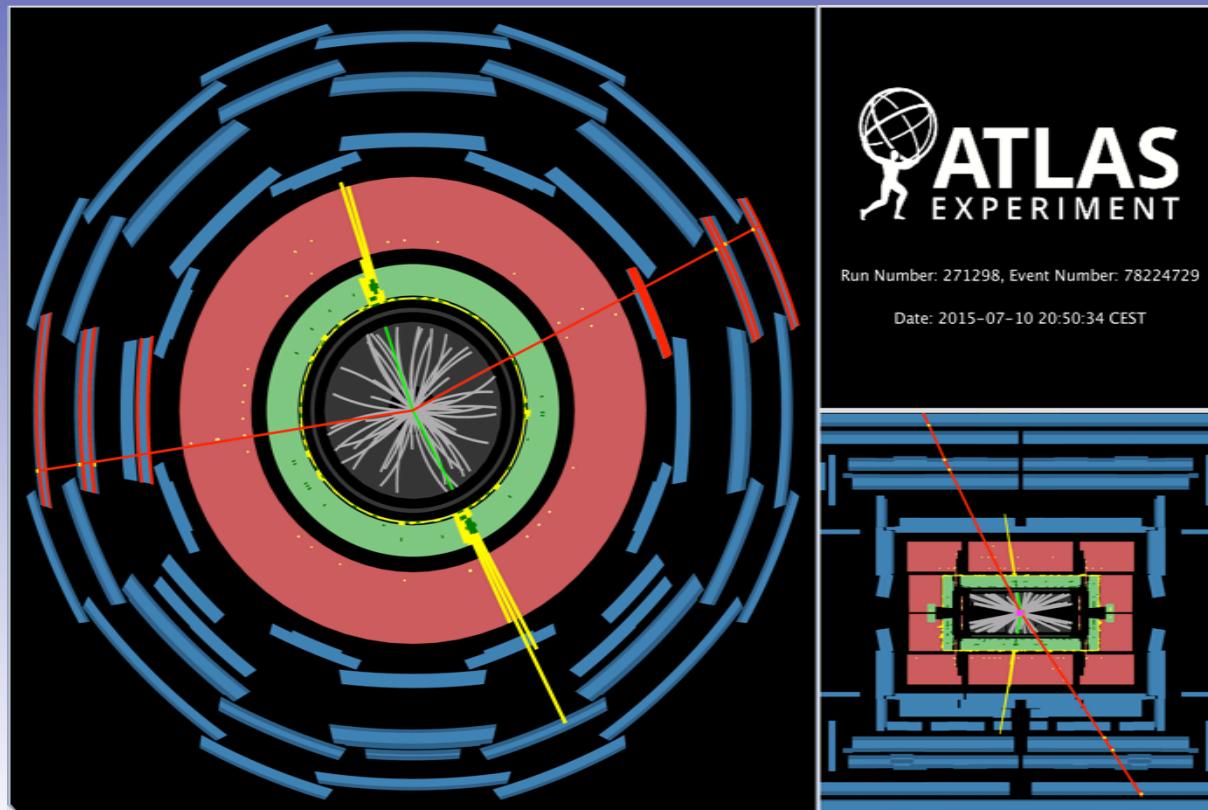


Recent diboson measurements from ATLAS

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On behalf of the ATLAS Collaboration



Motivations and outline

- ◆ The production and scattering of two **electroweak vector bosons (V) @ LHC** are sensitive to terms of SM & Beyond SM(BSM) Lagrangian well beyond the reach of previous experiments
 - Measurements of dibosons final states are of great interest:
 - to test of the SM at the TeV scale (EW and QCD corrections & calculations)
 - to search for New Physics
- ◆ VV final states are irreducible background to Higgs and BSM searches
 - important to validate present MC modelling

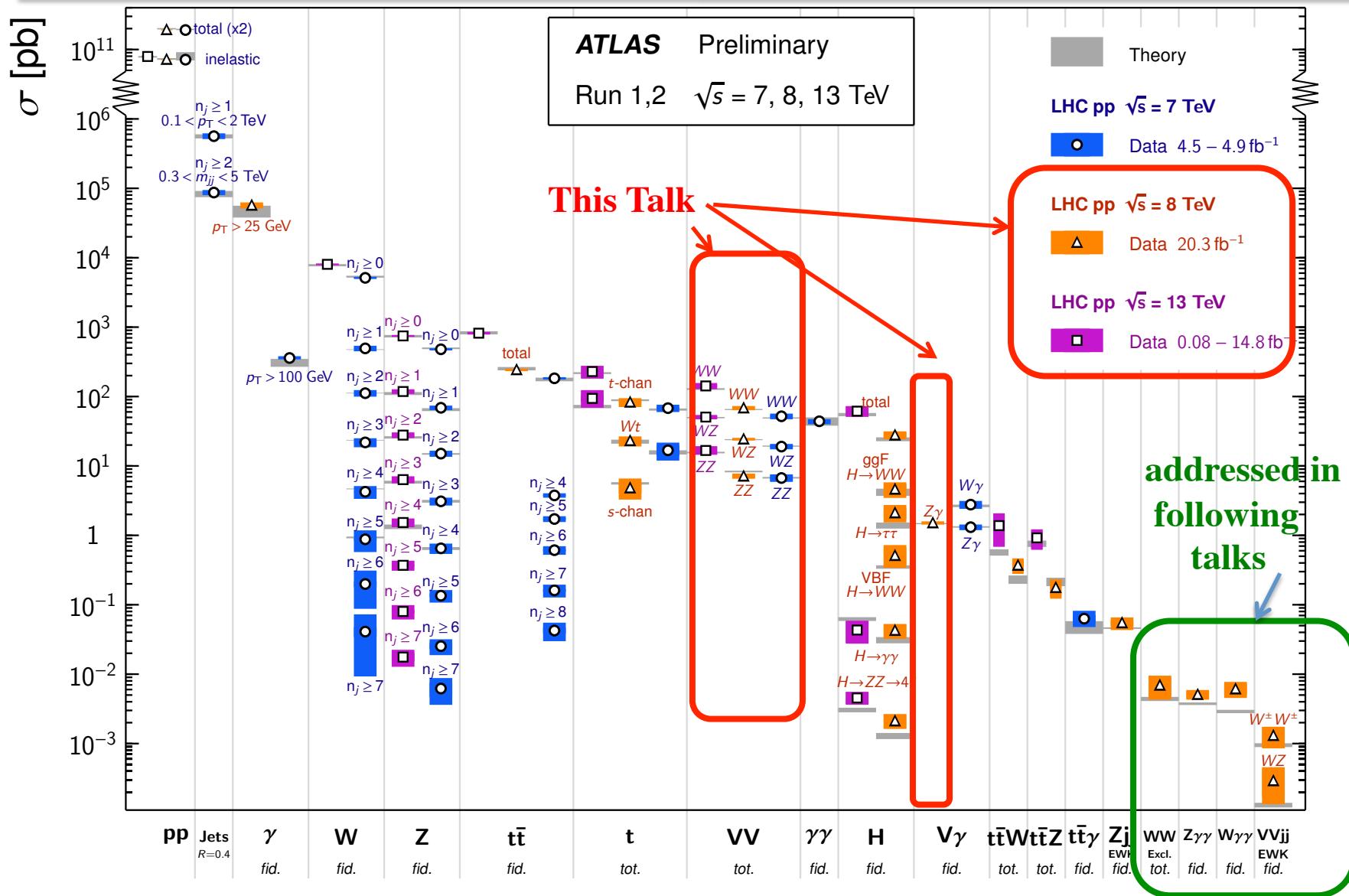
VV production have to be well understood and measured

Outline of the talk :

- **WW cross sections @ $\sqrt{s} = 8 \text{ & } 13 \text{ TeV}$**
- **WZ cross sections @ $\sqrt{s} = 8 \text{ & } 13 \text{ TeV}$**
- **ZZ cross sections @ $\sqrt{s} = 8 \text{ & } 13 \text{ TeV}$**
- **$Z\gamma$ cross sections @ $\sqrt{s} = 8 \text{ TeV}$**
- **Charged Triple Gauge self-Couplings (TGC) @ $\sqrt{s} = 8 \text{ TeV (WW), 8 \& 13 (WZ) TeV}$**
- **Neutral TGC ($Z\gamma$) @ 8 TeV**

Standard Model Production Cross Section Measurements

Status: August 2016



Measurement procedures

◆ Fiducial and total cross sections

$$\sigma_{\text{fid}} = \frac{N_{\text{obs}} - N_{\text{bkgd}}}{C \quad L}$$

$$\sigma_{\text{tot}} = \frac{\sigma_{\text{fid}}}{A \quad Br}$$

- **Fiducial phase space** defined following the analysis selection (minimal phase space extrapolation)
- **C** corrects for detector effects
- **σ_{tot}** for a more general comparison with theory and other experiments (but larger modelling uncertainties)
- **A** extrapolates from **fiducial** to **total phase space**

◆ Differential cross sections

Unfolded to particle level for a direct comparison with theory predictions
(Baysian unfolding)

◆ Anomalous Couplings among V

- non-Abelian structure of SM \rightarrow couplings among V $V=W, Z, \gamma$
- **Anomalous Couplings** appear as **enhanced rates at high p_T^V or m_T^{VV}** & changes in angular distributions
- **Fit detector-level distributions** to extract limits

WW @ $\sqrt{s} = 8$ TeV

Two isolated leptons $p_T > 25(20)$ GeV + E_T^{miss}

◆ 8 TeV (0 jets) : [arXiv:1603.01702](https://arxiv.org/abs/1603.01702)

- ee, $\mu\mu$ and $e\mu$ channels
- reject events with \geq one jet ($p_T > 25$ GeV) to suppress **top bkgd**

Jet veto involves an additional scale (jet p_T)
 \Rightarrow large log-terms in perturbative series

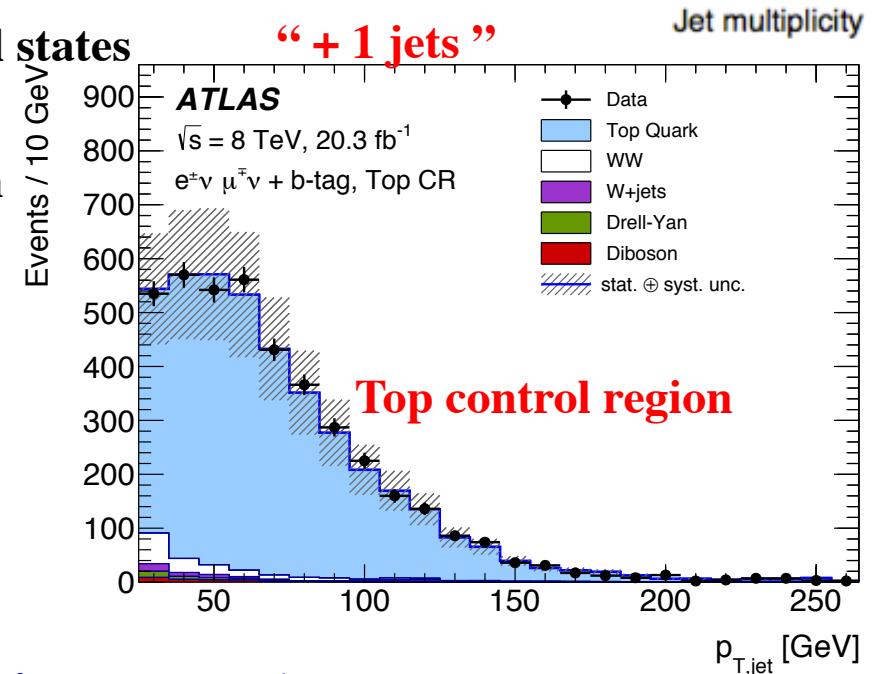
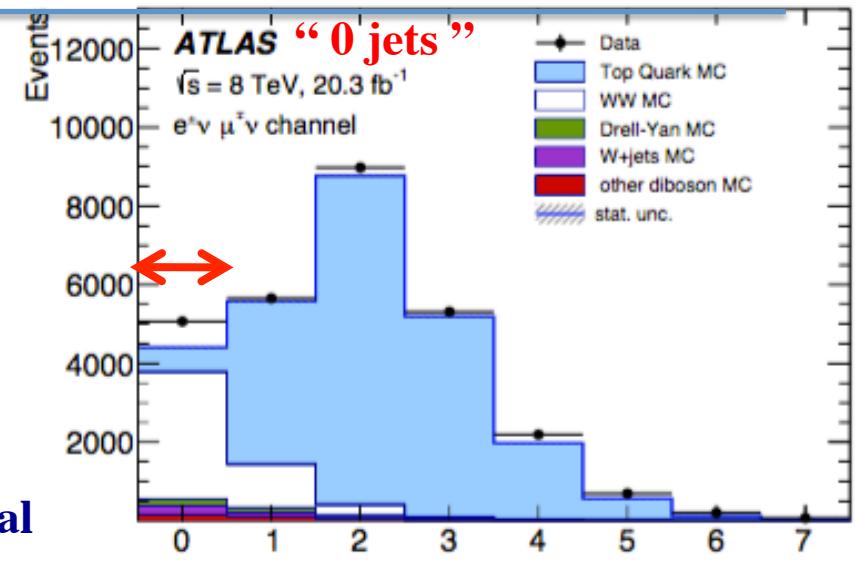
Theory: challenging to model jet-veto for signal

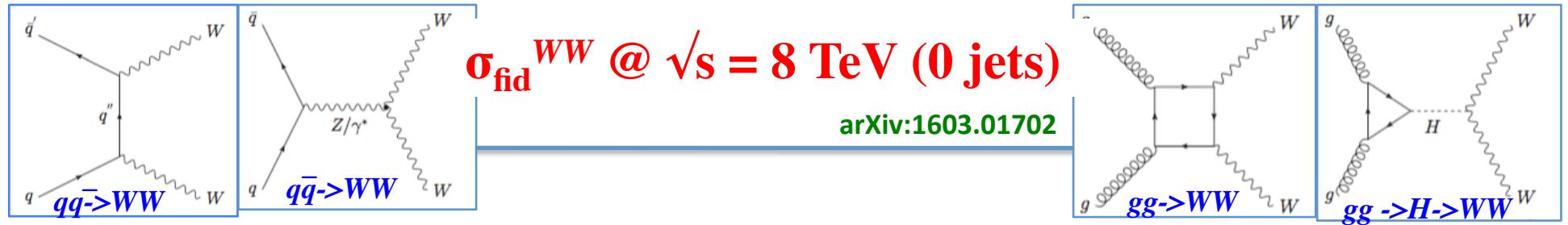
Extend the previous measurement to 1-jet final states

In combination with previous result
provide a **WW+≤ 1 jet fiducial cross section**
with reduced logarithmic dependence

◆ 8 TeV (WW+ 1 jets) : [arXiv:1608.03086](https://arxiv.org/abs/1608.03086)

- only $e\mu$ channel (larger signal acceptance wrt same flavour)
- reject top with **b-jet veto**
- largest bkgd **from top** ($\sim 40\%$, uncert. 5%)

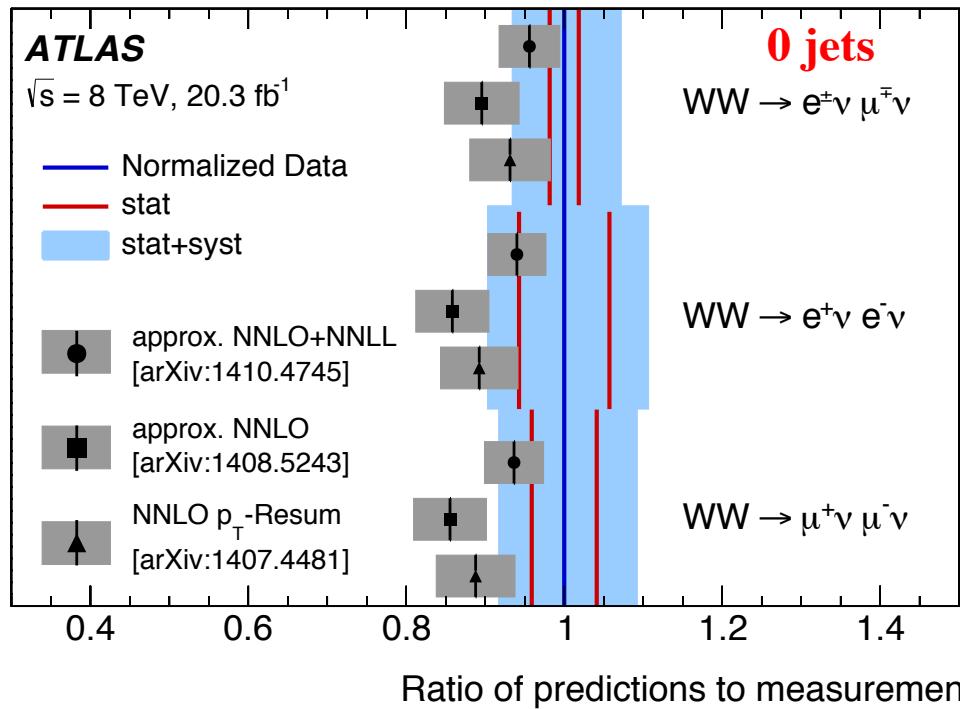




- ◆ Channel with smallest uncertainty ($\sim 7\%$) $e\mu$: $\sigma_{\text{fid}}^{\text{WW}e\mu} = 374 \pm 7(\text{stat})^{+25}_{-23}(\text{syst})^{+8}_{-7}(\text{lumi}) \text{ fb}$
- ◆ $\sigma_{\text{fid}}^{\text{WW}}$ syst. limited. Main contributions : JES ($\sim 4\%$), $W+\text{jets}$ bkgd ($\sim 3\%$), luminosity ($\sim 2\%$)
Theory $\sim 1\%$

Initial excess triggered many theory papers

Experimental results compared with NNLO_{tot} calculations



$$\text{NNLO}_{\text{tot}} = \bar{q}q \rightarrow WW (\alpha_s^2) + gg \rightarrow H \rightarrow WW (\alpha_s^4) + gg \rightarrow WW (\alpha_s^2)$$

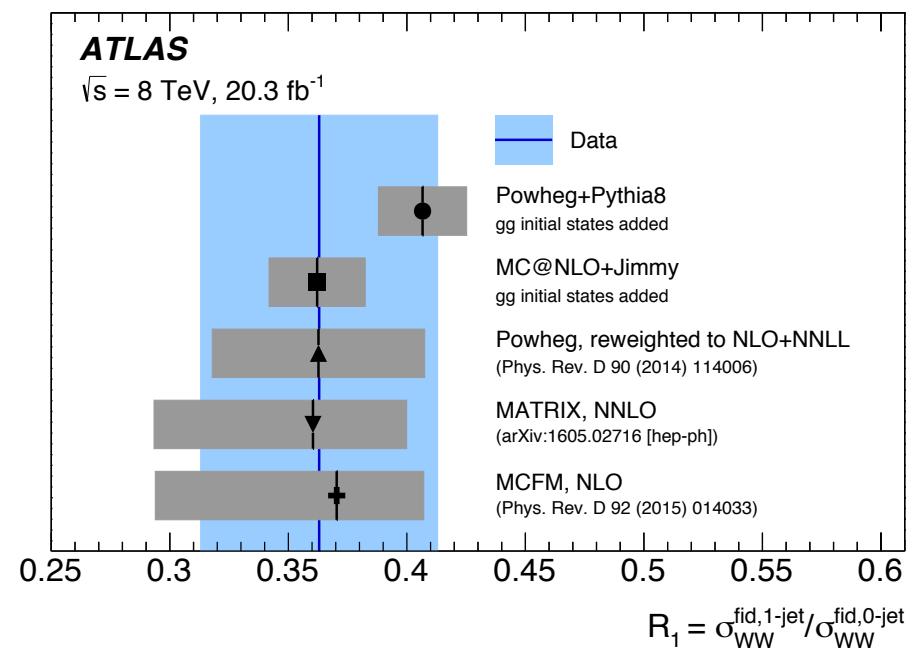
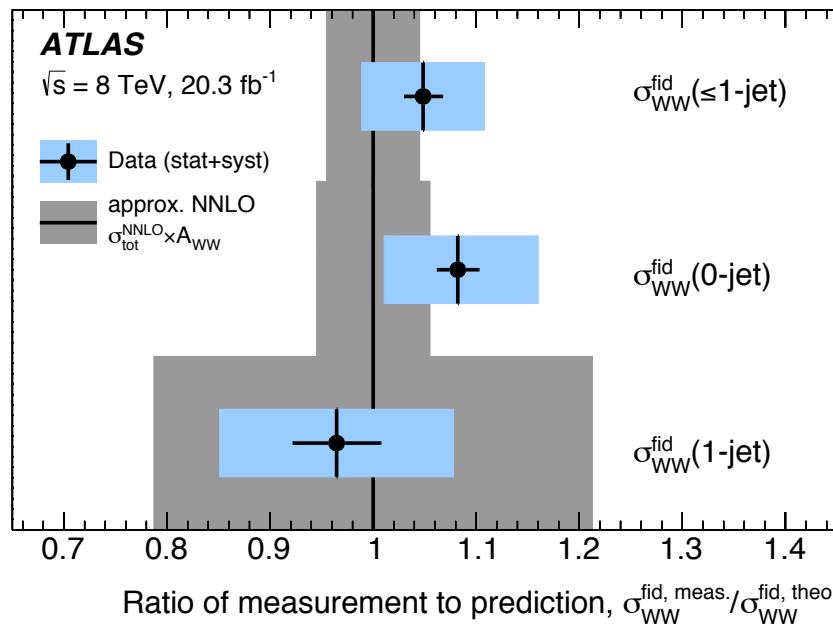
$$\text{approx. NNLO}_{\text{fid}} = A * \text{NNLO}_{\text{tot}}$$

A = acceptance from MC (Powheg+gg2WW)

◆ Results:

- $\sigma_{\text{fid}}^{\text{WW}}$ in agreement with calculations within 1-2 σ
- resummation improves agreement

- ◆ Uncertainties in 0-jet and 1-jet bin similar, except for JES, JER and b-tag
- ◆ Cancellation of uncertainties between 0-jet and 1-jet bin results in smaller uncertainties on $WW + \leq 1$ jet and on the extrapolation to $\sigma_{\text{tot}}^{\text{WW}}$
- ◆ Measurement uncertainty on the ratio (1 jet/0 jet) : $\sim 10\%$



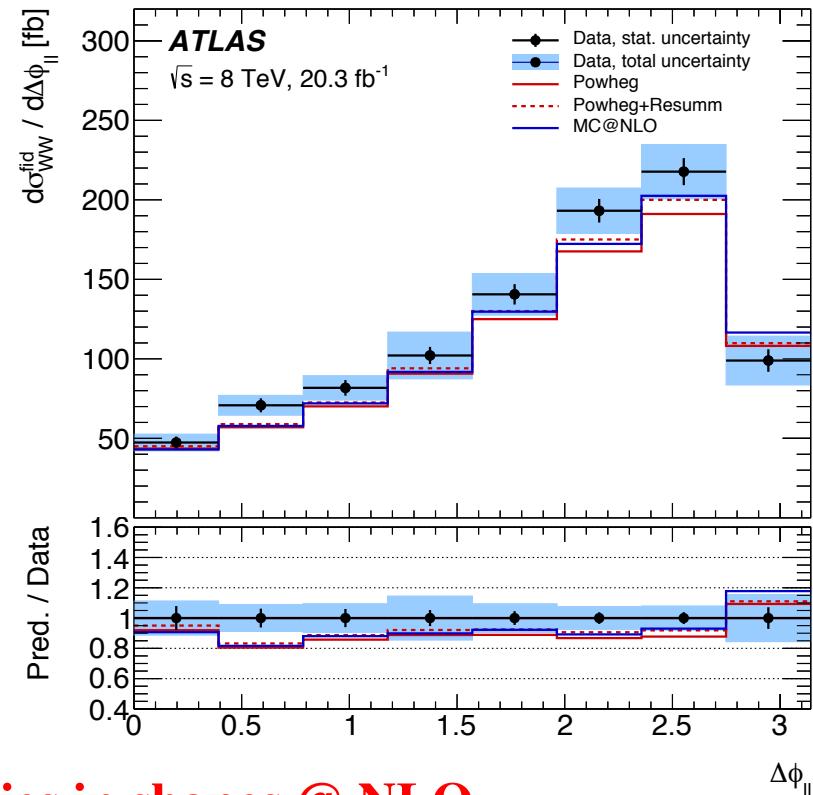
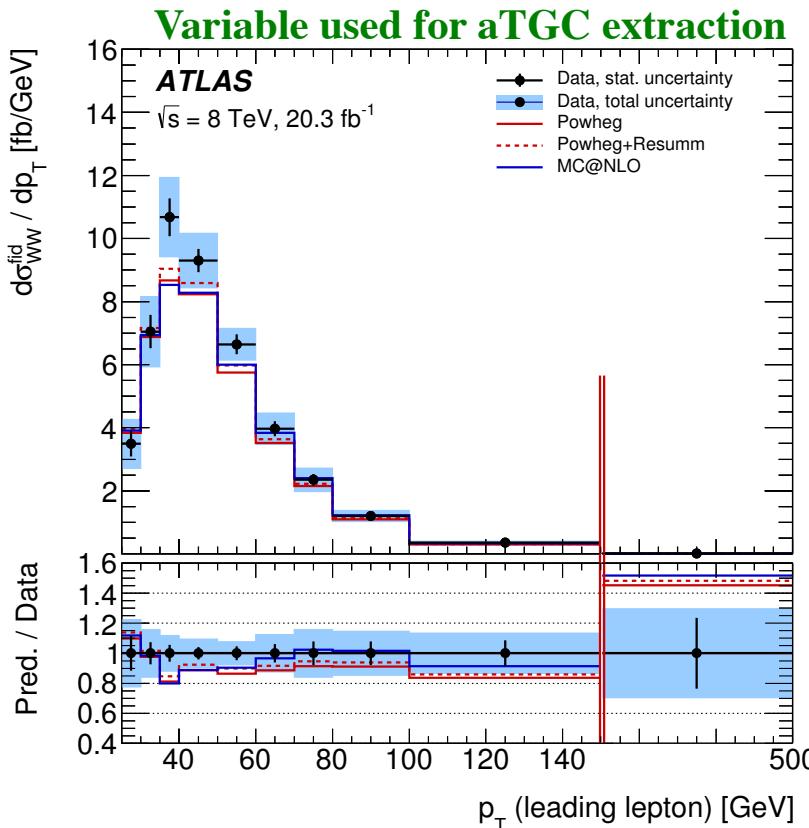
QCD calculations describe data within uncertainties

WW differential cross sections @ $\sqrt{s} = 8$ TeV

arXiv:1603.01702

- ◆ Use $e\mu$ channel
- ◆ Result compared to several predictions including $H \rightarrow WW$ contribution (typical contribution 2% per bin, at most 8.5%)
- ◆ NLO EW corrections on predictions important for the aTGC extraction

($p_T(\text{lead lept}) > 350$ GeV corr_{EW} = -24 ± 7 %)



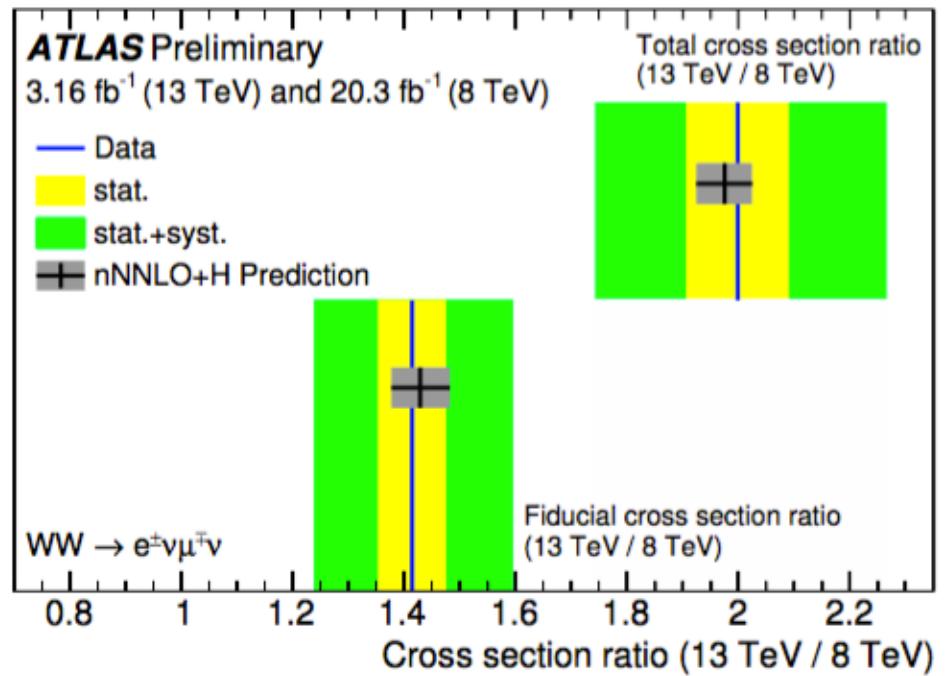
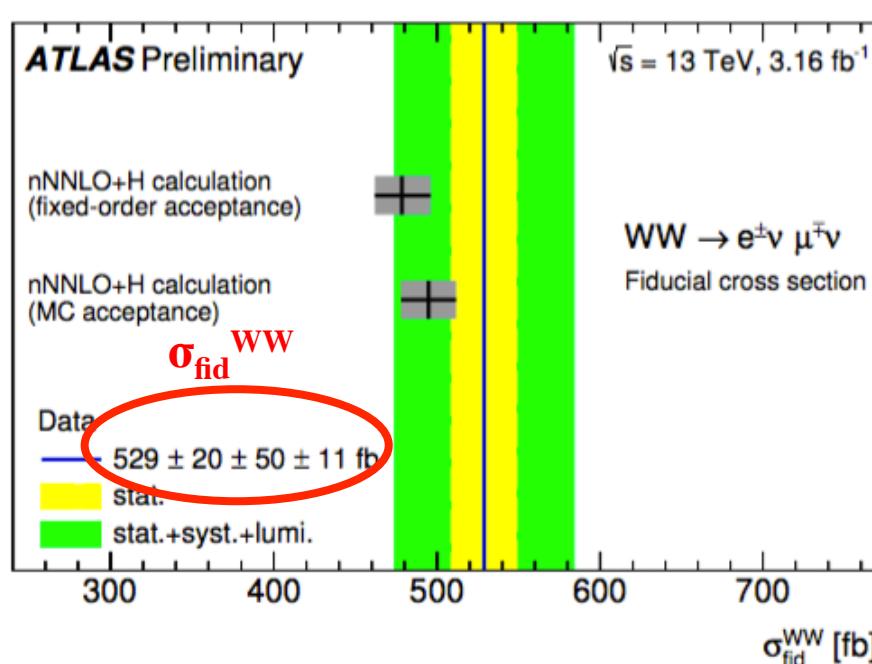
No obvious discrepancies in shapes @ NLO

◆ Measurements :

- use $e\mu$ channel
- $N_{\text{jets}} (\mathbf{p}_T > 25 \text{ GeV}) = 0$ and b-tag veto to reduce **top bkgd**
- σ_{fid} is extracted with a simultaneous fit of Signal Region, top and Drell-Yan control regions (in SR: Signal: ~71%, Top: ~16%)

◆ Theoretical calculations (nNNLO+H):

$$q\bar{q} \rightarrow WW (\alpha_s^2), gg \rightarrow WW (\alpha_s^3), gg \rightarrow H \rightarrow WW (\alpha_s^5 (\text{tot}), \alpha_s^4 (\text{fid}))$$



High-order QCD calculations describe data well

Inclusive WZ measurements @ $\sqrt{s} = 8$ and 13 TeV

Phys. Rev. D 93, 092004 (2016)

ATLAS-CONF-2016-043

◆ Inclusive selection : 3 leptons, an on-shell Z, $m_T^W > 30$ GeV

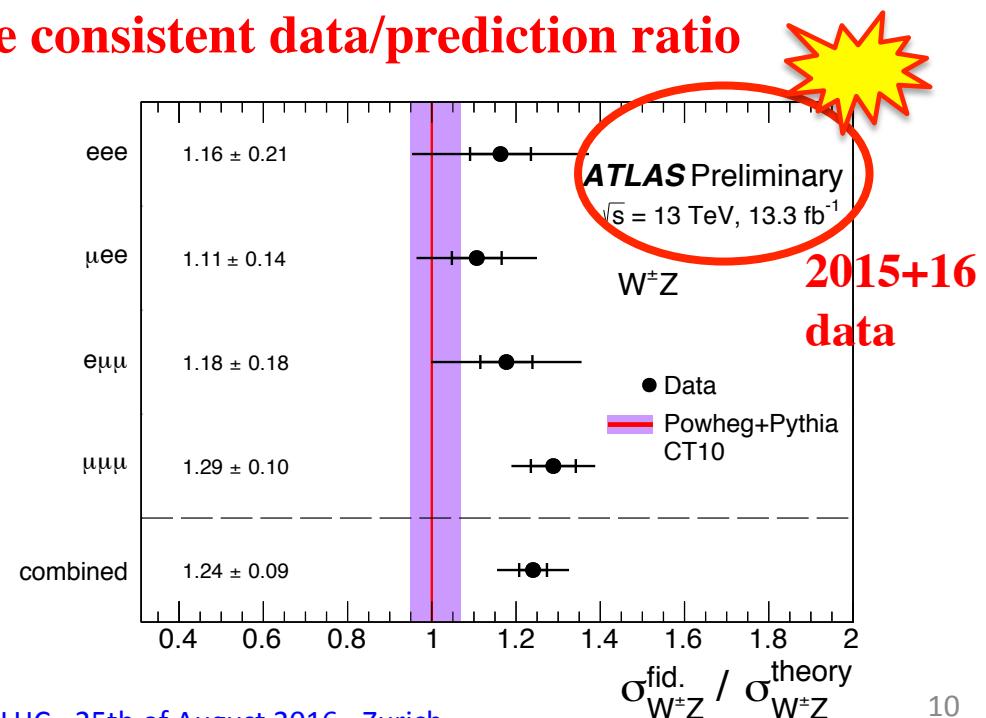
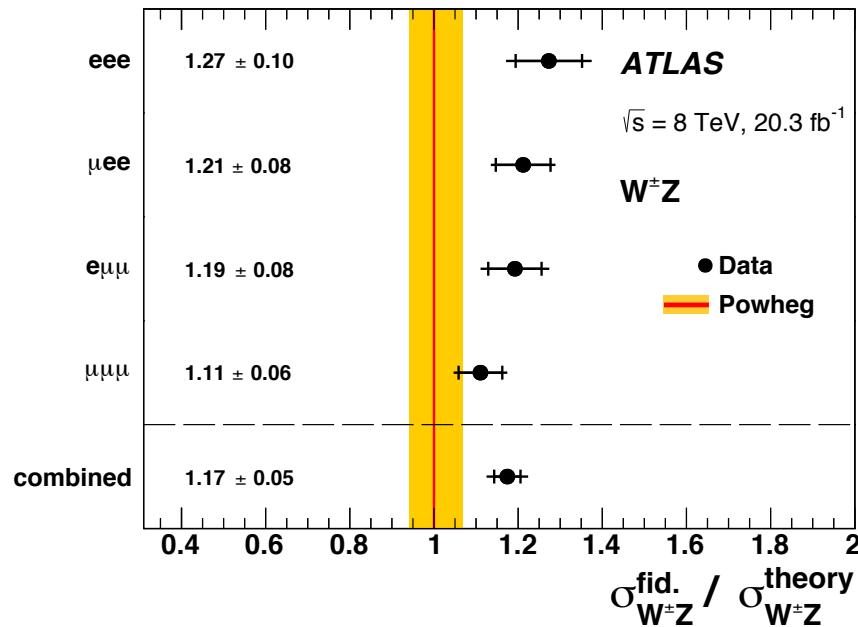
Main bkgd: **Z+jets** (data driven), **ZZ**

◆ $\sigma_{\text{fid}}^{\text{WZ}} @ 8 \text{ TeV}$: $\sigma_{W^\pm Z \rightarrow \ell' \nu \ell \ell}^{\text{fid.}} = 35.1 \pm 0.9(\text{stat}) \pm 0.8(\text{sys}) \pm 0.8(\text{lumi}) \text{ fb}$
 $\sim 4\%$ uncertainty, similar contributions from data statistics, systematics (leptons, bkgd estimation) and luminosity

◆ $\sigma_{\text{fid}}^{\text{WZ}} @ 13 \text{ TeV}$: $\sigma_{W^\pm Z \rightarrow \ell' \nu \ell \ell}^{\text{fid.}} = 66.2 \pm 1.8(\text{stat.}) \pm 3.6(\text{sys.}) \pm 2.1(\text{lumi.}) \text{ fb}$

◆ Signal predictions @NLO : Powheg

8 & 13 TeV results give consistent data/prediction ratio

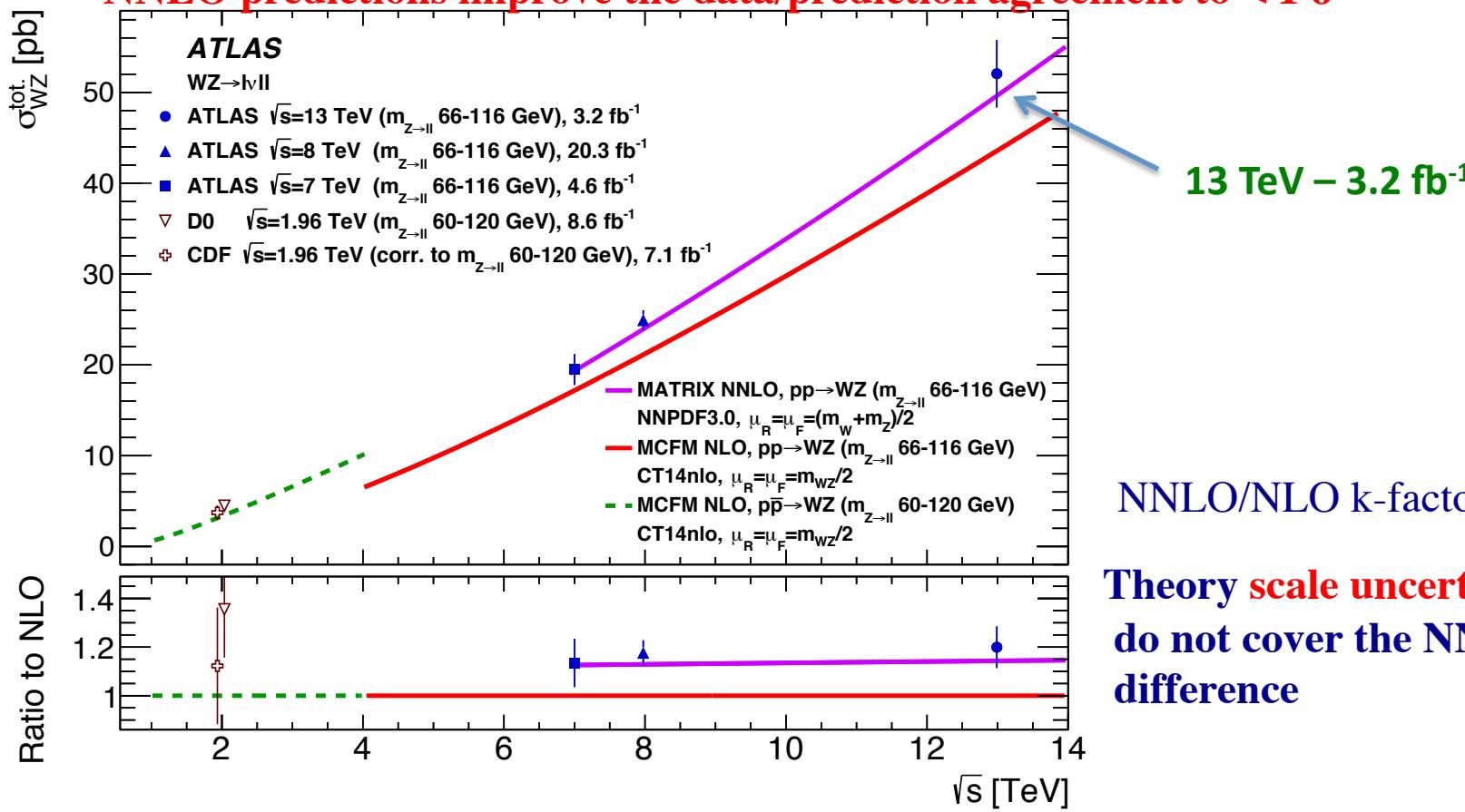


WZ total cross section

arXiv:1606.04017 accepted by PLB

- ◆ comparison to recent NNLO calculation by Grazzini et al. ([arXiv:1604.08576](#)) have explained the significant excess initially published by ATLAS @ 8 TeV

NNLO predictions improve the data/prediction agreement to < 1 σ



Higher orders needed to describe data

The Standard Model works very well ... too well !



WZ differential cross sections @ $\sqrt{s} = 8$ and 13 TeV

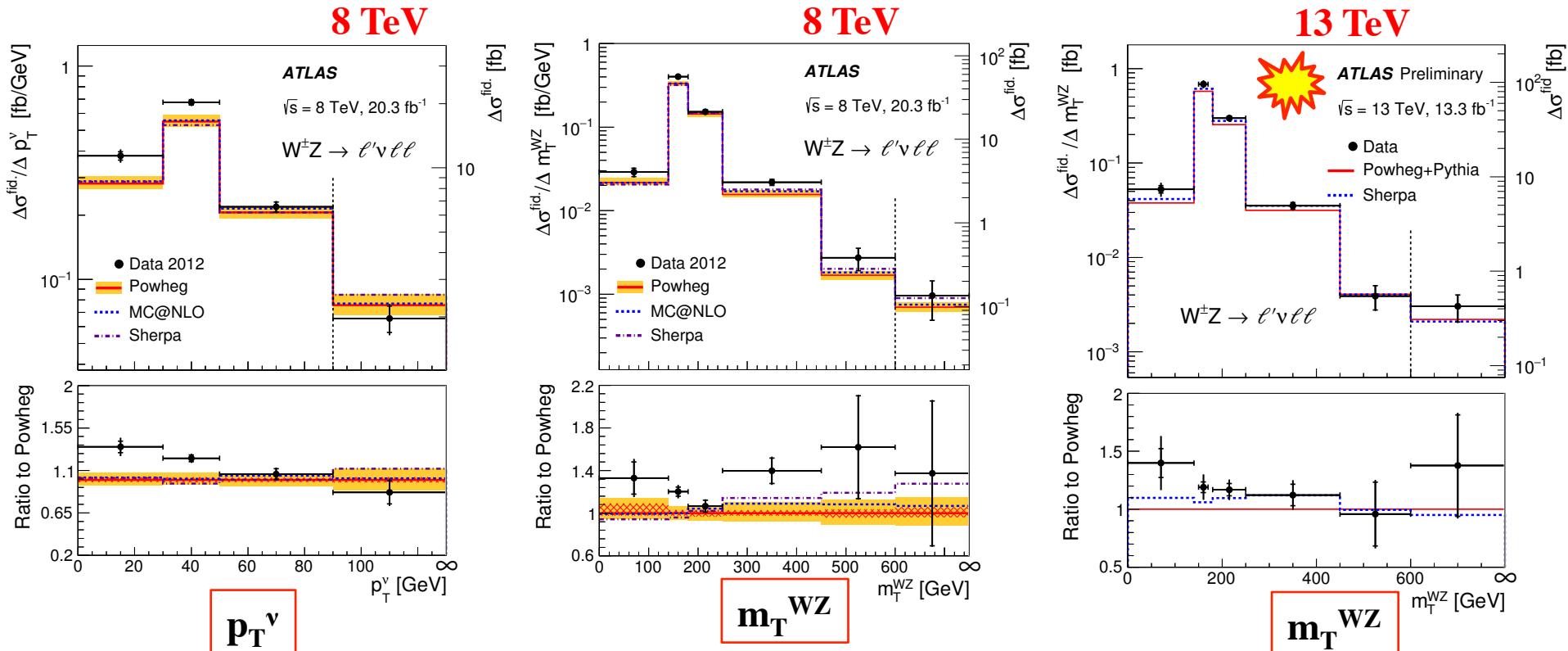
Phys. Rev. D 93, 092004 (2016)

ATLAS-CONF-2016-043

- ◆ Modelling issue in the low p_T^{ν} : NNLO differential predictions desirable

Otherwise no obvious discrepancies in shapes wrt NLO generators
(**PowHeg, MC@NLO and Sherpa**)

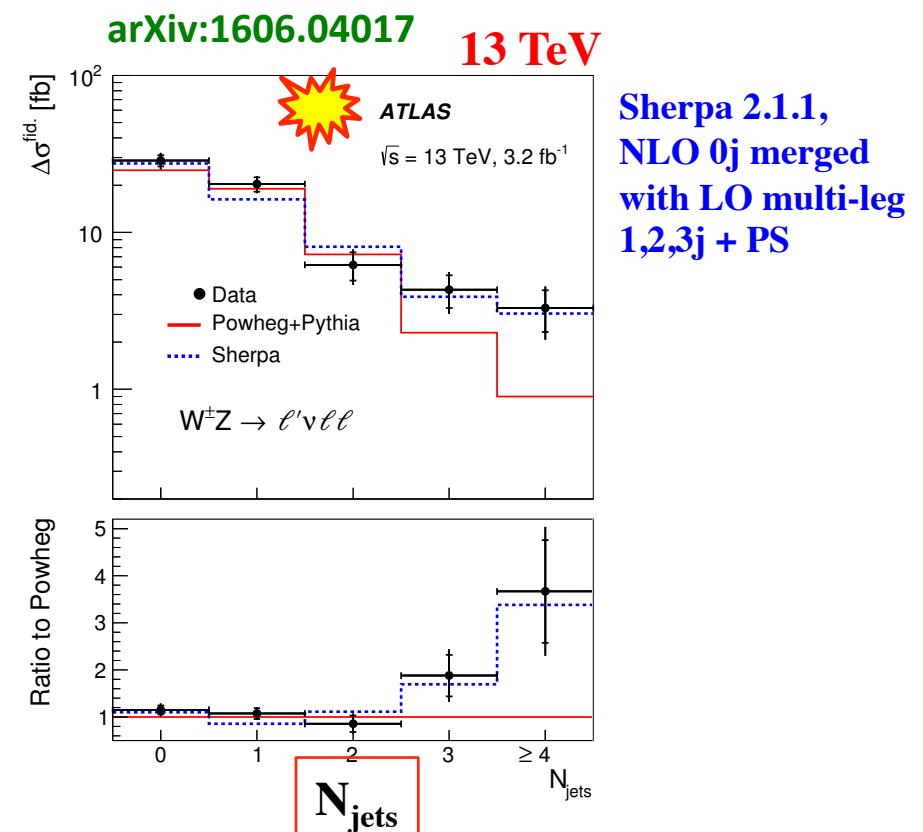
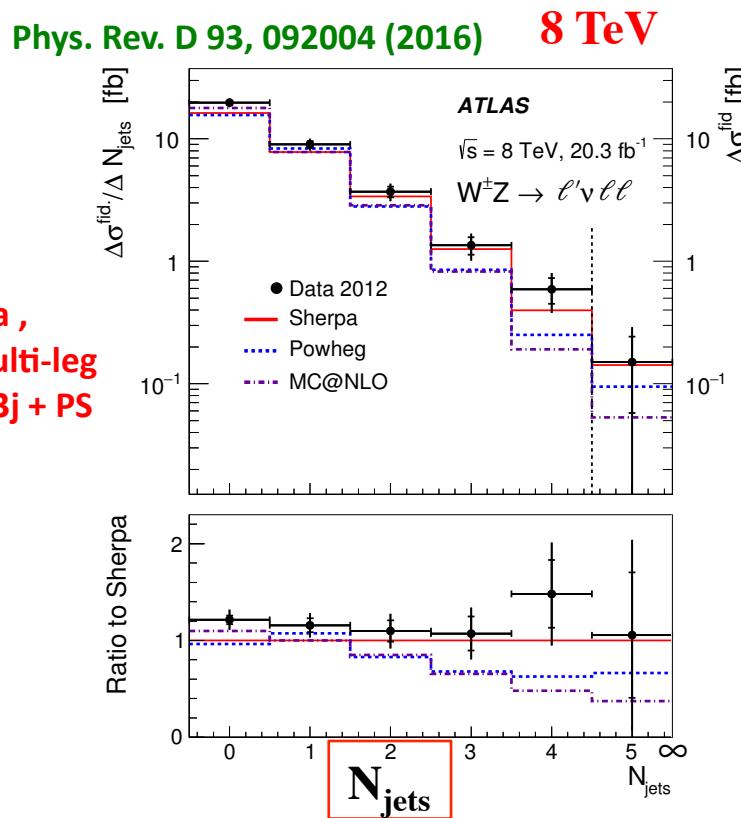
- ◆ To extract aTGC use m_T^{WZ} (smaller predicted QCD & EW h.o. effects than p_T^Z)



WZ differential cross sections @ $\sqrt{s} = 8$ and 13 TeV

- ◆ Investigate (exclusive) jet multiplicity ($p_T > 25$ GeV) :

help to understand jet-veto modelling in other channels (WW, ZZ) and bkgds in $VV+jets$ searches



- ◆ In both analyses ($\sqrt{s} = 8$ and 13 TeV) :

multi-leg formalism (Sherpa) describe high jet multiplicities well, better than NLO+PS approach

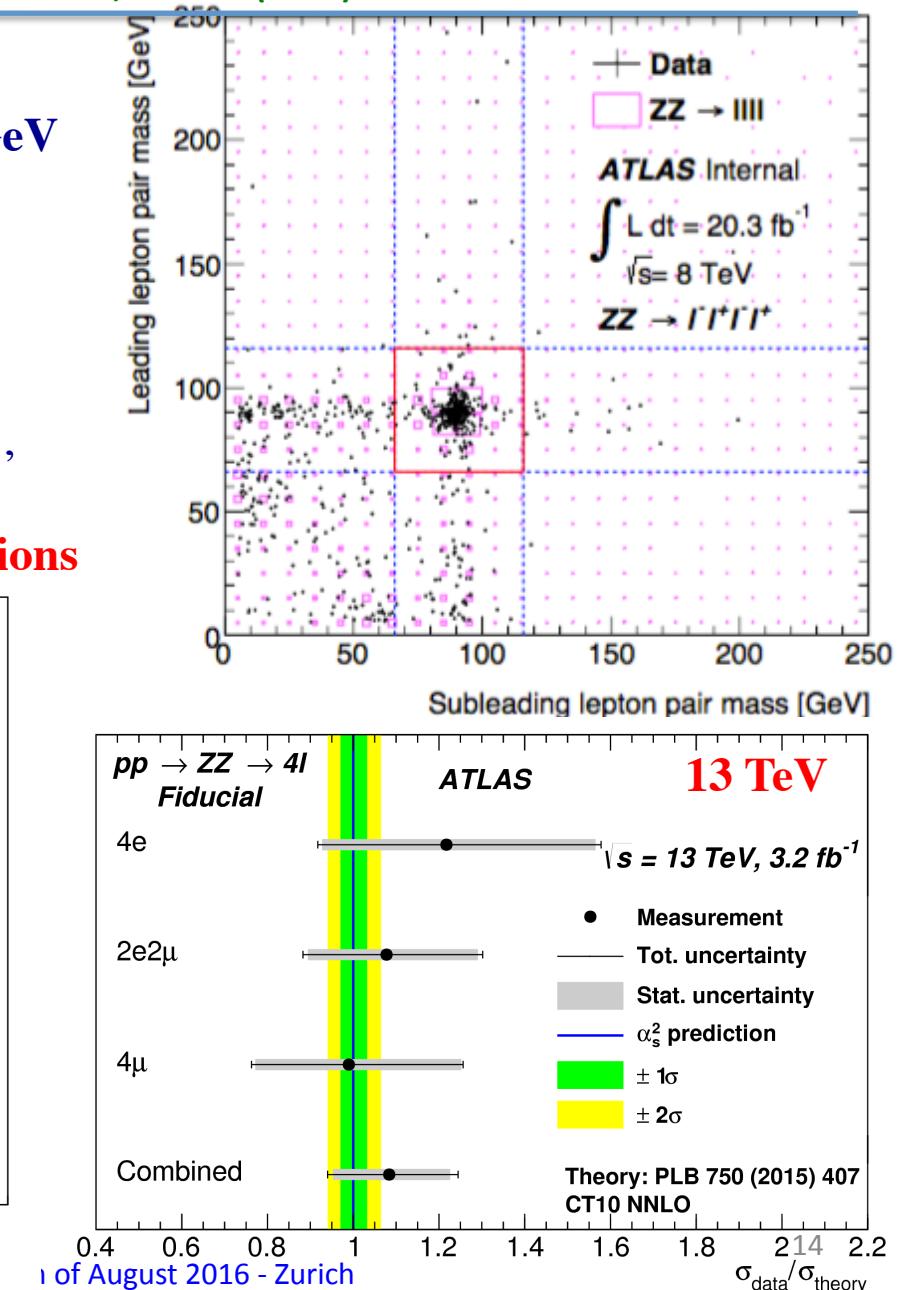
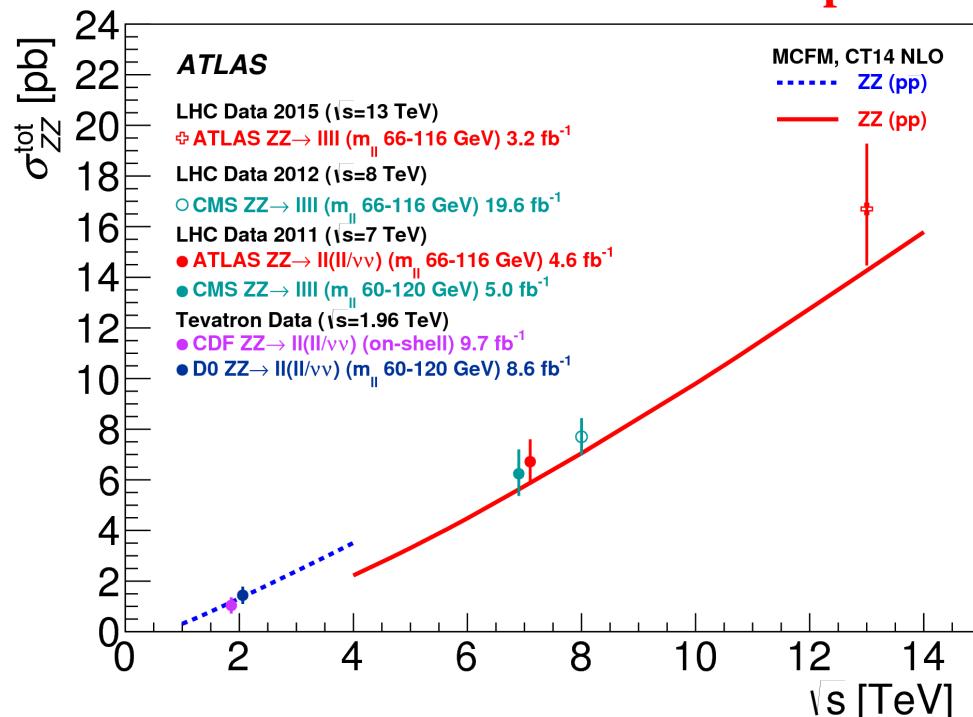
On-shell ZZ cross section @ $\sqrt{s} = 8$ and 13 TeV

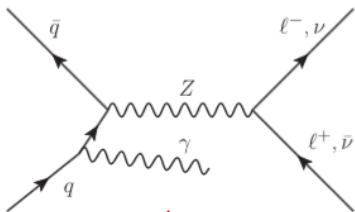
Phys. Rev. Lett. 116, 101801 (2016)

ATLAS-CONF-2013-020

- ◆ Channels : $4l, l = e, \mu$
both lepton pairs with **66 GeV $< m_{ll} < 116$ GeV**
- ◆ Clean process:
@ 8 TeV 305 candidates 7% bkgd
@ 13 TeV 63 candidates 1% bkgd
- ◆ Cross section : **14%** uncertainty (@ 13 TeV),
statistically limited

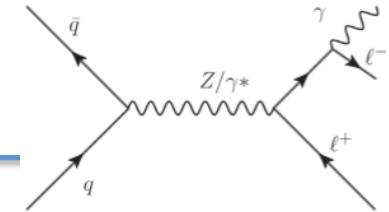
Measured σ consistent with predictions





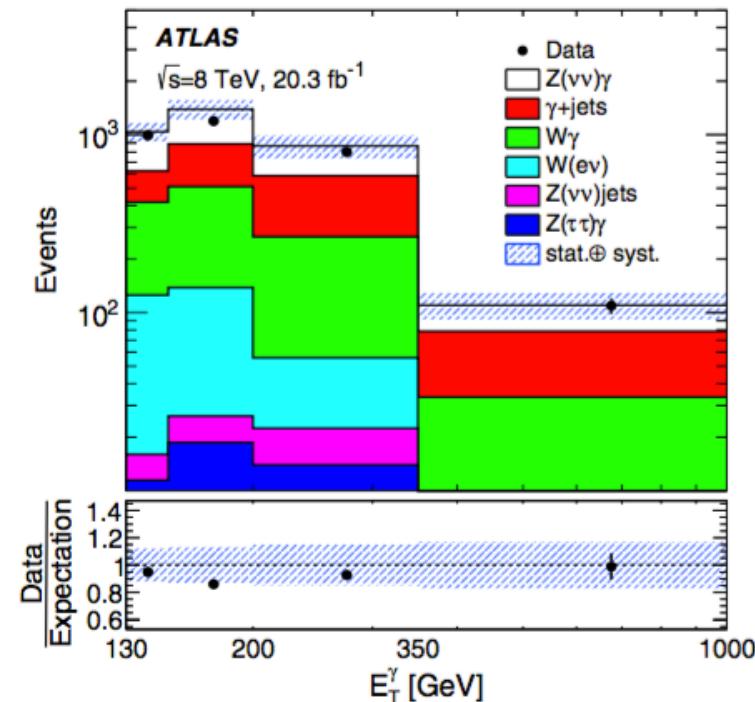
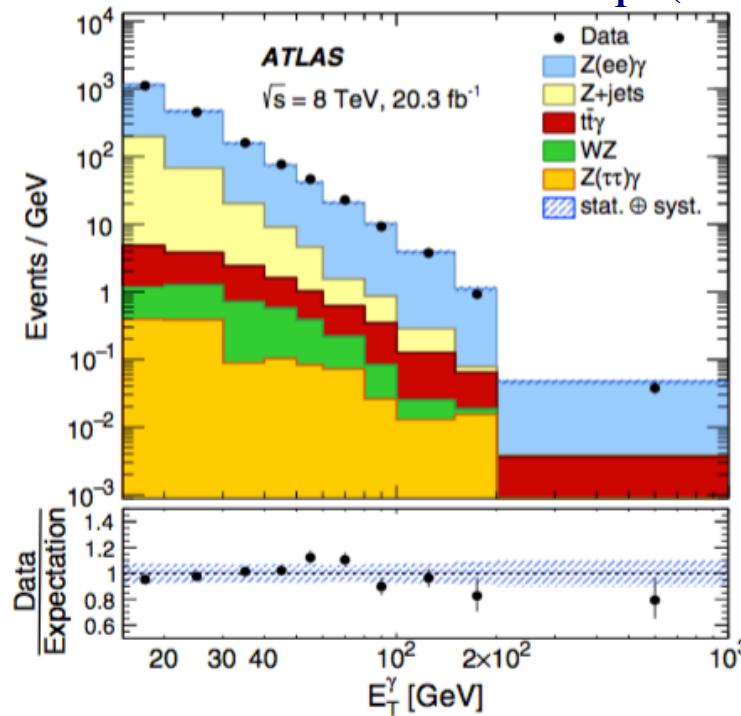
8 TeV $Z\gamma \sigma$ measurements ($Z \rightarrow l^+l^-$, $\nu\bar{\nu}$)

Phys. Rev. D 93, 112002 (2016)



- ◆ $Z \rightarrow ll \gamma$: two leptons $p_T > 25$ GeV, one or two γ $E_T^\gamma > 15$ GeV
major bkgd from **Z+jets** (data driven)
- ◆ $Z \rightarrow \nu\nu \gamma$: (MET (> 100 GeV), $E_T^\gamma > 130$ GeV, due to photon trigger threshold)
better statistics in high E_T^γ (important for aTGC fits) but higher bkgd
major bkgds from $\gamma + \text{jet}$ and **W+gamma** (both data driven)
- ◆ Exclusive channel defined with jet veto (for $p_T^{\text{jet}} > 30$ GeV)

Detector-level distributions of E_T^γ (used for aTGC measurements) :



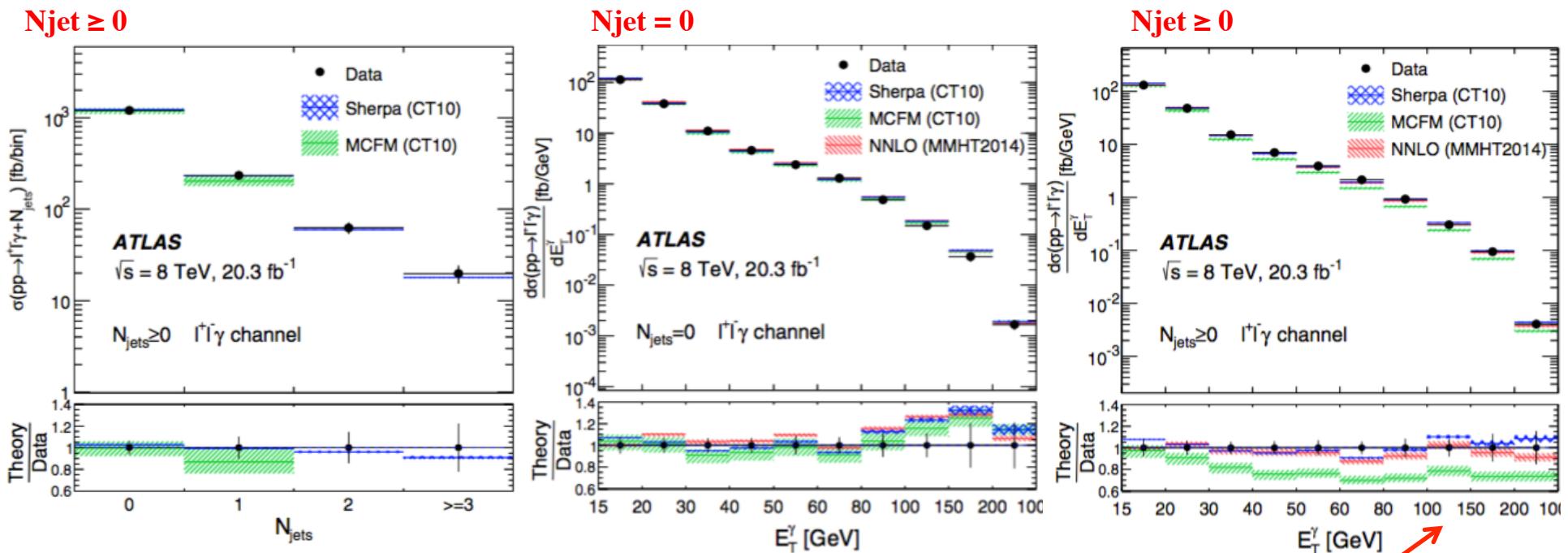
Z γ σ measurements (Z \rightarrow ll) @ $\sqrt{s} = 8$ TeV

Phys. Rev. D 93, 112002 (2016)

- ◆ Fiducial cross section: $\sigma = 1507 \pm 10(\text{stat})^{+78}_{-73}(\text{syst})^{+29}_{-28}(\text{lumi}) \text{ fb}$
uncertainty systematics dominated ($\sim 5\%$, main: e.m. energy scale, lepton isolation & i.p.)

Consistent with NNLO prediction ($\sim 2\%$ uncertainty)

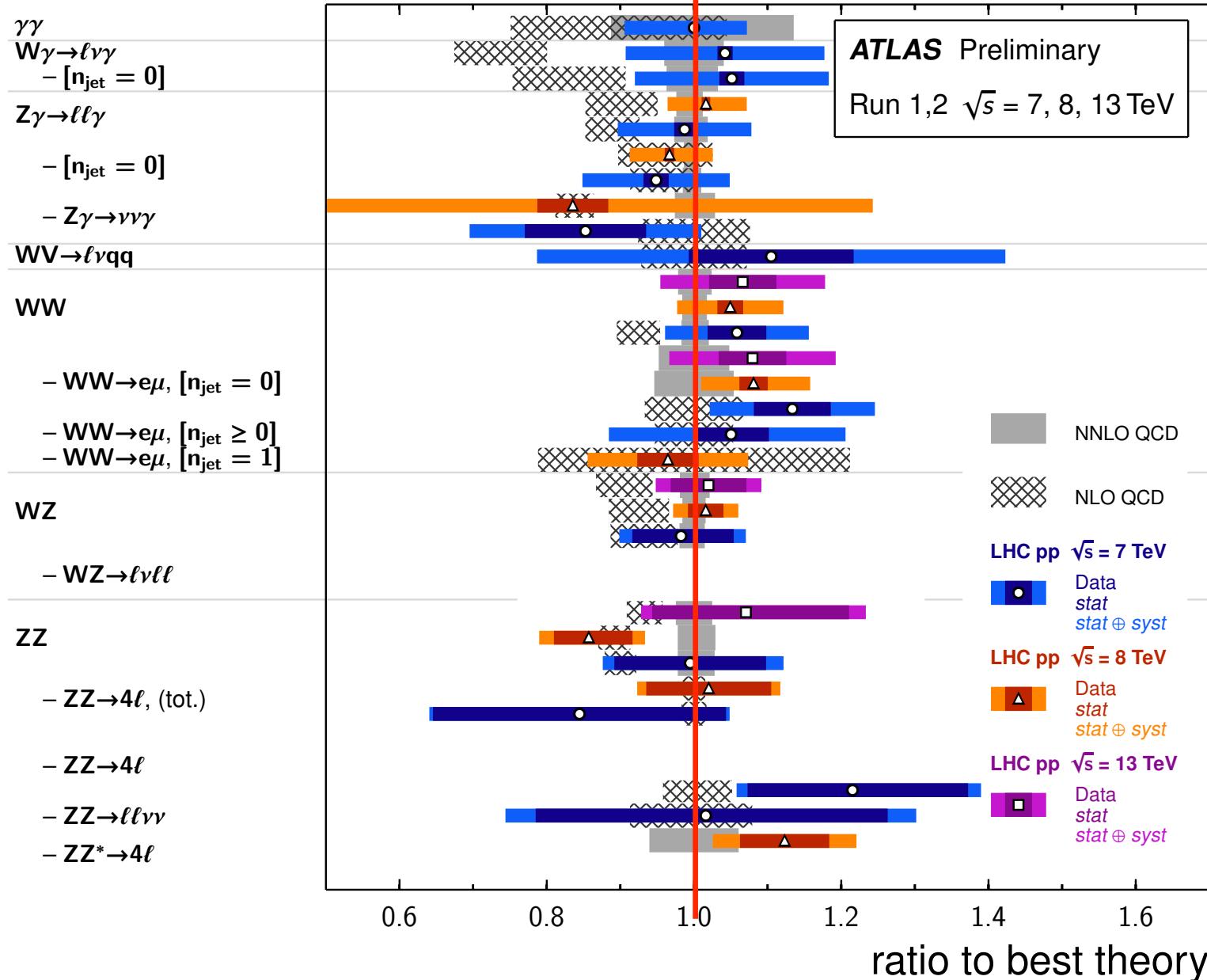
Differential cross sections:



High order QCD describe data well, NNLO effects clearly visible

Diboson Cross Section Measurements

Status: August 2016



Triple Gauge Couplings (TGC) description

- ◆ Effective lagrangian/vertex function formalism with gauge invariant, C/P conserving terms :

- Anomalous TGC ζ_i :

$$\text{CHARGED } (WWZ, WW\gamma) : \zeta_i \equiv g_1 - 1, k^V - 1, \lambda^V \quad V \equiv Z, \gamma$$

$$\text{NEUTRAL } (ZZZ, Z\gamma\gamma, ZZ\gamma) : \zeta_i \equiv h_3^V, h_4^V, f_4^V, f_5^V \quad \text{in SM} : \zeta_i = 0$$

- To avoid **unitarity violation** @ high energy → introduce a cutoff scale Λ_{FF} replacing ζ_i

$$\zeta_i \rightarrow \frac{\zeta_i}{(1 + \hat{s}/\Lambda_{FF}^2)}^n$$

- ◆ Operator $O_i^{(d)}$ expansion (EFT) approach

- Valid description for energies $E \ll \Lambda$

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

- Leading **CP-even** gauge boson operators ($d = 6$) generating **TGC**

in SM : $c_i = 0$

→ Study coefficients of O_{WWW}, O_W, O_B :

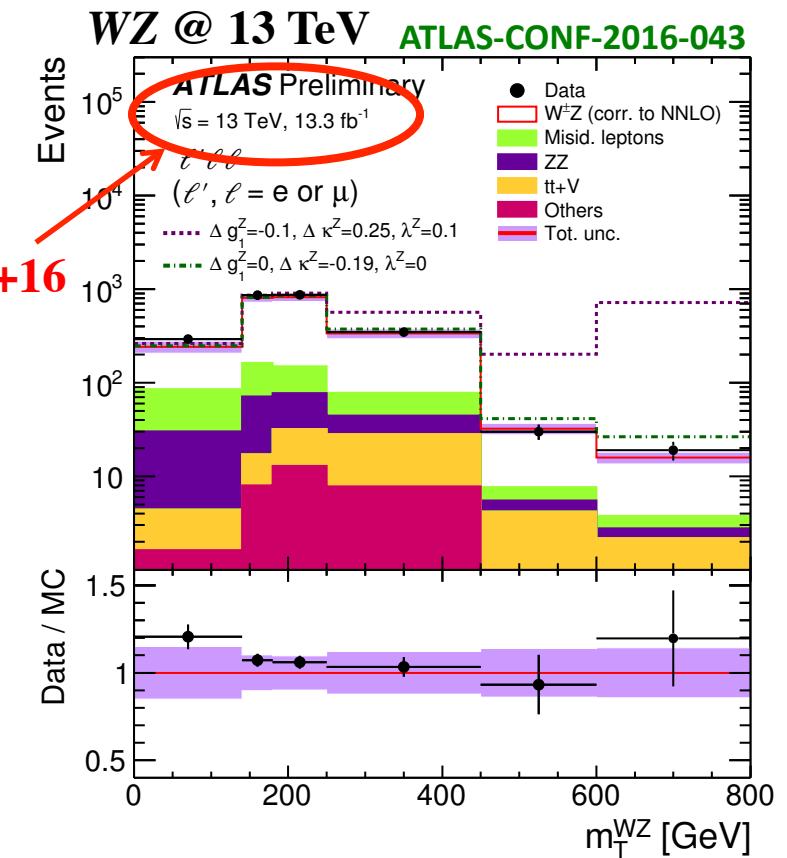
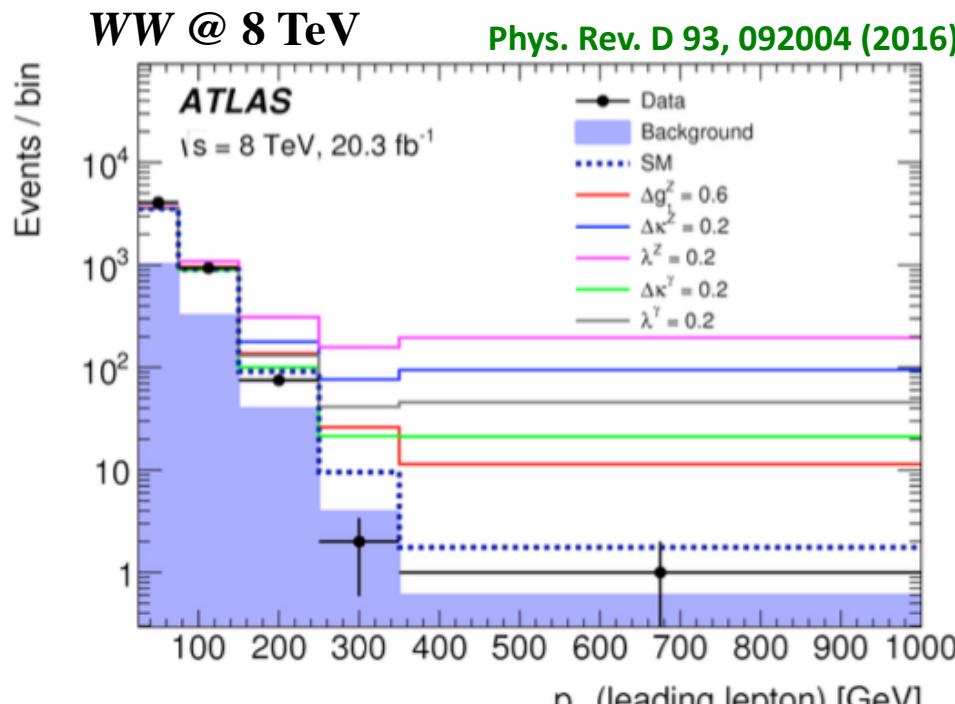
$$c_{WWW}/\Lambda^2, c_W/\Lambda^2, c_B/\Lambda^2$$

$O_{WWW} = \text{Tr}[W_{\mu\nu} W^{\nu\rho} W_\rho^\mu]$
$O_W = (D_\mu \Phi)^\dagger W^{\mu\nu} (D_\nu \Phi)$
$O_B = (D_\mu \Phi)^\dagger B^{\mu\nu} (D_\nu \Phi)$

- CHARGED ζ_i related to $c_{WWW}/\Lambda^2, c_W/\Lambda^2, c_B/\Lambda^2$
- NEUTRAL couplings only at $d = 8$:
- Some operators affect both Higgs and TGC (WW and WZ)

Charged aTGCs from 8 TeV WW, 8 & 13 TeV WZ

- ◆ Extracted fitting detector-level distributions
(p_T (lead lepton) in WW case, m_T^{WZ} in WZ)



WW @ 8 TeV

Parameter	Expected [TeV^{-2}]	Observed [TeV^{-2}]
C_{www}/Λ^2	[-7.62, 7.38]	[-4.61, 4.60]
C_B/Λ^2	[-35.8, 38.4]	[-20.9, 26.3]
C_W/Λ^2	[-12.58, 14.32]	[-5.87, 10.54]

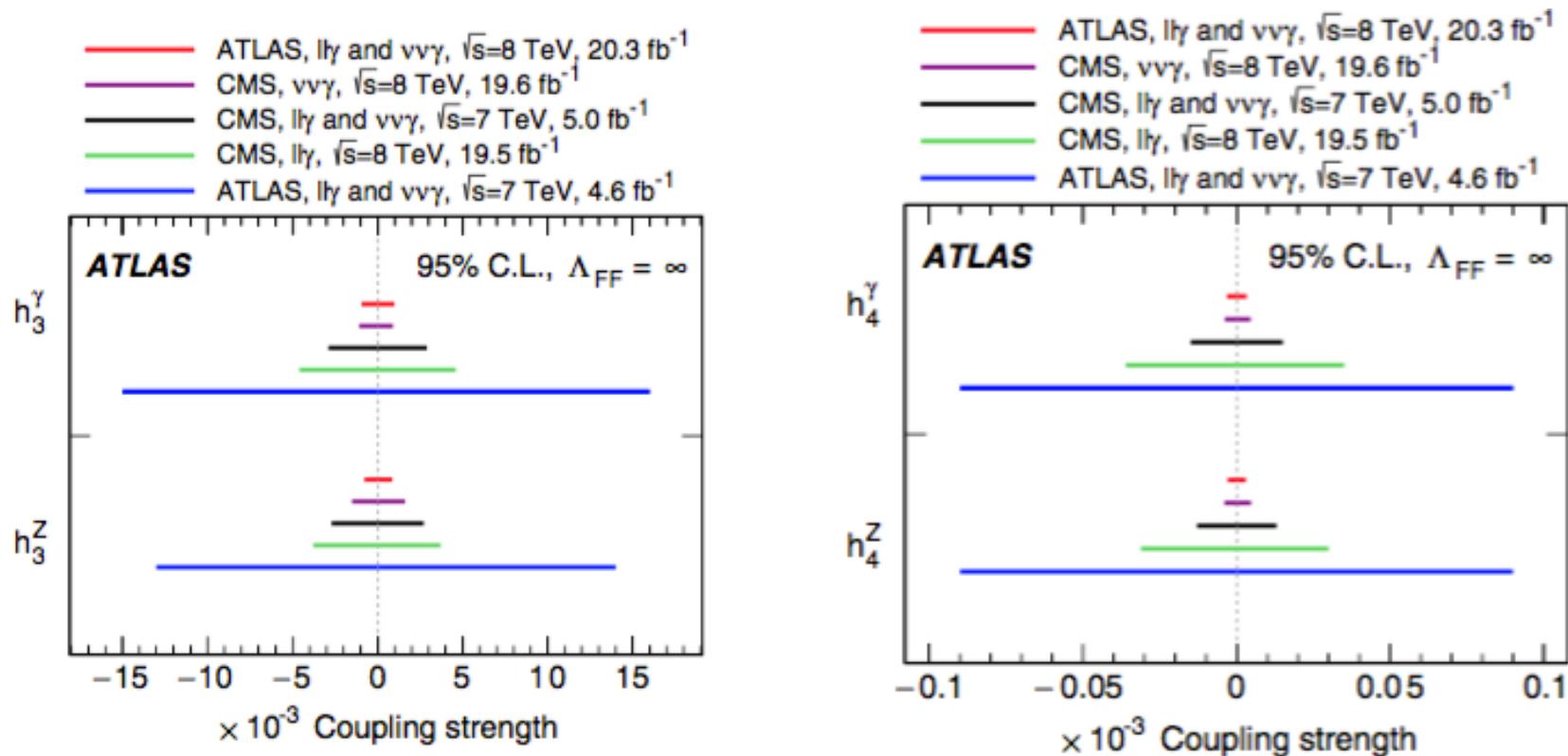
WZ @ 8+13 TeV

Coupling	Expected [TeV^{-2}]	Observed [TeV^{-2}]
$c_W/\Lambda_{\text{NP}}^2$	[-3.4; 6.9]	[-3.6; 7.3]
$c_B/\Lambda_{\text{NP}}^2$	[-221; 166]	[-253; 136]
$c_{www}/\Lambda_{\text{NP}}^2$	[-3.2; 3.0]	[-3.3; 3.2]

Neutral aTGCs from $Z\gamma$ @ $\sqrt{s} = 8$ TeV

Phys. Rev. D 93, 112002 (2016)

- ◆ Use event yield in **high E_T^γ region** (> 200 GeV ($ll\gamma$), 400 (γ)) with **Njet = 0**
- ◆ **No obvious excess wrt SM** → set 1D and 2D constraints on the four CP-conserving neutral couplings $h_{3,4}^Z$ (from $ZZ\gamma$ vertex) and $h_{3,4}^\gamma$ ($Z\gamma\gamma$)

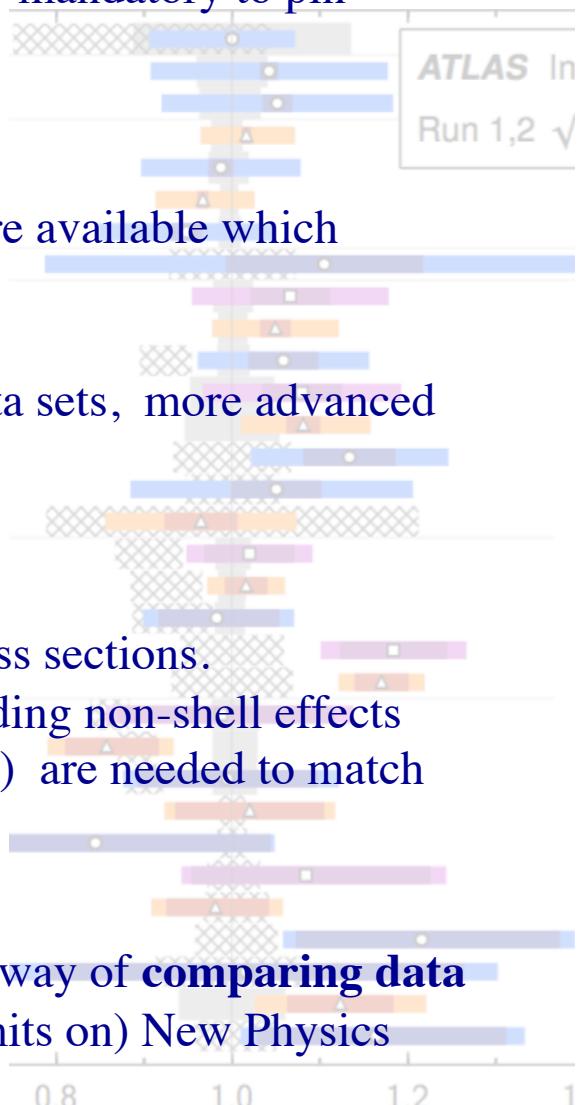


Conclusion and Outlook

- ◆ Understanding of the production of 2 or more gauge bosons is mandatory to pin down the SM and search for New Physics

From the experimental point of view:

- ◆ LHC has produced many data → many experimental results are available which challenge the precision of the theoretical predictions (@ 8 TeV : WW: 7%, WZ: 4%, Z γ : 6%, ZZ: 11%)
- ◆ Significant improvement is expected from the use of larger data sets, more advanced analysis techniques, additional variables (i.e. angular).

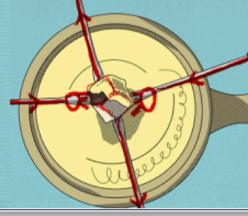


From the theoretical point of view:

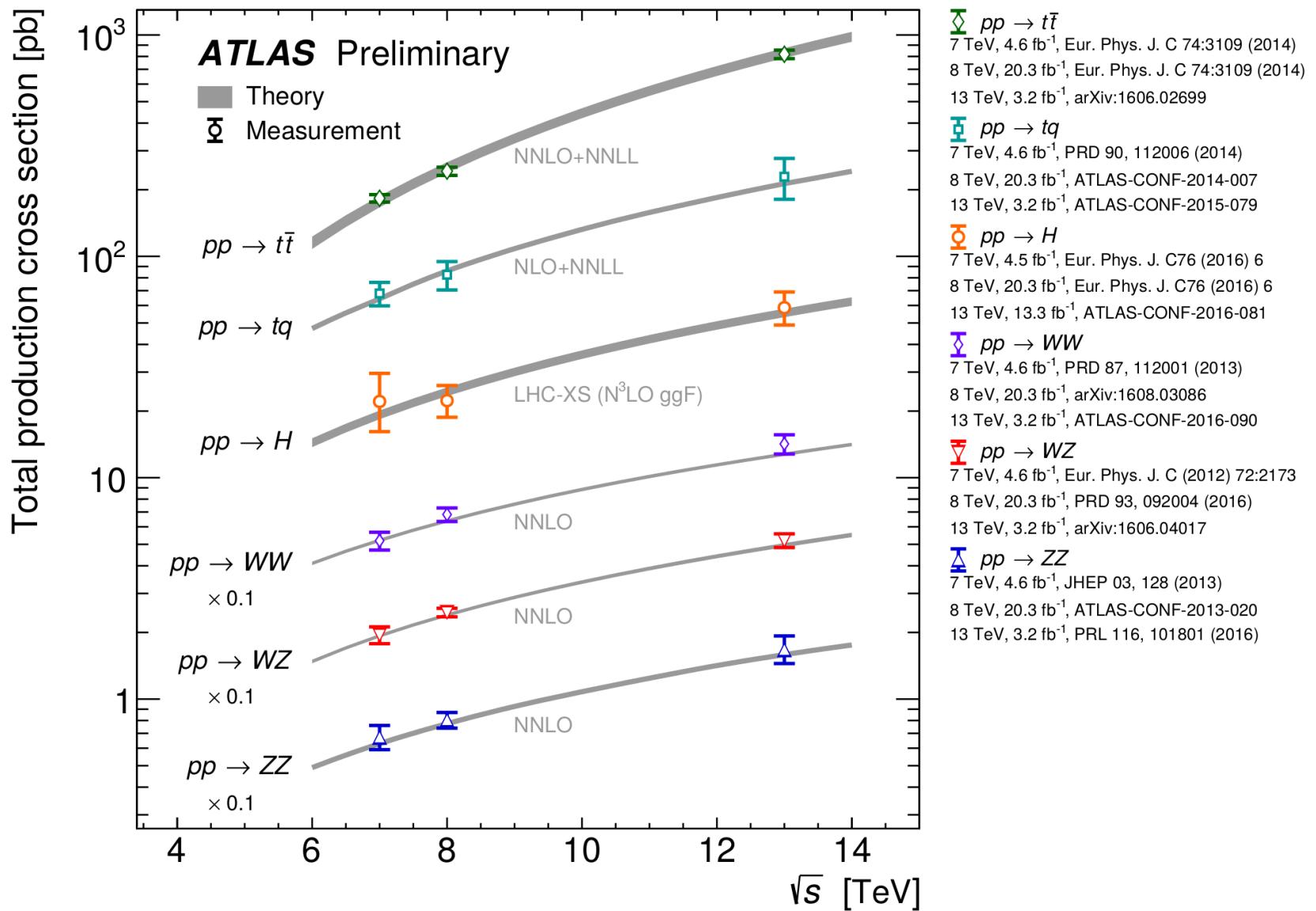
- ◆ Much progress in theory calculations in particular for total cross sections.
- ◆ Full NNLO QCD calculations and NLO EW corrections including non-shell effects and differential distributions (in particular of angular variables) are needed to match the improving experimental precision
- ◆ Other key aspects are the understanding of the most effective way of **comparing data with theory** and more **comprehensive ways** of extracting (limits on) New Physics

QCD@LHC

22ND-26TH AUGUST
INTERNATIONAL CONFERENCE ZURICH 2016



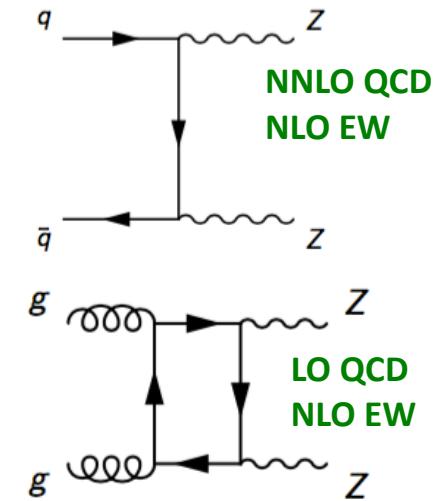
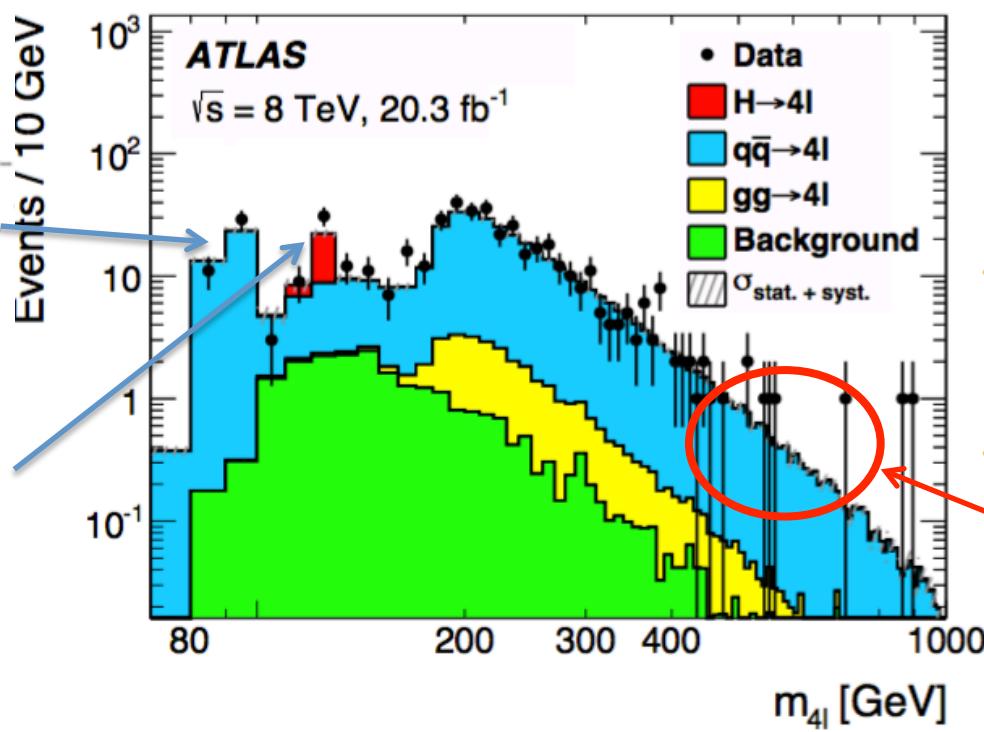
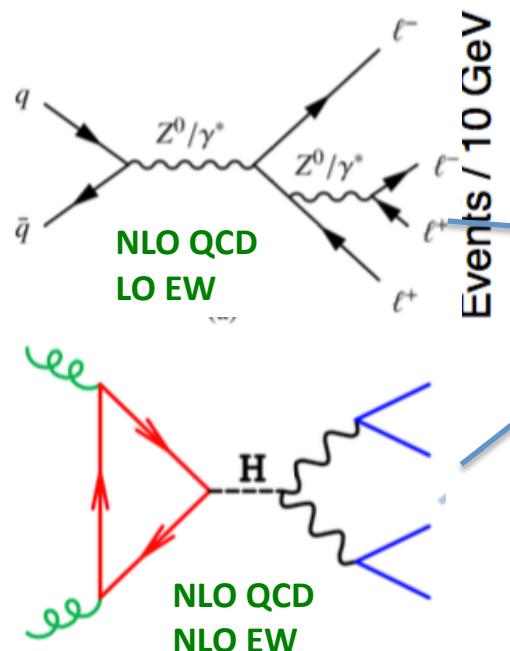
Back-up



Inclusive 4 lepton analysis @ $\sqrt{s} = 8 \text{ TeV}$

Physics Letters B 753 (2016) 552-572

- ❖ Require 4 leptons (e or μ), **loose cut on masses of dilepton pair**, low p_T thresholds for 3rd/4th leptons, \rightarrow 476 candidates with 5% bkgd
- ❖ Test SM in a wide range $80 < m(4l) < 1000 \text{ GeV}$ including interference effects



Region for Higgs width study (interference between $gg \rightarrow 4l$ and off-shell Higgs)

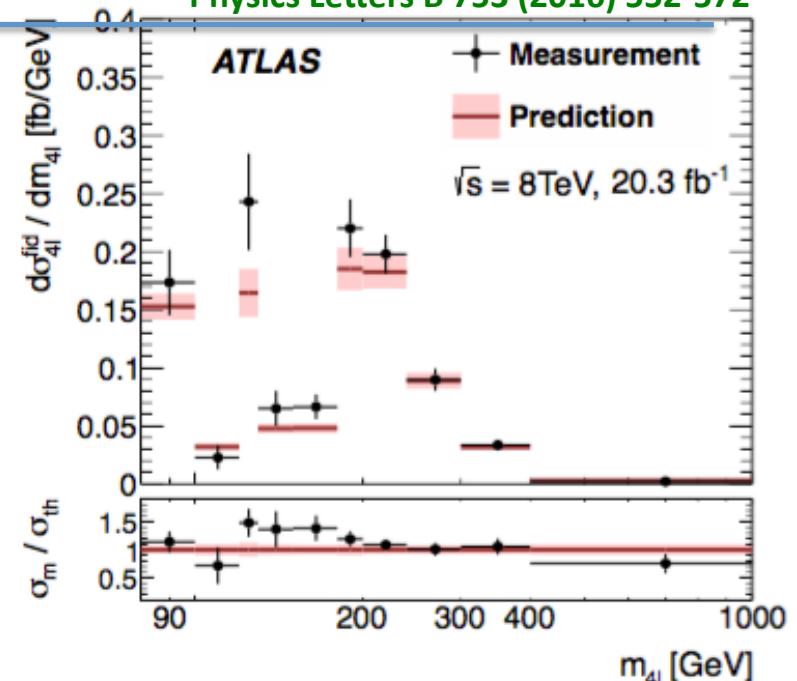
Inclusive 4 lepton analysis @ $\sqrt{s} = 8$ TeV

Physics Letters B 753 (2016) 552-572

◆ Unfolded m_{4l} spectrum in fiducial region:

Predictions:

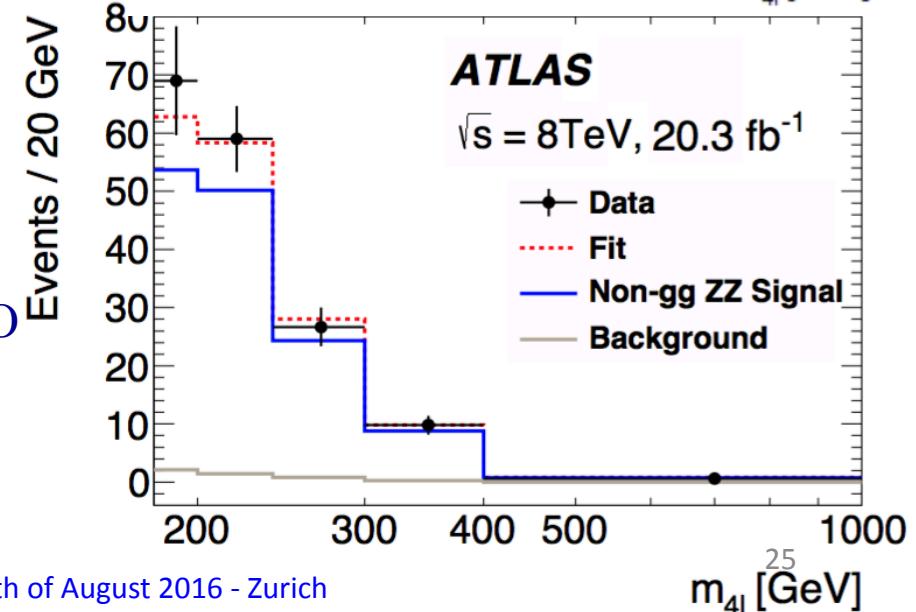
- Higgs pole and on-shell ZZ scaled to NNLO predictions
- PowHeg MC (NLO+PS) to predict signal acceptance
- NLO EWK corrections are applied

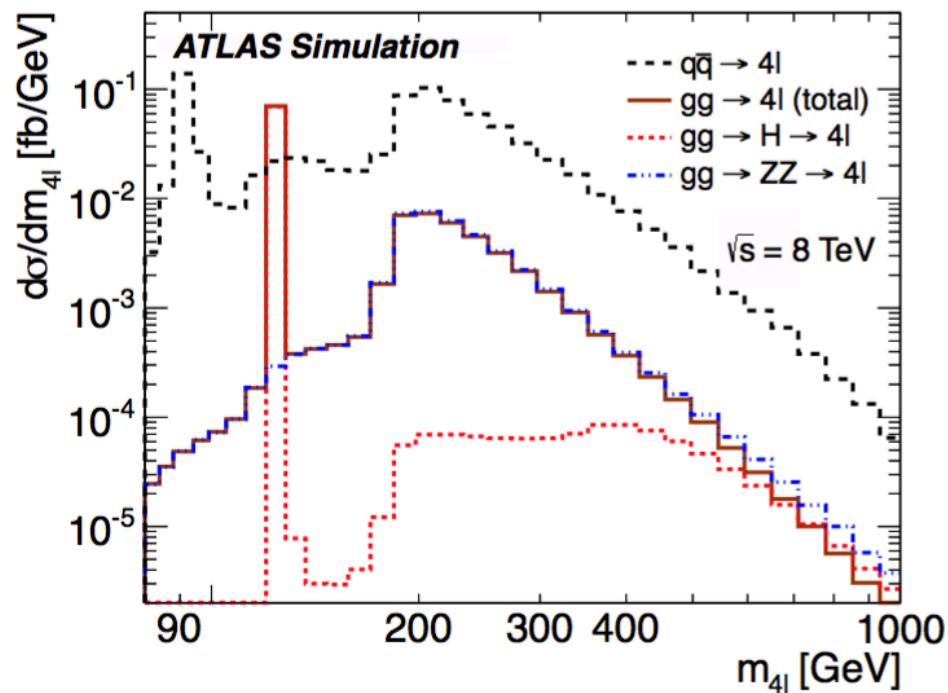


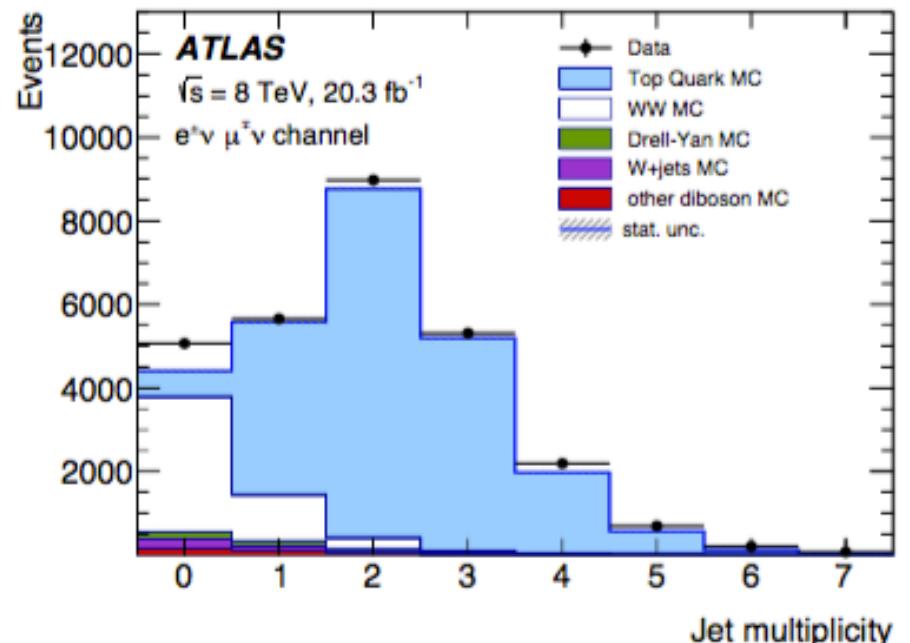
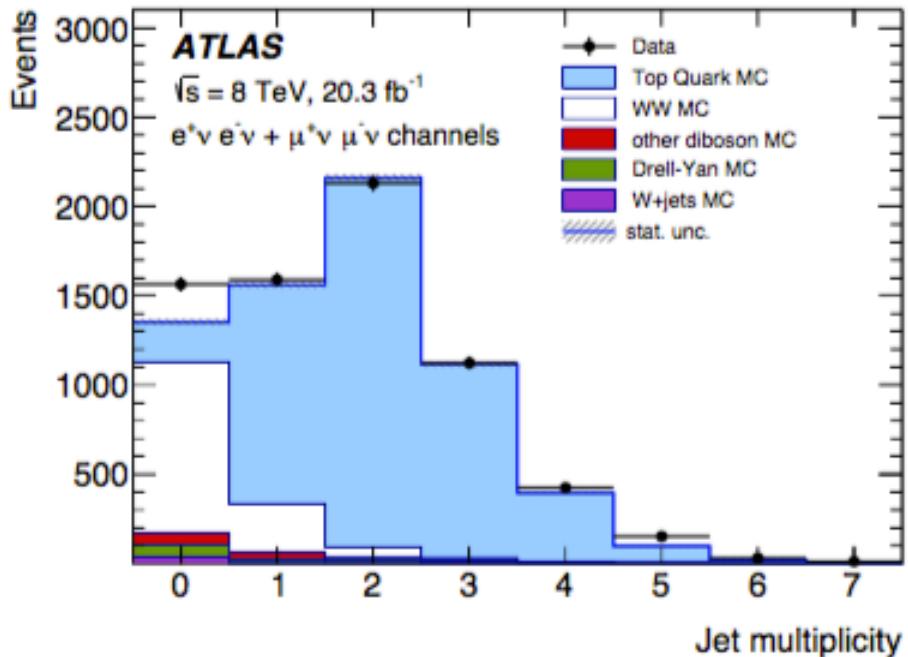
◆ Extract gg → 4l contribution in the region > 180 GeV

$$\mu = \sigma_{gg}^{\text{meas}} / \sigma_{gg}^{\text{LO}} = 2.4 \pm 1.0_{\text{stat}} \pm 0.5_{\text{syst}} \pm 0.8_{\text{th}}$$

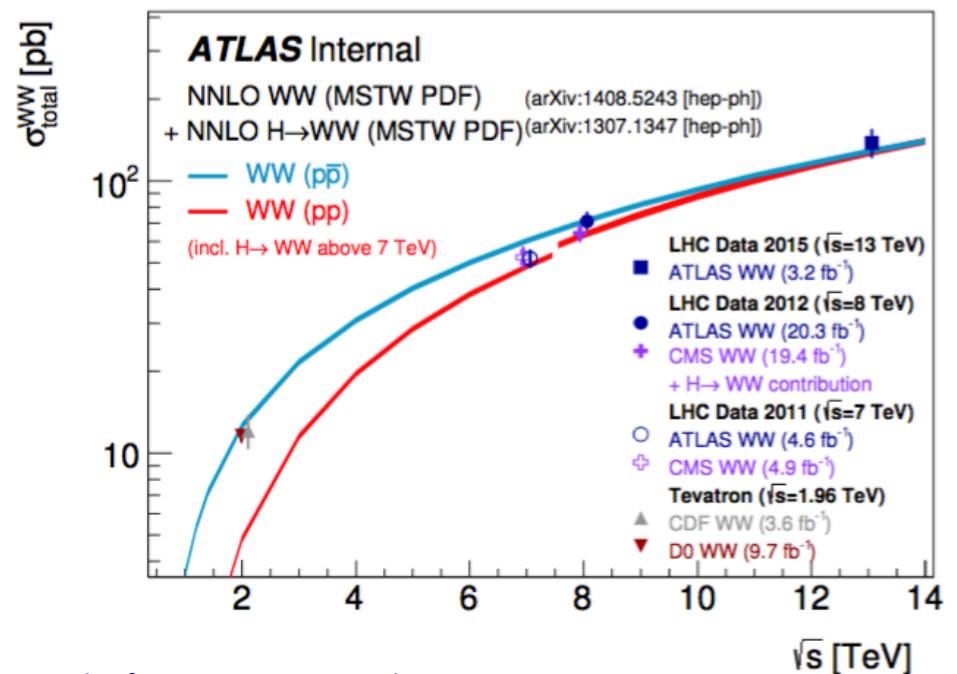
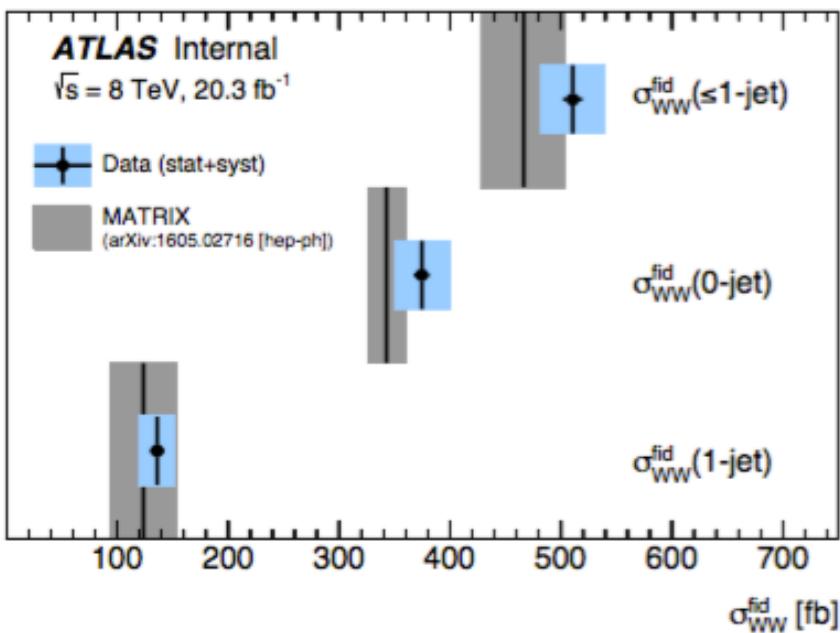
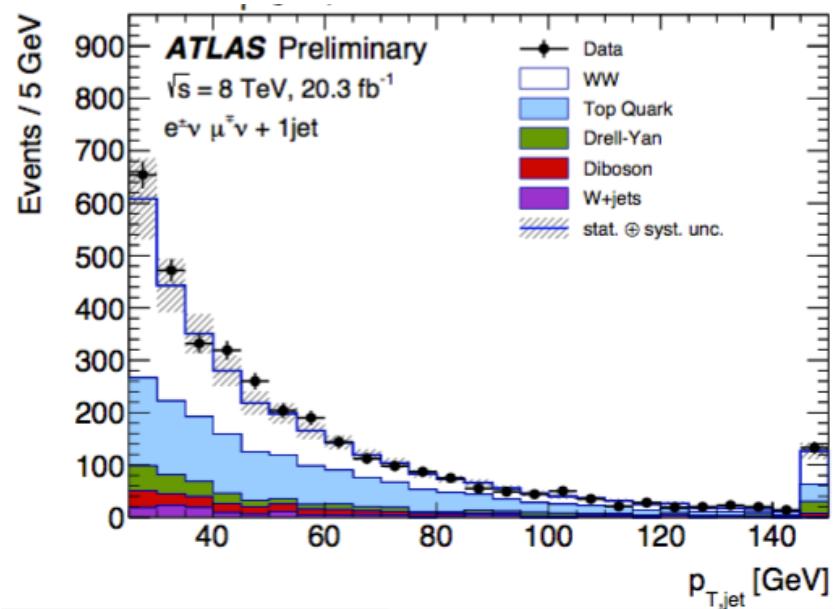
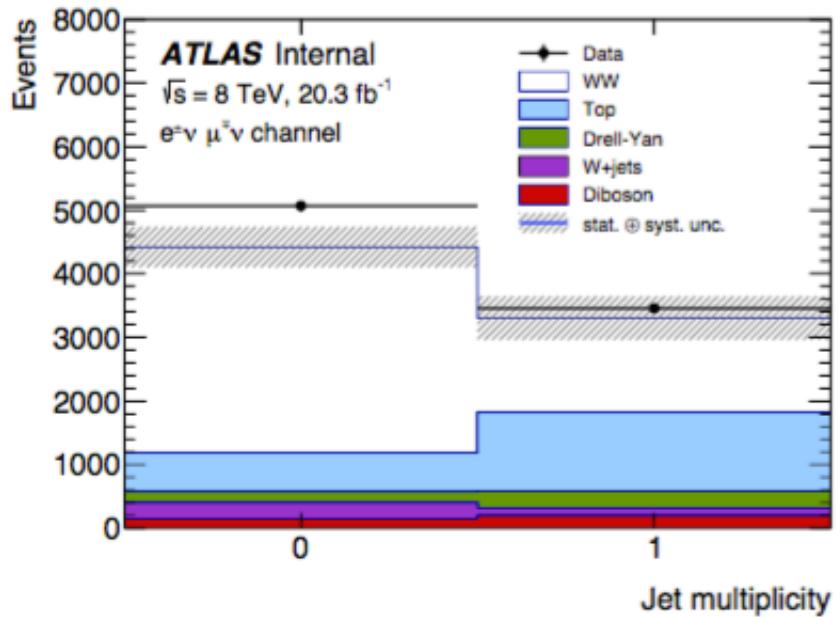
Compatible with recent calculation of NLO/LO k-factor of 1.5-2 (PhysRevD.92.094028)







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



process	WW+1-jet			WW+0-jet		
Observed Events	3458			5067		
Total expected events (Signal + background)	3310	\pm 50	\pm 340	4420	\pm 30	\pm 320
WW signal	1490	\pm 10	\pm 330	3240	\pm 10	\pm 280
Top Quark	1236	\pm 43	\pm 49	609	\pm 18	\pm 52
W+jets	121	\pm 15	\pm 50	250	\pm 20	\pm 140
Drell-Yan	267	\pm 12	\pm 49	175	\pm 3	\pm 18
Other diboson	195	\pm 5	\pm 53	150	\pm 4	\pm 30
Total background	1820	\pm 50	\pm 100	1180	\pm 30	\pm 150

	$\sigma(C_{WW}) [\%]$			$\sigma(A_{WW}) [\%]$			$\sigma(C_{WW} \times A_{WW}) [\%]$		
	$e\mu$	ee	$\mu\mu$	$e\mu$	ee	$\mu\mu$	$e\mu$	ee	$\mu\mu$
PDF	0.10	0.34	0.13	0.81	0.94	0.93	0.85	1.3	0.98
EWK corrections (SF _{EW})	0.01	0.06	0.04	0.46	0.41	0.43	0.47	0.34	0.40
Jet veto	—	—	—	3.4	3.4	3.4	3.4	3.4	3.4
Scale	0.62	0.62	0.62	0.22	0.22	0.22	0.66	0.66	0.66
Soft QCD	0.35	0.92	0.80	2.5	2.6	2.7	2.5	3.0	2.9
Total	0.70	1.2	1.0	4.3	4.4	4.5	4.4	4.8	4.6

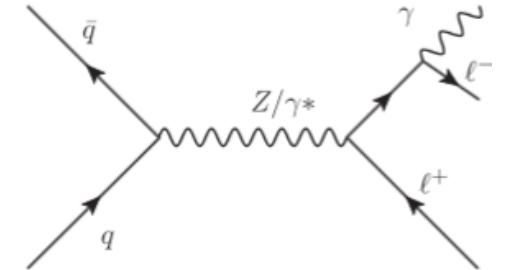
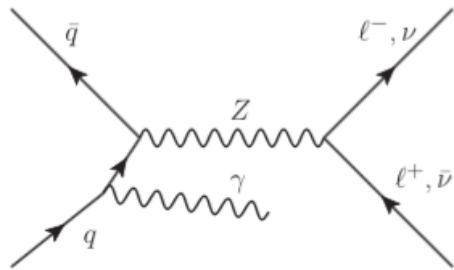


TABLE VII. Relative systematic uncertainties, in percentages, in the signal correction factor C for each channel in the inclusive $N_{\text{jets}} \geq 0$ (exclusive $N_{\text{jets}} = 0$) measurement.

	$e^+e^-\gamma$	$\mu^+\mu^-\gamma$	$\nu\bar{\nu}\gamma$	$e^+e^-\gamma\gamma$	$\mu^+\mu^-\gamma\gamma$	$\nu\bar{\nu}\gamma\gamma$
MC statistical uncertainty	0.3 (0.3)	0.2 (0.3)	0.1 (0.1)	1.9 (2.3)	1.8 (2.1)	0.6 (0.8)
Efficiencies:						
Trigger	0.2 (0.2)	0.5 (0.5)	1.9 (1.9)	0.1 (0.1)	0.5 (0.5)	0.2 (0.2)
Photon identification	1.5 (1.5)	1.5 (1.5)	0.5 (0.5)	2.1 (2.1)	2.1 (2.1)	1.9 (1.9)
Photon isolation	0.5 (0.5)	0.5 (0.5)	4.5 (4.3)	1.2 (1.2)	1.2 (1.2)	2.8 (2.8)
Lepton reconstruction and identification	1.6 (1.6)	0.9 (0.9)	– (–)	1.6 (1.6)	0.9 (0.9)	– (–)
Lepton isolation and impact parameter	2.2 (2.2)	2.2 (2.2)	– (–)	2.2 (2.2)	2.2 (2.2)	– (–)
Jet vertex fraction	– (0.5)	– (0.6)	– (0.1)	– (0.5)	– (0.6)	– (0.2)
Energy/momentum scale and resolution:						
Electromagnetic energy scale	2.3 (2.5)	1.2 (1.3)	2.1 (2.4)	2.5 (2.7)	1.8 (1.9)	2.0 (2.8)
Electromagnetic energy resolution	<0.05 (<0.05)	<0.05 (<0.05)	<0.05 (0.1)	0.2 (0.3)	0.3 (0.3)	0.4 (0.5)
Muon momentum scale	– (–)	0.1 (0.2)	– (–)	– (–)	0.3 (0.2)	– (–)
Muon momentum resolution	– (–)	<0.05 (<0.05)	– (–)	– (–)	0.5 (0.5)	– (–)
Jet energy scale	– (1.9)	– (1.9)	<0.05 (2.2)	– (2.2)	– (1.8)	0.7 (2.9)
Jet energy resolution	– (1.2)	– (1.4)	<0.05 (1.0)	– (1.2)	– (0.8)	0.1 (1.9)
E_T^{miss} soft-term energy scale	– (–)	– (–)	0.3 (0.5)	– (–)	– (–)	1.3 (1.7)
E_T^{miss} soft-term energy resolution	– (–)	– (–)	<0.05 (<0.05)	– (–)	– (–)	0.4 (0.7)
Pileup simulation	0.8 (0.8)	0.6 (0.7)	0.2 (0.4)	0.8 (1.0)	1.1 (1.1)	0.6 (0.9)
Total, without MC statistical uncertainty	4.0 (4.7)	3.2 (4.1)	5.3 (5.9)	4.5 (5.3)	4.1 (4.6)	4.3 (6.0)