Electroweak Physics (di-boson production) measurements with ATLAS

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On behalf of the ATLAS Collaboration

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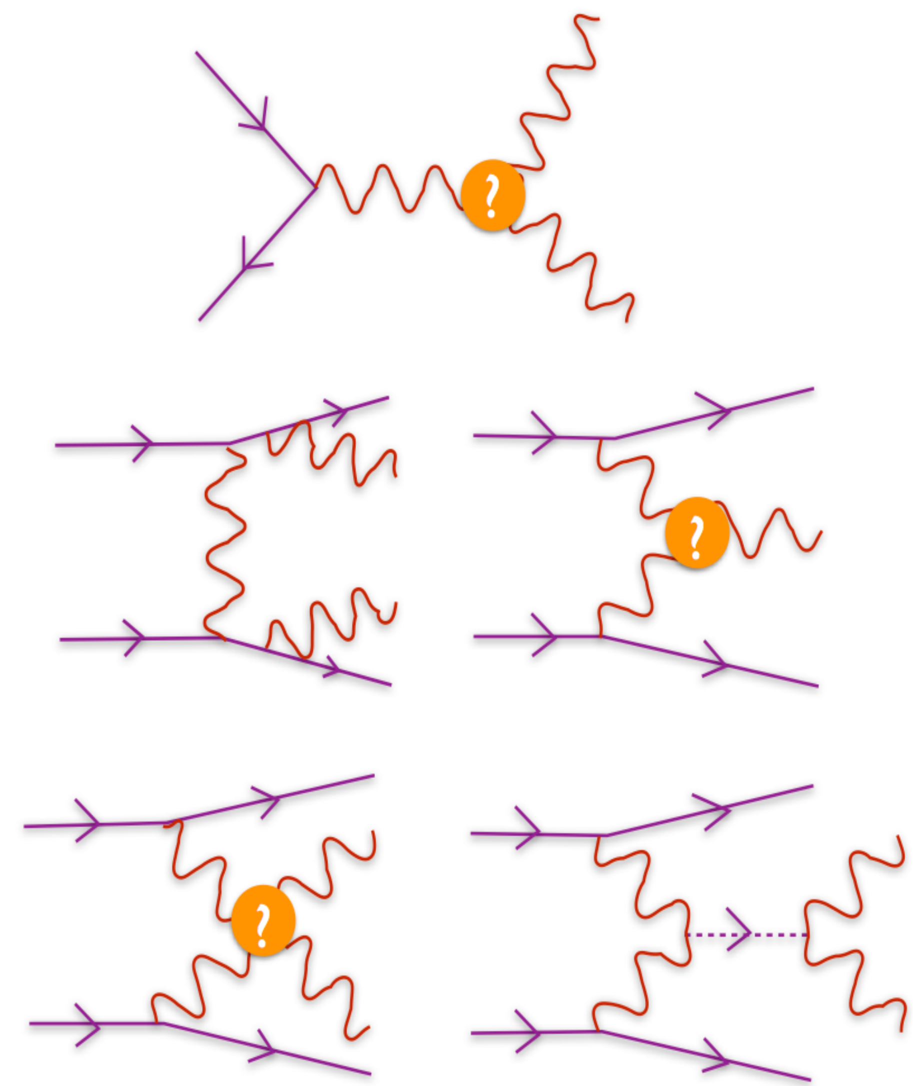
Di-boson physics overview

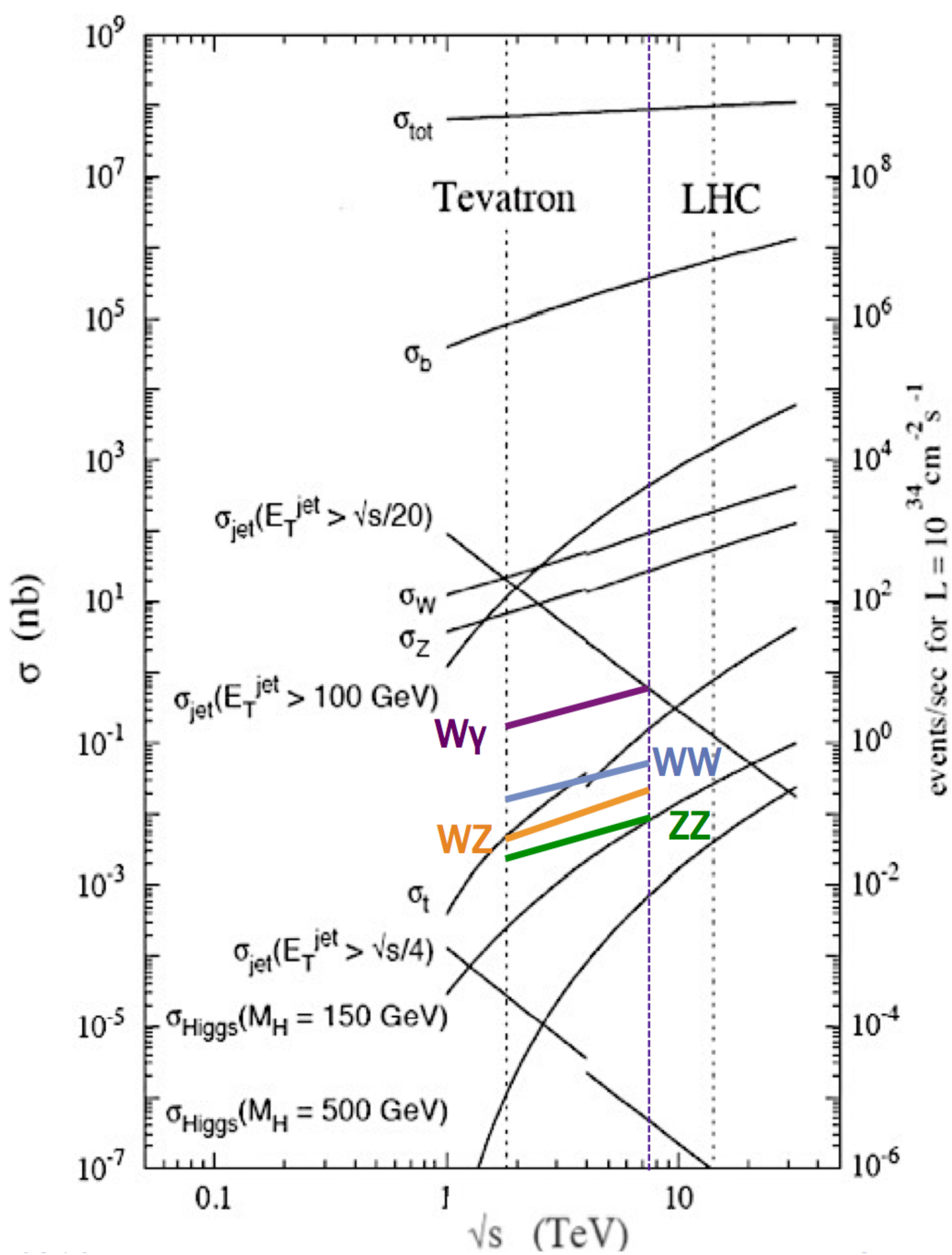
- **Diboson production cross-section measurements**
  - High energy test of Standard Model (SM) predictions at TeV scale
  - Irreducible background to Higgs
  - Sensitivity to new heavy particles decaying to diboson
- **Anomalous Triple/Quartic Gauge Couplings (aTGCs,aQGCs)**
  - Vector boson self-couplings fundamental prediction of the Electroweak Sector of the SM
  - Probe to new physics through deviations of measured cross sections from predictions



QCD and V+jets measurements: see Kristof Schmieden's talk!

Di-boson production at the LHC

- **Measurement of di-boson processes involving combinations of W, Z and ɣ**
  - $W^{\pm}W^{\mp}$, WZ, ZZ, W/Zɣ , $W^{\pm}W^{\pm}$
- **Measured mainly through their leptonic final states**
  - Advantage: relatively low backgrounds
  - Disadvantage: low Branching Ratios
    - *BR(W→lν) = 0.108, BR (Z→ll) = 0.03366*
- **Small cross sections O(1-100pb)**
- **Gluon contribution up to ~10% depending on the channel**



Common signatures and backgrounds

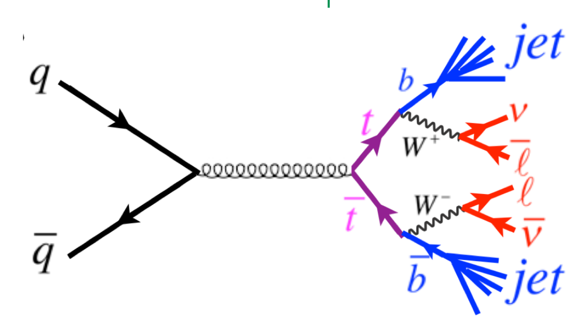
Signatures

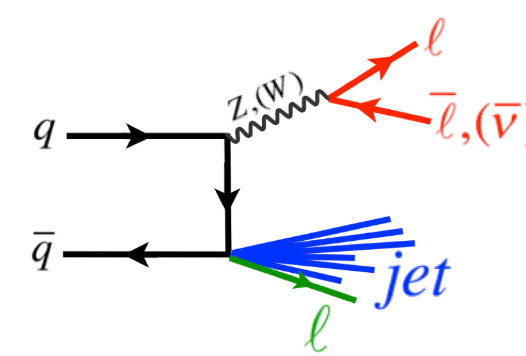
- **Leptons/photons**
  - High-p_T, isolated, electrons/ muons and/or photons
- **Z Bosons**
  - Invariant mass in windows around the Z pole
- **W Bosons**
  - Large Missing E_T to account for the neutrino
    - *Calculated from jets, leptons and calorimetric clusters*
  - Transverse mass selection

Background

Estimated with data driven methods

- **V+jets**
  - Genuine high-pt leptons from boson decay
  - Leptons from heavy flavour decays
  - Jets misidentified as leptons/photons
  - Particles outside the detector acceptance → Missing E_T





- **tt(bar) and single top**
  - Prompt isolated leptons from W leptons
  - Large Missing ET

- **Di-boson processes**
  - Act as background for each other

Estimated from MC

Cross section measurements strategy

- **"Cut and count" analysis yields observed events**
- **Background estimation from Data or/and MC**
- **Measurement of fiducial cross section**
  - Defined as the phase space of the detector's acceptance + our selection requirements
  - Minimizes the extrapolation to unmeasured regions, more model independent

$$\sigma_{fid} = \frac{N_{data} - N_{bkg}}{C \cdot \int L dt}$$

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

$$\sigma_{tot} = \frac{N_{data} - N_{bkg}}{A \cdot C \cdot BR \cdot \int L dt}$$

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

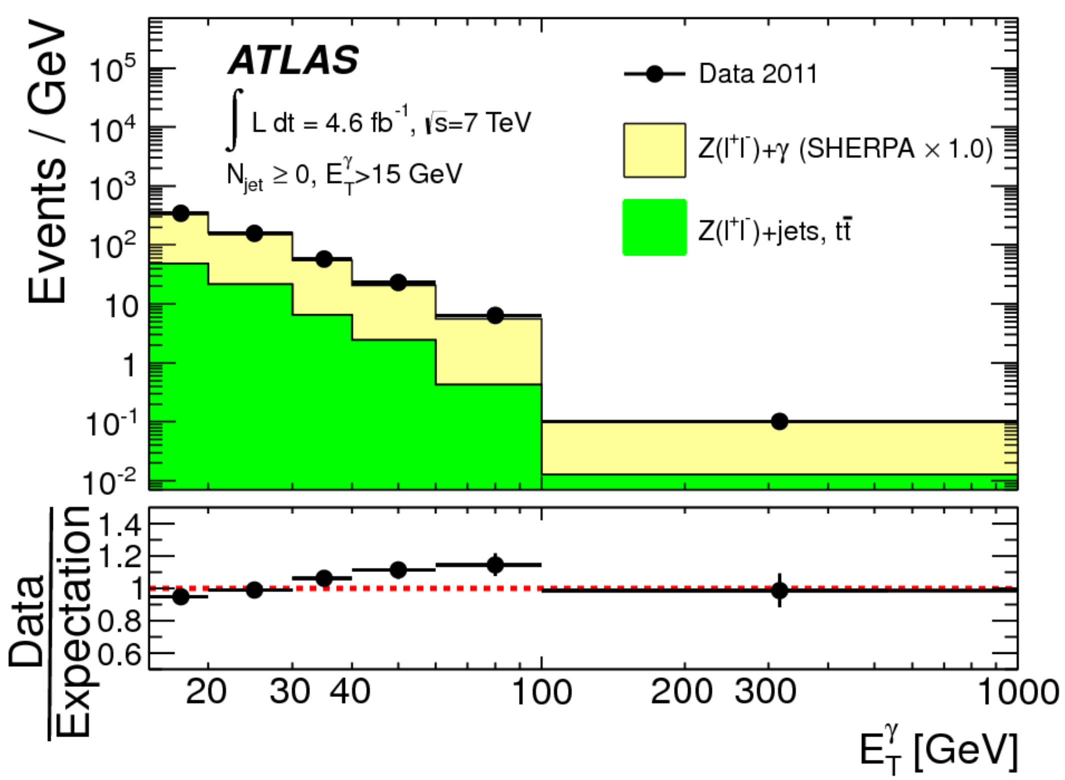
- **Extrapolate measurement to total phase space**
- **Optionally provide differential cross sections in fiducial volume**
  - Distributions "unfolded" from detector effects

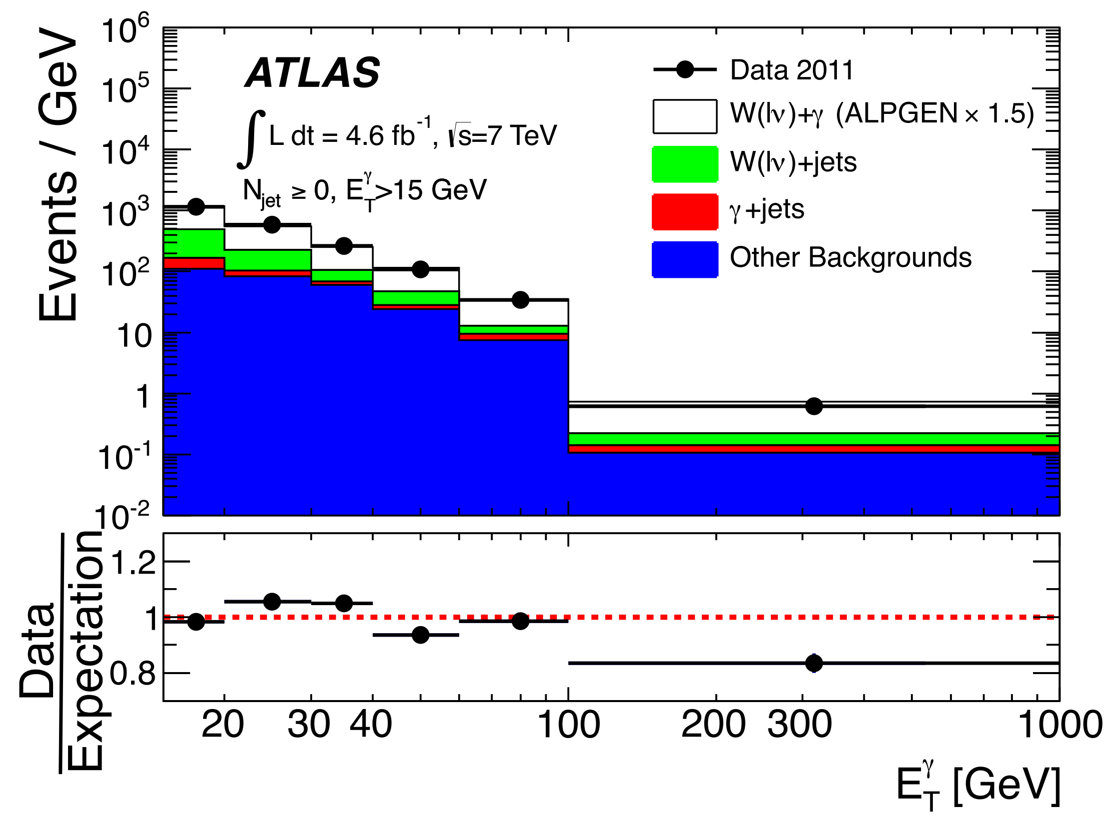
Phys. Rev. D 87,112003

Wɣ, Zɣ production (I)

- **Final states measured:**
  - $\ell^{\pm}\nu\gamma$, $\ell^{\pm}\ell^{\mp}\gamma$, $\nu\nu\gamma$
- **Backgrounds:**
  - W/Z + jets (dominant for leptonic channels), ɣ+jet , W→eν (dominant in ννɣ channel)
- **Systematic uncertainties dominate**
  - Photon ID, background normalization, jet energy scale

Selection Highlights
Require an isolated high-ET photon and isolated high-pT lepton(s), and/or MissingET
Suppress FSR cutting on angular separation of lepton and photon ΔR > 0.7
Exclusive measurement vetoes jets with pT > 30 GeV

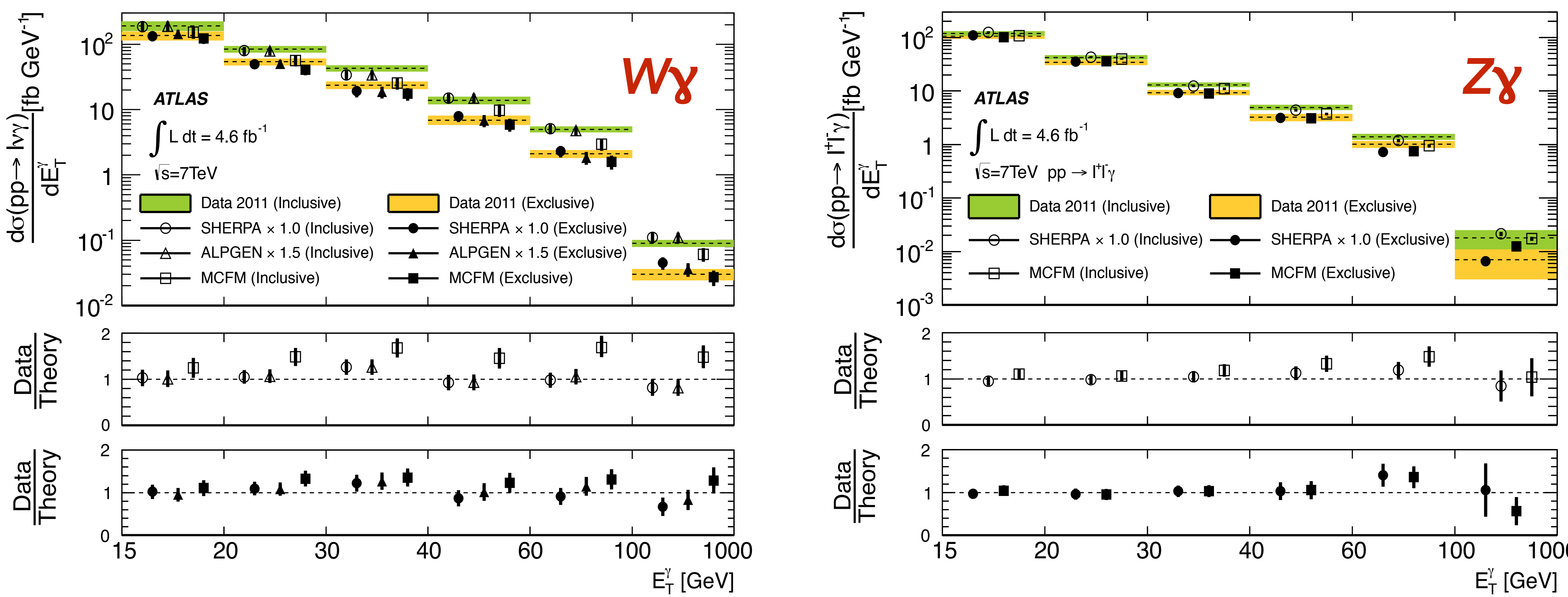




Wɣ, Zɣ production (II)

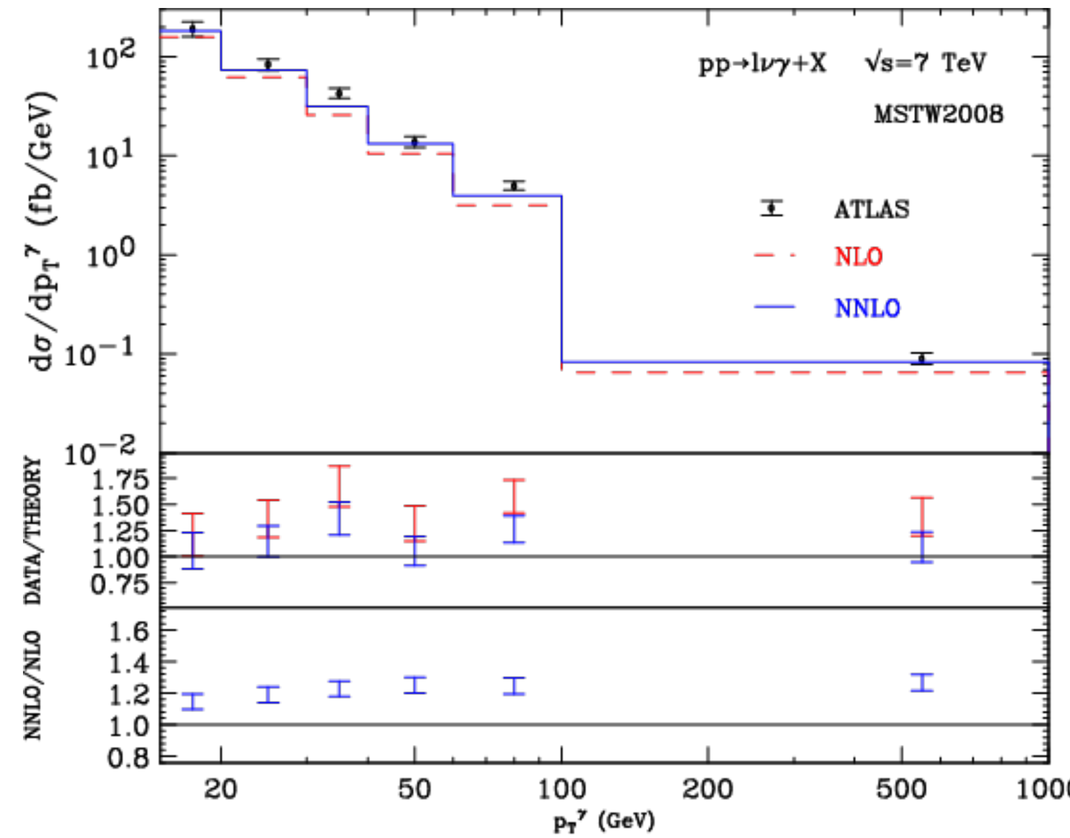
- **Inclusive Wɣ measurement above NLO theoretical prediction (MCFM) by 1-2 σ**
  - Discrepancy worst at high transverse Eɣ and jet multiplicity
    - *Missing higher order QCD corrections*
- **Fair agreement for Zɣ**
- **Interesting how these 7 TeV results compare to new NNLO calculations! (next slide)**

Channel	Measurement (pb)	Theory (pb)
Wɣ→ℓνɣ	2.77 ±0.03(stat.) ±0.33 (syst.) ±0.14(lumi.)	1.96 ± 0.17
Zɣ→ℓℓɣ	1.31 ±0.02(stat.) ±0.11(syst.) ±0.05(lumi.)	1.18 ±0.05
Zɣ→ννɣ	0.133 ±0.013(stat.) ±0.02(syst.) ±0.005(lumi.)	0.156±0.012



Wɣ, Zɣ production (III)

- **NNLO QCD corrections have sizeable effect**
  - Corrections are higher for Wɣ than Zɣ
    - *Wɣ : arXiv:1407.1618v1 [hep-ph]*
    - *Zɣ : Phys. Lett. B731 (2014) 204*
- **Better agreement with measurement now**

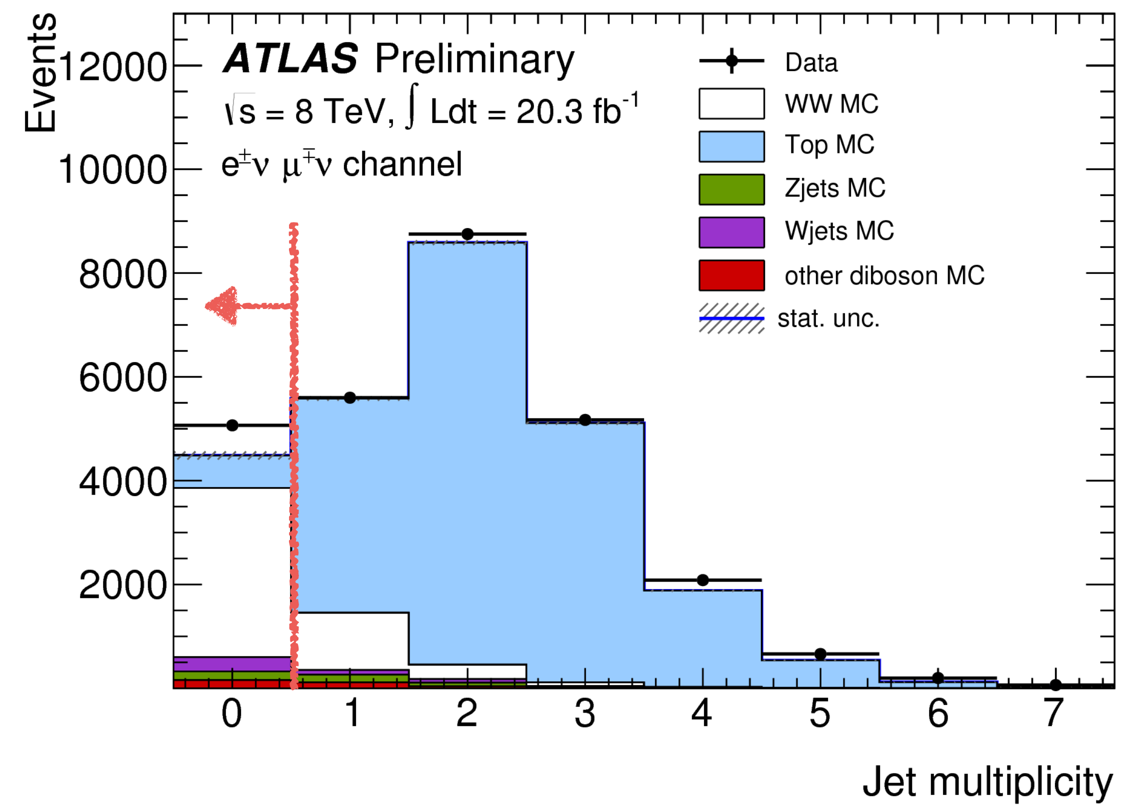


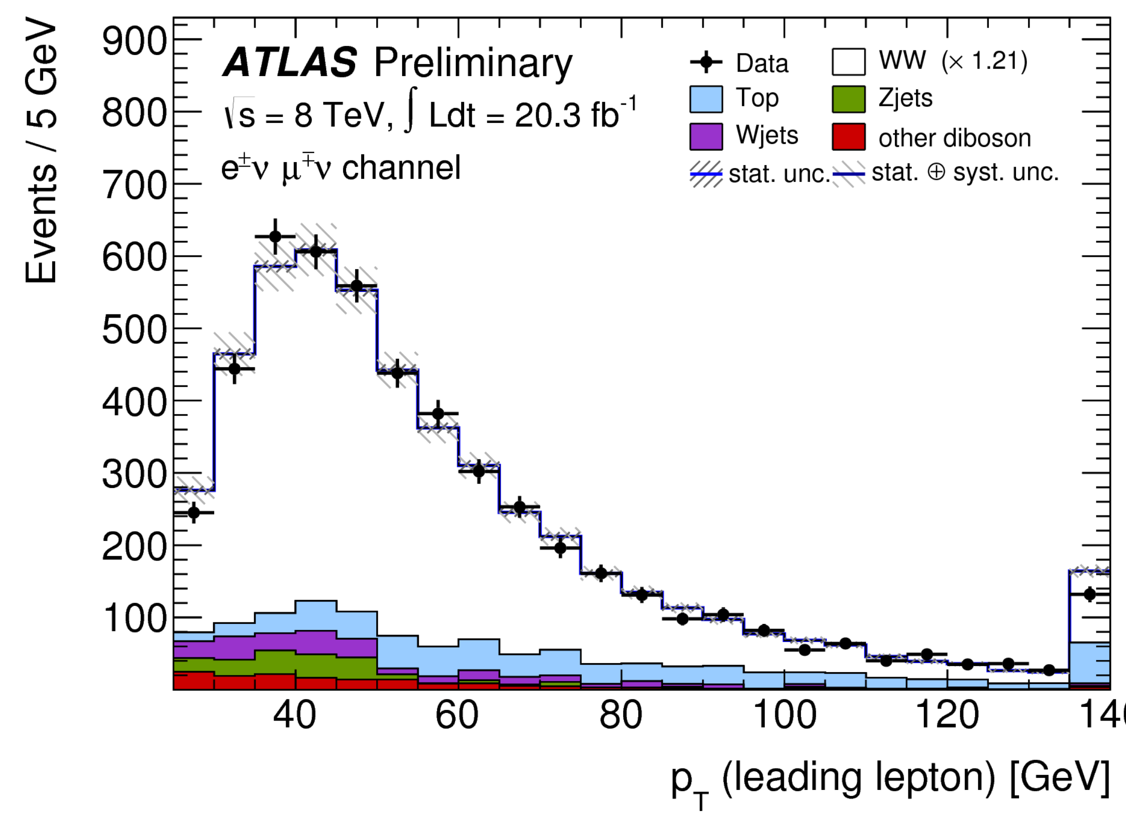
	LO (fb)	NLO (fb)	NNLO (fb)	Measurement (fb)
$\sigma_{Z\gamma\to\ell\ell\gamma}$	850.7 ± 0.2	1226.2 ± 0.4	1305 ± 3	1310 ± 20 (stat) ± 110 (syst) ± 50 (lumi)
$\sigma_{W\gamma\to\ell\nu\gamma}$	906.3 ± 0.3	2065.2 ± 0.9	2456 ± 6	2770 ± 30(stat) ± 330(syst) ± 140(lumi)

$W^{\pm}W^{\mp}$ production (I)

- **Final states measured:**
  - $\ell^{\pm}\nu\ell^{\mp}\nu$ (ℓ=e,μ) in 0-jet bin
- **Backgrounds:**
  - Top (15%), Drell-Yan (5%), W+jets (5%) and other dibosons
- **Measurement is dominated by systematic uncertainties**
  - ETmiss (2-4%)
  - Jet energy scale 2%
  - Jet veto requirement 4-5%
  - Background uncertainty 3-6%

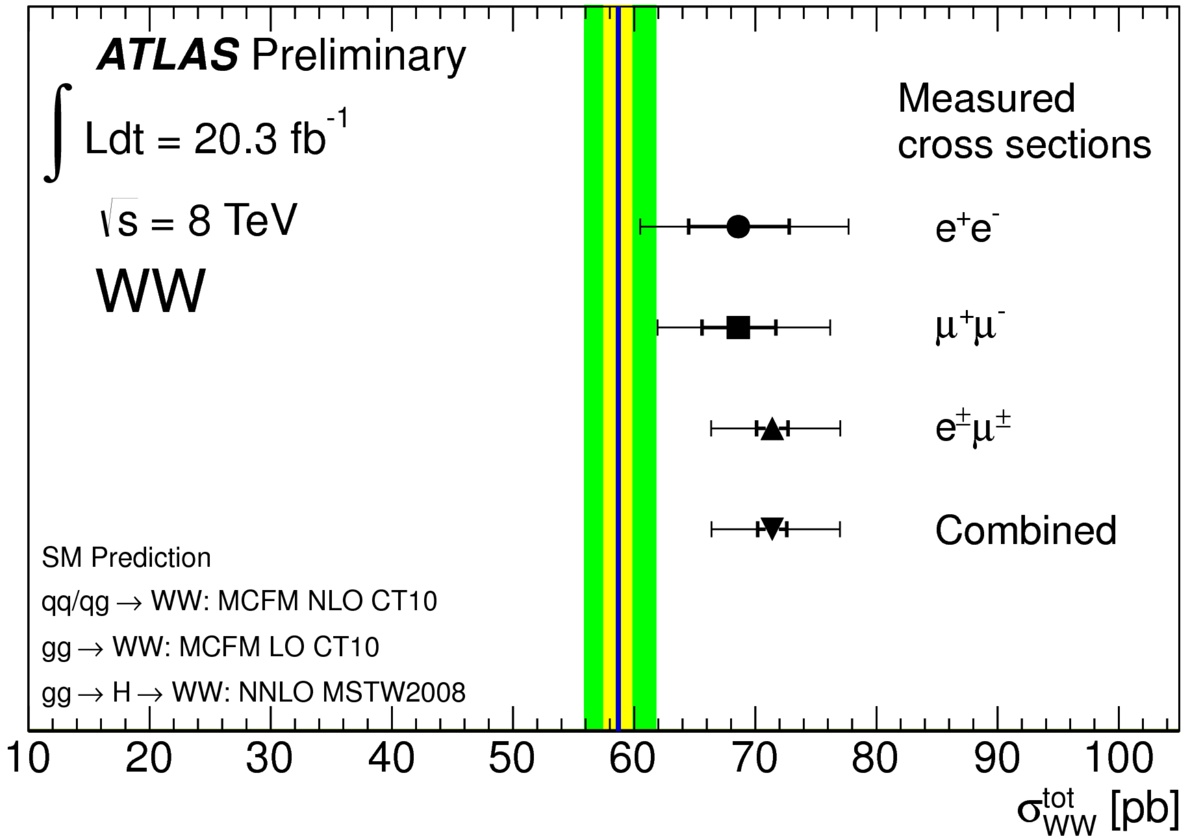
Selection Highlights
2 isolated high-pT leptons and MissingET
Hard jet veto to reject $t\bar{t}$ and single-top events
Z veto (|mZ −mll| >15 GeV) to suppress Drell-Yan background in same flavour channels

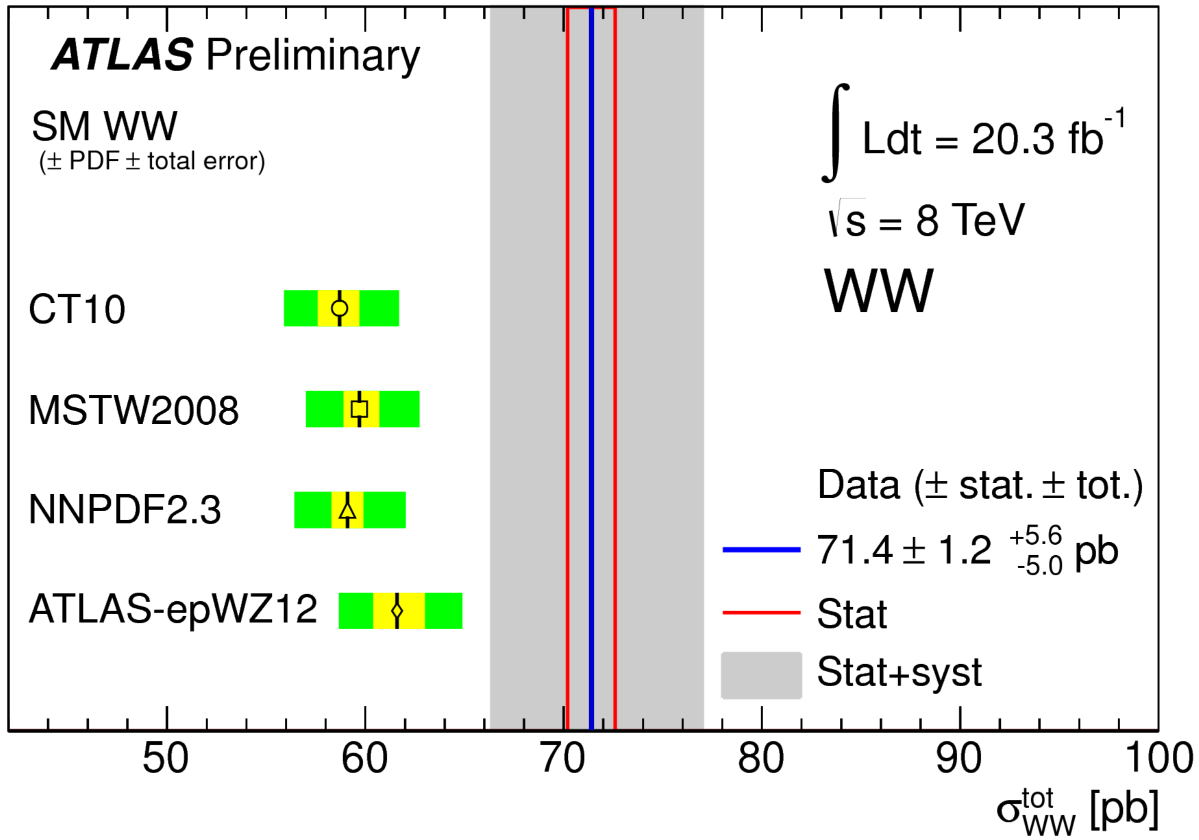




More details in Jun Gao's talk

$W^{\pm}W^{\mp}$ production (II)





- **Measured cross section higher than SM prediction by ~2.1σ**
- **NNLO corrections: Enhancement of cross-section by ~10%** *(arXiv:1408.5243)*
- **Resummation of large logs: Enhancement of cross-section can partially explain the excess** *(arXiv:1407.4537, arXiv:1407.4481)*

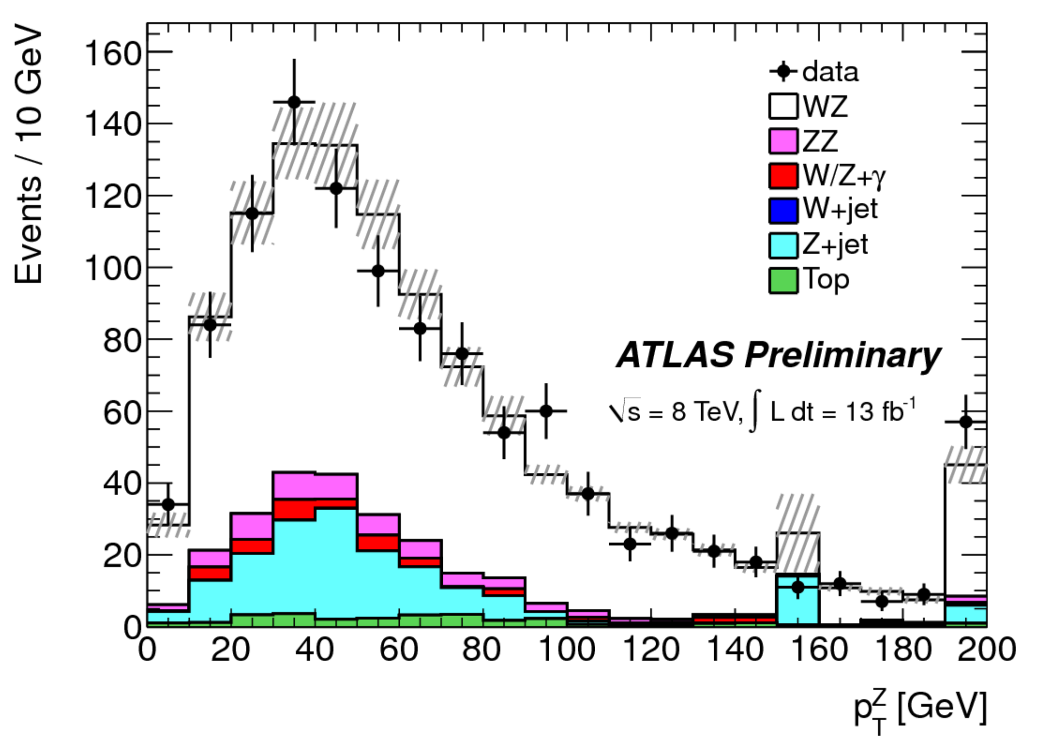
√s	∫ℒdt [fb⁻¹]	Measurement [pb]	Theory [pb]
7 TeV	4.6	51.9 ± 2.0(stat.) ± 3.9(syst.) ± 2.0(lumi)	44.7
8 TeV	20.3	$71.4 \pm 1.2(\text{stat.})^{+5.0}_{-4.4}(\text{syst.})^{+2.2}_{-2.1}(\text{lumi})$	58.7

Including Higgs

$W^{\pm}Z$ production (I)

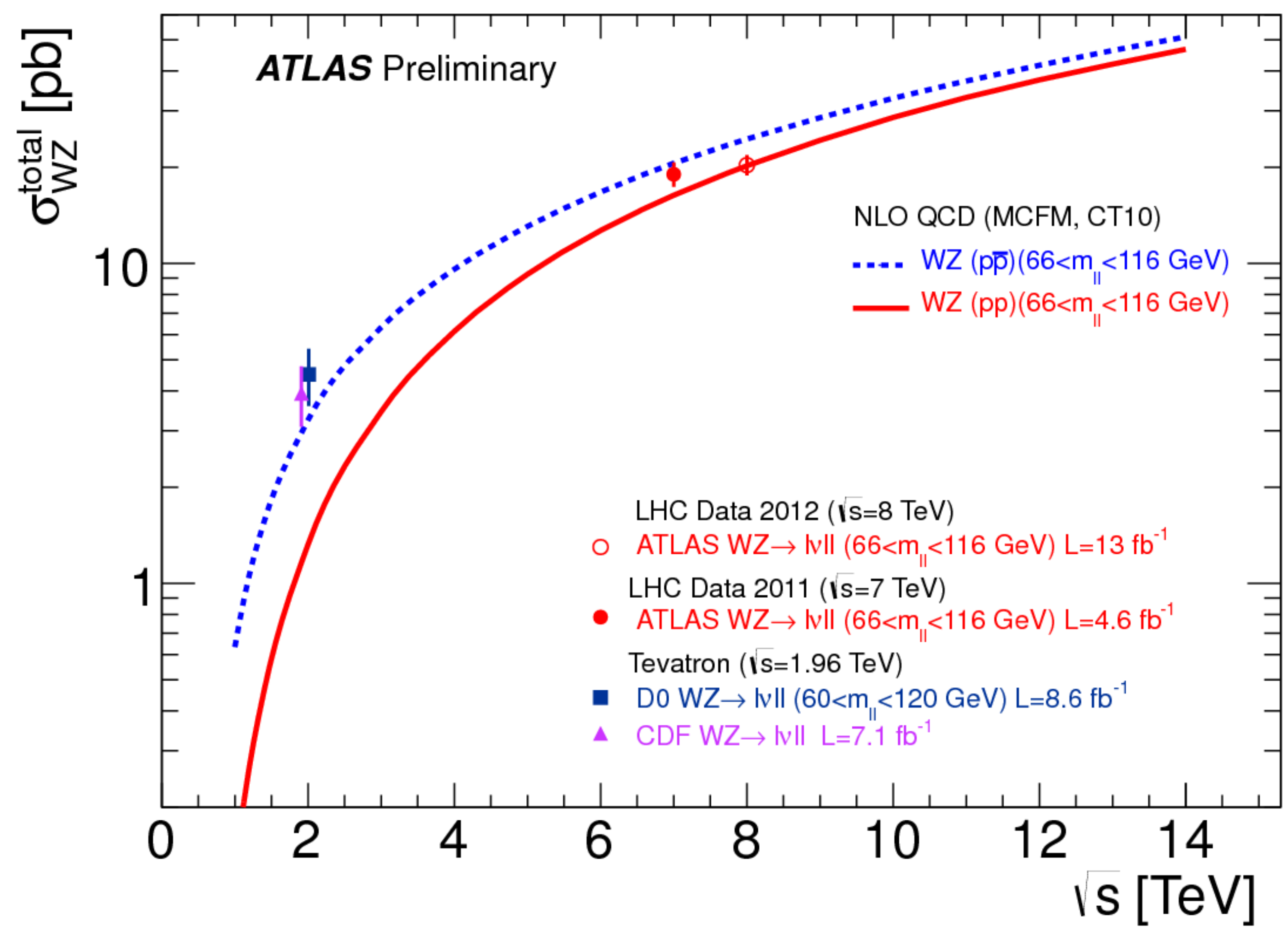
- **Final states measured: $\ell^{\pm}\nu\ell^{\pm}\ell^{\mp}$ (ℓ=e,μ)**
- **Backgrounds:**
  - Z+jets (~15%), ZZ (~5%),Top (~4%),W/Z+γ (~3%)
  - Z+jets, and Top backgrounds estimated with data driven methods
  - ZZ and W/Z γ estimated from MC

Selection Highlights
3 isolated high-pT leptons and MissingET > 25 GeV
Tight Z mass window requirement $\|M_{ll} - M_{PDG}\| < 10GeV$
Tight isolation and ID criteria on the W-lepton



W±Z production (II)

- **Measurement at 8 TeV dominated by systematic uncertainties**
  - Systematic from data driven background estimation is the prominent one
- **Preliminary results compatible with SM expectation (from MCFM)**



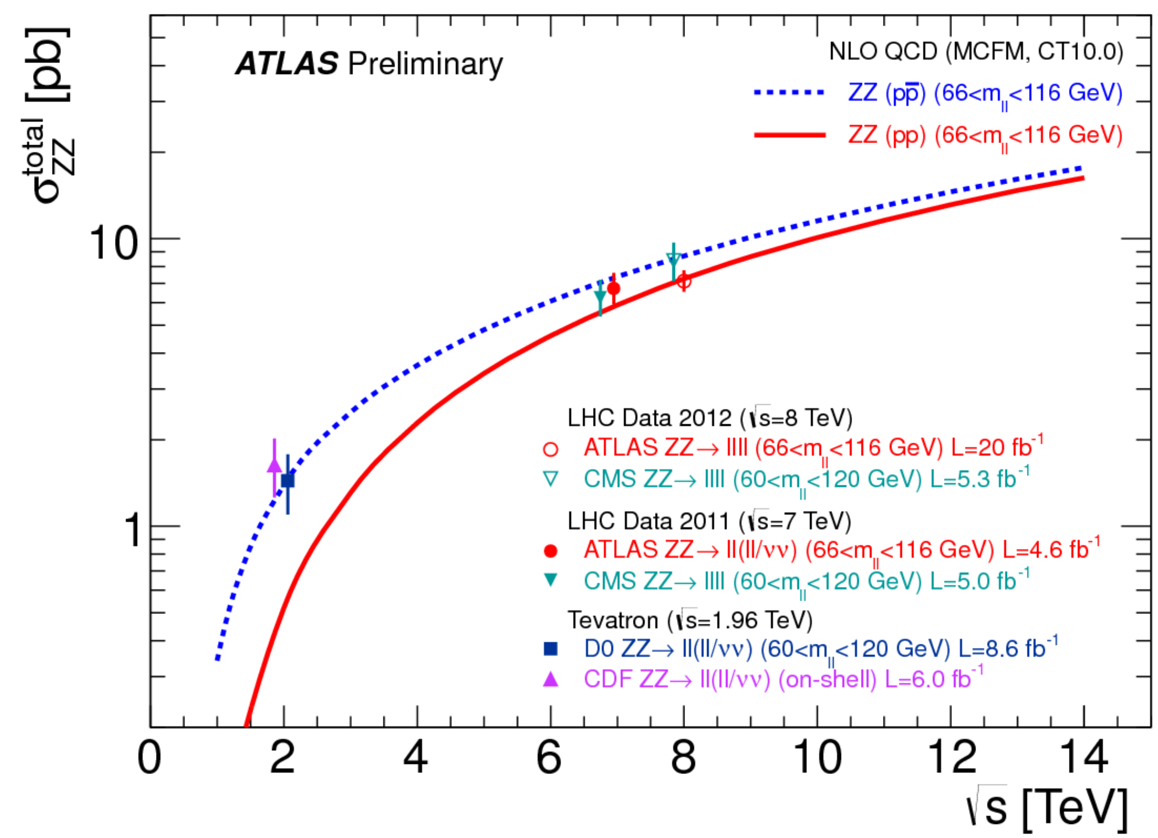
$\sqrt{s}$	$\int\mathcal{L}dt$ [fb^{-1}]	Measurement [pb]	Theory [pb]
7 TeV	4.6	$19.0^{+1.4}_{-1.3}$(stat.)$^{+0.9}_{-0.9}$(syst.)$^{+0.4}_{-0.4}$(lumi)	$17.6^{+1.1}_{-1.0}$
8 TeV	13	$20.3^{+0.8}_{-0.7}$(stat.)$^{+1.2}_{-1.1}$(syst.)$^{+0.7}_{-0.6}$(lumi)	20.3±0.8

ZZ production

- **Final states measured:**
  - ℓ±ℓ∓ℓ±ℓ∓ (ℓ=e,μ) and ℓ±ℓ∓νν (7 TeV only)
- **Main backgrounds (significant mainly for ℓ±ℓ∓νν)**
  - W/Z+jets, Top, WW, WZ
  - Estimated with data-driven methods

Selection Highlights
4 isolated high-pT leptons
Enhanced muon acceptance |η| < 2.7
(2ℓ2ν): Require axial-ETmiss > 80 GeV to suppress Drell-Yan background

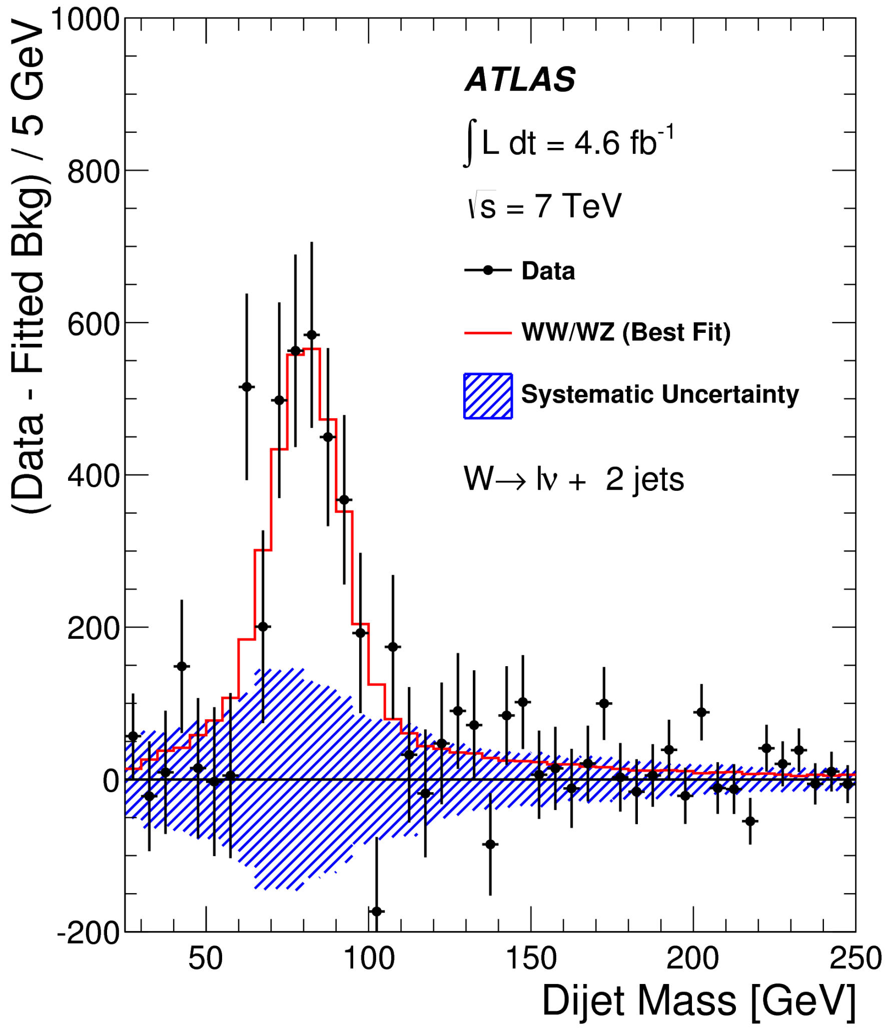
- **Measurement is dominated by statistical uncertainties**
  - Systematic dominated by lepton identification and resolution
- **Results compatible with SM predictions**



√s	∫ℒdt [fb⁻¹]	Measurement [pb]	Theory [pb]
7 TeV	4.6	$6.7^{+0.7}_{-0.7}$(stat.)$^{+0.4}_{-0.3}$(syst.)$^{+0.3}_{-0.3}$(lumi)	$5.89^{+0.22}_{-0.18}$
8 TeV	20.3	$7.1^{+0.5}_{-0.4}$(stat.)$^{+0.3}_{-0.3}$(syst.)$^{+0.2}_{-0.2}$(lumi)	$7.2^{+0.3}_{-0.2}$

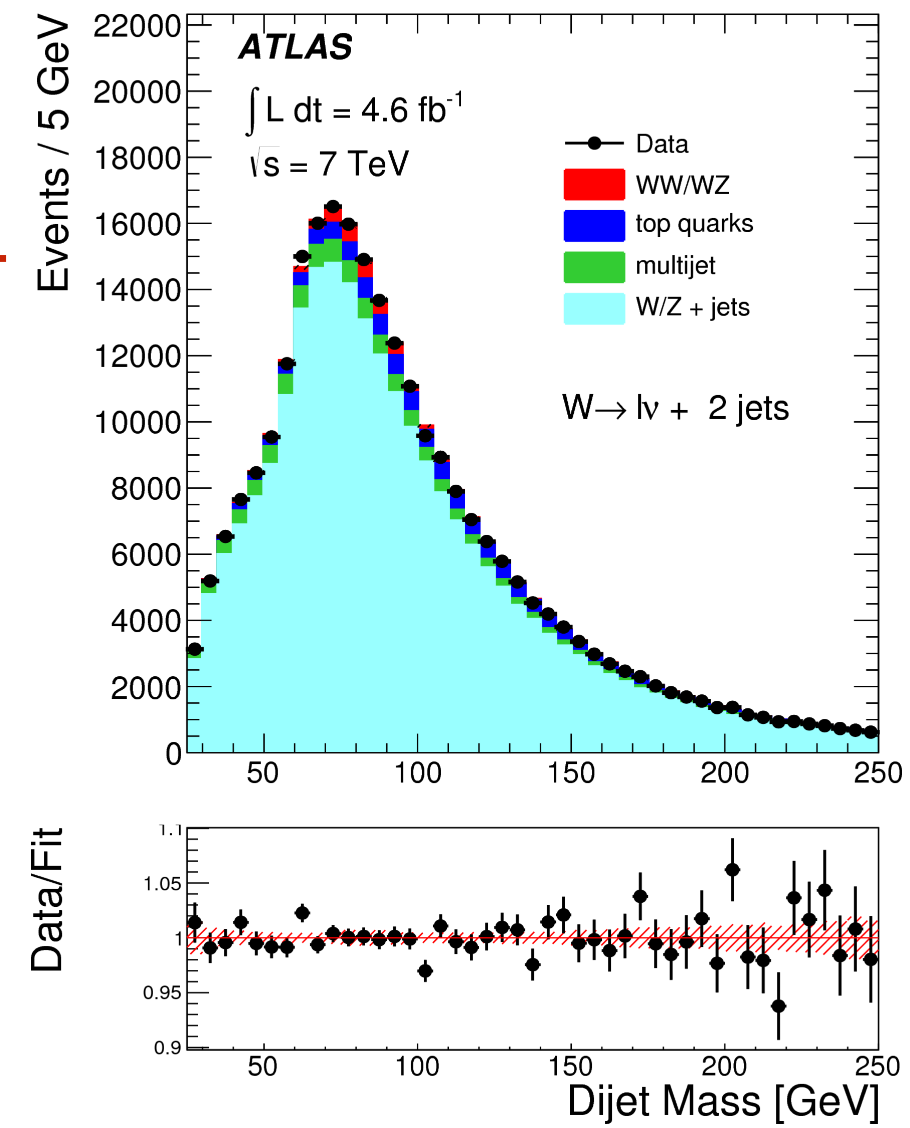
JHEP01(2015)049

$W^{\pm}W^{\mp}/W^{\pm}Z$ production in semi-leptonic final state



√s	∫ℒdt [fb⁻¹]	Measurement σ_{tot} [pb]	Theory [pb]
7 TeV	4.6	68 ± 7(stat.) ± 19(syst.)	61.1 ± 2.2

observed significance is 3.4σ



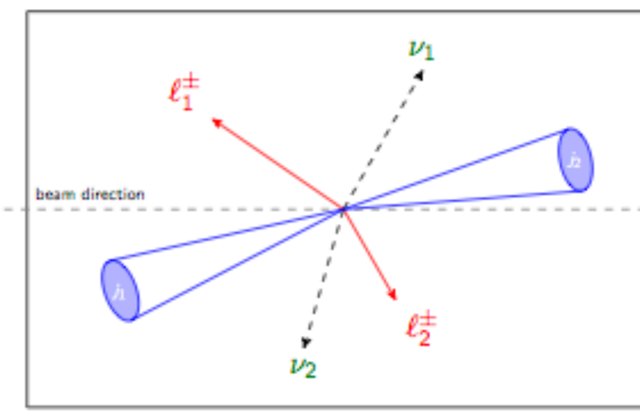
- **Final states : WW/WZ→ℓν jj (ℓ=e, μ)**
- **Main Backgrounds**
  - W/Z + jets (~89%), Multijet (~5%), top (~4%)
  - W/Z+jets and multijet estimated using data driven methods
  - Top and diboson using MC
- **Combined WW +WZ signal yield extracted from a fit to mjj distribution**

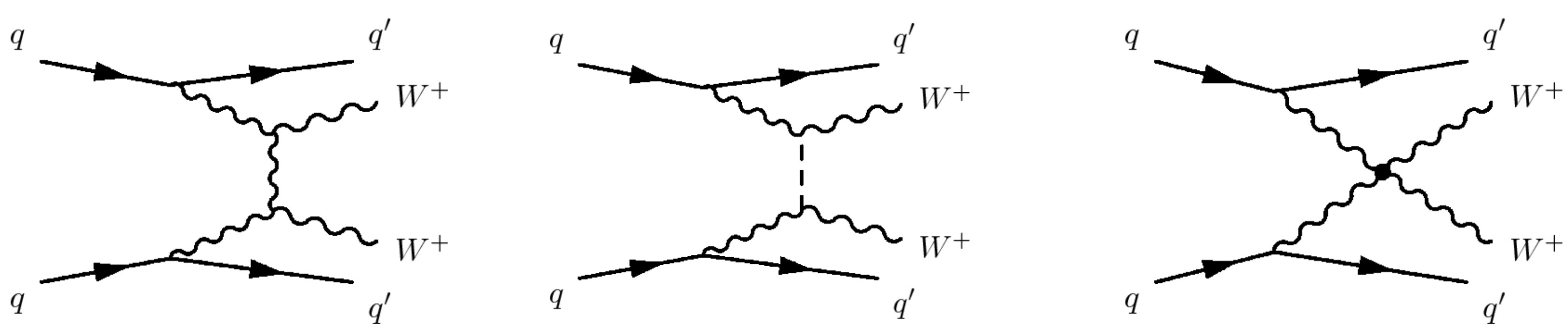
PRL 113, 141803 (2014)

W±W±+2jets production (I)

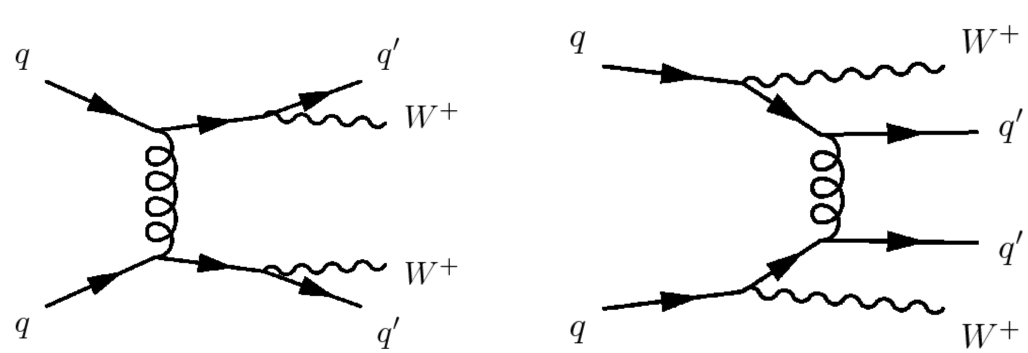
- **Same charge WWjj scattering (VBS) is a key process to experimentally probe the SM nature of EWSB**
- **WWjj production process classification**
  - Pure EWK WWjj production (VBS contribution)
  - Strong + Ewk WWjj production (inclusive)
- **W±W± has the best ratio of σ(VVjj-Ewk)/σ(VVjj-strong)**

Characteristic signature
2 forward jets with high dijet mass
Jets well separated in rapidity





WWjj-Ewk

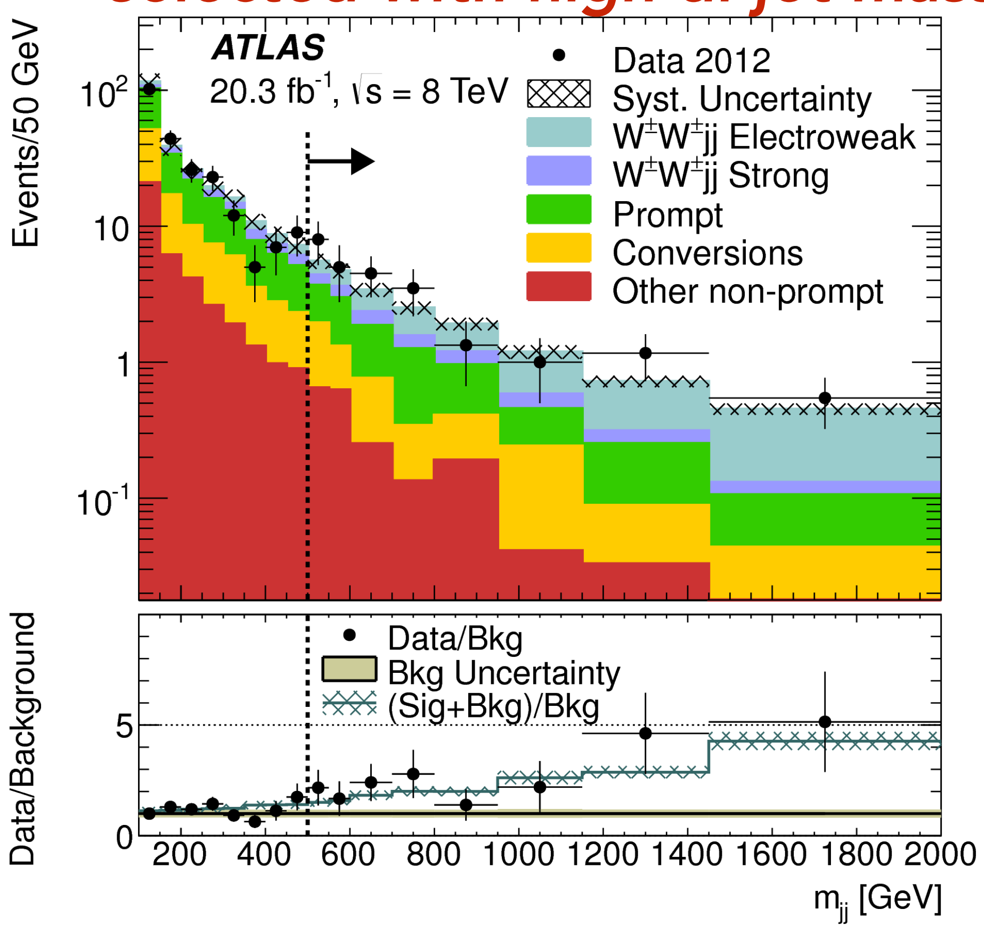


WWjj-strong

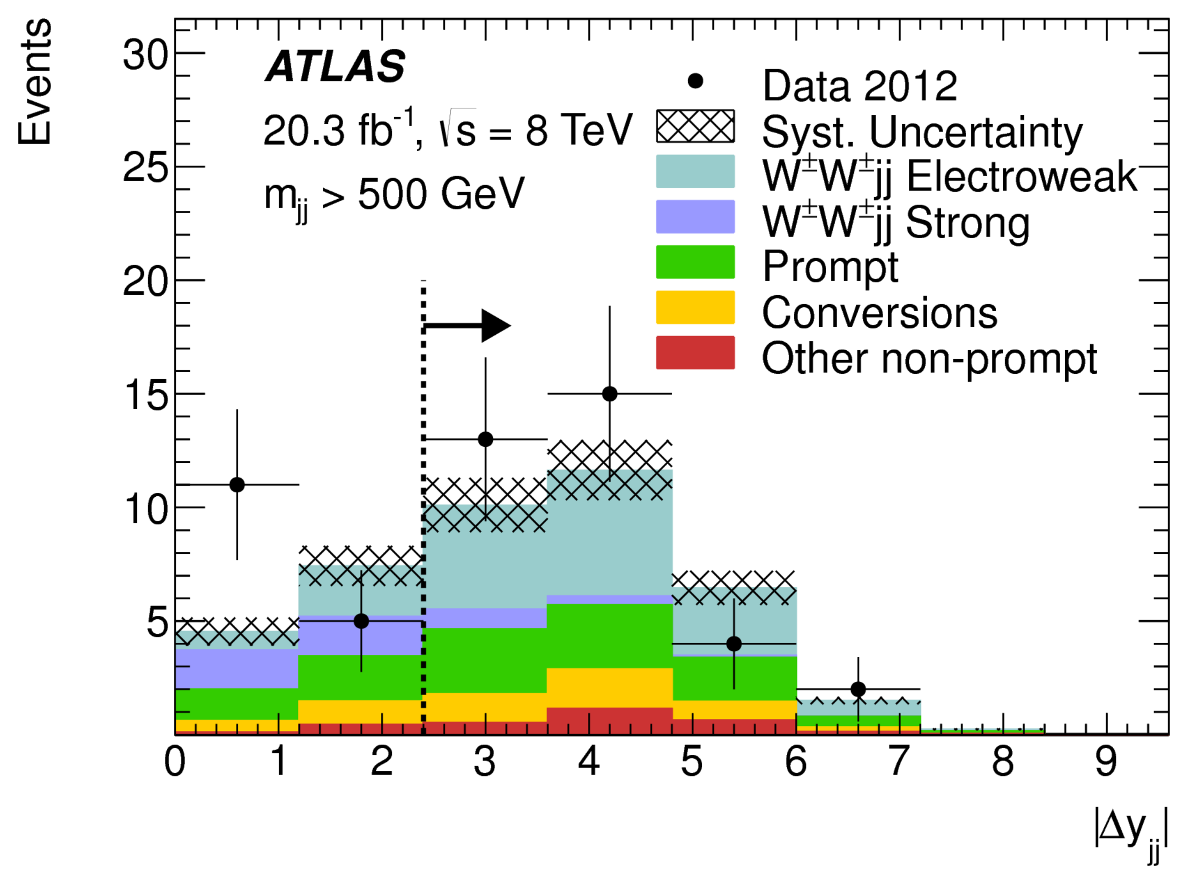
$W^{\pm}W^{\pm}$+2jets production (II)

- **Final states: ℓ±νℓ±ν + jj (ℓ=e,μ)**
- **Main backgrounds:**
  - WZ+2jets , Wɣ+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**

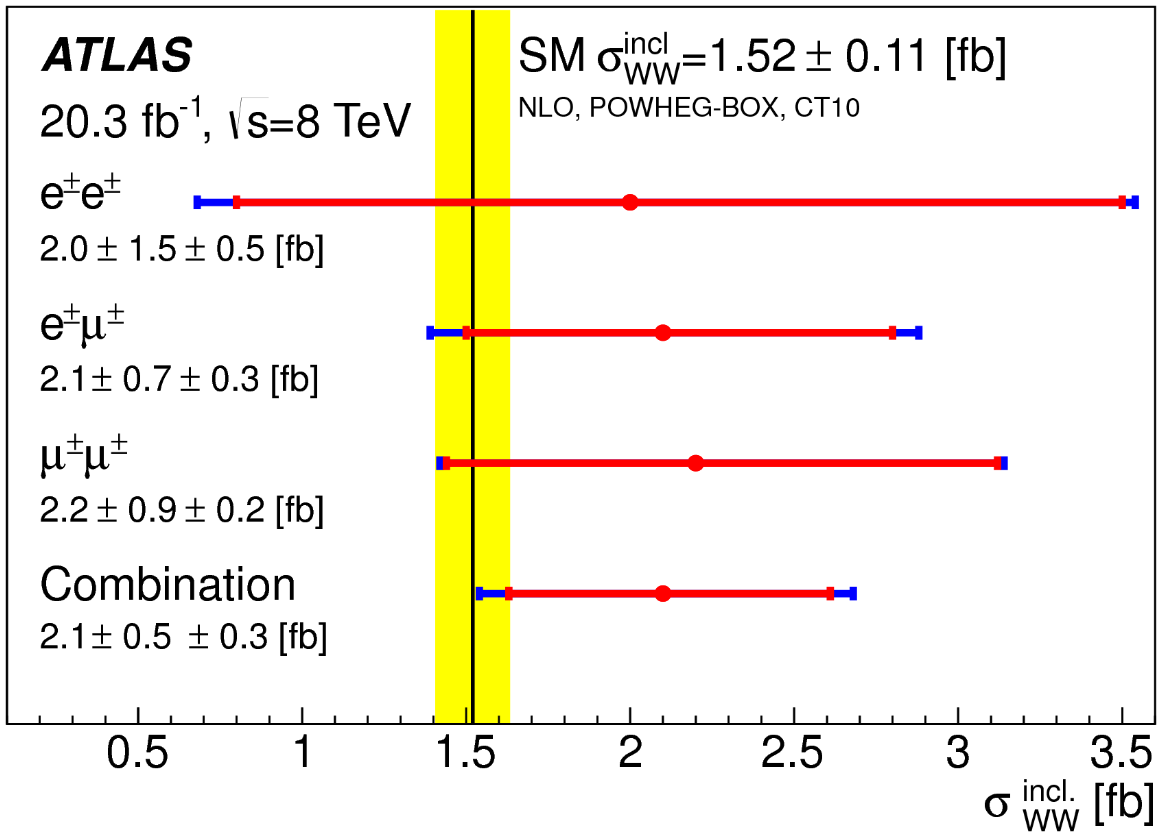
measurement of EW + strong production selected with high di-jet mass

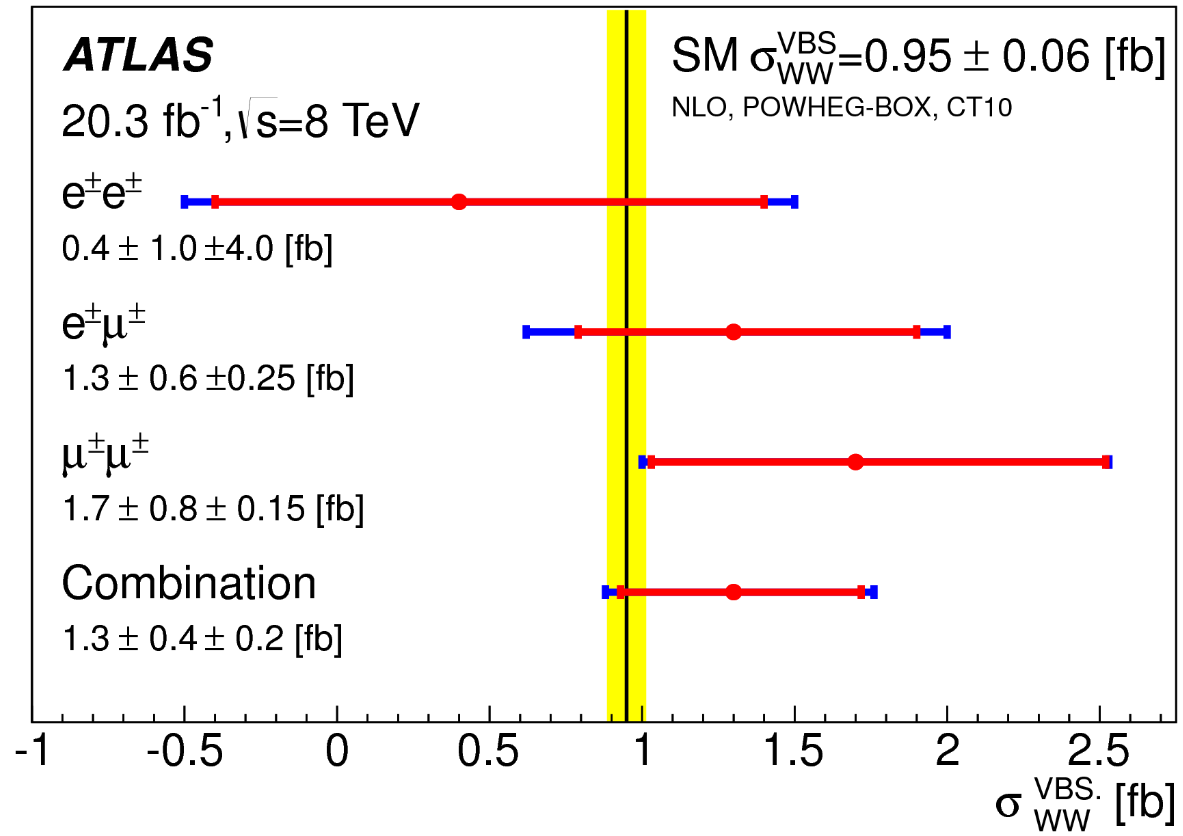


measurement of EW only selection enhanced by ΔYjj cut



$W^{\pm}W^{\pm}$+2jets production (III)





	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 !**

Anomalous gauge boson interactions

- **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

Characteristics
Anomalous couplings can manifest as increase cross sections and modification of kinematic distributions

- **Anomalous triple or quartic coupling terms (aTGCs, aQGCs) are in the effective Lagrangian**
- **Di-boson production is modified by certain dimension-6 and dimension-8 operators**

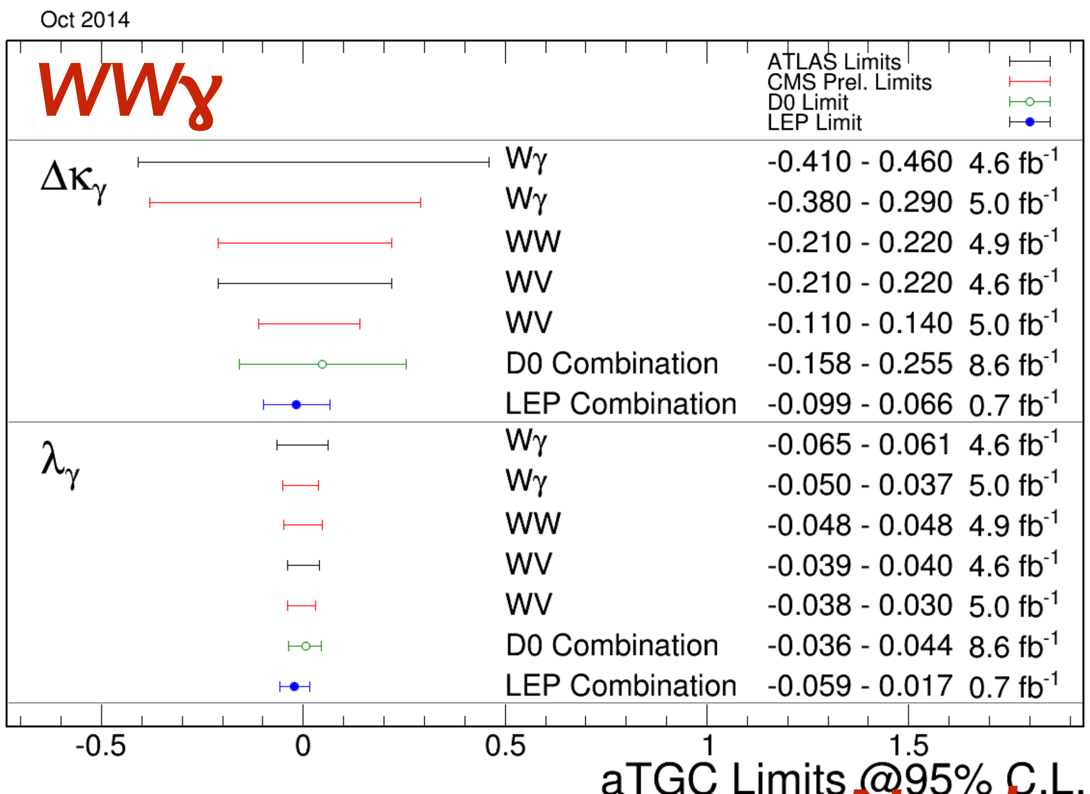
TGC

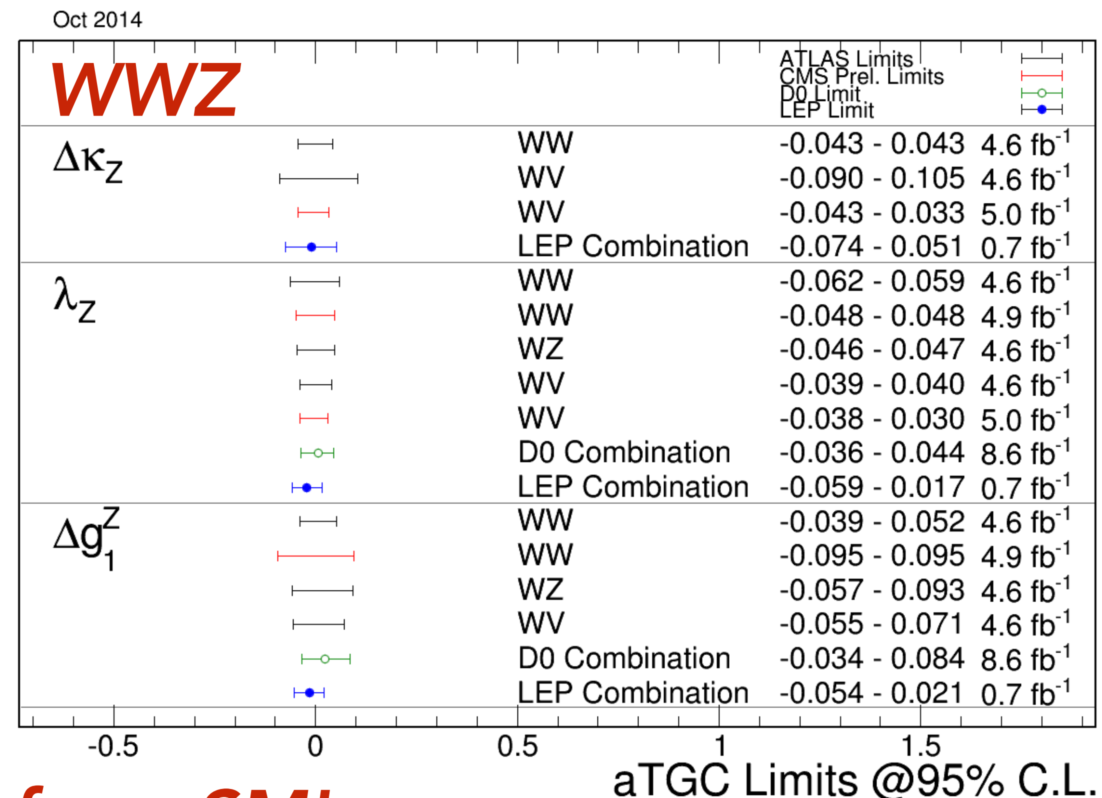
Coupling	Parameter	Channel
WWɣ	$\lambda_\gamma, \Delta\kappa_\gamma$	WW,Wɣ
WWZ	$\lambda_Z, \Delta\kappa_Z, \Delta g_1^Z$	WW,WZ
ZZɣ	h_3^Z, h_4^Z	Zɣ
Zɣɣ	h_3^γ, h_4^γ	Zɣ
ZɣZ	f_{40}^Z, f_{50}^Z	ZZ
ZZZ	$f_{40}^\gamma, f_{50}^\gamma$	ZZ

QGC

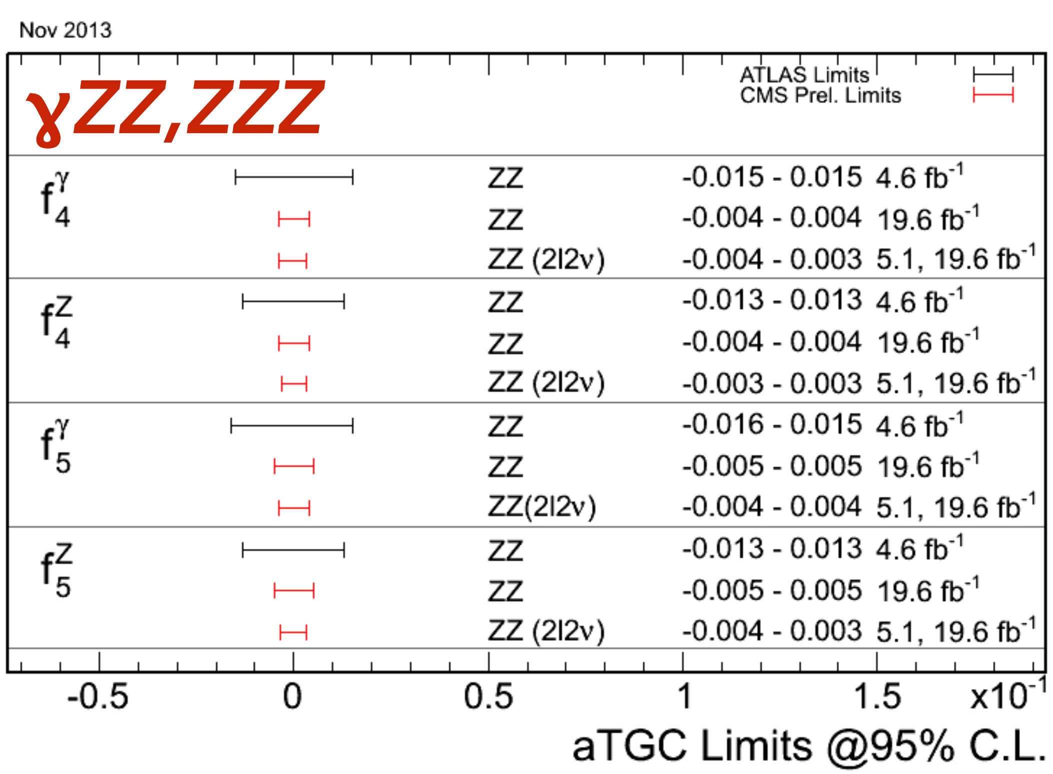
Coupling	Parameter	Channel
WWZZ,WWWW	$\alpha 4, \alpha 5$	WW,WZ

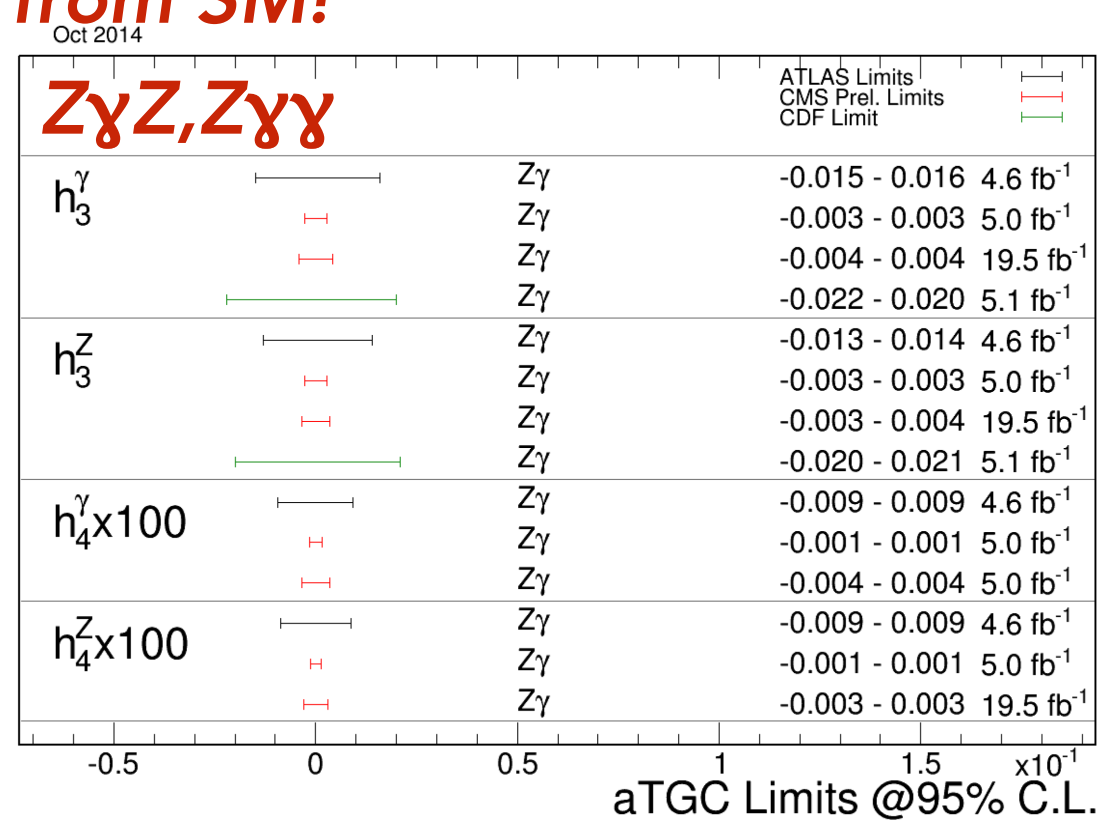
Summary of aTGC limits





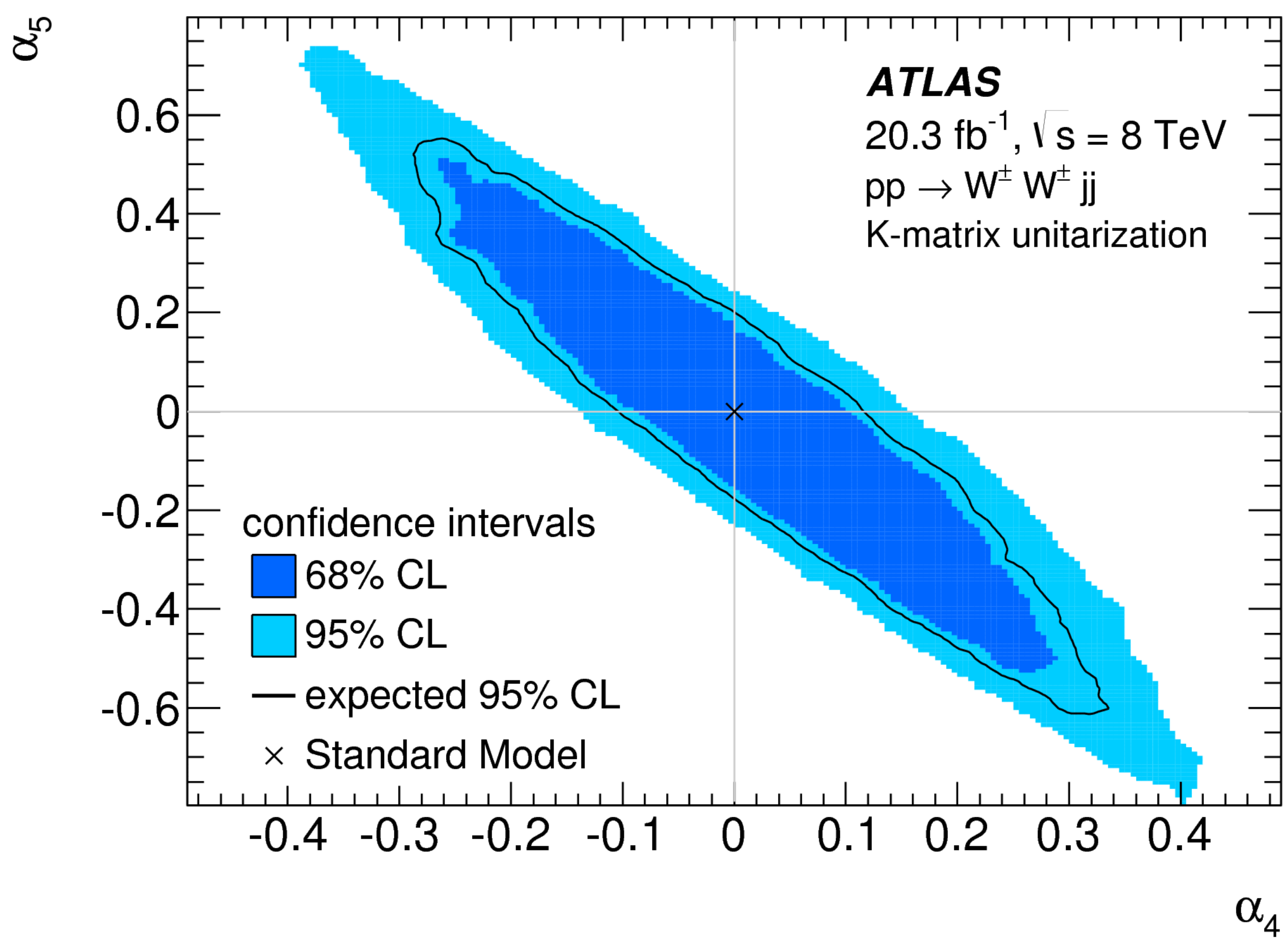
No deviations from SM!





First limits on aQGC

- **Measurement of VBS allows for setting limits on anomalous quartic couplings**
- **Deviations from SM parametrized in terms of parameters α4 and α5**
  - Limits on aQGCs extracted from $W^{\pm}W^{\pm}jj$ cross section in VBS phase space



parameter	observed limit	expected limit
α4	-0.139, 0.157	-0.104, 0.116
α5	-0.229, 0.244	-0.180, 0.199

Summary

- **Excellent performance of the LHC has provided high quality/quantity data in Run-1**
- **Di-boson measurements with ATLAS**
  - Fiducial, total and differential cross sections have been measured at 7 and 8 TeV.
  - Very accurate measurements of a few percent level
- **TGC limits consistent with the SM**
  - Sensitivity for aTGC limits expected to increase with increased centre-of-mass energy and integrated luminosity
- **Evidence for the same sign WW +2jets electroweak production with a significance of 3.6 σ**
- **First limits on aQGCs**
- **In Run-2 and Run-3 at 13,14 TeV, Di-boson, Tri-boson, VBS, and quartic gauge couplings will become the main probe for New Physics !**

Backup Slides

ssWW: selection requirements

- **Lowest order: W±W± + 2jets, there is no SM inclusive W±W±**
- **for EW+strong measurement ("inclusive signal phase space")**
  - exactly 2 high pT same-sign leptons with pT > 25 GeV in $|\eta| < 2.5$
  - $m_{\ell\ell}$>20 GeV, $\Delta R_{\ell\ell}$>0.3
  - ≥ 2 jets with p_T>30 GeV, $|\eta| < 4.5$
  - ETmiss > 40 GeV (from W decays)
    - *reduces Z+jets with charge mis-identification*
  - veto events containing b-jets
    - *reduces $t\bar{t}$ events (lepton from b-decays)*
  - Z-veto in ee channel: |mee − mZ | > 10 GeV
    - *reduces Z+jets with charge mis-identification*
  - mjj >500GeV
- **for EW-only measurement ("VBS signal phase space")**
  - additional cut on $|\Delta Y_{jj}| > 2.4$

ssWW: Background composition

- **prompt background:**
  - 3 or more prompt leptons
    - *WZ/γ_*+jets (Sherpa) normalized to NLO with VBFNLO (uncertainty ~14% and 11% in inclusive and VBS regions respectively)*
    - *ZZ+jets (Sherpa) theory uncertainty 19%*
    - *$t\bar{t}$ + W/Z (Madgraph+Pythia8) theory uncertainty 30%*
    - *tZj (Sherpa) negligible*
- **Conversions**
  - prompt photon conversion
    - *Wγ (Alpgen+Herwig/Jimmy, Sherpa for Ewk) total theory uncertainty 17%*
  - charge mis-ID due to bremsstrahlung with conversion (data driven)
    - *Z/γ_*+jets*
    - *Drell-Yan and $t\bar{t}$ decays*
- **Other non-prompt (data-driven)**
  - leptons from hadron decays in jets
    - *W+jets*
    - *semi-leptonic $t\bar{t}$ decays*
    - *di-jet events*

ssWW: Yields and interference effect

	Inclusive region			VBS region		
	$e^{\pm}e^{\pm}$	$e^{\pm}\mu^{\pm}$	$\mu^{\pm}\mu^{\pm}$	$e^{\pm}e^{\pm}$	$e^{\pm}\mu^{\pm}$	$\mu^{\pm}\mu^{\pm}$
Prompt	3.0 ± 0.7	6.1 ± 1.3	2.6 ± 0.6	2.2 ± 0.5	4.2 ± 1.0	1.9 ± 0.5
Conversions	3.2 ± 0.7	2.4 ± 0.8	...	2.1 ± 0.5	1.9 ± 0.7	...
Other nonprompt	0.61 ± 0.30	1.9 ± 0.8	0.41 ± 0.22	0.50 ± 0.26	1.5 ± 0.6	0.34 ± 0.19
$W^{\pm}W^{\pm}jj$ Strong	0.89 ± 0.15	2.5 ± 0.4	1.42 ± 0.23	0.25 ± 0.06	0.71 ± 0.14	0.38 ± 0.08
$W^{\pm}W^{\pm}jj$ Electroweak	3.07 ± 0.30	9.0 ± 0.8	4.9 ± 0.5	2.55 ± 0.25	7.3 ± 0.6	4.0 ± 0.4
Total background	6.8 ± 1.2	10.3 ± 2.0	3.0 ± 0.6	5.0 ± 0.9	8.3 ± 1.6	2.6 ± 0.5
Total predicted	10.7 ± 1.4	21.7 ± 2.6	9.3 ± 1.0	7.6 ± 1.0	15.6 ± 2.0	6.6 ± 0.8
Data	12	26	12	6	18	10

- **Interference between electroweak and strong production is studied at leading-order accuracy using SHERPA**
- **Interference increases the combined strong and electroweak cross section by 12% in the inclusive region and 7% in the VBS region**
- **Included in EW W±W±jj prediction**

ssWW: Systematic uncertainties

Systematic Uncertainties $ee/e\mu/\mu\mu$ (%) - Inclusive SR			
Background		Signal	
Jet uncertainties	11/13/13	Jet uncertainties	5.7
Theory WZ/γ^*	5.6/7.7/11	Theory $W^\pm W^\pm jj$-ewk	4.7
MC statistics	8.2/5.9/8.4	Theory $W^\pm W^\pm jj$-strong	3.1
Fake rate	3.5/7.1/7.2	Luminosity	2.8
OS lepton bkg/ Conversion rate	5.9/4.2/–	MC statistics	3.5/2.1/2.8
Theory $W+\gamma$	2.8/2.6/–	E_T^{miss} reconstruction	1.1
E_T^{miss} reconstruction	2.2/2.4/1.8	Lepton reconstruction	1.9/1.0/0.7
Luminosity	1.7/2.1/2.4	b-tagging efficiency	0.6
Lepton reconstruction	1.6/1.2/1.2	trigger efficiency	0.1/0.3/0.5
b-tagging efficiency	1.0/1.1/1.0		
Trigger efficiency	0.1/0.2/0.4		

Systematic Uncertainties $ee/e\mu/\mu\mu$ (%) - VBS SR			
Background		Signal	
Jet uncertainties	13/15/15	Theory $W^\pm W^\pm jj$-ewk	6.0
Theory WZ/γ^*	4.5/5.4/7.8	Jet uncertainties	5.1
MC statistics	8.9/6.4/8.4	Luminosity	2.8
Fake rate	4.0/7.2/6.8	MC statistics	4.5/2.7/3.7
OS lepton bkg/ Conversion rate	5.5/4.4/–	E_T^{miss} reconstruction	1.1
E_T^{miss} reconstruction	2.9/3.2/1.4	Lepton reconstruction	1.9/1.0/0.7
Theory $W+\gamma$	3.1/2.6/–	b-tagging efficiency	0.6
Luminosity	1.7/2.1/2.4	trigger efficiency	0.1/0.3/0.5
Theory $W^\pm W^\pm jj$-strong	0.9/1.5/2.6		
Lepton reconstruction	1.7/1.1/1.1		
b-tagging efficiency	0.8/0.9/0.7		
Trigger efficiency	0.1/0.2/0.4		

WW/WZ: Signal modelling

- **Signal events are generated with mc@nlo interfaced to Herwig with CT10 PDF**
- **NLO cross sections from mc@nlo: 43.7 ± 1.9 pb and 17.4 ± 1.1 pb for WW and WZ, respectively.**
  - Using factorisation and renormalisation scales equal to $\sqrt{(m^2_W + p^2_{T,W} + m^2_V + p^2_{T,V})/2}$
- **gg → WW and H → WW processes are not included in the signal samples nor in the cross-section prediction,**
  - contributions are small compared to the expected sensitivity of this measurement
  - gg → W W would increase the total predicted WV cross section by about 2–4%.
  - H → WW process would increase the WV cross section by about 5%,
    - *After applying all event selection criteria would only increase the expected number of signal events by about 2%*
- **γγ → WW process is neglected**
- **NNLO corrections would increase the total W V cross section by about 4% (arXiv:1408.5243)**

WW/WZ: Backgrounds

- **Dominant background: W/Z +jets**
  - Modelled using alpgen with cteq6l1 PDF
  - Scaled to the QCD NNLO inclusive cross section times branching fraction for a single lepton species
  - Shapes from MC
  - Rates from data-driven methods
- **$t\bar{t}$ events produced using mc@nlo with CT10 PDF**
  - shapes and rates from MC
  - calculated at NNLO in QCD including resummation of next-to-next-to-leading logarithmic (NNLL)
- **Single-top events from the Wt and s-channel processes are generated using mc@nlo with CT10**
- **ZZ background generated using herwig with MRST PDF**
- **Multijet (5.3% and 3.7% in e and mu channels)**
  - Rate and shape estimated with data-driven methods

Data-driven method:
Estimate ETmiss shape from control samples

Use ETmiss shape in template fit and obtain multijet and W/Z+jet rate

WW/WZ: Selection requirements and yields

- **Exactly one high-pT lepton**
  - suppresses the Z+jets and $t\bar{t}$ backgrounds
- **Isolated leptons with pT>25 GeV, |d0/σ(d0)| < 3 (10) for muons (electrons), |z0| <1 mm**
- **ETmiss > 30 GeV, m_T,W > 40 GeV**
  - highly suppress the multijet background
- **Exactly two jets with pT > 25 GeV and |η| < 2.8 (pT > 30 GeV for the leading jet)**
- **Azimuthal angular separation between the leading jet pT and the ETmiss vectors must fulfil |Δφ(ETmiss,j1)| > 0.8**
- **|Δη(j1,j2)| < 1.5, ΔR(j1, j2) > 0.7 if the pT of the dijet system is less than 250 GeV**
- **25 < mjj < 250 GeV**

Signal processes	e	μ
WW	1435 ± 70	1603 ± 79
WZ	334 ± 23	370 ± 26
Background processes		
$W+$ jets	$(107 \pm 21) \times 10^3$	$(116 \pm 23) \times 10^3$
$Z+$ jets	$(55 \pm 11)\times10^2$	$(46.3 \pm 9.3)\times10^2$
$t\bar{t}$	$(47.2 \pm 7.1)\times10^2$	$(47.2 \pm 7.1)\times10^2$
Single-top	$(20.2 \pm 3.0)\times10^2$	$(20.5 \pm 3.1)\times10^2$
Multijet	$(67 \pm 10)\times10^2$	$(50.5 \pm 7.6)\times10^2$
ZZ	19.2 ± 3.8	21.1 ± 4.2
Total SM prediction	$(128 \pm 17)\times10^3$	$(135 \pm 19)\times10^3$
Total Data	127 650	134 846

WW/WZ:Cross section extraction

$$\sigma_{\text{fid}} = \sum_{\ell=e,\mu} \frac{N_\ell^{WV}}{\mathcal{L} \cdot D_{\text{fid},\ell}}, \qquad D_{\text{fid},\ell} = f_{\text{fid}}^{WW} \cdot C_\ell^{WW} + (1 - f_{\text{fid}}^{WW}) \cdot C_\ell^{WZ}$$

$$\sigma_{\text{tot}} = \sum_{\ell=e,\mu} \frac{N_\ell^{WV}}{\mathcal{L} \cdot D_{\text{tot},\ell}}, \qquad D_{\text{tot},\ell} = f_{\text{tot}}^{WW} \cdot C_\ell^{WW} \cdot \mathcal{B}_\ell^{WW} \cdot A_\ell^{WW} + (1 - f_{\text{tot}}^{WW}) \cdot C_\ell^{WZ} \cdot \mathcal{B}_\ell^{WZ} \cdot A_\ell^{WZ}$$

$$\sigma_{\text{fid}} = 1.37 \pm 0.14\ (\text{stat.}) \pm 0.37\ (\text{syst.})\ \text{pb}$$

- **$D_{fid,l}$ account for the fact that WW → lνjj and WZ → lνjj contribute to the signal yield with different cross sections, acceptances and correction factors**
- **f^{WW} represents the ratio of the WW fid to the WW + W Z fiducial cross sections**
    - Fixed to the SM value of 0.82

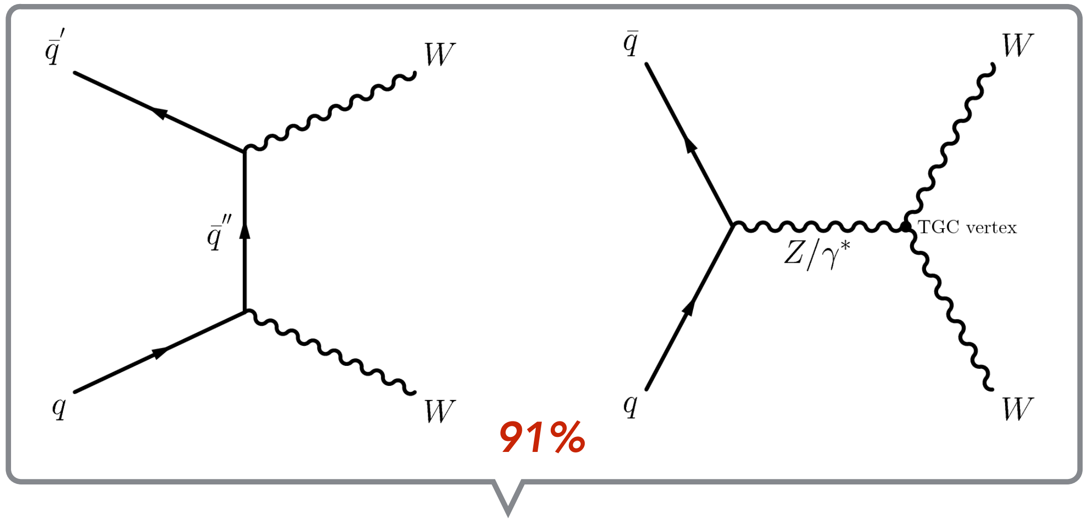
WW/WZ: Systematic uncertainties

- **W/Z+jets rate and shape modelling estimated from scale variations, cross-section, MC modelling, JES, and JER uncertainties**
- **Finite size of the MC event samples limits the precision with which the mjj templates are known**
- **The multijet rate and shape uncertainties are determined in validation region with modified selection criteria**
- **Main impact of the JES and JER is on the shapes of the background distributions**
- **Signal shape modelling assessed by considering alternative templates from Pythia**

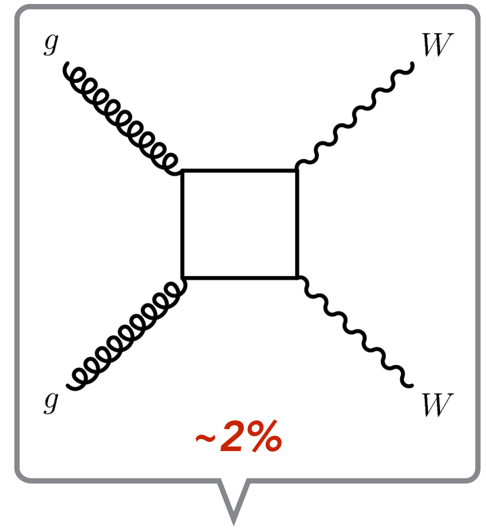
Source	σ_{fid}	σ_{tot}
	N_ℓ^{WV}	
Data statistics	± 10	
MC statistics	± 12	
$W/Z +$ jets rate and shape modelling	± 17	
Multijet shape and rate	± 8	
Top rate and initial/final-state radiation shape modelling	± 6	
Jet energy scale (background and signal shapes)	± 9	
Jet energy resolution (background and signal shapes)	± 11	
WV shape modelling	± 5	
	D_{fid}	D_{tot}
JES/JER uncertainty	± 6	± 6
Signal modelling	± 4	± 5
Jet veto scale dependence	-	± 5
Others (loss of spin-corr information, lepton uncertainties, PDF)	± 1	± 4
Luminosity	± 1.8	
Total systematic uncertainty	± 27	± 28

Summary of the % contributions to the systematic uncertainties on the cross sections

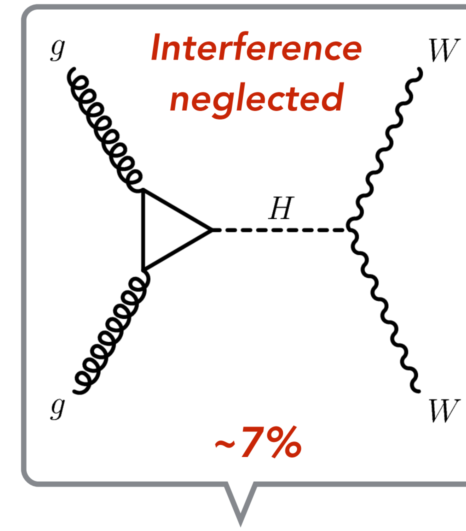
WW: Theoretical predictions



MCFM NLO



MCFM LO



NNLO MSTW2008

- **Standard Model prediction is : 58.7 $^{+3.0}_{-2.7}$ (pb)**
- **Contributions neglected in this prediction:**
  - gg → WW (LO → NNLO+NNLL k-factor) up to +2.8 pb
  - Electroweak corrections -0.5 pb
  - γγ-induced WW +0.5 pb
  - Vector boson scattering <+0.5 pb
  - Double parton interaction +0.04 pb

WW: Selection requirements

Leptons	Jets	ETmiss	pTmiss
Isolated	anti-kt, R=0.4	vectorial sum of calorimeter deposits	vectorial sum of tracks pileup-robust
pT>25(20) GeV leading (subleading)	pT>25 GeV	Emiss ×sin|Δϕ(met_j,l)| > 15(45) GeV em (ee,mm)	pmiss > 20 (45) GeV em (ee,mm)
$\|\eta\|$ <2.5	$\|\eta\|$ <4.5	if Δϕ > π/2, then Emiss,rel is equal to Emiss	$\|\eta\|$ <2.5
transverse impact parameter significance < 3.0			

- **Event selection**
  - Single or dilepton triggers
  - \|mll – mZ \| > 15 GeV for same flavour channels
  - mll > 10 GeV for emu channel

Channel	$e^{\pm}\mu^{\mp}$	$e^{+}e^{-}$	$\mu^{+}\mu^{-}$
Observed Events	5067	594	975
Total expected events	$4376 \pm 26 \pm 280$	$536 \pm 10 \pm 42$	$873 \pm 12 \pm 63$
MC *WW* signal	$3224 \pm 10 \pm 248$	$346 \pm 3 \pm 32$	$610 \pm 5 \pm 56$
Top(data-driven)	$609 \pm 18 \pm 52$	$92 \pm 7 \pm 8$	$127 \pm 9 \pm 11$
W+jets(data-driven)	$220 \pm 15 \pm 112$	$14 \pm 5 \pm 9$	$3 \pm 5 \pm 6$
Z+jets (data-driven)	$166 \pm 3 \pm 26$	$55 \pm 1 \pm 23$	$96 \pm 2 \pm 27$
Other dibosons (MC)	$157 \pm 4 \pm 31$	$30 \pm 2 \pm 5$	$39 \pm 1 \pm 5$
Total background	$1152 \pm 24 \pm 130$	$190 \pm 9 \pm 26$	$264 \pm 11 \pm 30$

WW:Systematic uncertainties

- **Data and MC control samples of Z→ l+l– events are used to determine the data-to-MC correction factor for the efficiency of the jet-veto requirement**
  - $\varepsilon_{data,WW} = \varepsilon_{MC,WW} \times fZ$
  - $fZ = \varepsilon_{data,Z}/\varepsilon_{MC,Z} = 0.990 \pm 0.029$ (exp) ± 0.032 (theo).
- **The overall systematic uncertainty on the WW selection acceptance ($A_{WW} \times C_{WW}$) is 5.9% for the combination of the three dilepton channels**

Sources	$e^{\pm}\mu^{\mp}$	$e^{+}e^{-}$	$\mu^{+}\mu^{-}$
C_{WW} **experimental uncertainties**			
Pileup	1.3%	1.9%	2.0%
e trigger efficiency	0.3%	2.5%	–
μ trigger efficiency	0.3%	–	2.8%
Muon MS resolution	0.0%	–	0.1%
Muon ID resolution	0.5%	–	1.5%
Muon scale	0.1%	–	0.4%
Muon efficiency	0.4%	–	0.8%
Muon isolation/IP	0.6%	–	1.1%
Electron resolution	0.0%	0.2%	–
Electron energy scale	0.4%	1.4%	–
Electron efficiency	0.9%	2.0%	–
Electron isolation/IP	0.2%	0.4%	–
Jet vertex fraction	0.2%	0.2%	0.2%
Jet energy scale	2.6%	2.6%	2.6%
Jet energy resolution	2.3%	2.2%	2.9%
$E_{\mathrm{T}}^{\mathrm{miss}}$ soft term resolution	0.3%	0.3%	0.5%
$E_{\mathrm{T}}^{\mathrm{miss}}$ soft term scale	2.3%	4.2%	3.8%
$p_{\mathrm{T}}^{\mathrm{miss}}$ soft term resolution	0.1%	0.0%	0.2%
$p_{\mathrm{T}}^{\mathrm{miss}}$ soft term scale	0.3%	0.6%	0.5%
Total experimental uncertainties	3.7%	6.3%	6.3%
C_{WW} **theoretical uncertainties**			
Jet-veto requirement (theory)	3.2%	3.2%	3.2%
PDF	0.4%	0.6%	0.1%
Scale	0.6%	1.7%	0.7%
Total theoretical uncertainties	3.3%	3.7%	3.3%
Total (exp.+theo.)	5.0%	7.3%	7.1%
$A_{WW} \times C_{WW}$ **theoretical uncertainties**			
Jet-veto requirement (theory)	3.3%	3.3%	3.3%
PDF	1.3%	1.6%	0.8%
Scale	1.5%	2.0%	1.8%
Total theoretical uncertainties	3.9%	4.2%	3.8%
Total (exp.+theo.)	5.4%	7.6%	7.4%

WW: Data-driven backgrounds

- **Top background (~15 %):**
  - Jet veto efficiency applied to MC events to obtain normalization determined from a data control sample of top events with large scalar sum of lepton and jet pT
- **W+jets background (eμ 4% / ee+μμ 1%):**
  - extract normalization and shape
  - efficiencies for fake and real leptons for loose and tight cuts
  - determine signal and background components with matrix method
- **Z+jets background (eμ 0.3% / ee+μμ 1%):**
  - fit to data control region to extract normalization

W/Zγ selection requirements

- Single lepton or photon triggers:
  - Electrons: 20-22 GeV
  - Muons: 18 GeV
  - Photons: 80 GeV
- $|d_0|/\sigma_{d_0} < 10(3)$ e(μ)
- $|z_0| < 1mm$
- Calorimeter isolation in cone $\Delta R < 0.3$ less than 6 GeV (e)
- p_T isolation in cone $\Delta R < 0.3$ less than 15% of the μ p_T
- $W\gamma$ modelled with ALPGEN (CTEQ6L1)
- $Z\gamma, \nu\nu\gamma$ modelled with Sherpa (CTEQ6.6M)

Cuts	$pp \to \ell\nu\gamma$	$pp \to \ell^+\ell^-\gamma$	$pp \to \nu\bar{\nu}\gamma$
Lepton	$p_T^\ell > 25$ GeV	$p_T^\ell > 25$ GeV	—
	$\lvert\eta_\ell\rvert < 2.47$	$\lvert\eta_\ell\rvert < 2.47$	—
	$N_\ell = 1$	$N_{\ell^+} = 1, N_{\ell^-} = 1$	$N_\ell = 0$
	$p_T^\nu > 35$ GeV	—	—
Boson	—	$m_{\ell^+\ell^-} > 40$ GeV	$p_T^{\nu\bar{\nu}} > 90$ GeV
Photon	$E_T^\gamma > 15$ GeV	$E_T^\gamma > 15$ GeV	$E_T^\gamma > 100$ GeV
	$\lvert\eta^\gamma\rvert < 2.37, \Delta R(\ell,\gamma) > 0.7$		
	$\epsilon_h^p < 0.5$		
Jet	$E_T^{\text{jet}} > 30$ GeV, $\lvert\eta^{\text{jet}}\rvert < 4.4$		
	$\Delta R(e/\mu/\gamma, \text{jet}) > 0.3$		
	Inclusive : $N_{\text{jet}} \geq 0$, Exclusive : $N_{\text{jet}} = 0$		

W/Zγ systematics

Source	$pp \to e\nu\gamma$	$pp \to \mu\nu\gamma$	$pp \to e^+e^-\gamma$	$pp \to \mu^+\mu^-\gamma$	$pp \to \nu\bar{\nu}\gamma$
Relative systematic uncertainties on the signal correction factor $C_{V\gamma}$ [%]					
γ identification efficiency	6.0 (6.0)	6.0 (6.0)	6.0 (6.0)	6.0 (6.0)	5.3 (5.3)
γ isolation efficiency	1.9 (1.8)	1.9 (1.7)	1.4 (1.4)	1.4 (1.4)	2.8 (2.8)
Jet energy scale	0.4 (2.9)	0.4 (3.2)	- (2.2)	- (2.4)	0.6 (2.0)
Jet energy resolution	0.4 (1.5)	0.6 (1.7)	- (1.7)	- (1.8)	0.1 (0.5)
unassociated energy cluster in $E_{\mathrm{T}}^{\mathrm{miss}}$	1.5 (1.6)	0.5 (1.0)	- (-)	- (-)	0.3 (0.2)
μ momentum scale and resolution	- (-)	0.5 (0.4)	- (-)	1.0 (0.8)	- (-)
EM scale and resolution	2.3 (3.0)	1.3 (1.6)	2.8 (2.8)	1.5 (1.5)	2.6 (2.7)
Lepton identification efficiency	1.5 (1.6)	0.4 (0.4)	2.9 (2.5)	0.8 (0.8)	- (-)
Lepton isolation efficiency	0.8 (0.8)	0.3 (0.2)	2.0 (1.6)	0.5 (0.4)	- (-)
Trigger efficiency	0.8 (0.1)	2.2 (2.1)	0.1 (0.1)	0.6 (0.6)	1.0 (1.0)
Total	7.1 (8.0)	6.8 (7.8)	7.6 (7.9)	6.5 (7.1)	6.6 (7.0)