma\gamma$ events

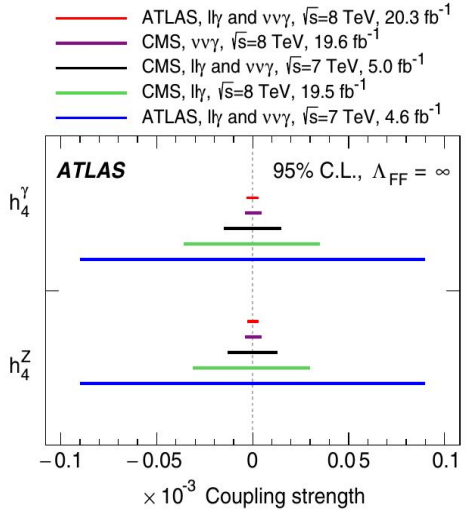
- **$Z\rightarrow\ell\ell\gamma(\gamma)$:**
  - Two opposite sign leptons and at least one (two) isolated photons, E_T>15 GeV
- **$Z\rightarrow\nu\nu\gamma(\gamma)$:**
  - $E_{\mathrm{T}}^{\mathrm{miss}} > 100(110)\,\mathrm{GeV}$ and at least one (two) photons with E_T>130 (22) GeV
- **Backgrounds:**
  - Most important backgrounds are Z+jets and Z+γj(j), estimated from data

$Z\gamma$- and $Z\gamma\gamma$ Production - aQGC Limits

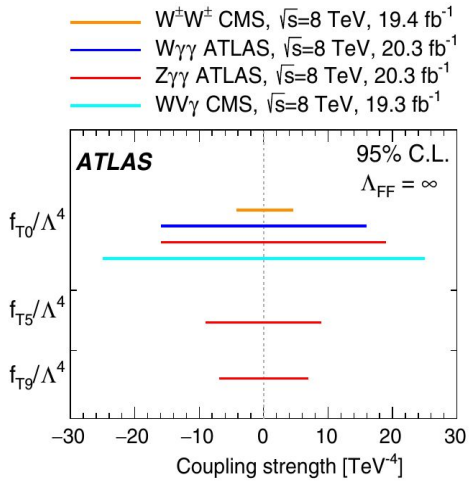
Phys. Rev. D 93, 112002

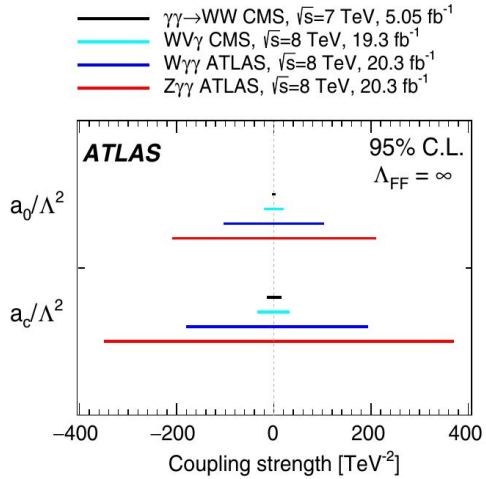
- Limits on **aTGCs** derived for $h_{3,4}^{V}$ using **high E^{T}_{γ}** events in the **exclusive** zero-jet **selection** (significant reduction of SM background)





- For limits on **aQGCs** using exclusive cross section with additional requirement $m_{\gamma\gamma}$>300 (200) GeV for $\nu\nu\gamma\gamma$ ($\ell\ell\gamma\gamma$)



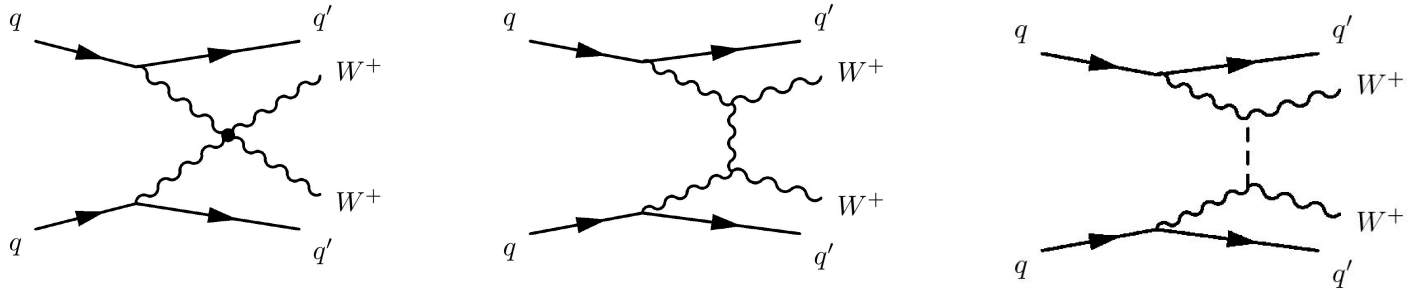


$W^{\pm}W^{\pm}(\rightarrow \ell^{\pm}\nu\ell^{\pm}\nu)jj$ production @ 8 TeV

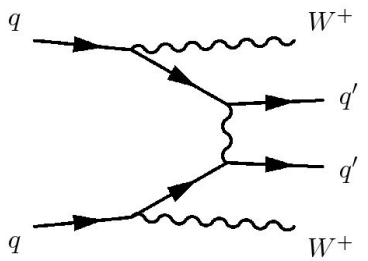
- First time ever measurement of $W^{\pm}W^{\pm}jj$ production
- Sensitive to anomalous quartic gauge boson couplings
- Low contamination from strong production (EW / strong ~ 1/1)

Phys. Rev. Lett. 113, 141803

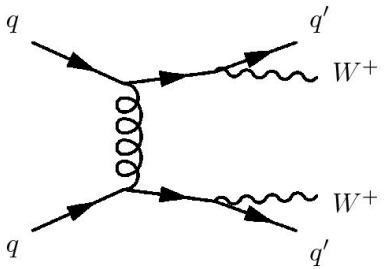
- **Electroweak vector boson scattering:**



- **Electroweak non-VBS:**



- **Strong Production:**



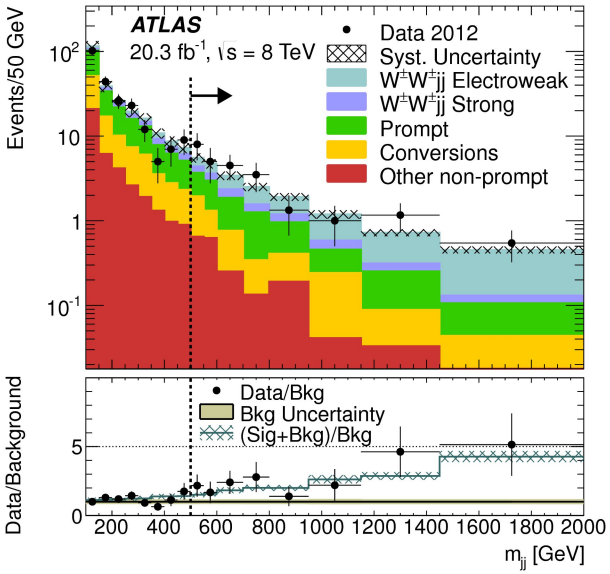
- Signal Regions:
  - **Inclusive signal region (EW + strong):**
    - Two central same sign leptons with p_T>25 GeV and $|\eta|$<2.5
    - At least two jets (p_T>30 GeV, $|\eta|$< 4.5, and m_{jj}>500 GeV)
    - $m_{\ell\ell}$ >20 GeV, E_T^{Miss}>40 GeV,
  - **Exclusive VBS region (EW only):**
    - Additional requirement: $\Delta|y_{jj}|$>2.4
    - Used to set limit on aQGCs

$W^{\pm}W^{\pm}(\rightarrow \ell^{\pm}\nu\ell^{\pm}\nu)jj$ - Cross Section

- **Backgrounds:**
  - Prompt leptons from WZ/γ*, estimated from simulation
  - Conversion background, e.g. Wγ, also estimated from simulation
  - Non-prompt backgrounds, e.g. W+jets, ttbar, data-driven estimation

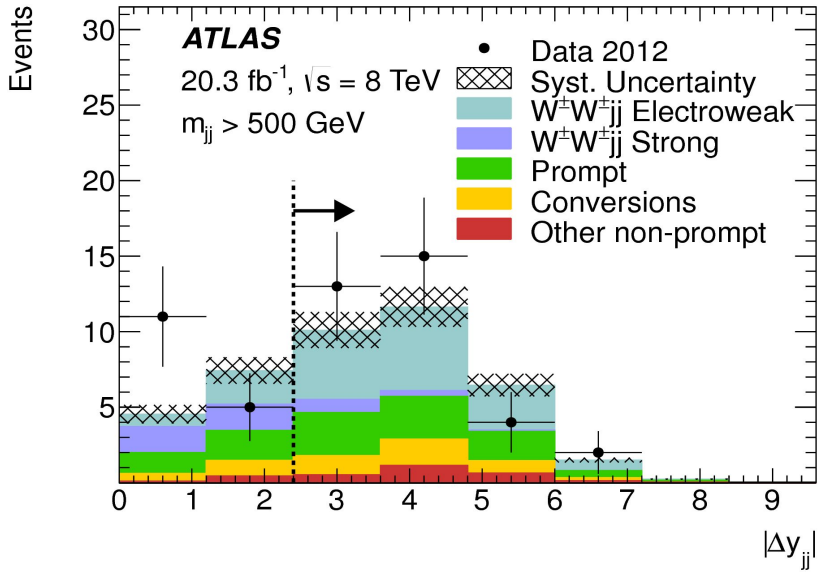
Phys. Rev. Lett. 113, 141803

Inclusive:



- The observed (expected) significance of strong + EW production in inclusive region is 4.5 (3.4) σ
- σ_{Meas}^{fid} = 2.1± 0.5 (stat) ± 0.3 (syst) fb
- σ_{Pred}^{fid} = 1.52 ± 0.11 fb (NLO in α_S)

VBS only:

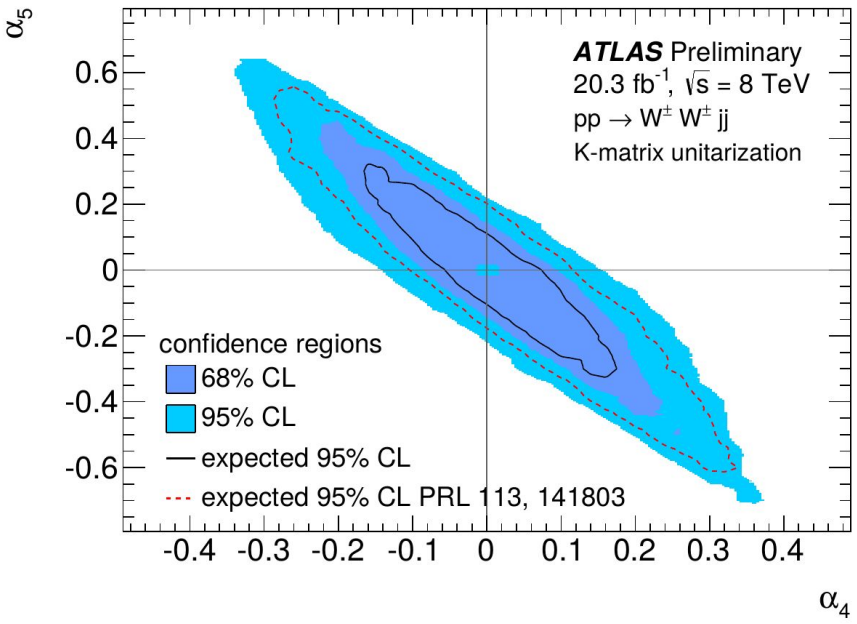


- The significance of EW-only production amounts to 3.6 σ (observed) and 2.8 σ (expected)
- σ_{Meas}^{fid} = 1.3 ± 0.4 (stat) ± 0.2 (syst) fb
- σ_{Pred}^{fid} = 0.95 ± 0.06 fb (NLO in α_S)

$W^{\pm}W^{\pm}(\rightarrow \ell^{\pm}\nu\ell^{\pm}\nu)jj$ - aQGCs

- Limits on **aQGCs** have been derived using VBS region
- Analysis was **updated recently** (preliminary results from July 2016) with an optimized event selection targeting improved constraints on aQGCs
- Several kinematic variables were tested

Submitted to PRD



- Final choice:
  Cut on the **transverse mass** of the WW system, m_{WW}>400 GeV, additionally to the VBS selection
- Expected limits improve by **around 35%** with respect to previous publication

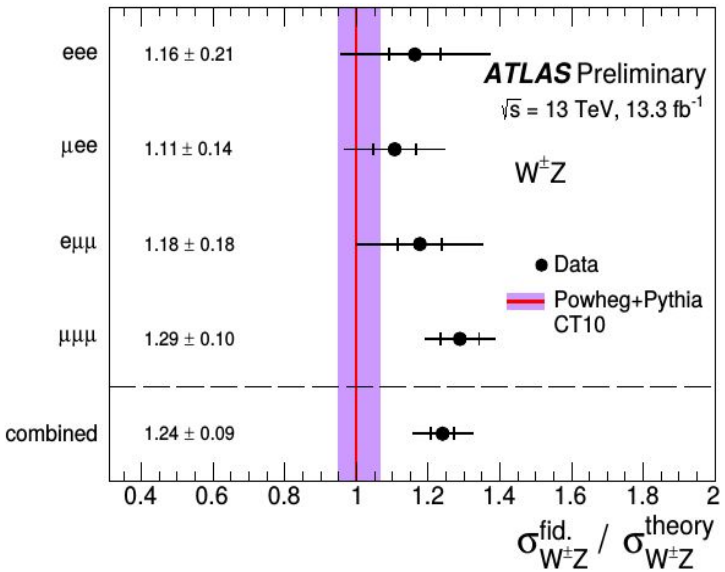
Expected:
- α_4 = [-0.06, 0.07]
- α_5 = [-0.10, 0.11]

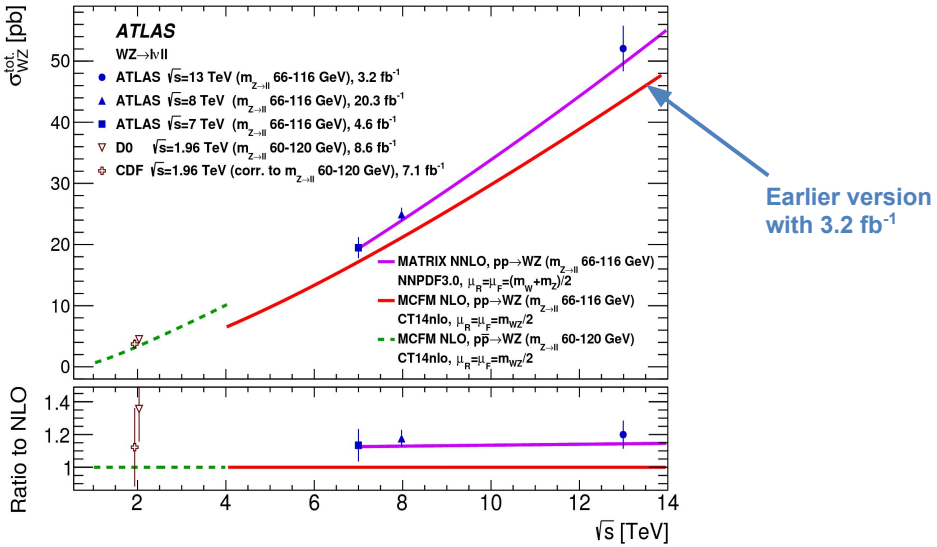
Observed:
- α_4 = [-0.14, 0.15]
- α_5 = [-0.22, 0.22]

Inclusive and differential WZ cross section @ 13 TeV

ATLAS-CONF-2016-043

- **Inclusive selection:**
  - 3 leptons, 2 of same flavor and opposite sign and compatible with the Z mass, m_T^W >30 GeV
- **Dominant backgrounds:** Z+Jets, Zγ, ttbar (data-driven) and ZZ, ttbar+V (Powheg and Sherpa)
- **Fiducial cross section:** $\sigma^{\text{fid.}}_{W^\pm Z\to\ell'\nu\ell\ell} = 63.2 \pm 3.2\,(\text{stat.}) \pm 2.6\,(\text{sys.}) \pm 1.5\,(\text{lumi.})$ fb
- **Total cross section:** $\sigma^{\text{tot.}}_{W^\pm Z} = 50.6 \pm 2.6\,(\text{stat.}) \pm 2.0\,(\text{sys.}) \pm 0.9\,(\text{th.}) \pm 1.2\,(\text{lumi.})$ pb
- **NLO prediction for total cross section:** $\sigma^{\text{tot.}}_{W^\pm Z} = 42.4 \pm 0.8\,(\text{PDF}) \pm 1.6\,(\text{scale})$ pb





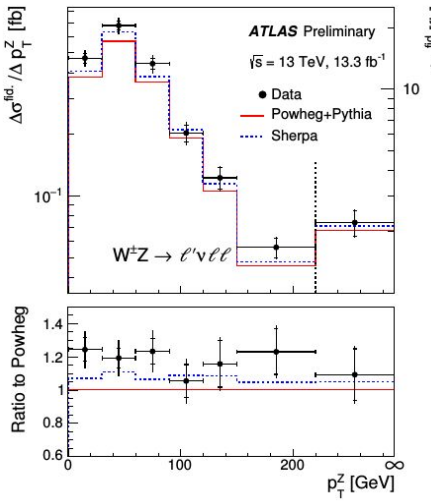
- Cross section in all channels consistently larger than NLO prediction (Powheg)
- Recent NNLO calculations from Grazzini et al. (arXiv:1604.08576) explain significant excess in total cross section:

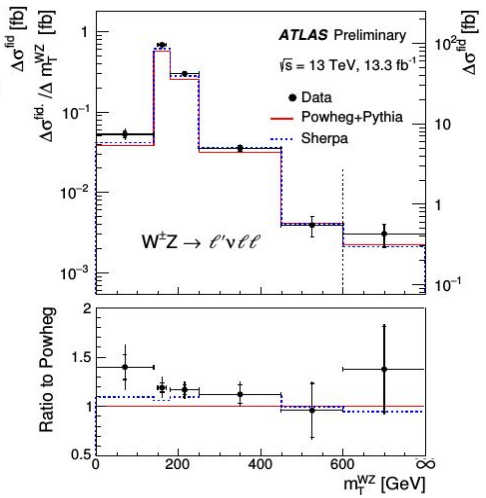
$$\sigma^{\text{tot.}}_{W^\pm Z} = 48.2^{+1.1}_{-1.0}\,(\text{scale})\ \text{pb}$$

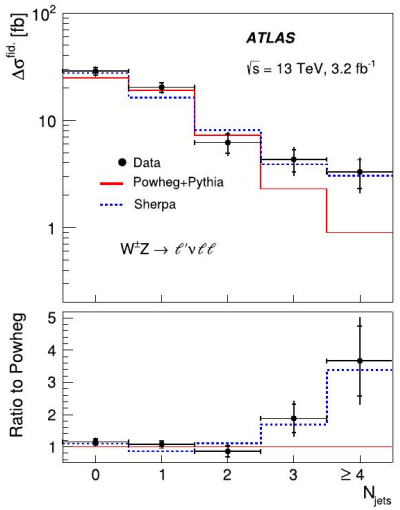
Inclusive and differential WZ cross section @ 13 TeV

ATLAS-CONF-2016-043

- Differential cross sections as function of p_T^Z, m_T^{WZ} and jet multiplicity are measured
- Good description by MC is observed for p_T^Z and m_T^{WZ}
- Matrix element description (Sherpa NLO-0j merged with LO multi-leg 1,2,3j +PS) superior to NLO+PS approach (Powheg)



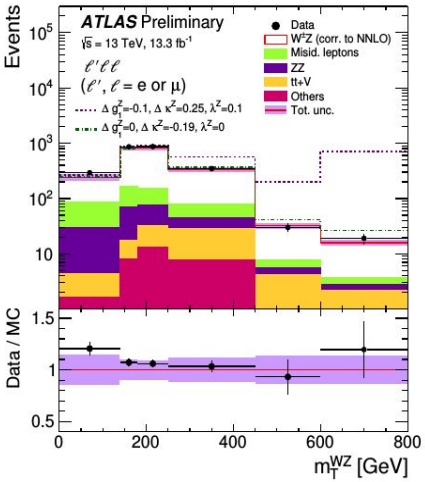


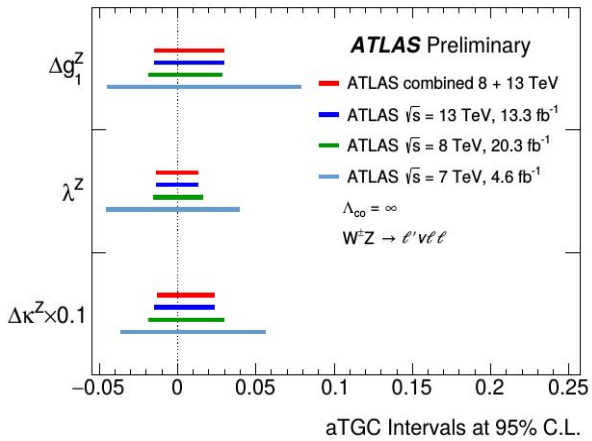


Phys. Lett. B 762 (2016) 1

- m_T^{WZ} used to extract aTGC limits (less sensitive to higher order EW and QCD effects)
- Improvement of limits of up to 25% w.r.t. 8 TeV analysis

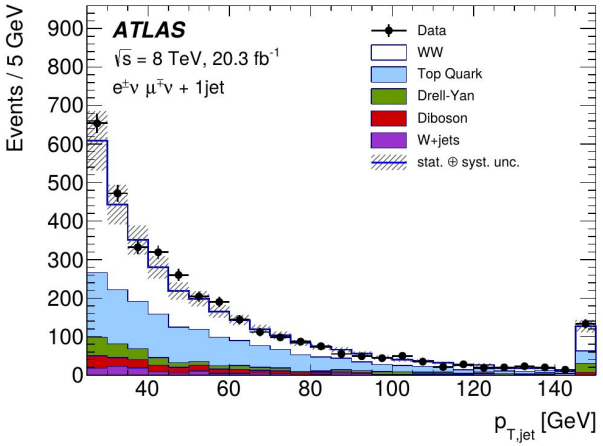
Dataset	Coupling	Expected	Observed
8 and 13 TeV	Δg_1^Z	[-0.014; 0.029]	[-0.015; 0.030]
	$\Delta\kappa_1^Z$	[-0.15; 0.21]	[-0.13; 0.24]
	λ^Z	[-0.013; 0.012]	[-0.014; 0.013]

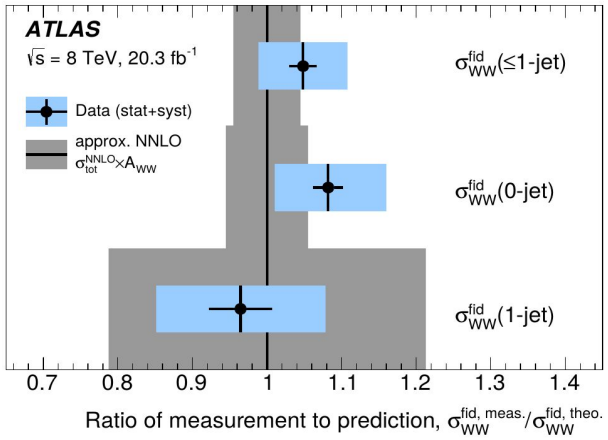


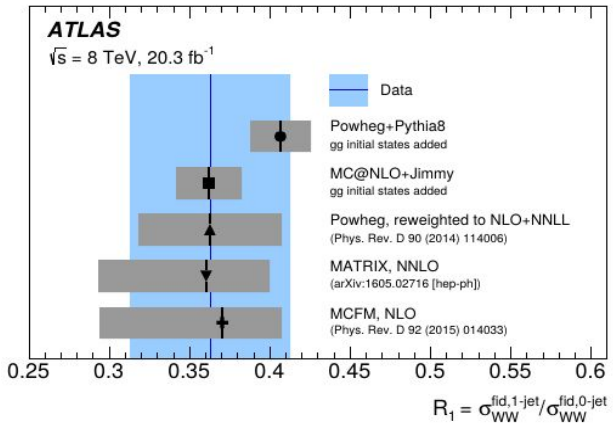


WW+1jet @ 8 TeV

- **Measurement:**
  - WW production in association with **exactly one jet**
  - Earlier WW+0 jet cross section measurements **showed excess** compared to SM prediction
  - Proposed solution was connected to logarithms arising from a selection on the number of jets (arXiv:1507.02565v2)
  - Resummation at NNLL is now available
  - WW+1j measurement confronts calculation with experimental data and extends earlier WW+0j measurement (arXiv:1603.01702)
- **Event Selection:**
  - Exactly two leptons ($e\mu$-channel), $N_{jets}(p_T>25$ GeV$)=1$, b-jet veto
  - Dominant background top quark production (data-driven)







- Ratio of $\sigma^{\mathrm{fid}}_{\mathrm{WW}}(1\mathrm{j})/\sigma^{\mathrm{fid}}_{\mathrm{WW}}(0\mathrm{j})$ also in good agreement with SM

- **Results:**
  - $\sigma^{\mathrm{fid,1\text{-}jet}}_{WW} = 136 \pm 6\,(\mathrm{stat}) \pm 14\,(\mathrm{syst}) \pm 3\,(\mathrm{lumi})$ fb
  - Combination with WW+0j: $\sigma^{\mathrm{fid},\leq 1-\mathrm{jet}}_{WW} = 511 \pm 9\,(\mathrm{stat}) \pm 26\,(\mathrm{syst}) \pm 10\,(\mathrm{lumi})$ fb
  - $\sigma^{\mathrm{tot}}_{WW} = 68.2 \pm 1.2(\mathrm{stat}) \pm 3.4(\mathrm{syst}) \pm 2.8(\mathrm{theo}) \pm 1.4(\mathrm{lumi})$ pb
  - All in good agreement with SM prediction (approx. NNLO)

arXiv:1608.03086
submitted to PLB

WW cross section @ 13 TeV

- **Measurement:**
  - Exclusive WW production cross section ($N_{jets}(p_T>25$ GeV) =0)
  - Same selection as on previous slide except for N_{jets}
  - Fiducial cross section extracted by simultaneous fit of signal region and top and Drell-Yan control regions
- Significant progress in theoretical calculations:
  - qq→ WW @ NNLO $O(\alpha_S^2)$
  - gg→ WW @ NLO $O(\alpha_S^3)$
  - qq→ H→ WW @ NNLO $O(\alpha_S^5)$

  } referred to as nNNLO+H

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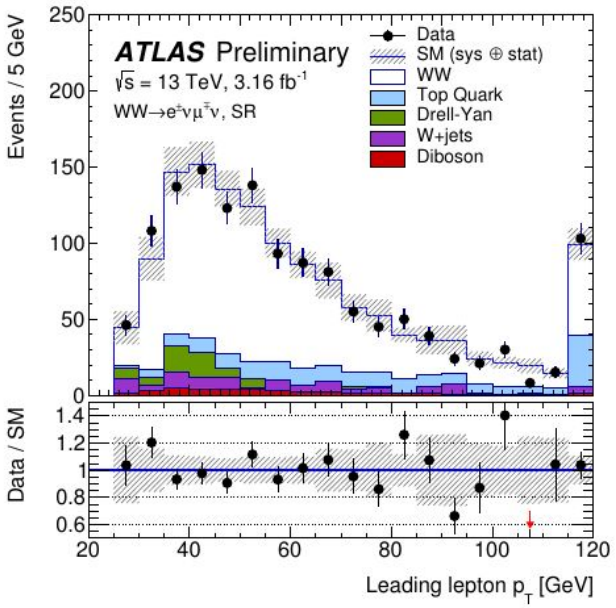
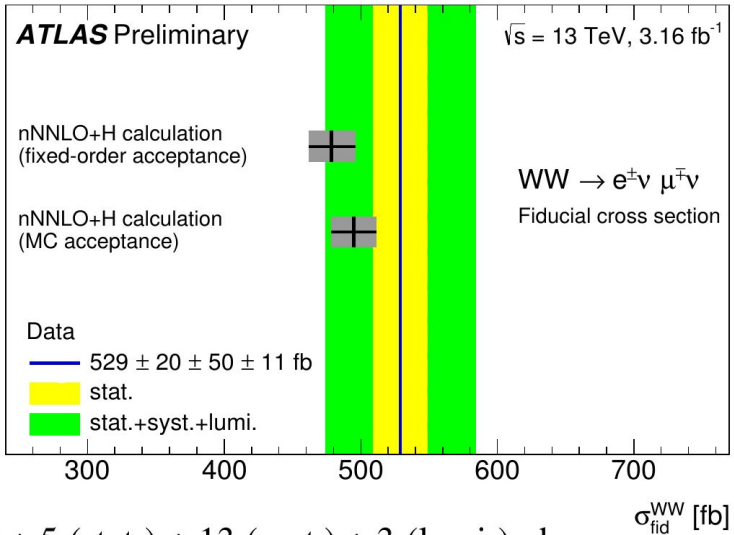


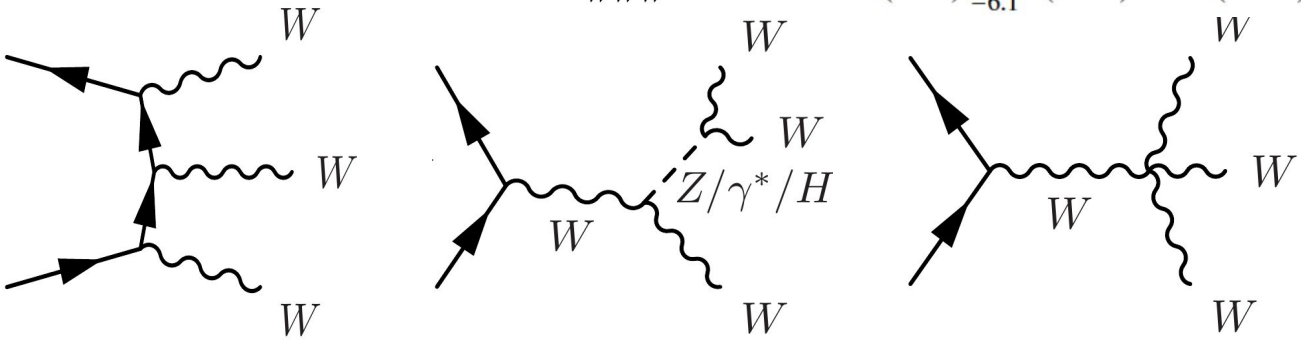
- $\sigma^{\text{fid}}_{WW\to e\mu} = 529 \pm 20\ (\text{stat.}) \pm 50\ (\text{syst.}) \pm 11\ (\text{lumi.})\ \text{fb}$
- $\sigma^{\text{theo}}_{WW\to e\mu} = 478 \pm 17\ \text{fb}$



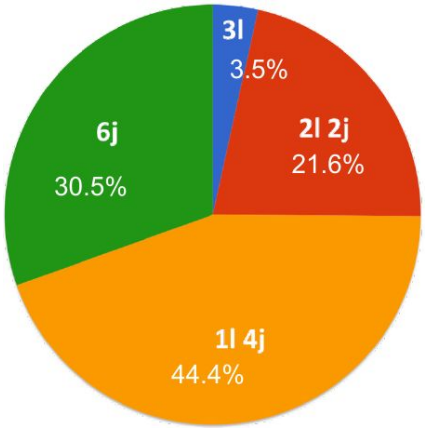
- $\sigma^{\text{tot}}_{WW} = 142 \pm 5\ (\text{stat.}) \pm 13\ (\text{syst.}) \pm 3\ (\text{lumi.})\ \text{pb}$
- $\sigma^{\text{theo}}_{WW} = 128.4^{+3.5}_{-3.8}\ \text{pb}$
- Fiducial and total cross section in agreement with theory prediction

WWW @ 8 TeV

- Never-before observed process
- $W^{\pm}W^{\pm}W^{\mp}$ production sensitive to aTGCs (WWZ/γ) and aQGCs (WWWW)
- Total expected cross section: $\sigma^{tot}_{WWW} = 241.5 \pm 0.1\ (\text{stat.})\ ^{+10.3}_{-6.1}\ (\text{PDF})\ \pm 6.3\ (\text{scale})\ \text{fb}$



- **Signal definition:**
  - **WWW→ ℓνℓνℓν:**
    - Low branching ratio but very clean
    - Events are classified by number of same-flavour opposite-sign (SFOS) leptons (0,1,2)
  - **WWW→ ℓνℓνjj:**
    - Higher branching ratio, larger background contamination
    - Classified as eejj,eμjj and μμjj

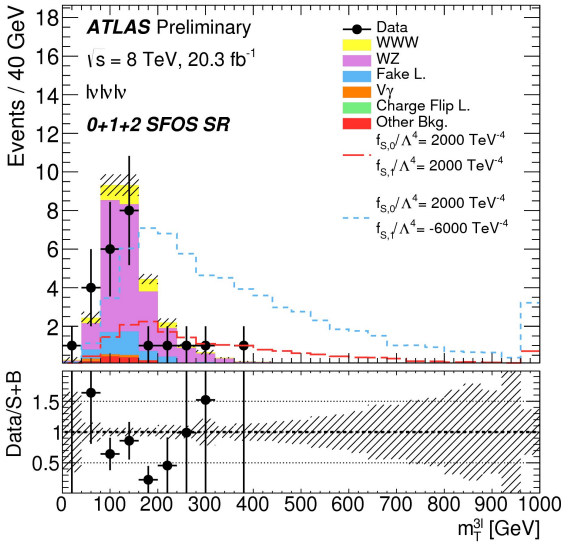


- **Main Backgrounds:**
  - WZ/γ*, Wγ+jets or Zγ+jets (MC)
  - Lepton charge misidentification (data-driven)
  - Lepton fakes from jets

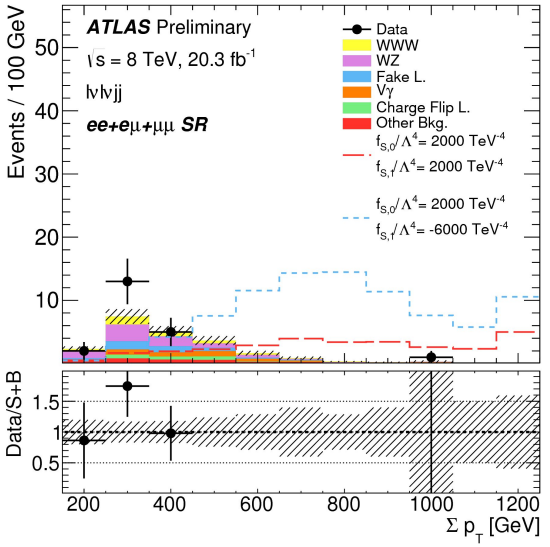
WWW @ 8 TeV

- Cut and count analysis used in the six signal regions (3 from each channel) to extract fiducial and total cross section (numbers not yet public - plots are)

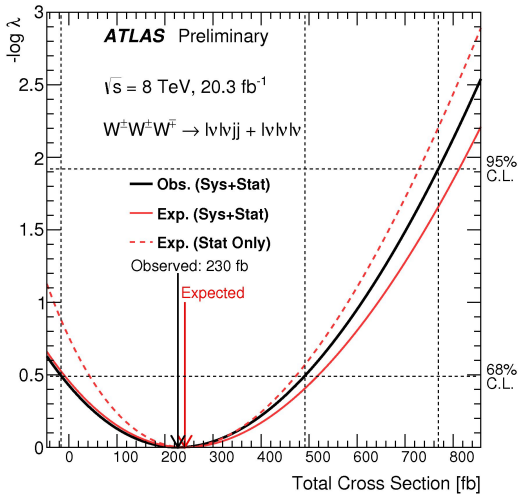
Fully leptonic:



Semileptonic:

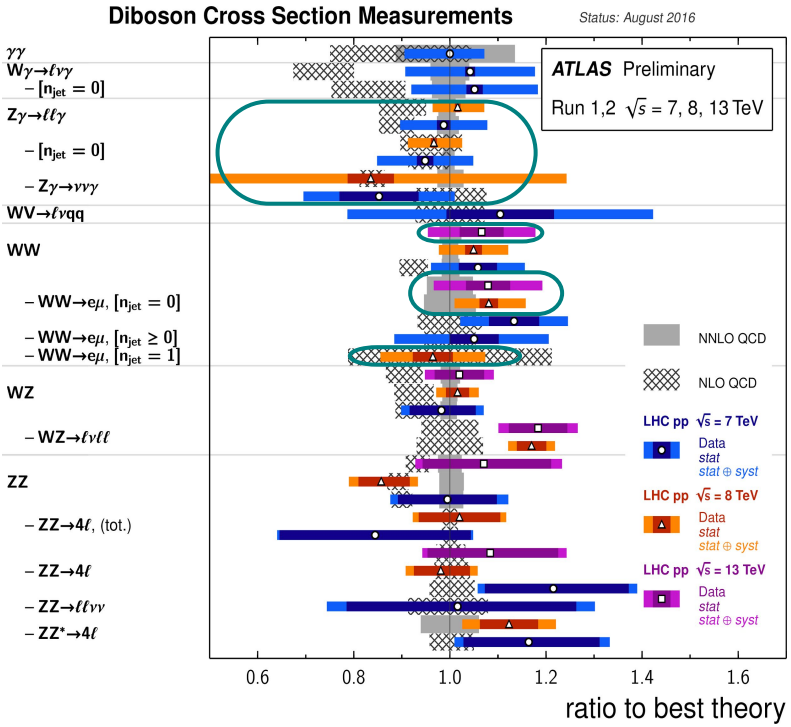


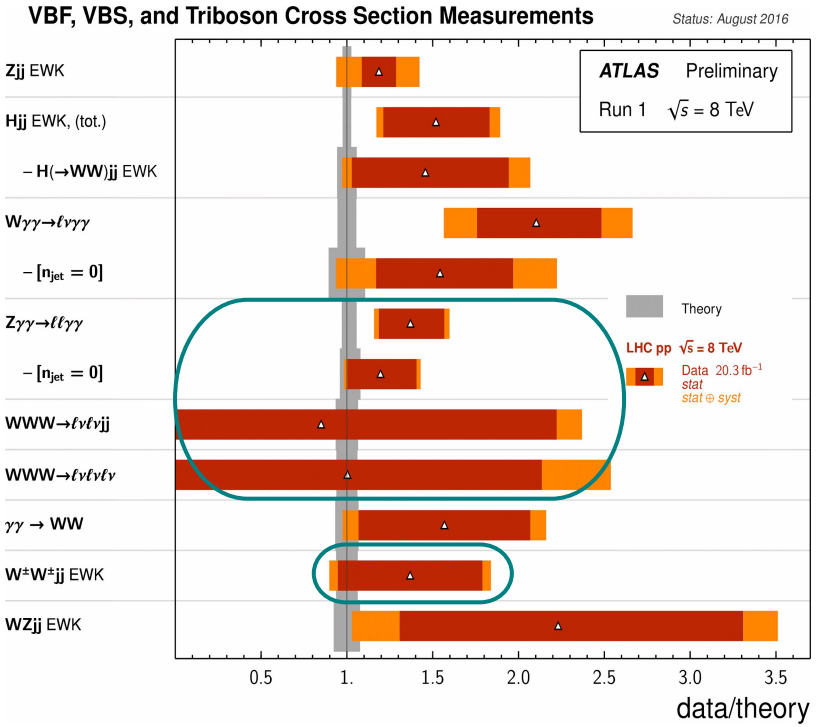
- No significant deviation from SM is observed
- Significance is low (<1σ)
- Limited by statistics



Conclusion and Outlook

- Production of two or more gauge bosons **key processes** for understanding gauge structure of SM and to investigate **anomalous gauge couplings**
- So far **no significant deviations** from SM expectations have been observed
- More and more stringent limits are placed on aTGCs and aQGCs



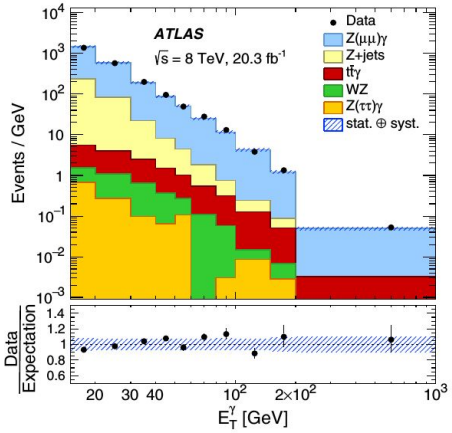


- Still expecting 8 TeV results to be finalized (e.g. VBS WV→ℓνjj+2jets , ZZ→4ℓ / 2ℓ2ν, WV→ ℓνjj resolved/boosted)
- 8 TeV analyses mostly **limited by statistics**
- At 13 TeV, already now 30 fb^{-1} of integrated luminosity are available, compared to 21 fb^{-1} recorded at 8 TeV
- **Look forward to results from Run 2**

Thank You!

Backup Slides

$Z\gamma$- and $Z\gamma\gamma$ Production



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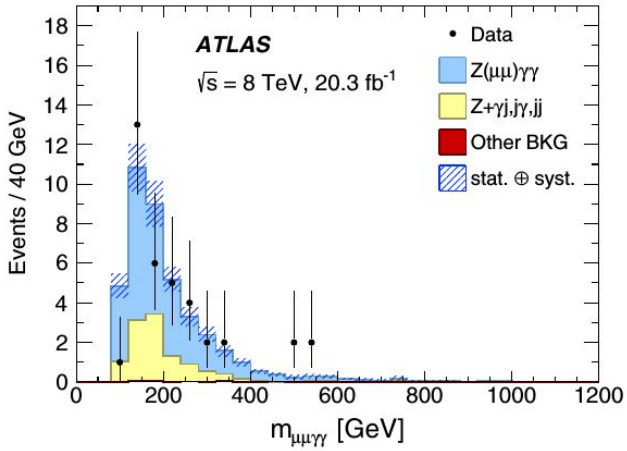

Measured and predicted cross sections:

Channel	Measurement (fb)	MCFM Prediction (fb)	NNLO Prediction (fb)
	$N_{\text{jets}} \geq 0$		
$e^+e^-\gamma$	$1510 \pm 15(\text{stat})^{+91}_{-84}(\text{syst})^{+30}_{-28}(\text{lumi})$		
$\mu^+\mu^-\gamma$	$1507 \pm 13(\text{stat})^{+78}_{-73}(\text{syst})^{+29}_{-28}(\text{lumi})$	1345^{+66}_{-82}	1483^{+19}_{-37}
$\ell^+\ell^-\gamma$	$1507 \pm 10(\text{stat})^{+78}_{-73}(\text{syst})^{+29}_{-28}(\text{lumi})$		
$\nu\bar{\nu}\gamma$	$68 \pm 4(\text{stat})^{+33}_{-32}(\text{syst}) \pm 1(\text{lumi})$	68.2 ± 2.2	$81.4^{+2.4}_{-2.2}$
	$N_{\text{jets}} = 0$		
$e^+e^-\gamma$	$1205 \pm 14(\text{stat})^{+84}_{-75}(\text{syst}) \pm 23(\text{lumi})$		
$\mu^+\mu^-\gamma$	$1188 \pm 12(\text{stat})^{+68}_{-63}(\text{syst})^{+23}_{-22}(\text{lumi})$	1191^{+71}_{-89}	1230^{+10}_{-18}
$\ell^+\ell^-\gamma$	$1189 \pm 9(\text{stat})^{+69}_{-63}(\text{syst})^{+23}_{-22}(\text{lumi})$		
$\nu\bar{\nu}\gamma$	$43 \pm 2(\text{stat}) \pm 10(\text{syst}) \pm 1(\text{lumi})$	$51.0^{+2.1}_{-2.3}$	$49.21^{+0.61}_{-0.52}$
	$N_{\text{jets}} \geq 0$		
$e^+e^-\gamma\gamma$	$6.2^{+1.2}_{-1.1}(\text{stat}) \pm 0.4(\text{syst}) \pm 0.1(\text{lumi})$		
$\mu^+\mu^-\gamma\gamma$	$3.83^{+0.95}_{-0.85}(\text{stat})^{+0.48}_{-0.47}(\text{syst}) \pm 0.07(\text{lumi})$	$3.70^{+0.21}_{-0.11}$	
$\ell^+\ell^-\gamma\gamma$	$5.07^{+0.73}_{-0.68}(\text{stat})^{+0.41}_{-0.38}(\text{syst}) \pm 0.10(\text{lumi})$		
$\nu\bar{\nu}\gamma\gamma$	$2.5^{+1.0}_{-0.9}(\text{stat}) \pm 1.1(\text{syst}) \pm 0.1(\text{lumi})$	$0.737^{+0.039}_{-0.032}$	
	$N_{\text{jets}} = 0$		
$e^+e^-\gamma\gamma$	$4.6^{+1.0}_{-0.9}(\text{stat})^{+0.4}_{-0.3}(\text{syst}) \pm 0.1(\text{lumi})$		
$\mu^+\mu^-\gamma\gamma$	$2.38^{+0.77}_{-0.67}(\text{stat})^{+0.33}_{-0.32}(\text{syst})^{+0.05}_{-0.04}(\text{lumi})$	$2.91^{+0.23}_{-0.12}$	
$\ell^+\ell^-\gamma\gamma$	$3.48^{+0.61}_{-0.56}(\text{stat})^{+0.29}_{-0.25}(\text{syst}) \pm 0.07(\text{lumi})$		
$\nu\bar{\nu}\gamma\gamma$	$1.18^{+0.52}_{-0.44}(\text{stat})^{+0.48}_{-0.49}(\text{syst}) \pm 0.02(\text{lumi})$	$0.395^{+0.049}_{-0.037}$	

$Z\gamma$- and $Z\gamma\gamma$ Production - Cross Sections

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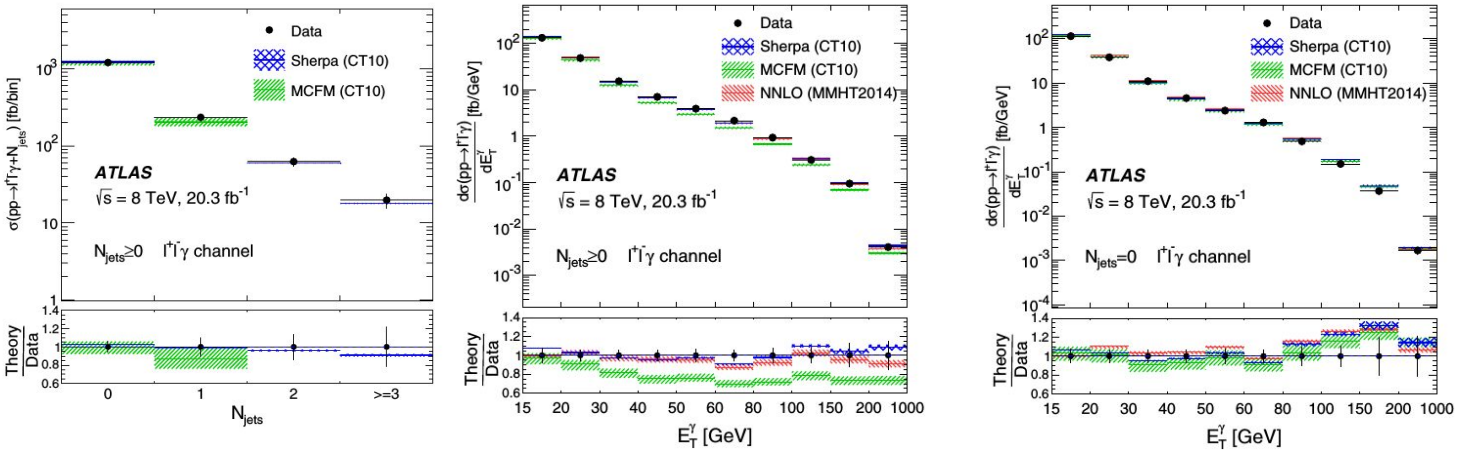
- Differential cross sections depending on E_T^{γ} and on N_{jets} measured for $Z\gamma$



- Good description obtained by high order Monte Carlo, effects of NNLO clearly visible

WWW @ 8 TeV

- Limits on aQCD parameters f_{S0}/Λ^4 and f_{S1}/Λ^4 are set