

Electroweak Physics at ATLAS

Géraldine Conti,
Harvard University,
on behalf of the ATLAS collaboration

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A large variety of results

W/Z Physics :

lepton charge asymmetry from W ($\sim 30\text{pb}^{-1}$, 2010)

ratio of the W and Z prod. cross section with 1 associated jet ($\sim 30\text{pb}^{-1}$, 2010)

High-Mass Drell-Yan (5fb^{-1} , 2011)

prod. cross sections :
($\sim 30\text{pb}^{-1}$, 2010):
 $W \rightarrow l\nu, Z \rightarrow ll, l = e, \mu, \tau$
W+jets, $Z/\gamma^* + \text{jets}$
inclusive μ, e
 $Wb(b)(5\text{fb}^{-1}, 2011), Z+b$

...

W polarization ($\sim 30\text{pb}^{-1}$, 2010)

$Z/\gamma^*/W p_T$ ($\sim 30\text{pb}^{-1}$, 2010)
using ϕ^* (5fb^{-1} , 2011)

τ polarization in $W \rightarrow \tau\nu$ decays ($\sim 30\text{pb}^{-1}$, 2010)

strange quark density of the proton from $W \rightarrow l\nu$ and $Z \rightarrow ll$ cross sections ($\sim 30\text{pb}^{-1}$, 2010)

Dibosons (WW, WZ, ZZ, W/Z γ) :

total and fiducial cross sections
(1fb^{-1} 2011, 5fb^{-1} 2011, 6fb^{-1} 2012)

limits on anomalous triple-gauge couplings (1fb^{-1} 2011,
 5fb^{-1} 2011, 6fb^{-1} 2012)

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...

W polarization (~30pb⁻¹, 2010)

$Z/\gamma^*/W p_T$
(~30pb⁻¹, 2010)
using ϕ^* (5fb⁻¹, 2011)

ZZ* added, new WW and ZZ results, 2012 result...

limits on anomalous triple-gauge couplings (1fb⁻¹ 2011, 5fb⁻¹ 2011, 6fb⁻¹ 2012)

Bibliography

Channel	Data	References
High mass DY	2011, 5fb^{-1}	ATLAS-CONF-2012-159
Wb(b)	2011, 5fb^{-1}	ATLAS-CONF-2012-156
Z pT with ϕ^*	2011, 5fb^{-1}	ATLAS-STDM-2012-06, to be submitted to Phys. Lett. B
WW $\rightarrow l\nu l\nu$	2011, 5fb^{-1}	arXiv:1210.2979
WW+WZ ($l\nu qq$)	2011, 5fb^{-1}	ATLAS-CONF-2012-191
WZ $\rightarrow l\nu ll$	2011, 5fb^{-1}	Eur. Phys. J. C (2012) 72:2173
W γ	2011, 1fb^{-1}	Physics Letters B, 717 (2012) 49
ZZ $\rightarrow llll$	2011, 5fb^{-1} , 2012, 6fb^{-1}	ATLAS-STDM-2012-02 to be submitted to JHEP, ATLAS-CONF-2012-090
ZZ $\rightarrow llvv$	2011, 5fb^{-1}	ATLAS-STDM-2012-02, to be submitted to JHEP
ZZ(*) total	2011, 5fb^{-1}	ATLAS-STDM-2012-02, to be submitted to JHEP
Z γ	2011, 1fb^{-1}	Physics Letters B, 717 (2012) 49

High Mass Drell-Yan (I)

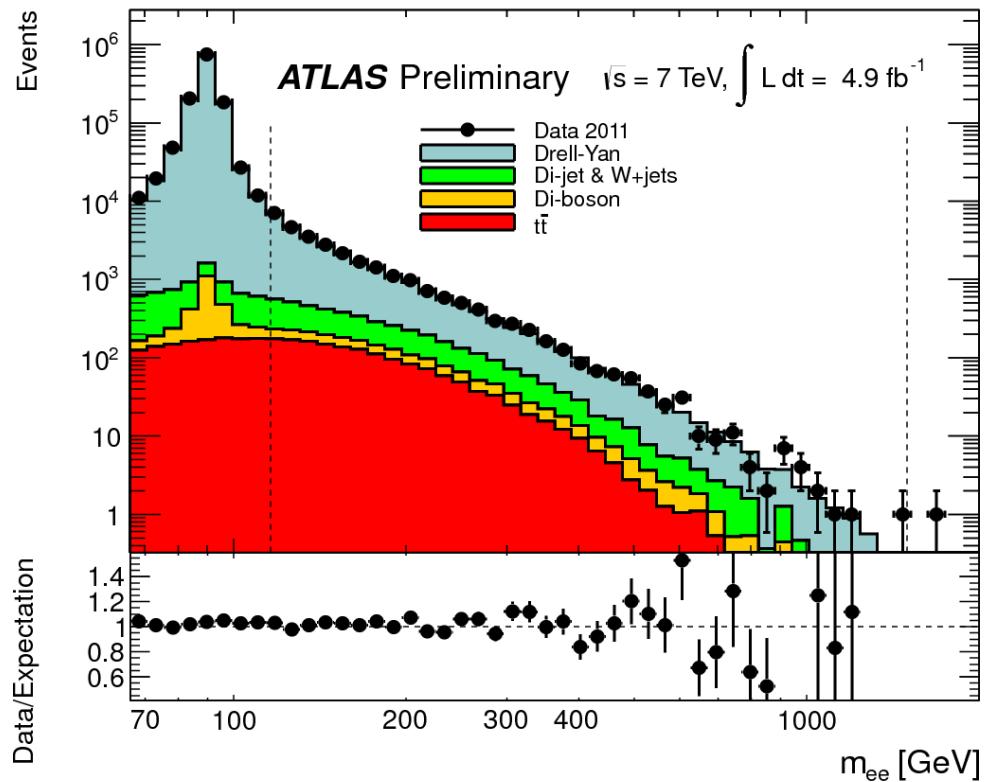
Drell-Yan differential cross-section measured in $116 < m_{ee} < 1500$ GeV ($E_T > 25$ GeV, $|\eta| < 2.5$)

Dominant background :

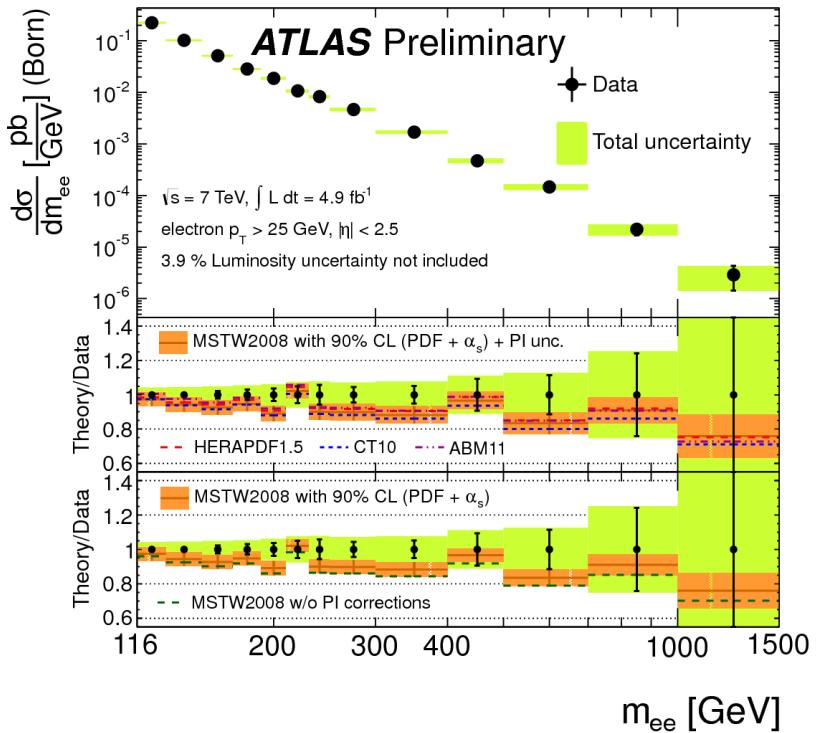
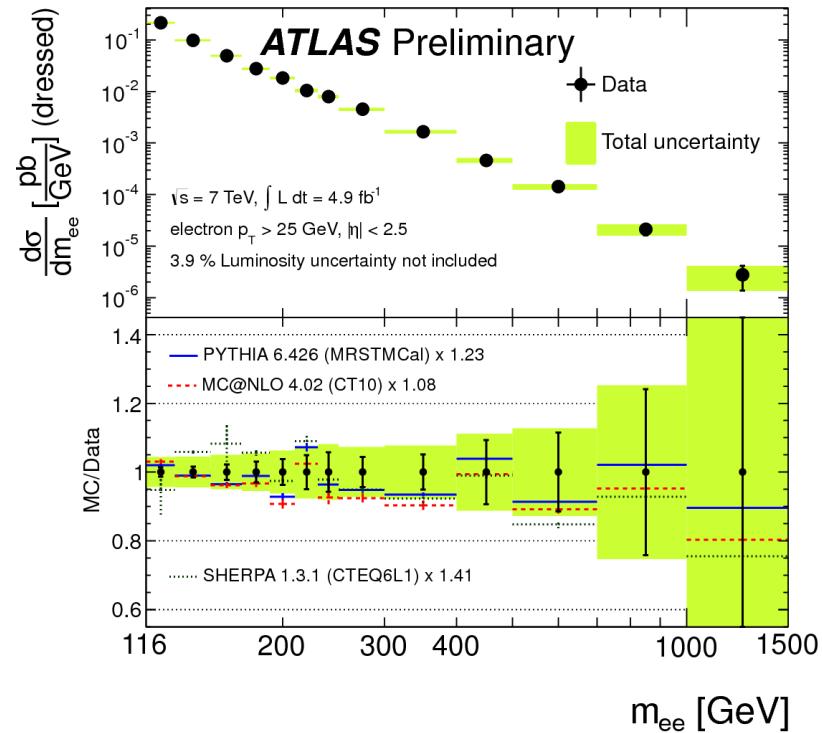
W+jets and di-jet (6-16% depending on m_{ee})
→ estimated from data

Dominant uncertainties :

- background estimate (1.3-8.2%)
- electron reconstruction and identification (2.8-3%)
- electron energy scale and resolution (2.1-3.3%)
- measurement limited by statistics for $m_{ee} > 400$ GeV



High Mass Drell-Yan (2)

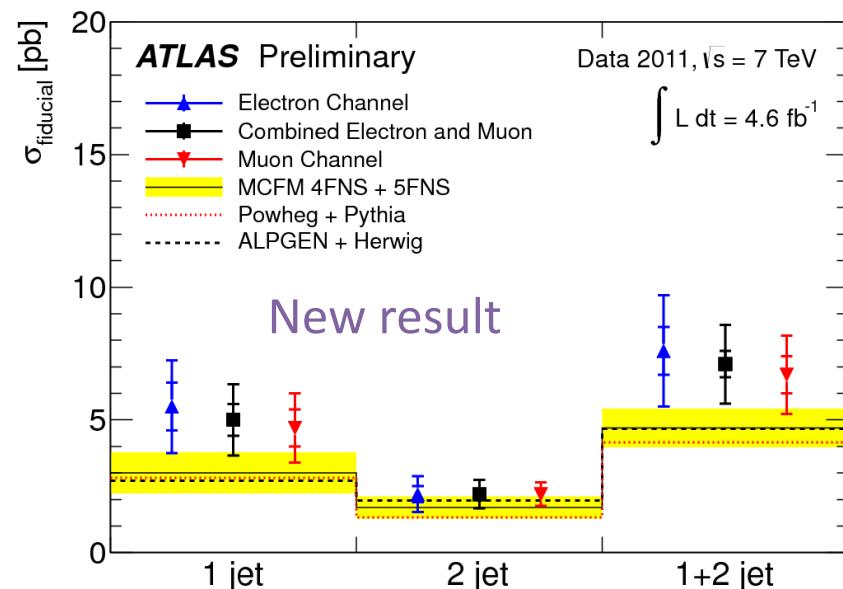
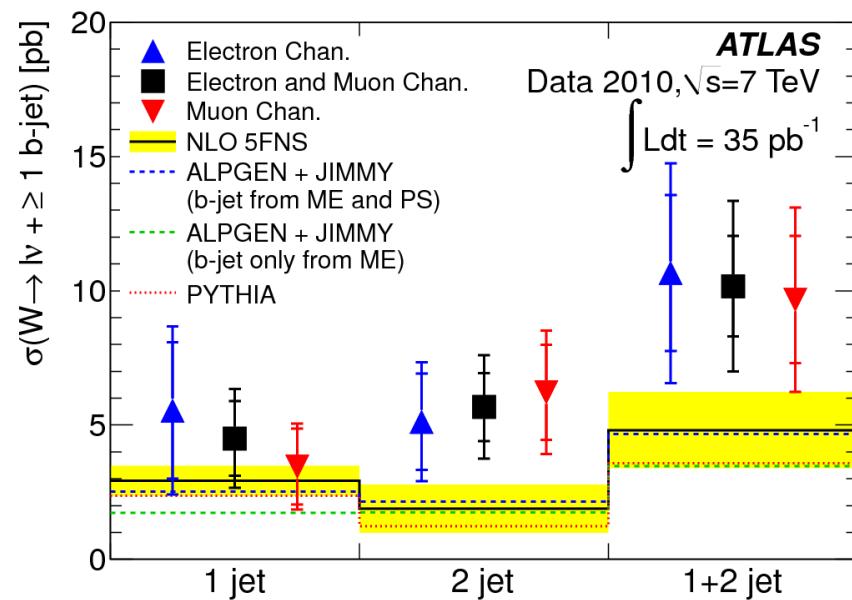


Good agreement between shape in data and *PYTHIA, MC@NLO and SHERPA generators.*

- Good agreement between shape in data and *predictions of perturbative QCD at NNLO* (FEWZ 3.1 framework, 4 sets of PDF used).
- Photon-induced corrections (irreducible non-resonant background $\gamma\gamma \rightarrow e^+e^-$) similar in size to the PDF+ α_s uncertainties

Wb(b) cross sections (I)

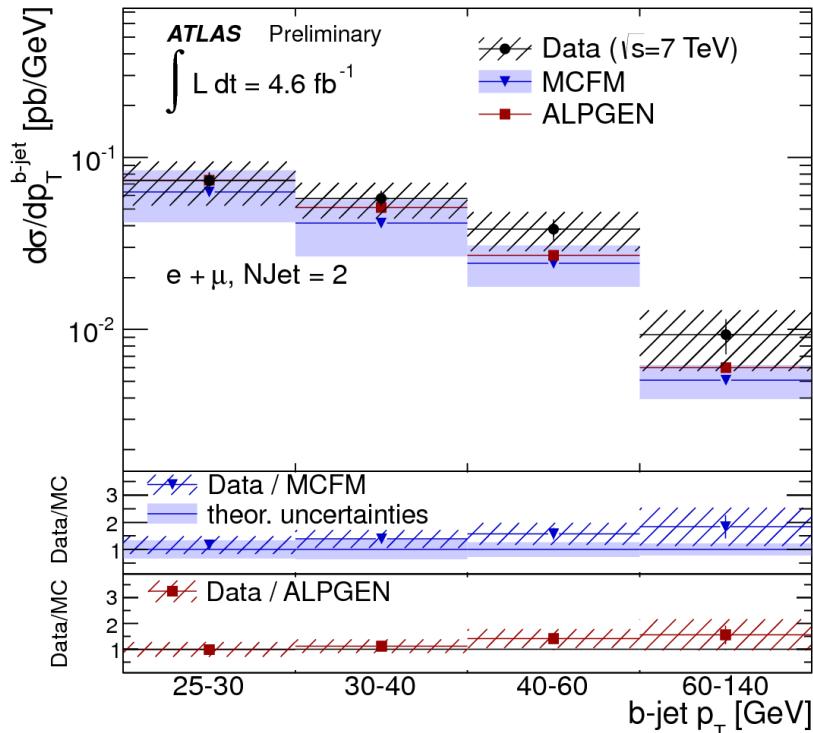
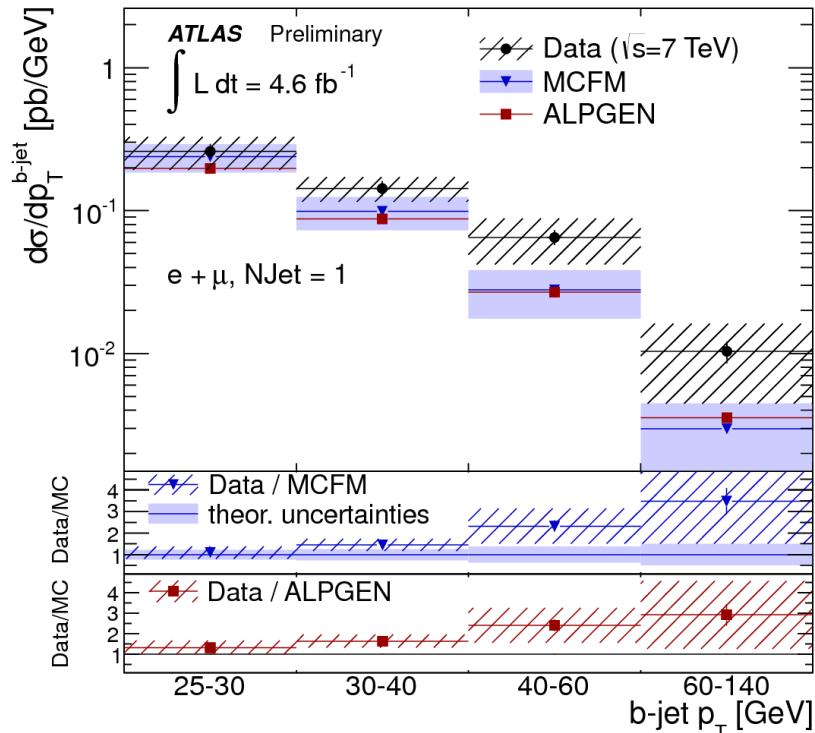
- *1-jet final state :* measurement consistent within 1.5σ with MCFM NLO predictions
- *2-jet final state (bb, bc, bl)*: good agreement
- *Combination :* $\sigma_{\text{fiducial}} = 7.1 \pm 0.5 \text{ (stat)} \pm 1.4 \text{ (syst)} \text{ pb}$



Disagreement in the 2-jet bin not present anymore with larger statistics

Wb(b) cross sections (2)

- Differential cross-section (jets p_T =[25,140]GeV) as a function of leading b-jet p_T :*



Measurement *larger than (N)LO predictions*, but compatible within theory+experimental uncertainties

Good agreement with theory

ϕ^* distribution of Z/γ^* (I)

- Direct measurement of Z/γ^* low p_T^Z ($< m_Z$) *limited by syst. uncertainties.*
- *New variable* to probe low p_T^Z domain
(Eur.Phys.J(2011) 71:1600) :

$$\phi^* = \tan(\phi_{acop}/2) \sin(\theta_\eta^*) \text{ with : } \phi_{acop} = \pi - \Delta\phi$$

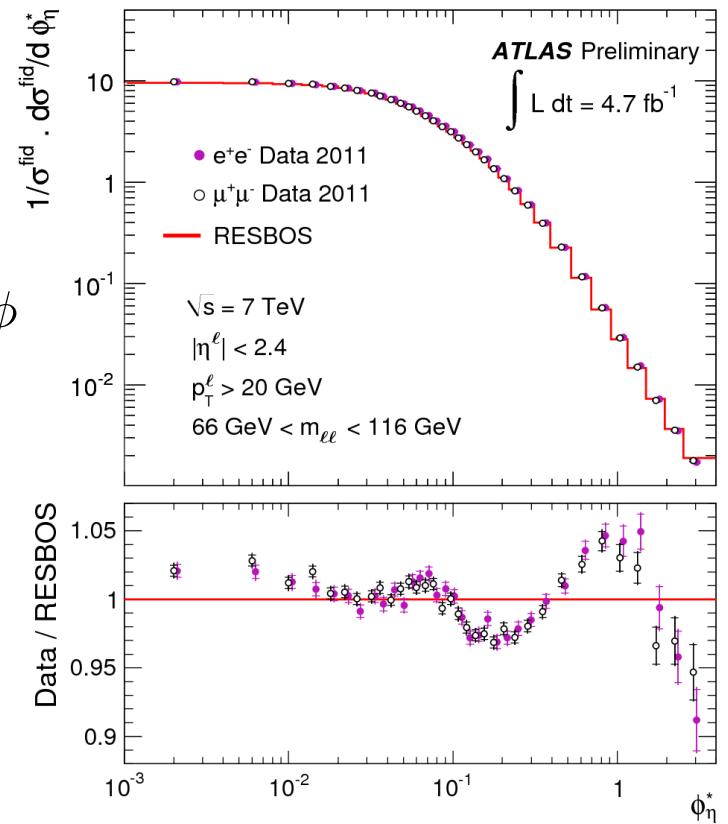
$$\cos(\theta_\eta^*) = \tanh\left(\frac{\eta^- - \eta^+}{2}\right)$$

azimuthal opening angle
between the leptons

scattering angle of leptons with respect to the beam direction in the rest frame of the dilepton system

→ *Angular dependence* of the leptons

→ *Correlated with $p_T^Z/m_{||}$* (same physics probed as p_T^Z)

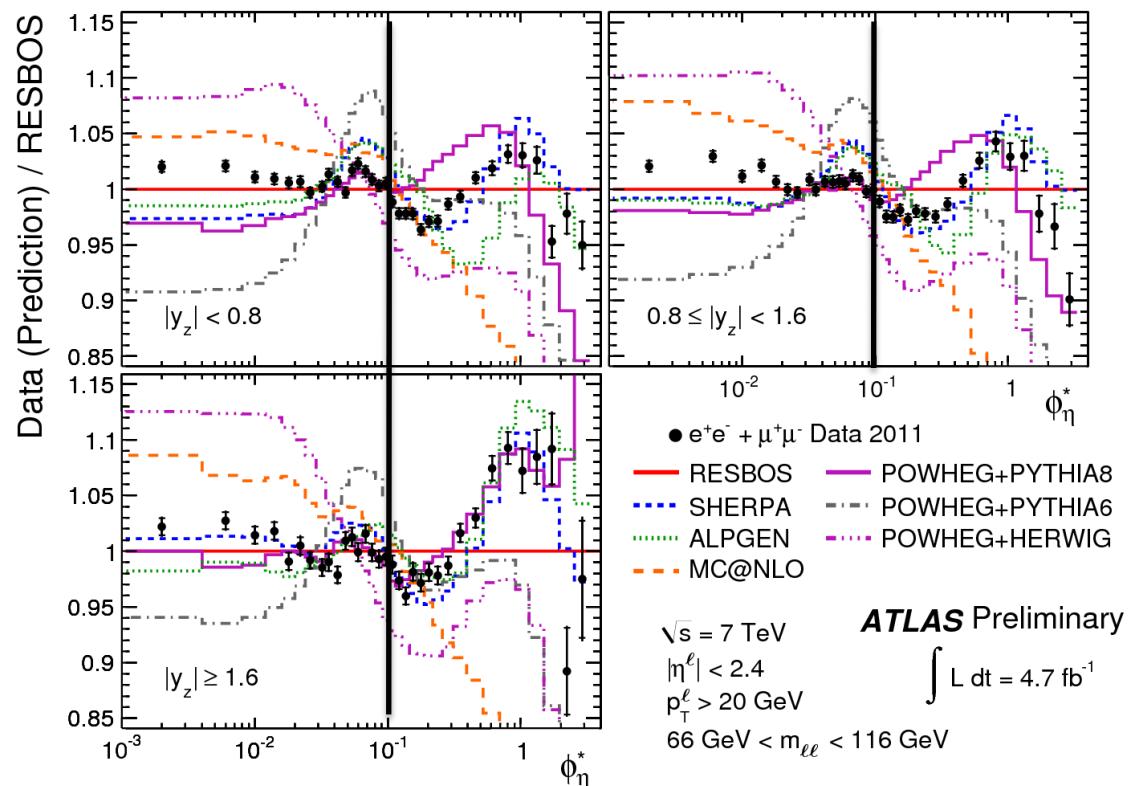


RESBOS : NNLL calculations

→ Reproduction of shape in data ~4%

ϕ^* distribution of $Z/\gamma^*(2)$

Result in three bins of $|y_Z|$: <0.8 , $[0.8,1.6]$, >1.6



Backgrounds (dominant) :

- low ϕ^* : QCD multijet
- high ϕ^* : ttbar and diboson

Uncertainty :

- $\phi^* < 0.5$: $< 0.5\%$
- $\phi^* > 0.5$: $\sim 0.8\%$

$\phi^* > 0.1$: Better description of shape in data by *SHERPA* than *RESBOS* over all $|y_Z|$ bins ($\sim 2\%$)

$\phi^* < 0.1$: Deviations of *SHERPA* and *ALPGEN* from data $\sim 5\%$ larger than of *RESBOS*

POWHEG+PYTHIA 8 describes data within $\sim 5\%$ over the whole ϕ^* range

Bad agreement with *MC@NLO(HERWIG)* for $\phi^* > 0.1$; 4-7% deviation from data for $\phi^* < 0.1$

Dibosons

Importance of measuring precisely **diboson production cross sections** :

- *Very good test of the SM* : Discrepancies with SM could indicate presence of New Physics (NP).
- *Major irreducible background* to Higgs and NP scenarios.
- Both *total and fiducial cross sections* are provided. Fiducial cross sections reduce theory uncertainty and allow for easier comparison with theory prediction. Also, *differential cross sections in bins of variables sensitive to new theories* are provided.

Triple gauge-boson couplings (TGC), charged ones (WW γ , WWZ) and neutral ones (ZZ γ , Z $\gamma\gamma$, ZZZ) are also *a good probe for NP*.

Dibosons

Datasets :
 1.0 fb⁻¹ at 7 TeV
 4.7 fb⁻¹ at 7 TeV
 5.8 fb⁻¹ at 8 TeV

	Charged VV			Neutral VV	
diboson channels	WW	WZ	W γ	ZZ	Z γ
decay channels	ν ν	ν l	ν γ	lll	ll γ
	ν qq	ν qq		llvv	

Dibosons

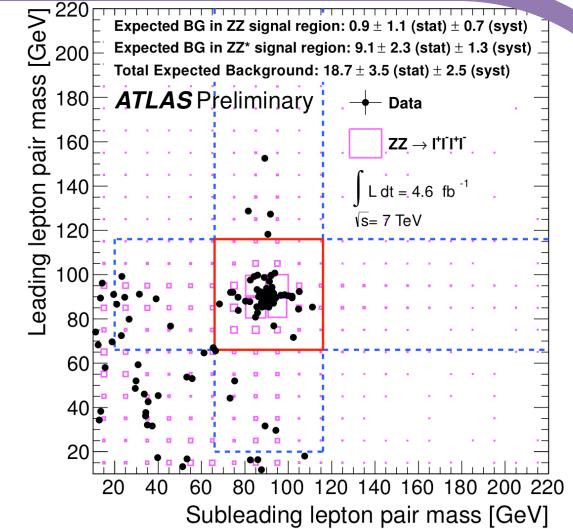
New results (first presented at HCP)

diboson channels	WW	WZ	W γ	ZZ ^(*)	Z γ
decay channels	lνlν lνqq	lνll	lνγ lνqq	llll llνν	llγ llνν

→ New analysis (first presented at HCP)

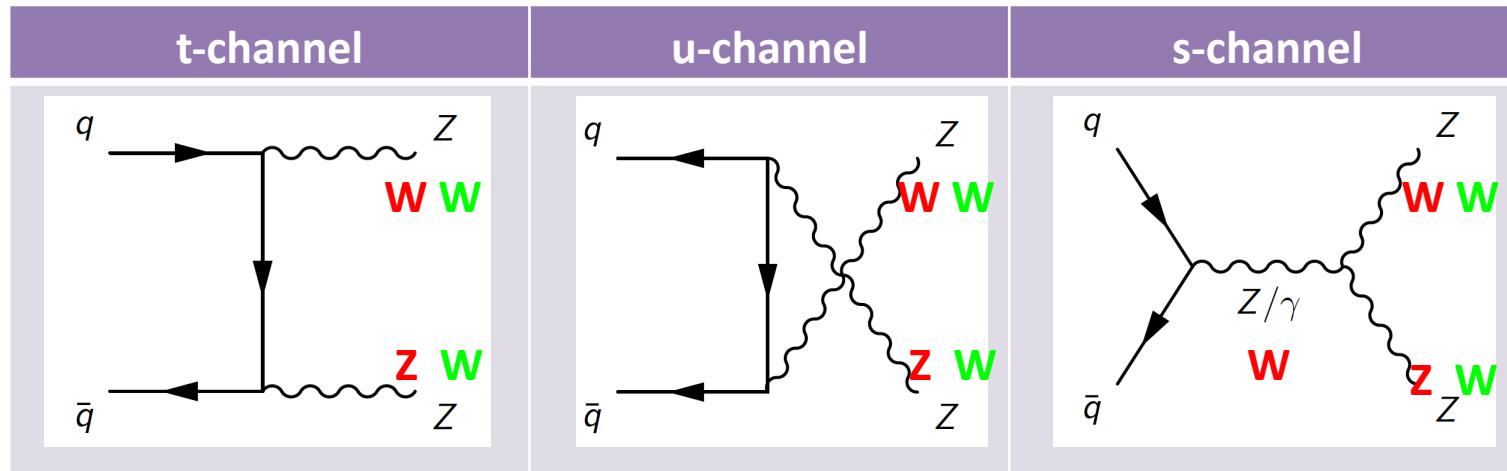
→ Larger backgrounds than fully leptonic decays

→ Larger Branching Ratio



Diboson Production

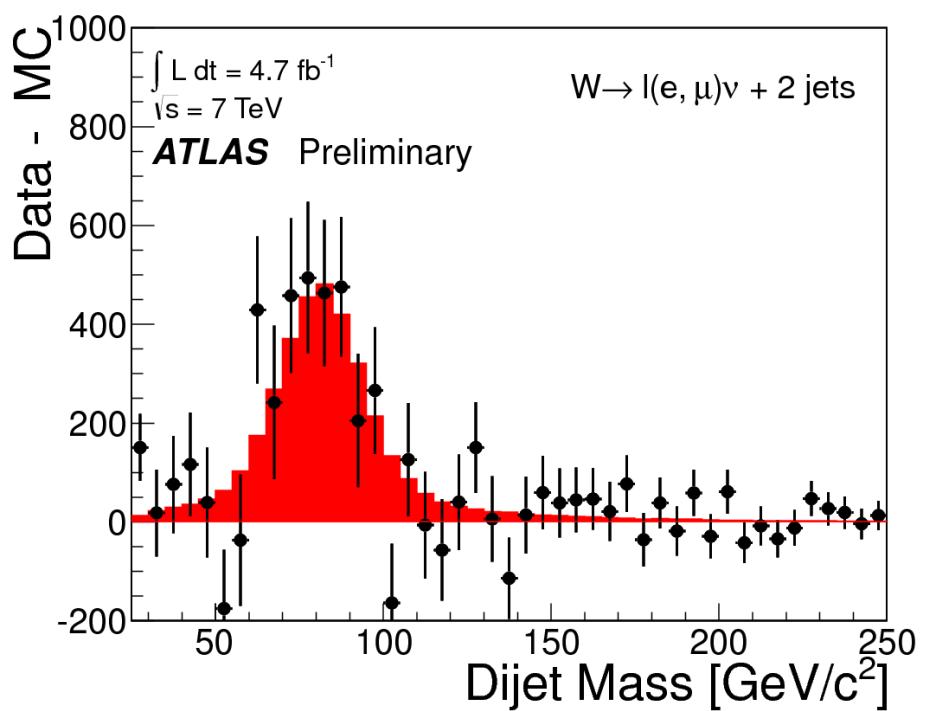
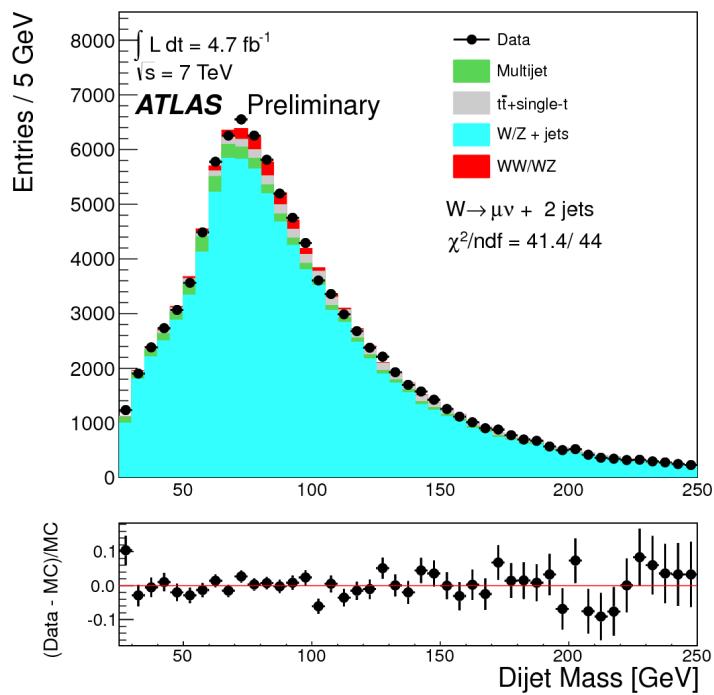
- Production via $q\bar{q}$ (LO, NLO) and gluon-gluon fusion (NLO).
 - gluon-gluon production cross section $\sim 3\text{-}6\%$ of total
- Charged triple gauge boson couplings allowed in SM (WWZ , $WW\gamma$), not neutral ones *at tree level* ($ZZ\gamma$, $Z\gamma\gamma$, ZZZ) (*anomalous*).



WW, WZ, ZZ (W/Zg production diagrams in back-up slides)

WW/WZ (lνqq)

MET>30 GeV, m_T >40 GeV, Exactly two jets ($p_T(j_1)>30\text{GeV}$, $p_T(j_2)>25\text{GeV}$, $|\eta|<2.5$, $\Delta\phi(\text{MET}, j_1)>0.8$, $\Delta R(j_1, j_2)>0.7$, $|\Delta\eta(j_1, j_2)|<1.5$)

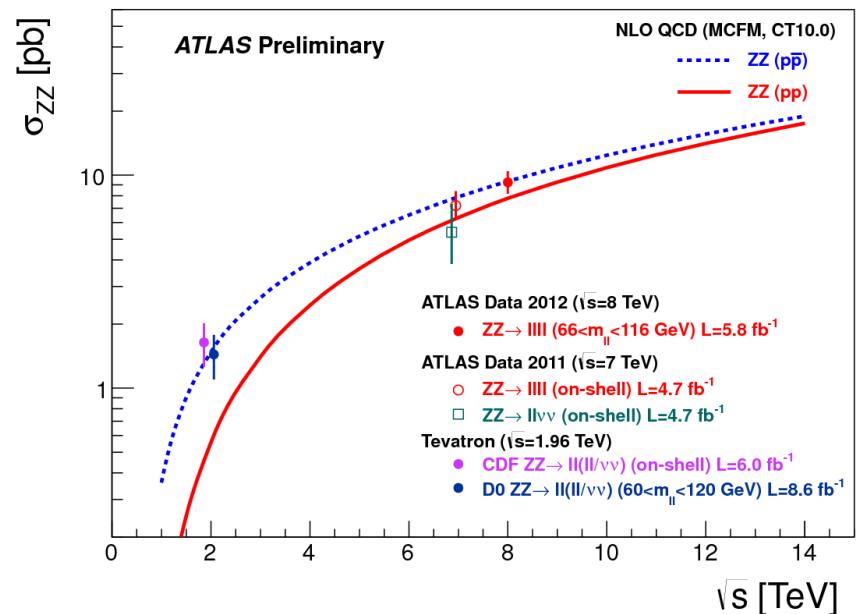
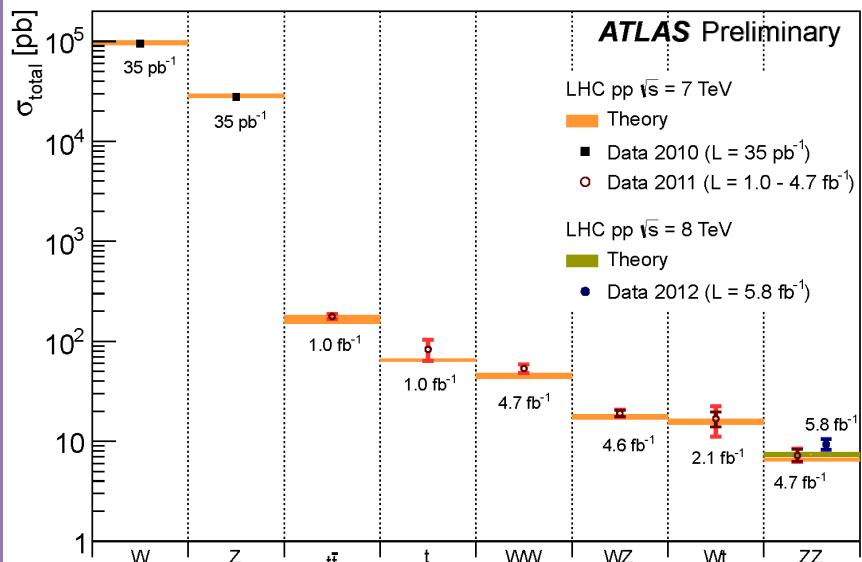


Evidence of diboson WW+WZ production decaying into lνqq channel (3.3σ)

Systematic Uncertainties

Channel	Main Uncertainties
$WW \rightarrow l\nu l\nu$	jet veto (3.6%)
$W(W/Z) \rightarrow l\nu q\bar{q}$	jet energy scale (12%), $W/Z+jets$ normalization (11%)
$WZ \rightarrow l\nu ll$	electron identification efficiency (3.5% for eee, 2.3% for eem) muon reconstruction efficiency (0.8% for $\mu\mu\mu$, 0.5% for $\mu\mu e$)
$W\gamma$	photon identification (11% for $E_T > 15\text{GeV}$, 4.5% for $E_T > 60,100\text{GeV}$)
$ZZ \rightarrow llll$	electron identification efficiency (3.8% for eeee, 1.9% for ee $\mu\mu$) muon reconstruction efficiency (1.0% for $\mu\mu\mu\mu$, 0.5% for ee $\mu\mu$)
$ZZ \rightarrow ll\nu\nu$	jet veto (5.3%)
$Z\gamma$	photon identification (11% for $E_T > 15\text{GeV}$, 4.5% for $E_T > 60,100\text{GeV}$)

Total Cross Sections (I)



Total Cross Sections (2)

Total cross-sections	Data	σ (pb)	δ stat	δ syst	δ lumi	σ_{th} (pb)	$\delta\sigma^{\text{NLO}}$
$WW \rightarrow l\nu l\nu$	7TeV (5fb $^{-1}$)	51.9	± 2.0	± 3.9	± 2.0	44.7	± 2.8
$WW+WZ (l\nu qq)$	7TeV (5fb $^{-1}$)	71.2	± 8.5	± 15.2	± 12.8 (Mcstat)	63.4	± 2.6
$WZ \rightarrow l\nu ll$	7TeV (5fb $^{-1}$)	19.0	+1.4/-1.3	± 0.9	± 0.4	17.6	+1.1/-1.0
$ZZ \rightarrow llll$	8TeV (6fb $^{-1}$)	9.3	+1.1/-1.0	+0.4/-0.3	± 0.3	7.4	± 0.4
$ZZ \rightarrow ll\nu\nu$	7TeV (5fb $^{-1}$)	5.4	+1.3/-1.2	+1.4/-1.0	± 0.2	6.5	+0.3/-0.2
$ZZ \rightarrow llll$ and $ZZ \rightarrow ll\nu\nu$	7TeV (5fb $^{-1}$)	6.7	± 0.7	+0.4-0.3	± 0.3	5.9	± 0.2

Measured total cross-sections *generally slightly higher than prediction*, however consistent within uncertainties.

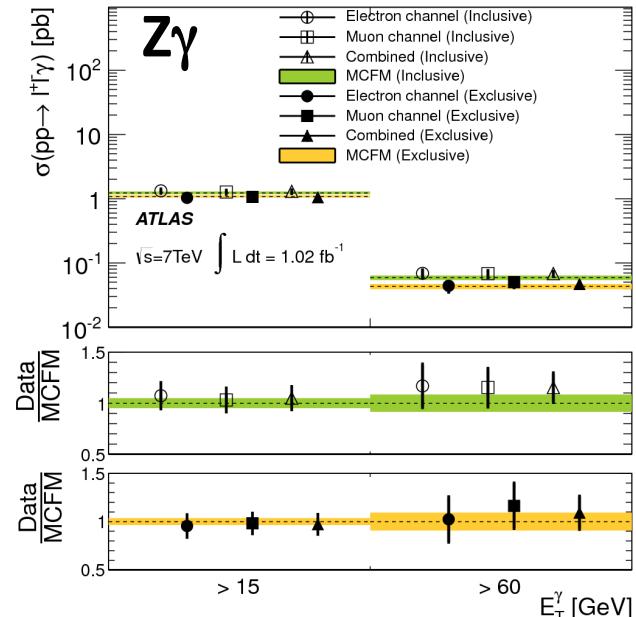
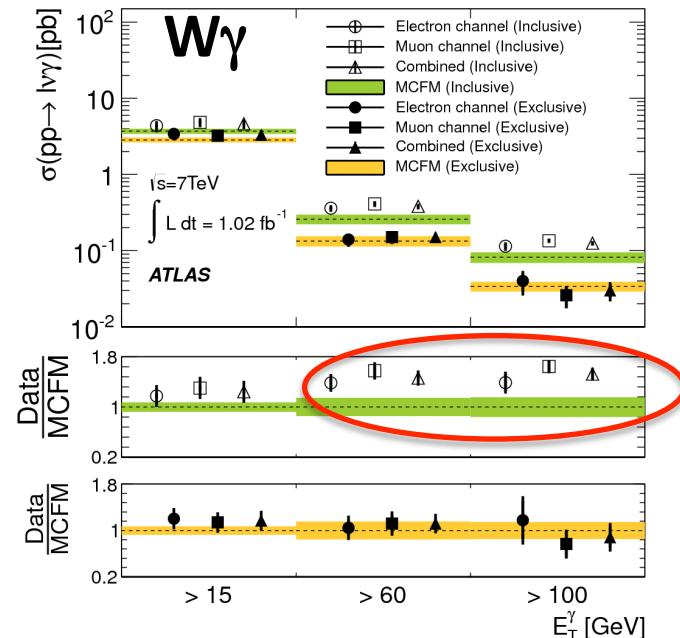
Fiducial W/Z γ Cross Sections (I)

Three(Two) photon p_T thresholds : >15GeV, >60GeV, (>100GeV) for W/Z γ

Exclusive measurement : hard jet (p_T >30GeV) veto applied

Inclusive measurement : no jet veto

Alpgen (W γ) describes well the photon p_T distribution in data



- MCFM-based cross-section predictions *30-40% lower* than data in high p_T region for *inclusive W γ measurement*.
- *Good agreement* for *exclusive measurement*.

Fiducial Cross Sections (2)

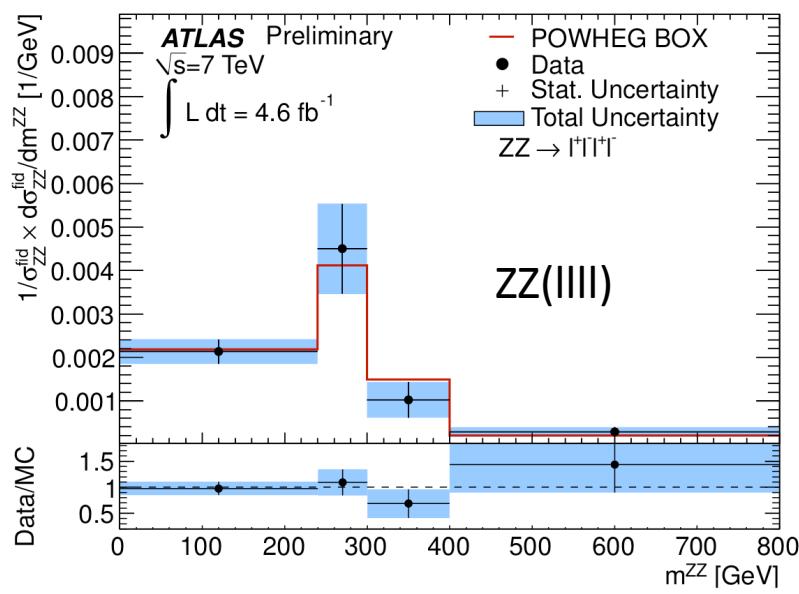
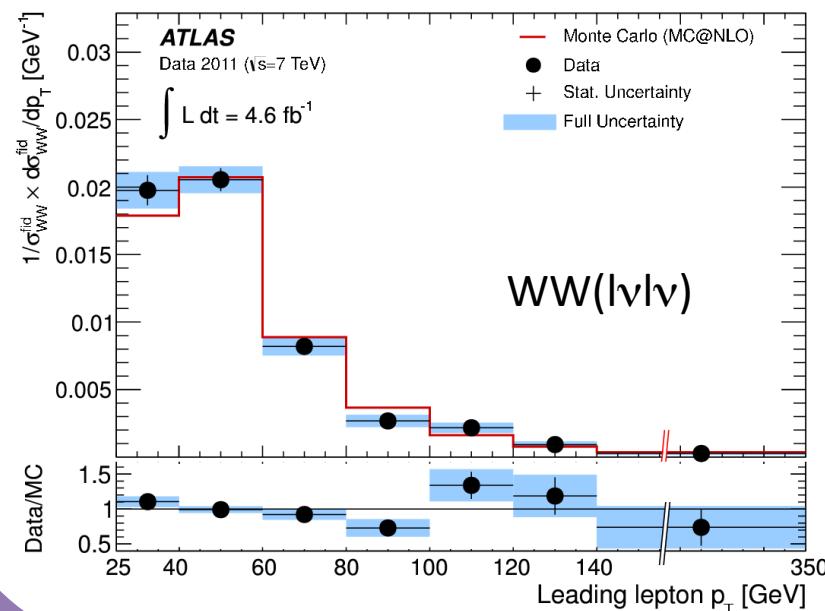
Fiducial	Data	σ (fb)	δ stat	δ syst	δ lumi	σ_{th} (fb)	$\delta\sigma^{\text{NLO}}$
$WW \rightarrow e\nu e\nu$	7TeV (5fb $^{-1}$)	56.4	± 6.8	± 9.8	± 2.2	54.6	± 3.7
$WW \rightarrow \mu\nu \mu\nu$	7TeV (5fb $^{-1}$)	73.9	± 5.9	± 16.9	± 2.9	58.9	± 4.0
$WW \rightarrow e\nu \mu\nu$	7TeV (5fb $^{-1}$)	262	+12	± 21	± 10	231	± 16
$WZ \rightarrow l\nu l\nu$	7TeV (5fb $^{-1}$)	92.3	+6.7/-6.3	± 4.3	+1.9/-1.8	90	+5/-7
$ZZ \rightarrow l l l l$	8TeV (6fb $^{-1}$)	21.0	+2.4/-2.2	+0.6/-0.5	± 0.8	16.8	± 1.0
$ZZ \rightarrow l l \nu \nu$	7TeV (5fb $^{-1}$)	12.7	+3.1/-2.9	+1.0/-1.1	± 0.5	12.5	+1.0/-1.1
$ZZ^* \rightarrow l l l l$	7TeV (5fb $^{-1}$)	29.8	+3.8/-3.5	+1.7/-1.5	± 1.2	25.6	+1.3/-1.1
$ZZ \rightarrow l l l l$	7TeV (5fb $^{-1}$)	25.4	+3.3/-3.0	+1.2/-1.0	± 1.0	20.9	+1.1/-0.9
$W\gamma$ ($E_T > 15$)	7TeV (1fb $^{-1}$)	4.6	± 0.1	± 6	± 0.2	3.7	± 0.3
$W\gamma$ ($E_T > 60$)	7TeV (1fb $^{-1}$)	0.38	± 0.02	± 0.03	± 0.01	0.26	± 0.04
$W\gamma$ ($E_T > 100$)	7TeV (1fb $^{-1}$)	0.13	± 0.02	± 0.01	± 0.00	0.08	± 0.01
$Z\gamma$ ($E_T > 15$)	7TeV (1fb $^{-1}$)	1.3	± 0.1	± 0.2	± 0.1	1.2	± 0.1
$Z\gamma$ ($E_T > 60$)	7TeV (1fb $^{-1}$)	0.07	± 0.01	± 0.01	± 0.00	0.06	± 0.01

Measured fiducial cross-sections *generally slightly higher than prediction*, however consistent within uncertainties.

Fiducial Cross Sections (3)

Differential fiducial cross sections in bins of variables sensitive to new theories provided (presence of anomalous triple gauge couplings (aTGCs)):

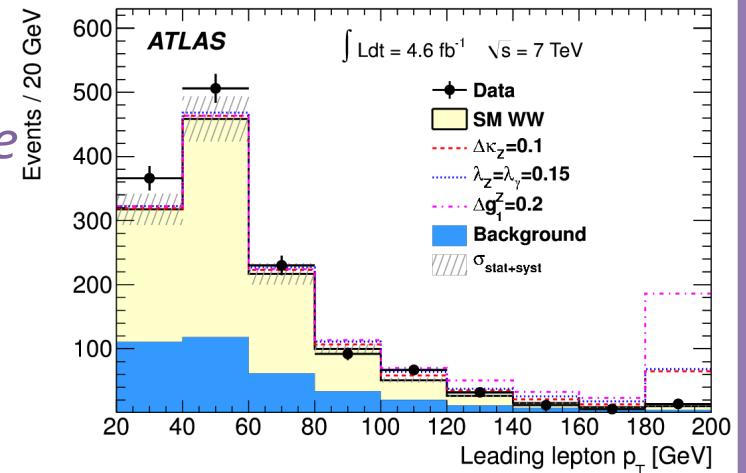
- p_T of leading lepton (WW)
- p_T of (leading) Z (WZ/ZZ)
- p_T of γ (W/Z γ)
- m_{ZZ} (ZZ)
- ...



Triple Gauge Couplings

- parameterized by **CP-violating** and **CP-conserving** complex parameters
 - Deviations from the SM values would *increase the production cross sections* and *alter kinematic distributions* (especially for large p_T).
- 95% CL determined using observed and expected *binned in some variables sensitive to new theories* (see previous slide).
- Several *limit setting approaches* :
 - Profile likelihood ratio (ZZ)
 - Frequentist limits (WZ)
 - Bayesian likelihood limits (WW/W γ /Z γ)

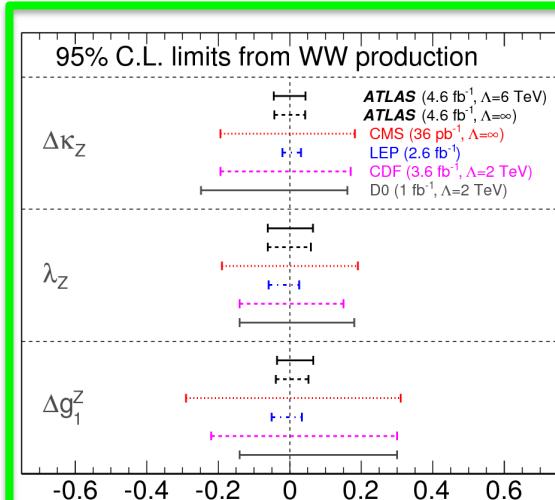
ZZZ	$ZZ\gamma$	WWZ	$WW\gamma$	$ZZ\gamma$	$Z\gamma\gamma$
$f_4^Z = 0$ $f_5^Z = 0$	$f_4^\gamma = 0$ $f_5^\gamma = 0$	$\Delta g_1^Z = g_1^Z - 1$ $\Delta \kappa_Z = \kappa_Z - 1$ $\lambda_Z = 0$	$\Delta \kappa_\gamma = \kappa_\gamma - 1$ $\lambda_\gamma = 0$	$h_3^Z = 0$ $h_4^Z = 0$	$h_3^\gamma = 0$ $h_4^\gamma = 0$



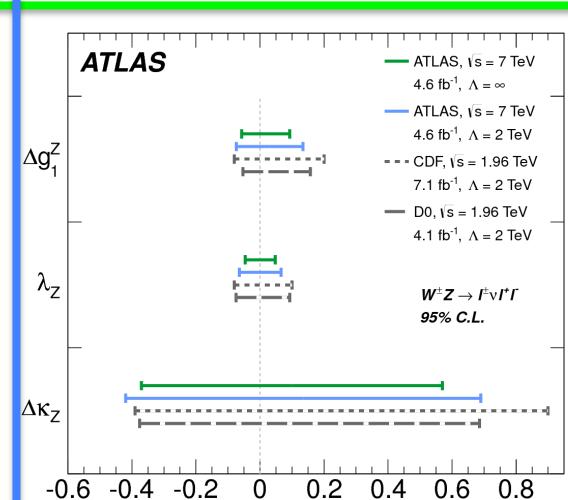
- **Systematic uncertainties included as nuisance parameters.**

Charged TGC Results

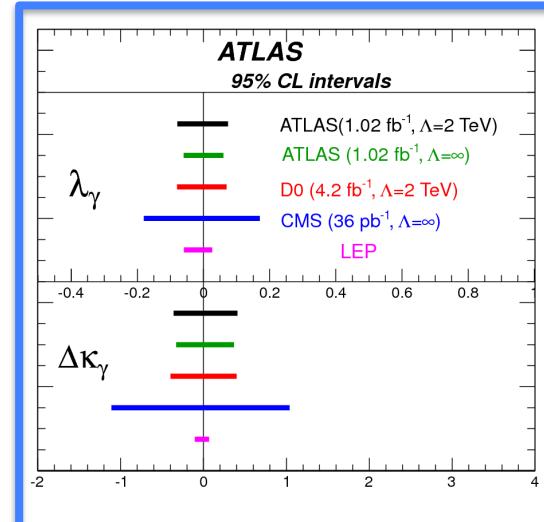
WW result :



WZ result :



Wγ result :



WWZ vertex : $(\Delta g_1^Z = g_1^Z - 1, \Delta\kappa_Z = \kappa_Z - 1, \lambda_Z = 0)$

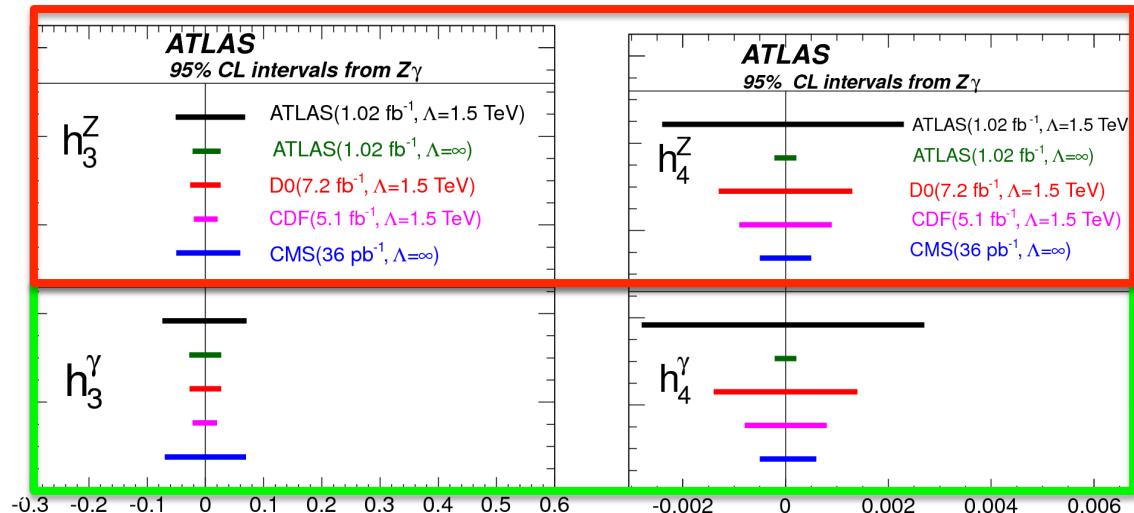
WWγ vertex : $(\Delta\kappa_\gamma = \kappa_\gamma - 1, \lambda_\gamma = 0)$

for WW, assumption that $\lambda_Z = \lambda_\gamma$ and $\Delta\kappa_Z = \Delta\kappa_\gamma$ (LEP scenario)

Higher energies and higher diboson productions at LHC allow for *better constraints than the Tevatron results and approach the LEP combined limits.*

Neutral aTGC Results

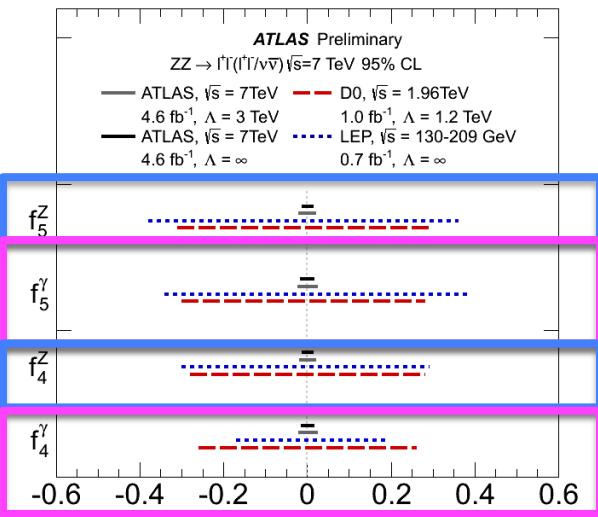
$Z\gamma$ result :



$Z\gamma\gamma$ vertex : $(h_3^\gamma = 0, h_4^\gamma = 0)$

$ZZ\gamma$ vertex : $(h_3^Z = 0, h_4^Z = 0)$

ZZ result :



$ZZ\gamma$ vertex : $(f_4^\gamma = 0, f_5^\gamma = 0)$

ZZZ vertex : $(f_4^Z = 0, f_5^Z = 0)$

More stringent limits than Tevatron and LEP results. The latest results from ZZ are approximately *~5 times more constraining* than previous ATLAS limits.

Conclusions

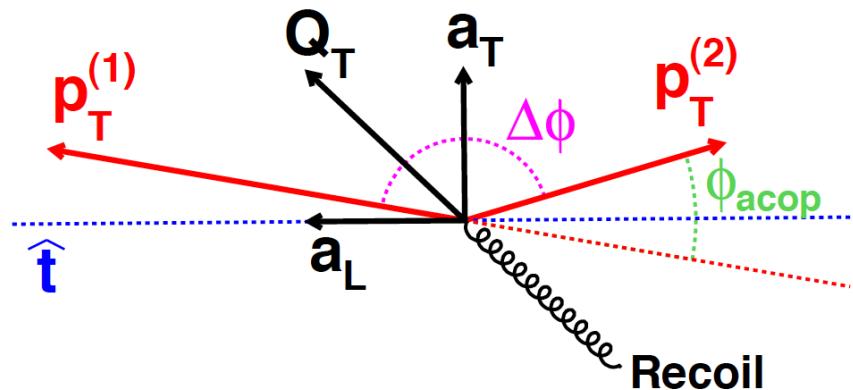
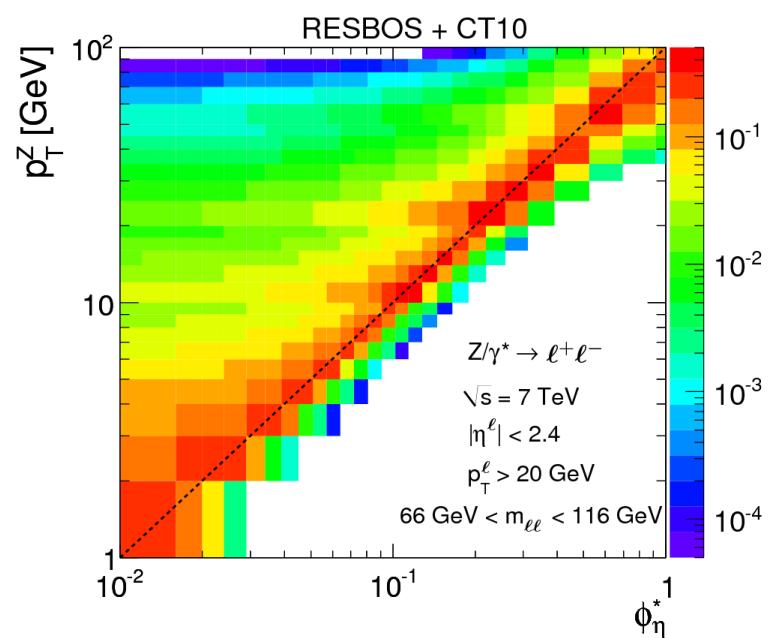
- A lot of electroweak measurements already performed by the ATLAS collaboration
 - Measurements challenging NNLO predictions
- Evidence of WZ+WW production in the $\ell\nu qq$ channel
- Diboson cross sections in agreement with expectation within uncertainties
- Tightened limits on possible non-SM anomalies
- Still a lot of measurements on-going ...

Back-Up Slides

ϕ^* distribution of Z/γ^*

$$\phi^* = \tan(\phi_{acop}/2) \sin(\theta_\eta^*) \text{ with : } \phi_{acop} = \pi - \Delta\phi$$

$$\cos(\theta_\eta^*) = \tanh\left(\frac{\eta^- - \eta^+}{2}\right)$$



Q_t = dilepton transverse momentum
 a_T, a_L = components of Q_t according to t^\wedge

Cross Section Definition

Fiducial cross section : reduces theory uncertainty and allows for easier comparison with theory prediction.

- fiducial volume mimics the detector acceptance
- final-state truth particles after showering used for cuts :
 - Leptons “redressed” with brem photons in $\Delta R=0.1$
 - Charged lepton and photon kinematics
 - Neutrino transverse energy
 - Vector boson mass calculated from leptons

$$\sigma_{\text{fiducial}} = \frac{N_{\text{obs}} - N_{\text{bkg}}}{\mathcal{L} \times C_{VV}}$$

Correction factor :

$$C_{VV} = \frac{N_{\text{reco,analysis cuts}}}{N_{\text{gen,fiducial cuts}}}$$

Total cross section :

$$\sigma_{\text{total}} = \frac{N_{\text{obs}} - N_{\text{bkg}}}{\mathcal{L} \times C_{VV} \times \mathcal{BF} \times A_{VV}}$$

Acceptance factor :

$$A_{VV} = \frac{N_{\text{gen,fiducial cuts}}}{N_{\text{gen,total}}}$$

Cross sections are obtained by performing a *maximum likelihood fit*.

Cross-section Extraction

Cross-sections are obtained by performing a *maximum likelihood fit*. For example, the likelihood for WW is : $i=1,2,3$ for the three channels

$$L(\sigma_{WW}^{\text{tot}}) = \ln \prod_{i=1}^3 \frac{e^{(-N_s^i + N_b^i)} \times (N_s^i + N_b^i)^{N_{\text{obs}}^i}}{N_{\text{obs}}^i!}$$

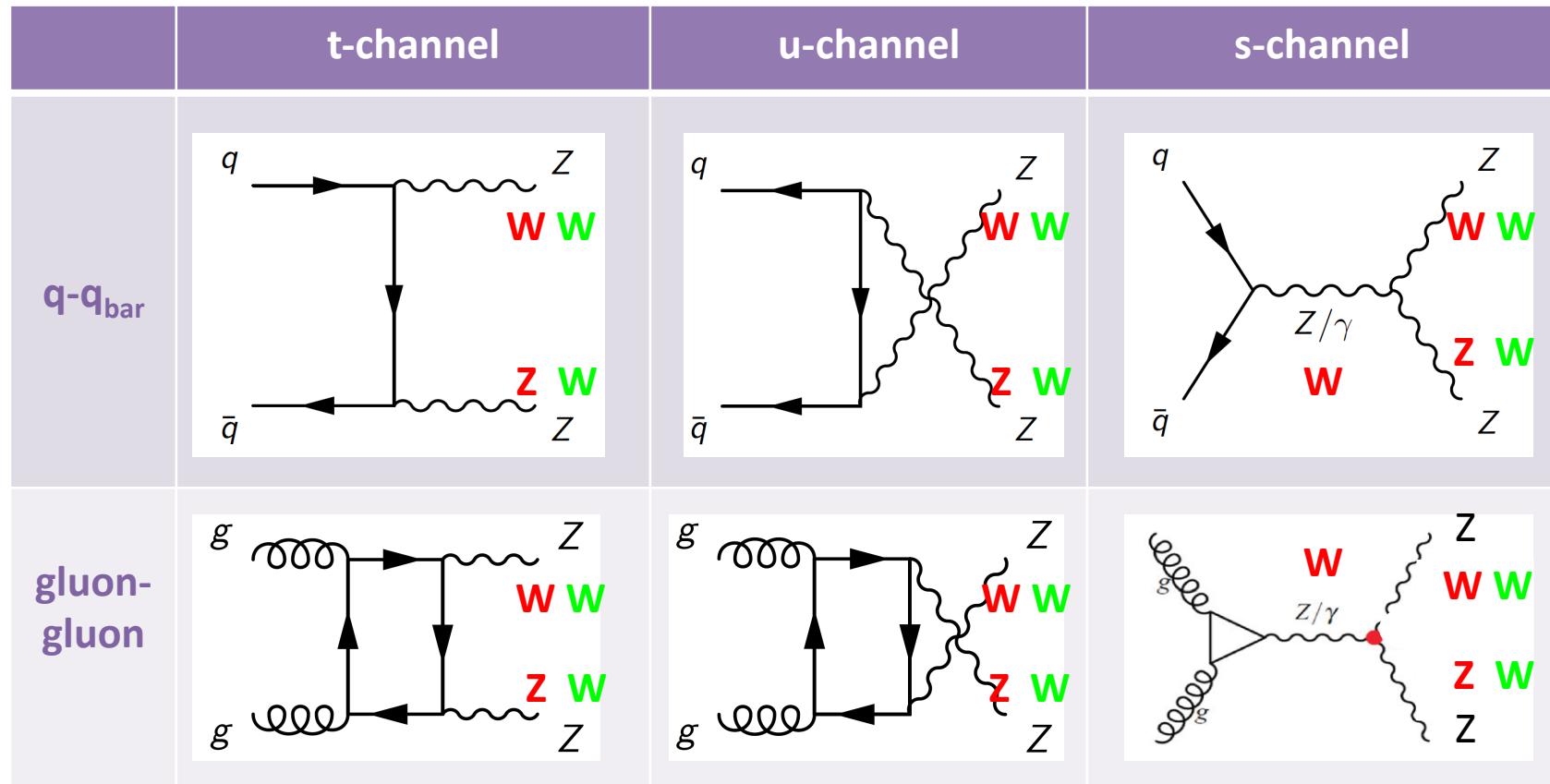
fiducial cross-section : $N_s^i = \sigma_{WW \rightarrow l\nu l\nu}^i \times \mathcal{L} \times C_{WW}^i$

total cross-section : $N_s^i = \sigma_{WW}^{\text{tot}} \times BR^i \times \mathcal{L} \times (A_{WW}^i \times C_{WW}^i)$

- Number of observed events is modeled by Poisson functions
- Systematic uncertainties are dealt with by either treating them as nuisance parameters in the max likelihood fit, or by error propagation

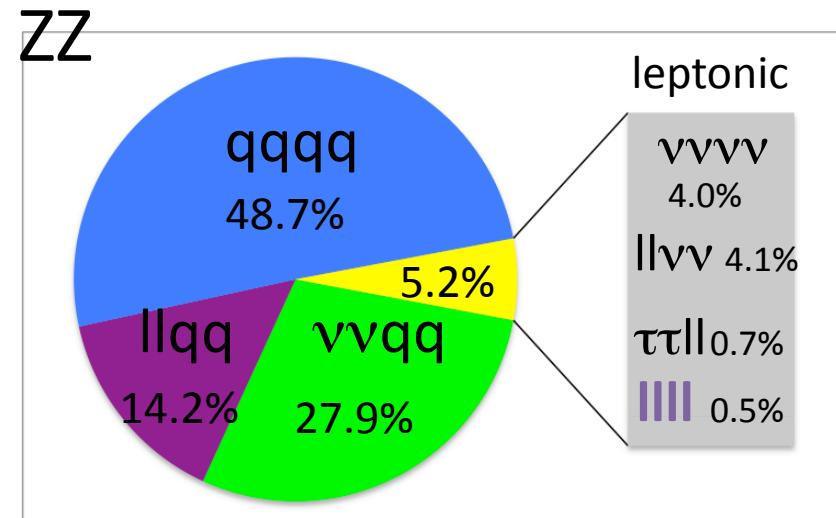
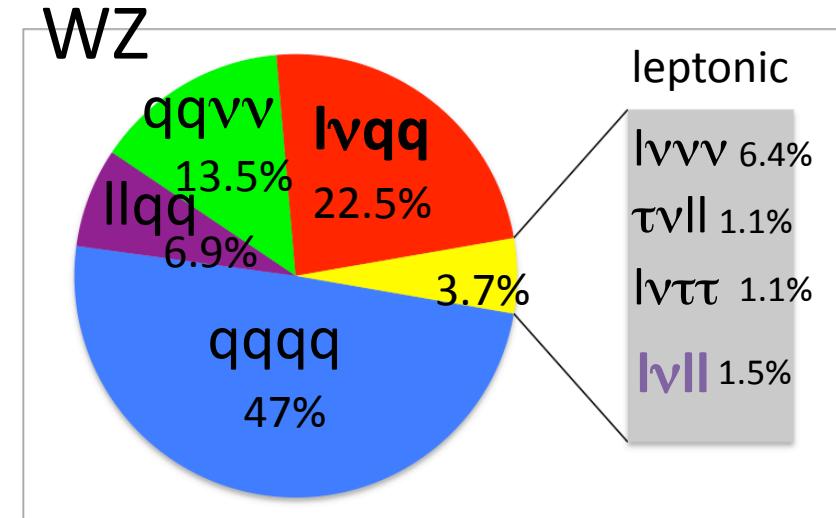
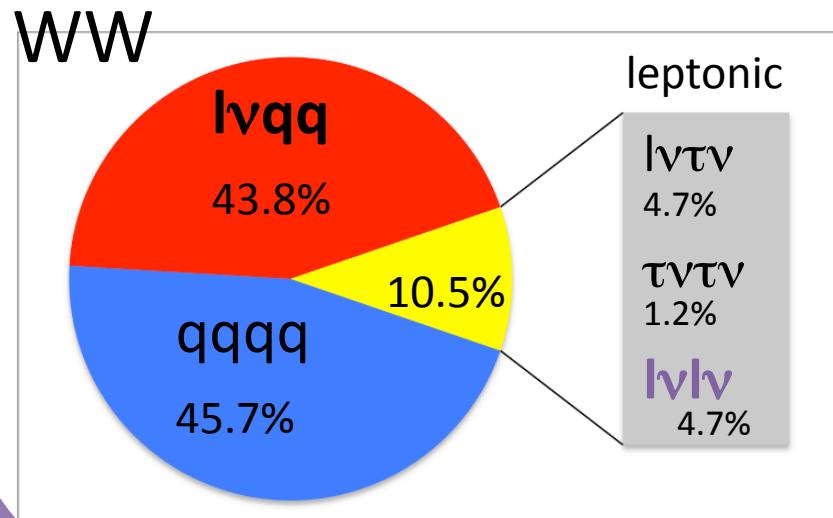
WW, WZ, ZZ Production

- Production via $q\bar{q}$ and gluon-gluon fusion.
- Charged triple gauge boson couplings allowed in SM (WWZ, WW γ), not neutral ones at tree level (ZZ γ , Z $\gamma\gamma$, ZZZ).

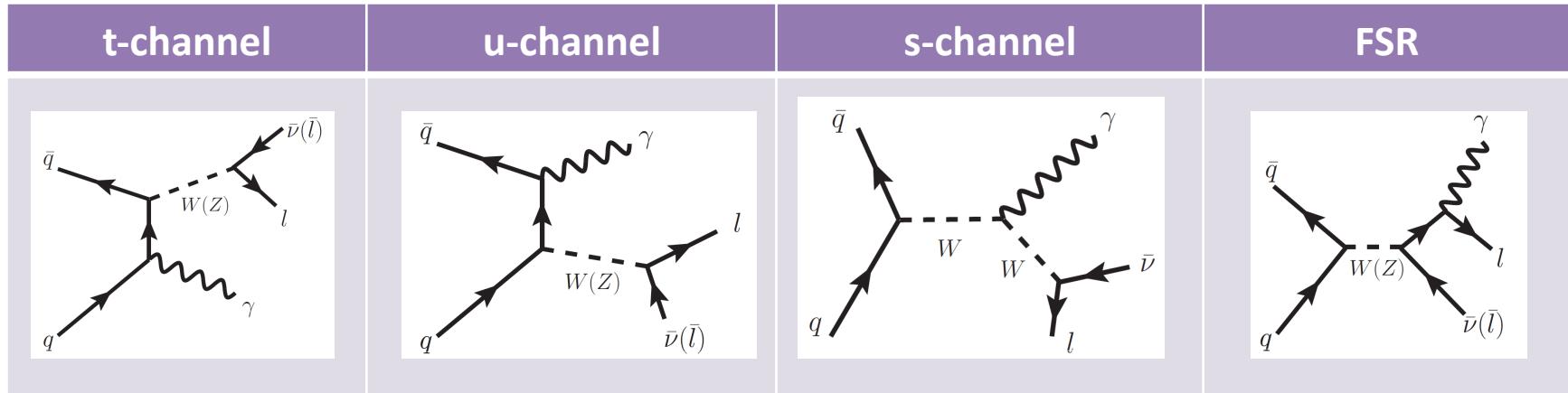


Diboson Decays

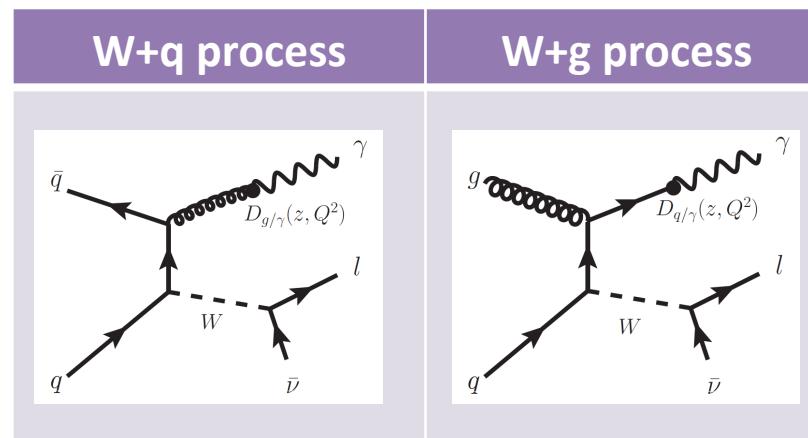
- **Leptonic decays :**
 - Small branching ratios
 - *Low backgrounds*
- **Semi-leptonic decays :**
 - *Higher branching ratios*
 - Large backgrounds



W/Z γ Production



Photon emerging from the hard fragmentation of the final state parton (quark or gluon) :



WW(lνlν)

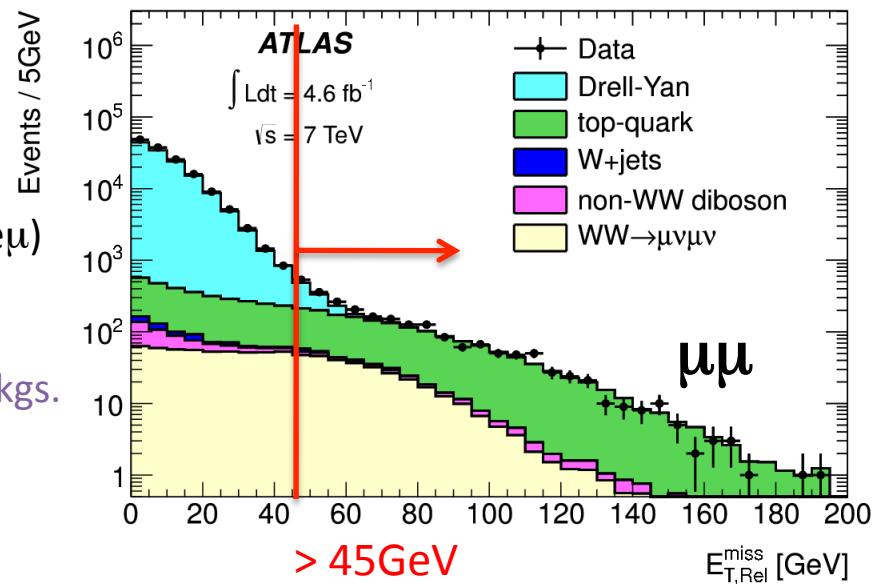
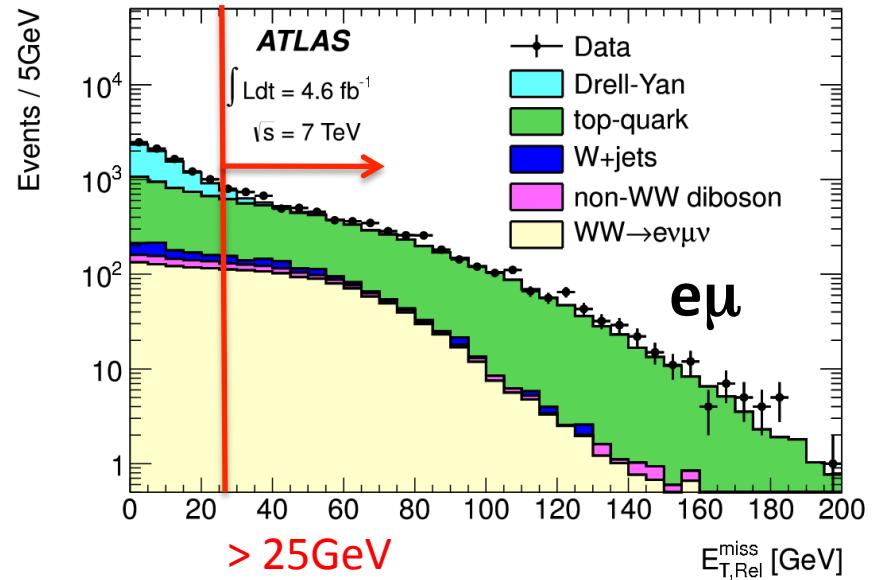
Relative missing energy :

$$= \begin{cases} E_T^{\text{miss}} \times \sin(\Delta\phi_{\ell,j}) & \text{if } \Delta\phi < \pi/2 \\ E_T^{\text{miss}} & \text{if } \Delta\phi \geq \pi/2 \end{cases}$$

to reduce the rate of bkg events that arise from mis-measured energies of leptons or jets, which can produce false Met.

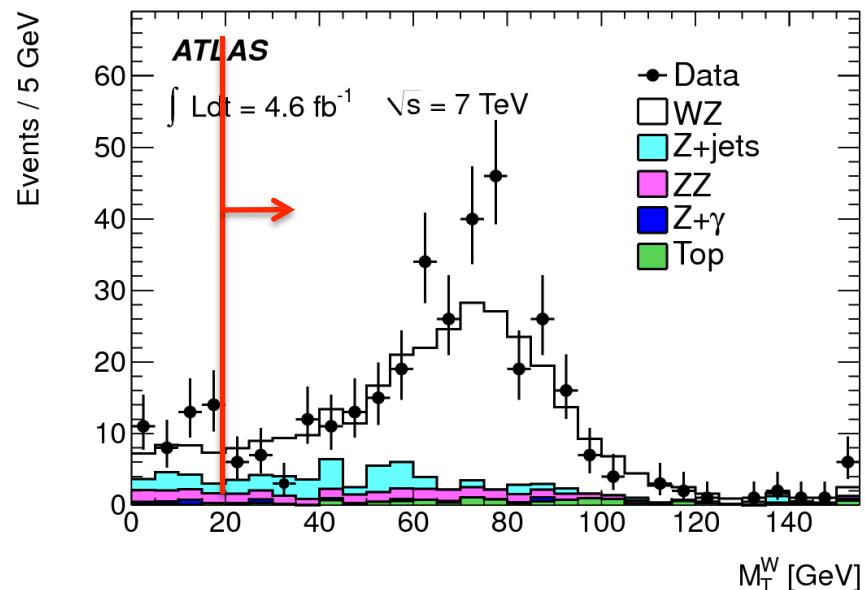
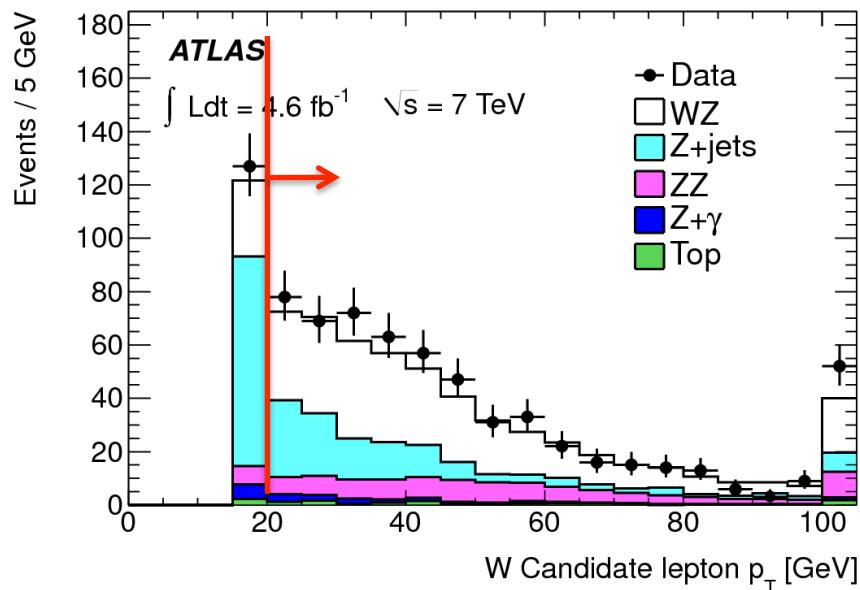
$\Delta\phi_{\ell,j}$ = difference between the Met and the nearest lepton or jet

- Cut on $E_{T,\text{rel}}^{\text{miss}}(>45\text{GeV for ee, }\mu\mu ; >25 \text{ for e}\mu)$
→ to suppress Drell-Yan background.
- Z veto ($\pm 15 \text{ GeV}$)
→ to suppress diboson and Drell-Yan bkgds.
- $m(\text{ll}) > 15\text{GeV (ee, }\mu\mu), > 10\text{GeV (e}\mu)$
→ removes low mass resonances.
- Jet veto ($pT > 25, |\eta| < 4.5$)
→ to further suppress top background.



WZ (lνll)

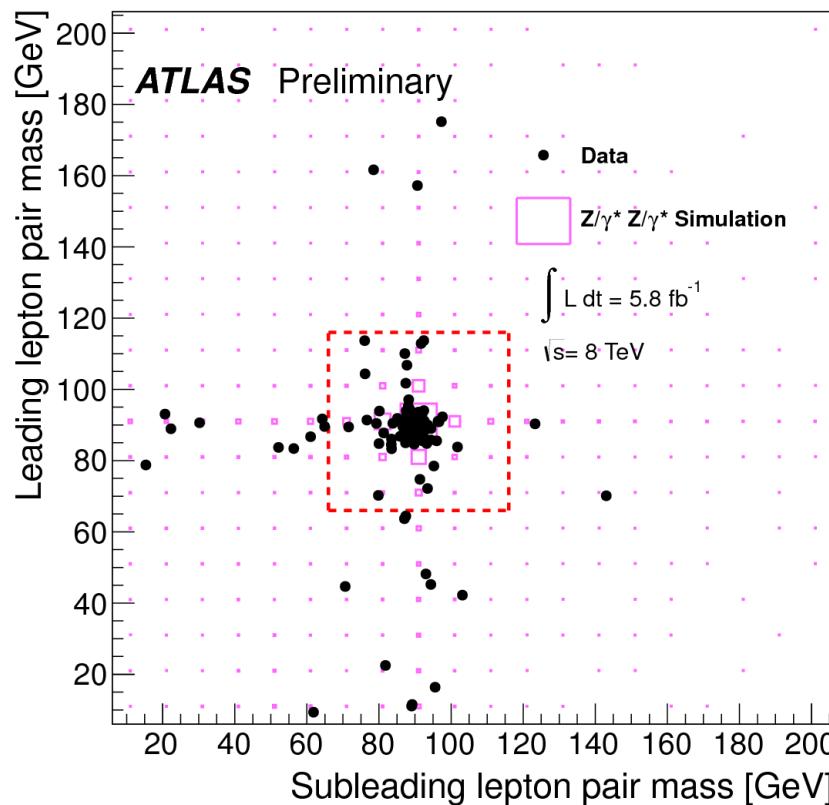
- Tighter cuts on lepton from the W to reduce Z+jets bkg ($pT > 20$ GeV).



- Cut on **transverse mass of the W boson > 20 GeV** and on **$\text{MET} > 25$ GeV** to further suppress Z+jets and diboson bkgs.
- Cut around the Z mass (± 10 GeV)

ZZ (llll)

- Invariant mass of the lepton pairs : $66\text{GeV} < m(\text{ll}) < 116\text{GeV}$



In eeee and $\mu\mu\mu\mu$ channels, choose the pairing which results in the smaller value of the sum of the two $|m_{\text{ll}} - m_Z|$ values.

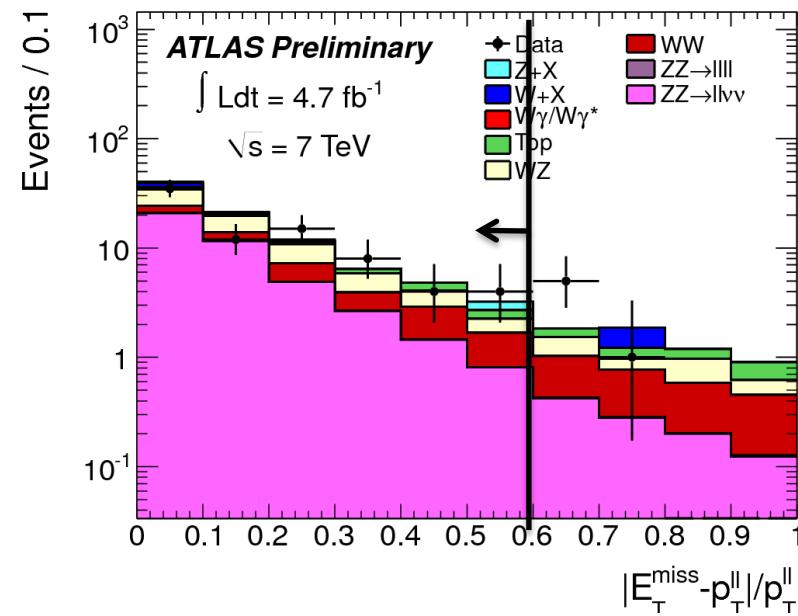
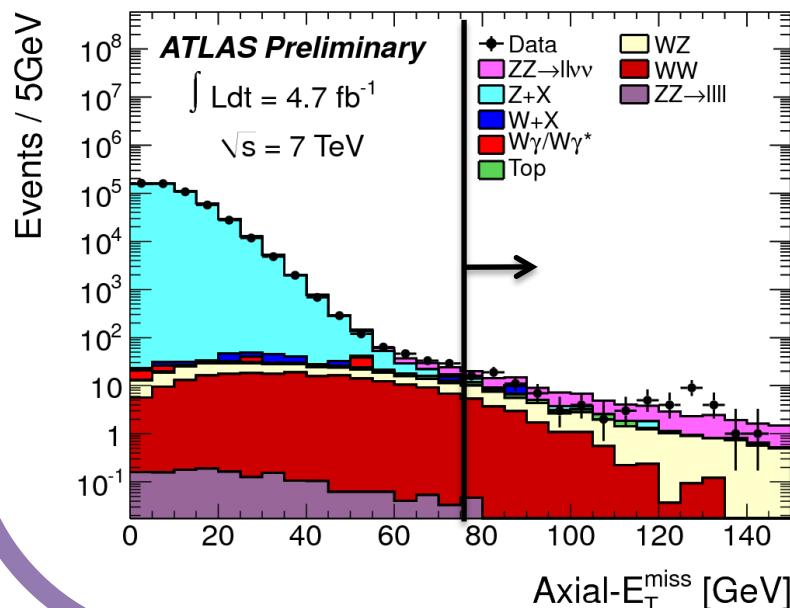
$WW + WZ$ ($l\nu qq$)

List of systematic uncertainties :

Source	$\Delta\sigma/\sigma[\%]$
Data Statistics	± 12
MC Statistics	± 18
$W/Z+jets$ normalization	± 11
W/Z jets shape variation	± 5
Multijet shape and normalization	± 5
Top normalization	± 6
Top ISR/FSR	± 1
Jet energy scale (all samples)	± 12
Jet energy resolution (all samples)	± 6
Lepton reconstruction (all samples)	± 1
WW/WZ ISR/FSR	± 2
JES uncertainty on WW/WZ normalization	± 6
PDF (all samples)	± 2
Luminosity	± 3.9
Total systematics	± 28

ZZ (llvv)

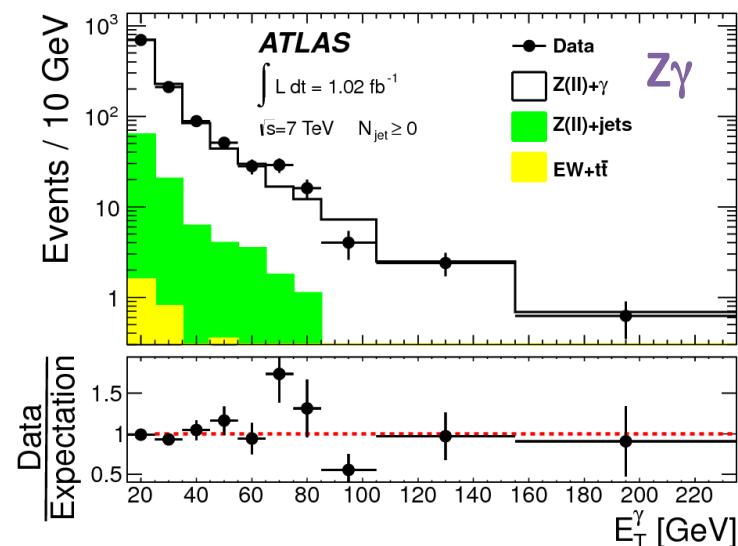
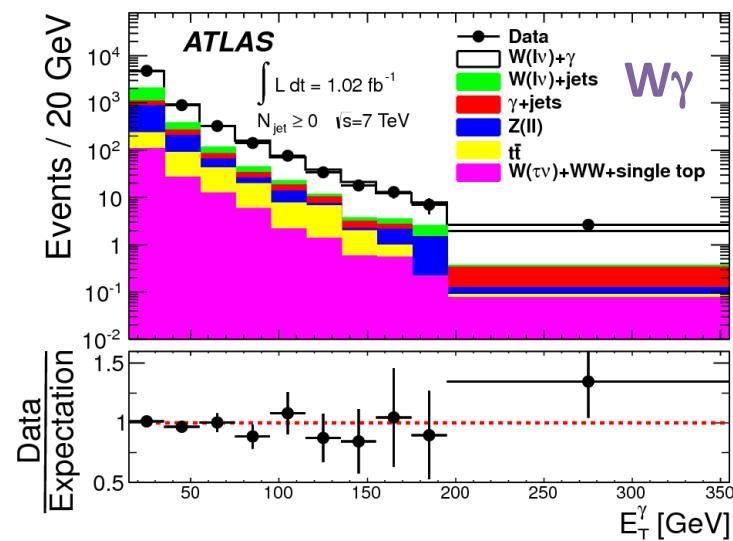
- **Axial Met** = missing transverse momentum anti-parallel to the direction in the transverse plane of the reconstructed Z boson
 - $\text{axial MEt} > 80\text{GeV}$ to reject $Z+\text{jets}$ events with small Met
- **Jet veto ($pT > 25\text{GeV}$, $|\eta| < 4.5$)** applied to suppress top and $Z+\text{jets}$.
- **Fractional pT difference** = $|\text{MEt}-p_T(Z)|/p_T(Z) < 0.6$ to suppress WW



$W/Z\gamma$

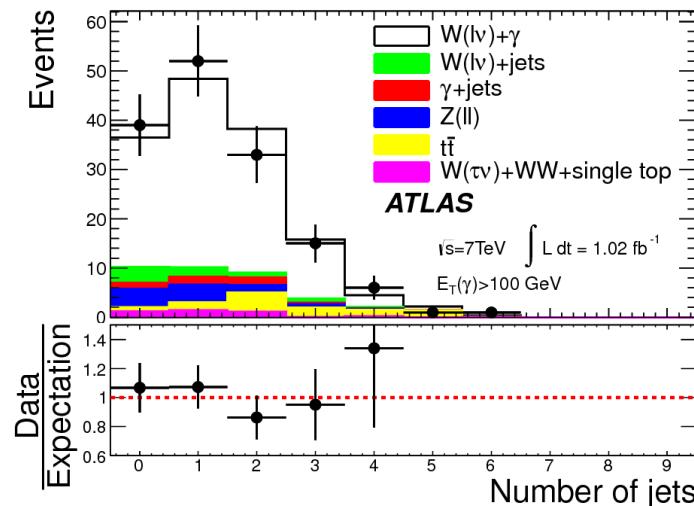
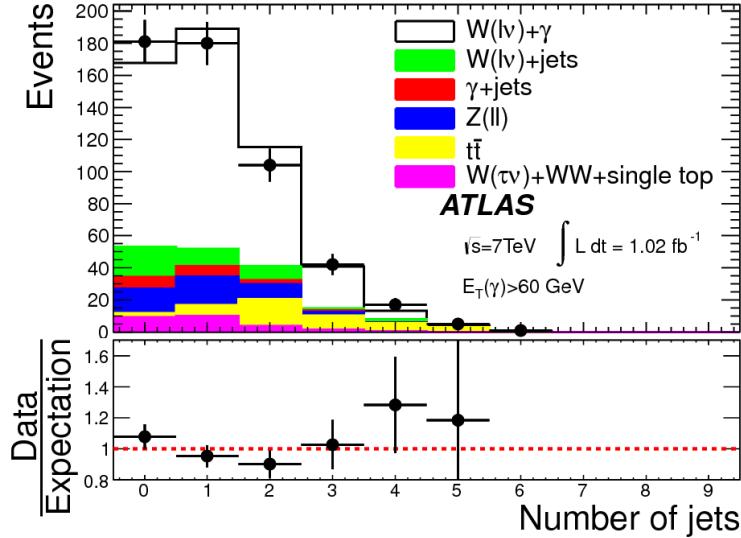
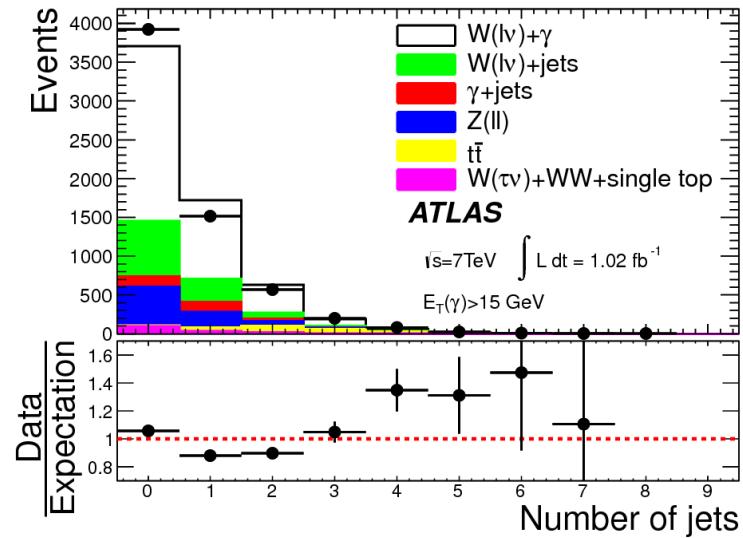
$W\gamma$	$Z\gamma$
$\text{MEt} > 25\text{GeV}$ $\text{mT}(\text{lepton},\nu) > 40\text{GeV}$ $Z \text{ veto for e channel : } \pm 10\text{GeV}$	$m(\text{ll}) > 40\text{GeV}$

Photon selection : $E_T > 15\text{GeV}$, $\Delta R(e/\mu,\gamma) > 0.7$, isolation $< 6\text{GeV}$



Jet selection : $pT > 30\text{GeV}$, $|\eta| < 4.4$, $\Delta R(\text{jet},\gamma) > 0.6$, $\Delta R(\text{jet},\text{leptons}) > 0.6$

W γ



Effective Lagrangian Approach



Express model independent triple gauge couplings as parameters in effective Lagrangian:

$$\frac{\mathcal{L}_{WWV}}{g_{WWV}} = i \left[g_1^V (W_{\mu\nu}^\dagger W^{\mu\nu} V^V - W_{\mu\nu} W^{\dagger\mu} V^\nu) + \kappa^V W_\mu^\dagger W_\nu V^{\mu\nu} + \frac{\lambda^V}{m_W^2} W_{\rho\mu}^\dagger W_\nu^\mu V^{\nu\rho} \right] \quad (\text{WW, WZ})$$

$$\mathcal{L}_{VZZ} = -\frac{e}{M_Z^2} \left[f_4^V (\partial_\mu V^{\mu\beta}) Z_\alpha (\partial^\alpha Z_\beta) + f_5^V (\partial^\sigma V_{\sigma\mu}) \tilde{Z}^{\mu\beta} Z_\beta \right] \quad (\text{ZZ})$$

- With non-SM coupling, the amplitudes for gauge boson pair production grow with energy.
- Tree level unitarity is violated at very high energy
- To avoid this, an effective Cutoff scale is introduced

$\sqrt{s^\wedge}$ = invariant mass
of the vector-boson pair

$$\alpha(\hat{s}) = \frac{\alpha_0}{(1 + \hat{s}/\Lambda^2)^n}$$

coupling value at
low energy limit

scale of new physics :
 $\Lambda=1.5, 2, 3, 6 \text{ TeV}$ preserves
unitarity
 $\Lambda=\infty$ violates unitarity

n : WW/WZ/Wg coupling parameters : $n=2$

ZZ

Zg

coupling parameters : $n=3$

coupling parameters : $n=3$ for h_3^V , $n=4$ for h_4^V