Electroweak measurements at the LHC

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Rencontres de Moriond

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A rich menu of results

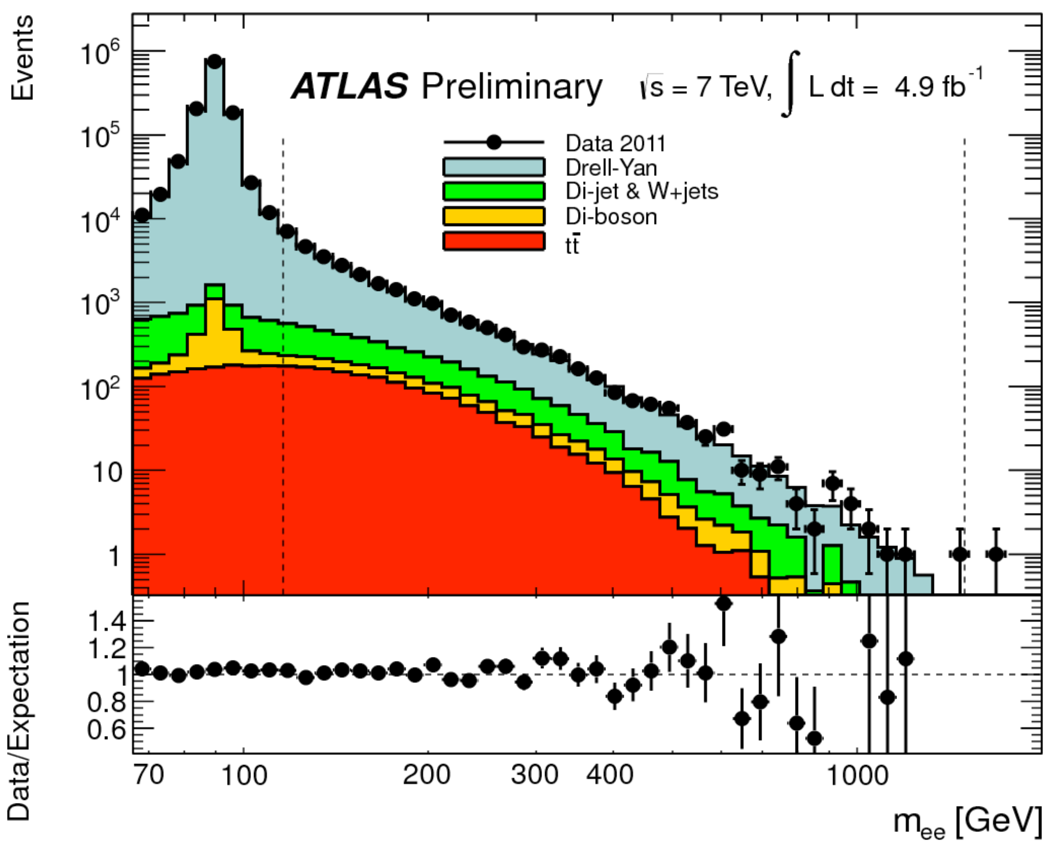
- **Electroweak Bosons**
  - Drell-Yan production
  - Z/γ^* Transverse Momentum ($d\sigma/d\phi^*_\eta(ll)$)
  - Differential Z/γ^* + jets cross section
  - Jet production in association with Z
  - W production in association with b jets

- **Diboson final states**
  - Wγ, Zγ, WW, WZ, ZZ production
  - Limits on anomalous Triple-Gauge Couplings

High Drell-Yan cross section (1)

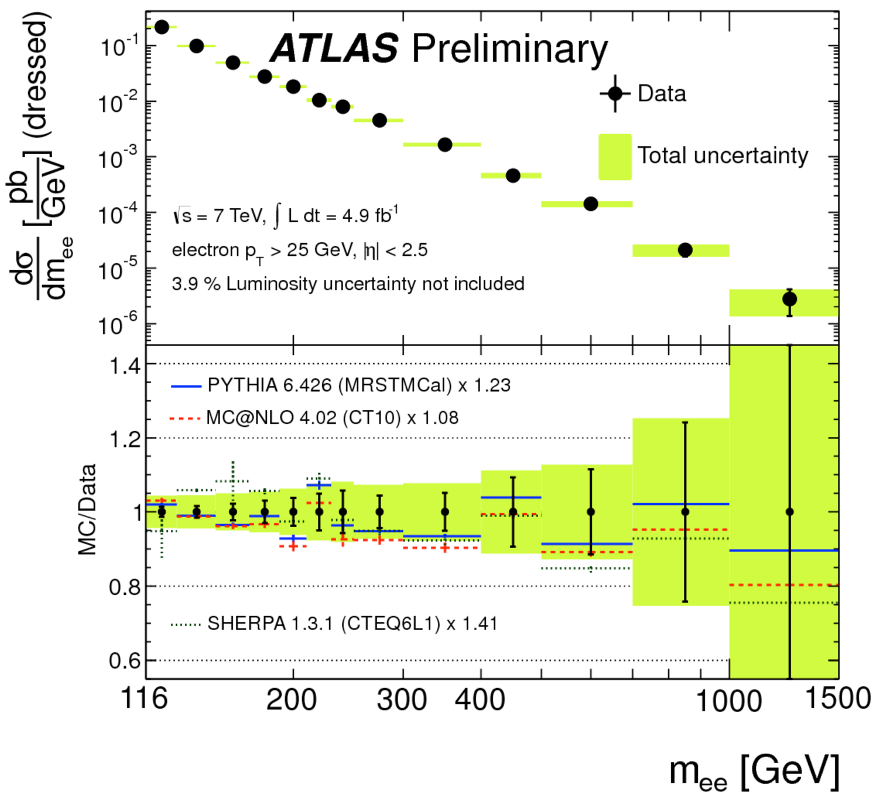
- Excellent test of perturbative QCD within SM, using latest NNLO PDFs and NLO EWK corrections

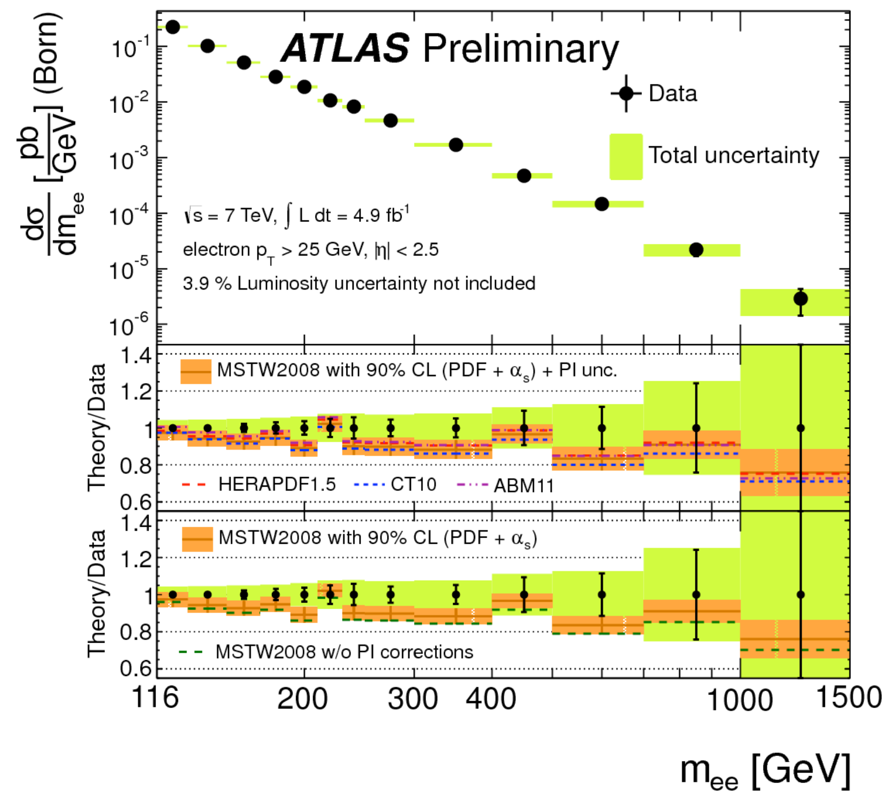
- **Drell-Yan differential cross section measured in 116 < m_{ee} <1500 GeV** (E_T >25 GeV, IηI<2.5)



- **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 the statistics for m_{ee} >400 GeV

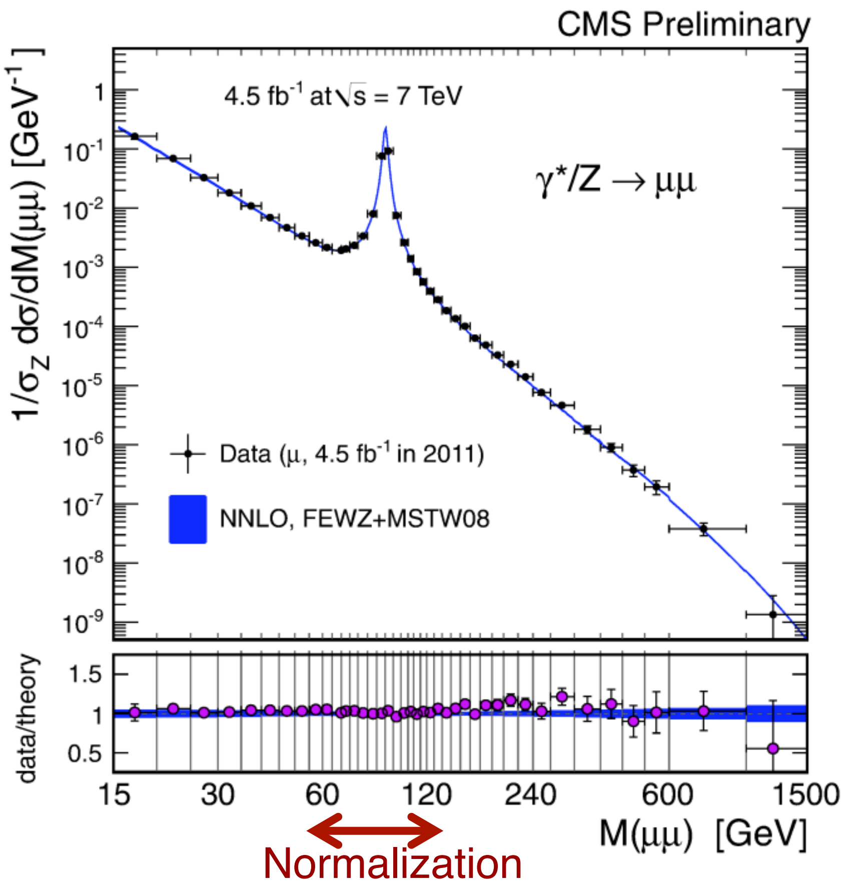
High Drell-Yan cross section(2)

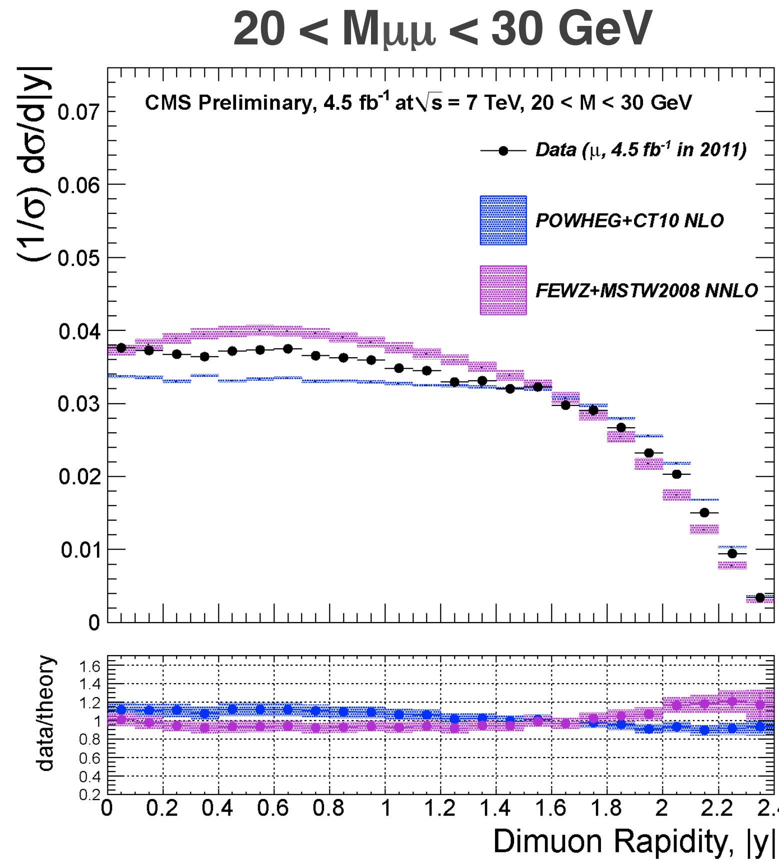




- Good agreement between shape in data with PYTHIA, MC@NLO and SHERPA
- Good agreement between shape in data and predictions of perturbative QCD at NNLO (FEWZ), within the uncertainty, with all the PDF sets considered.
- Comparing results with and without photon-induced background ($\gamma\gamma \rightarrow e^+e^-$), it is observed that this contribution is of similar size to the sum of the PDF and α_s uncertainties

Differential and double-differential Drell-Yan cross section

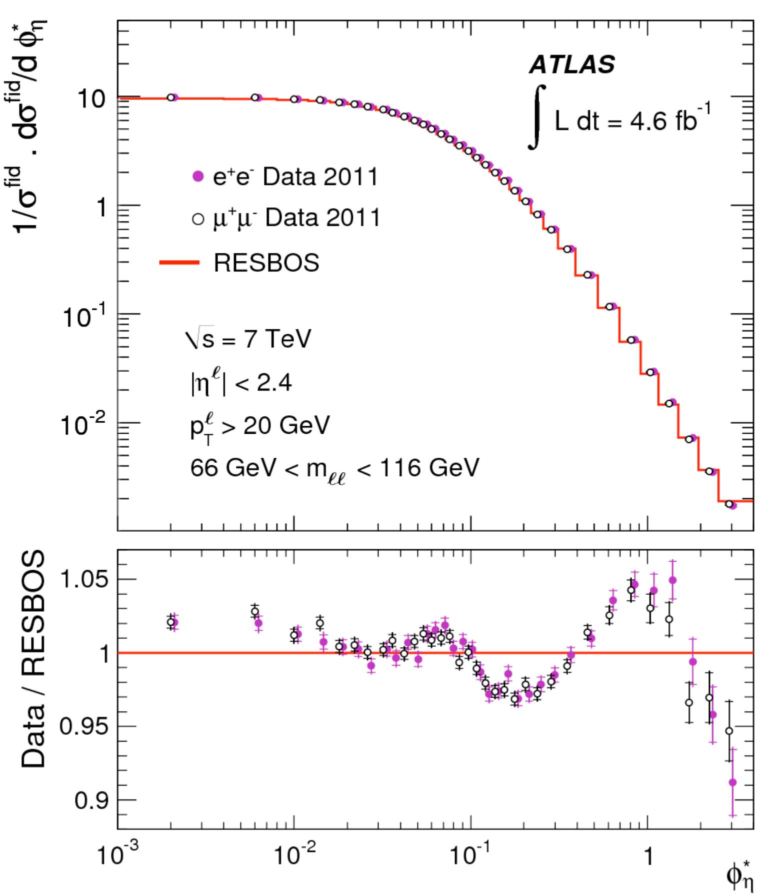


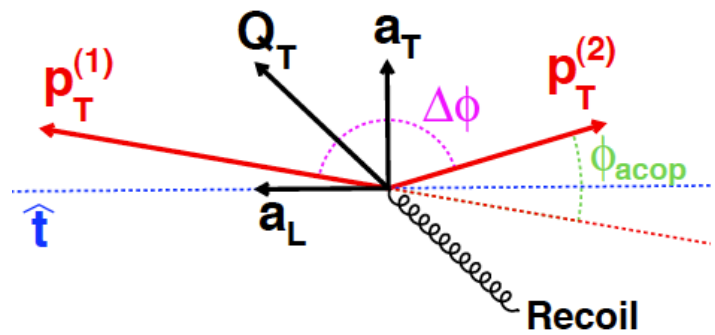


- Very good agreement on several orders of magnitude
- Double differential cross section normalized to the Z peak region and |Y| < 2.4
- Significant differences between data, POWHEG NLO and FEWZ NNLO calculations at low masses

Z/γ^* transverse momentum ($d\sigma/d\phi^*_\eta(ll)$)

- Use ϕ^*_η variable to probe modelling of p_T of Z boson in MC (ResBos(NNLL) and FEWZ)
- **Has advantage that angular resolution is better than p_T resolution**
- ϕ^*_η is highly correlated with a_T/M_{ll} and can be measured





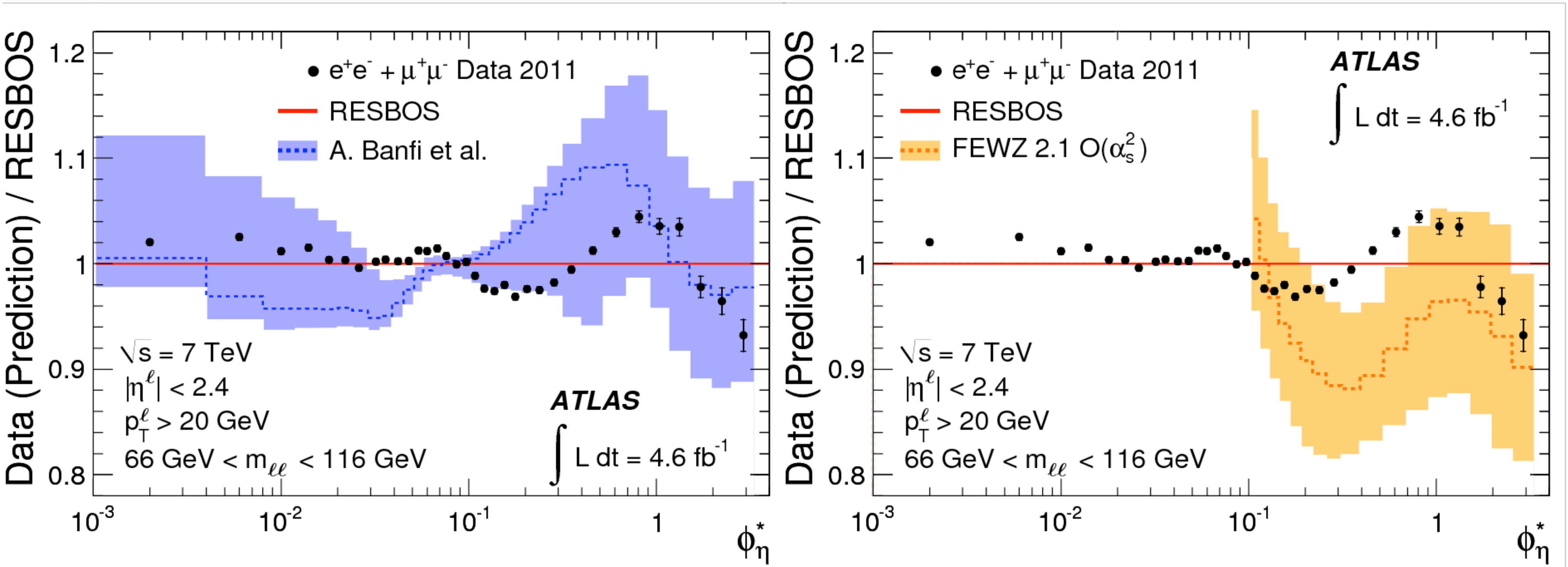
$$a_T / Q_T \approx \tan(\phi_{acop}/2)\sin\theta^*$$

$$\phi^* \equiv \tan(\phi_{acop}/2)\sin\theta^*$$

θ^* scattering angle of the leptons relative to the proton beam direction in the dilepton rest frame

- **Data-RESBOS difference within 2% for ϕ^*<0.1, increasing to 5% for higher ϕ^***

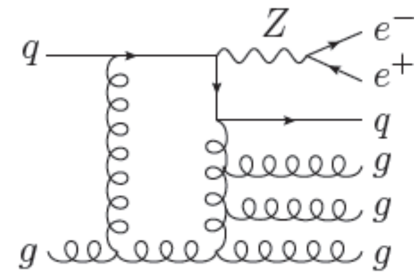
Z/γ^* transverse momentum ($d\sigma/d\phi^*_\eta(ll)$)

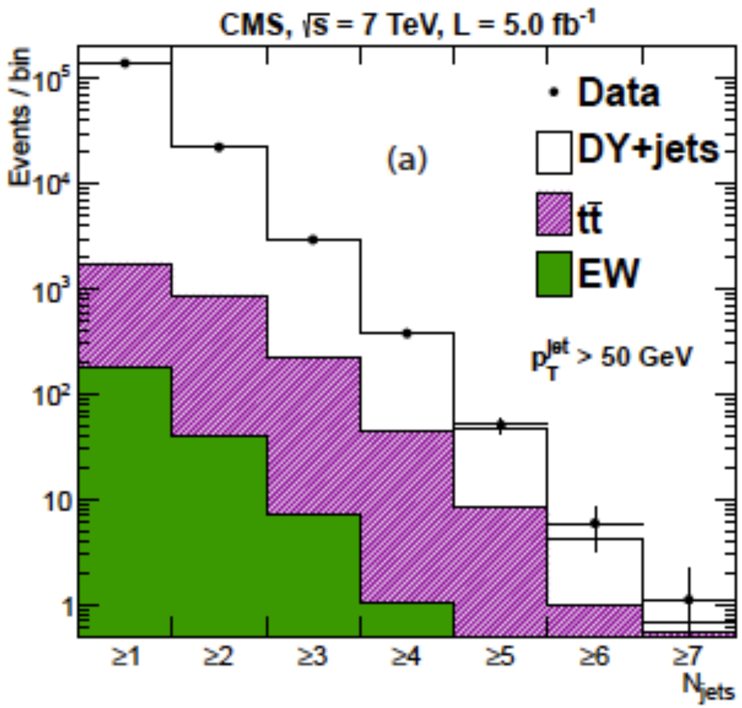


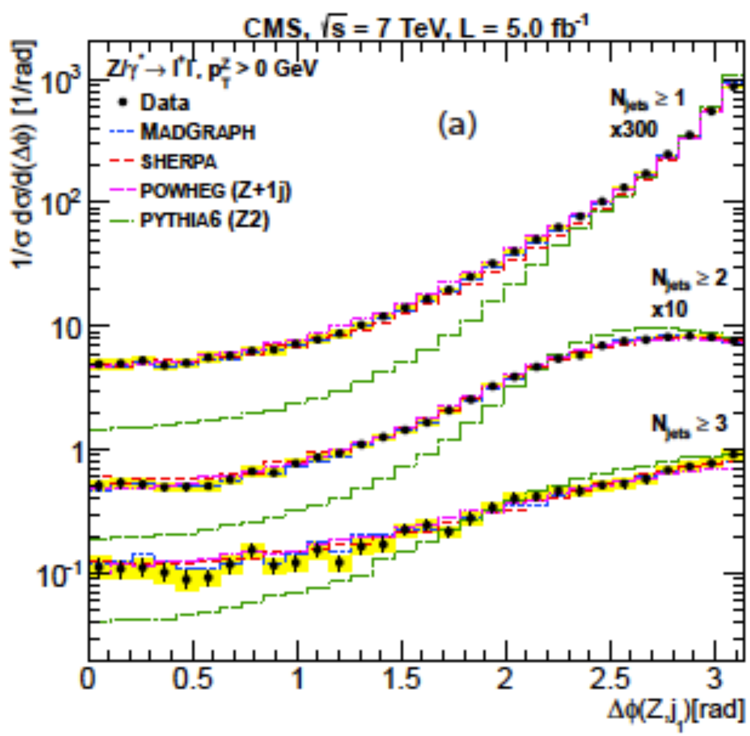
- Calculations from A. Banfi et al. (resummed QCD predictions+fixed-order pQCD) is less good than ResBos
- **Measurement precision about one order of magnitude lower than the present theoretical uncertainties**
- FEWZ predictions undershoot the data by ~10% which confirm previous CDF observation (PRD 86,052010)

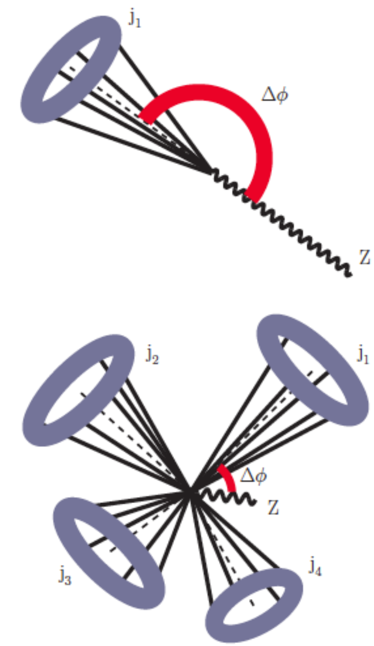
Azimuthal correlations in Z+Jets events

- **Jet multiplicities and azimuthal correlations $\Delta\Phi$(Z, Leading Jet)**
  - Selection : >=1 jet, 2 high p_T leptons, Z-mass requirement
  - Distributions unfolded back to particle level







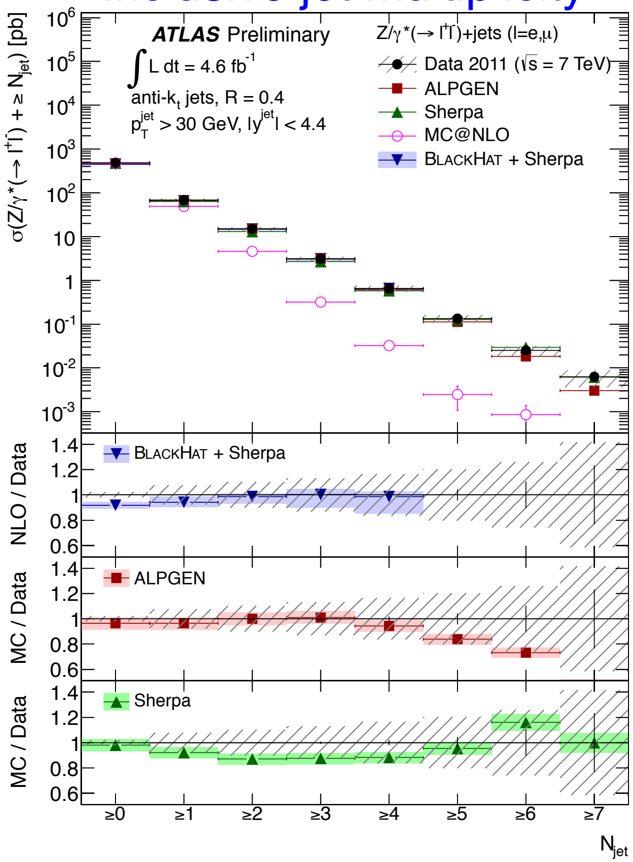


- **MADGRAPH, SHERPA describe data well**
  - Also true for other observables : $\Delta\Phi$(jet, jet), $\Delta\Phi$(Z, jet2), transverse event trust in two p_T(Z) regions > 0, 150 GeV

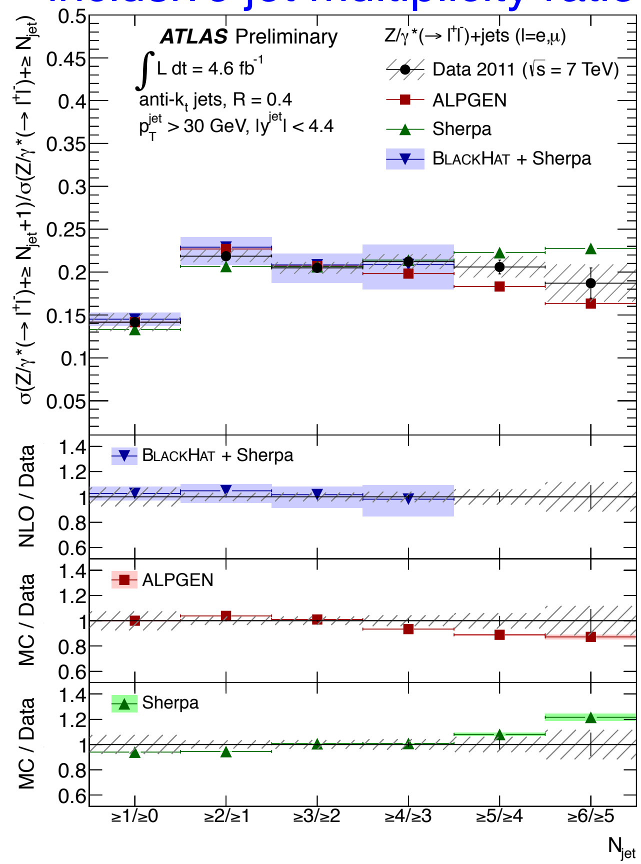
Differential Z/γ* + jets cross section (1)

- Test of recent NLO pQCD predictions for large jet multiplicities (not accessible before)
- Test of limitations of ME+PS generators and fixed order pQCD in regions where large logarithmic corrections and EW NLO corrections become important

inclusive jet multiplicity



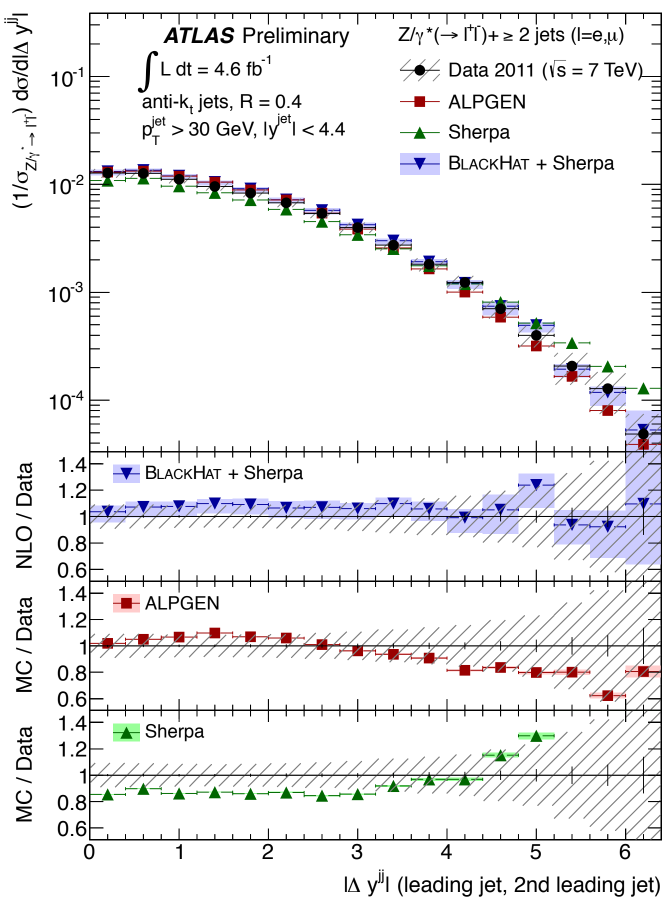
inclusive jet multiplicity ratio



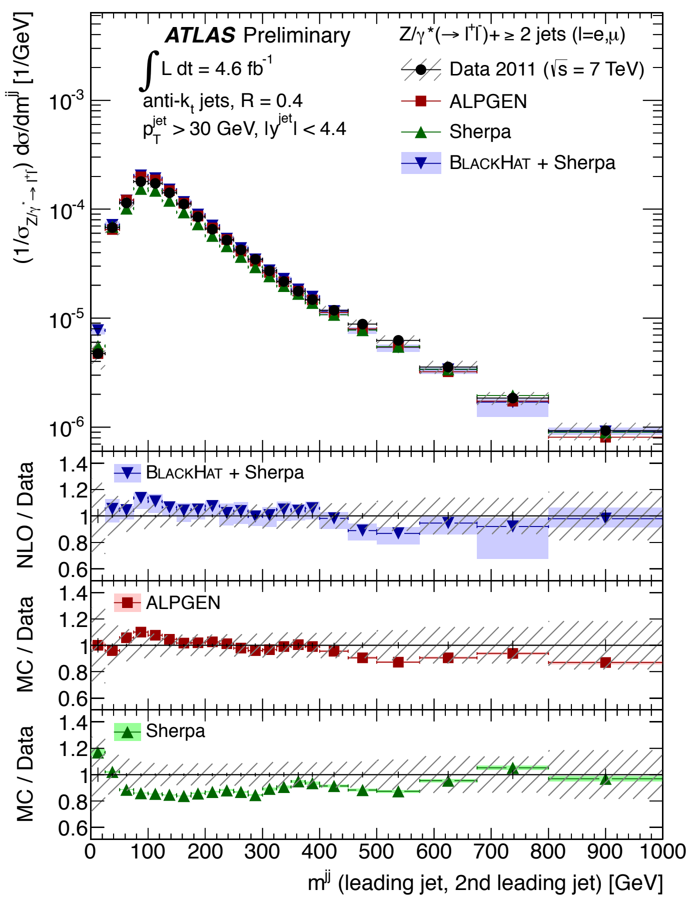
- **Jet multiplicity up to 7 jets: well described by ME+PS generators (up to 5 jets) and BlackHat+Sherpa, MC@NLO fails**

Differential Z/γ* + jets cross section (2)

Rapidity gap

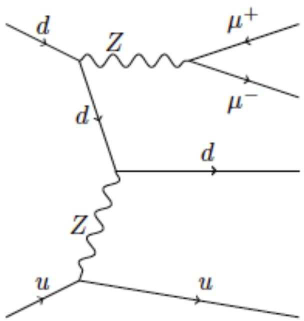


Dijet mass

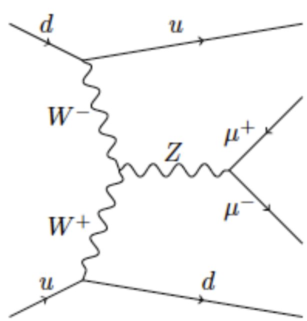


- The predictions by BlackHat+Sherpa and ALPGEN are consistent with the data
- Sherpa overestimates the cross section for large Δy^{jj} , consistent with the too wide rapidity spectra
- Important for VBF Higgs searches and other searches

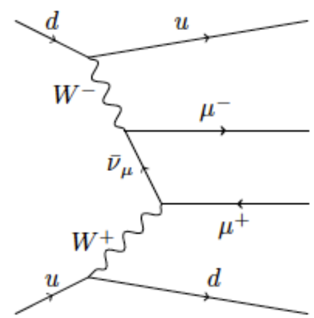
EWK production with 2 forward jets



bremsstrahlung



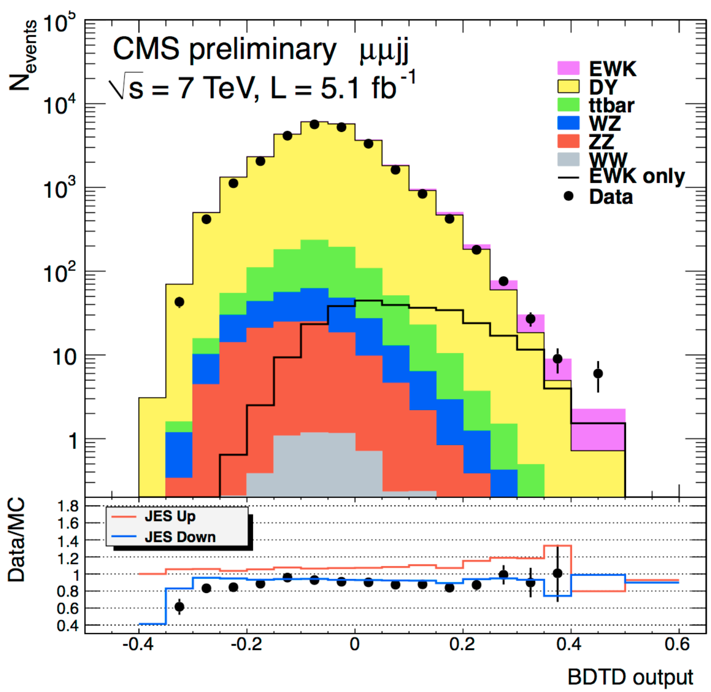
VBF



Multi-peripheral

- **Vector boson centrally produced**
- Jets well separated in rapidity
- Probe Triple gauge couplings
- Background to Higgs VBF searches

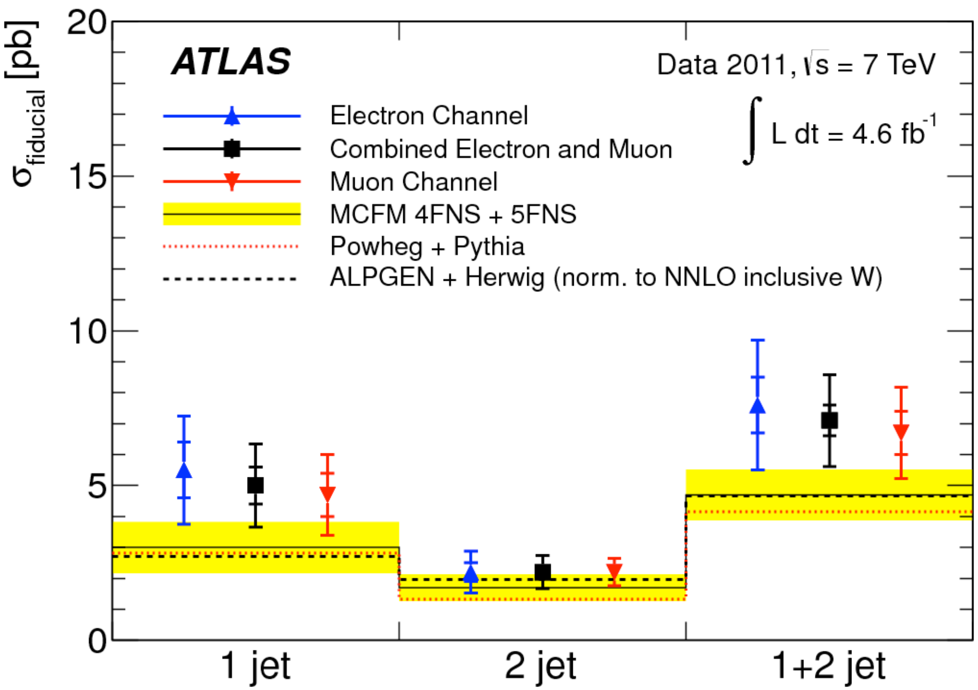
		Measured (fb)	VBFNLO NLO (fb)
CMS	7TeV	154 ± 24 (stat) ± 46 (syst) ± 27(theory) ± 3(lumi)	166



- Kinematic region of the reported cross section : M_{ll} >50 GeV, P_T(jet)>25 GeV, |η|<4, m_{jj} >120 GeV
- **Obtain the Signal contribution and Drell-Yan+jets from a fit to the BDT output**
- Signal and dominant background are simulated with Madgraph

W production in association with b jets (1)

- W+b-jets important background to Higgs boson production in WH, H→bb
- Irreducible background in BSM searches and single-top measurements



- Require $p_T^l > 25$ GeV, $|\eta^l| < 2.5$, $p_T^\nu > 25$ GeV, m_T (W) > 60 GeV:

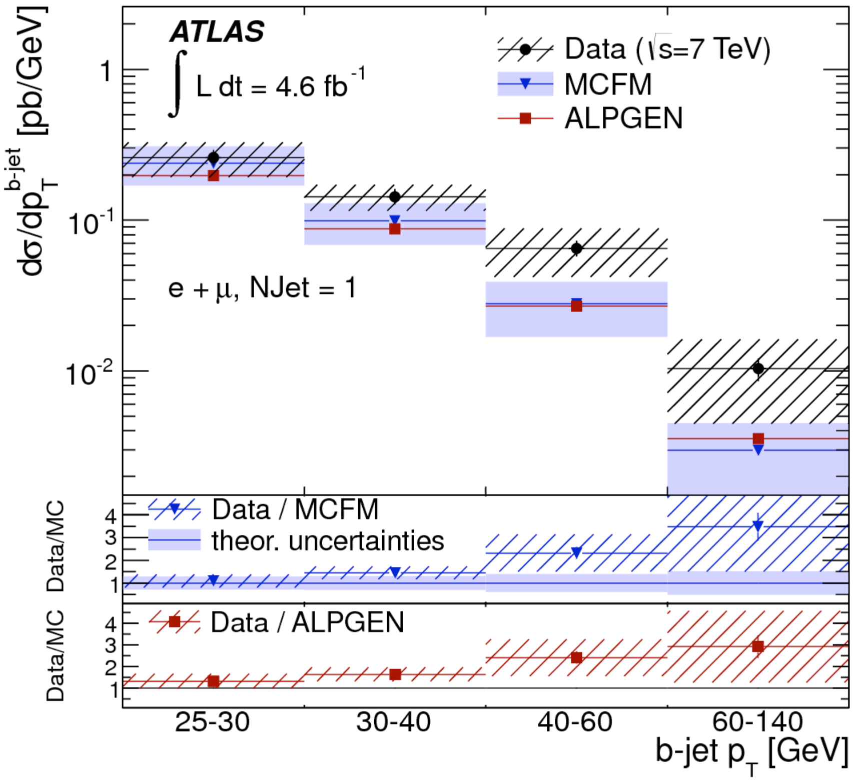
$$m_T(W) = \sqrt{2 p_T^l p_T^\nu (1 - \cos(\varphi^l - \varphi^\nu))}$$

up to 2 jets each with $p_T^j > 25$ GeV, $|y^j| < 2.1$

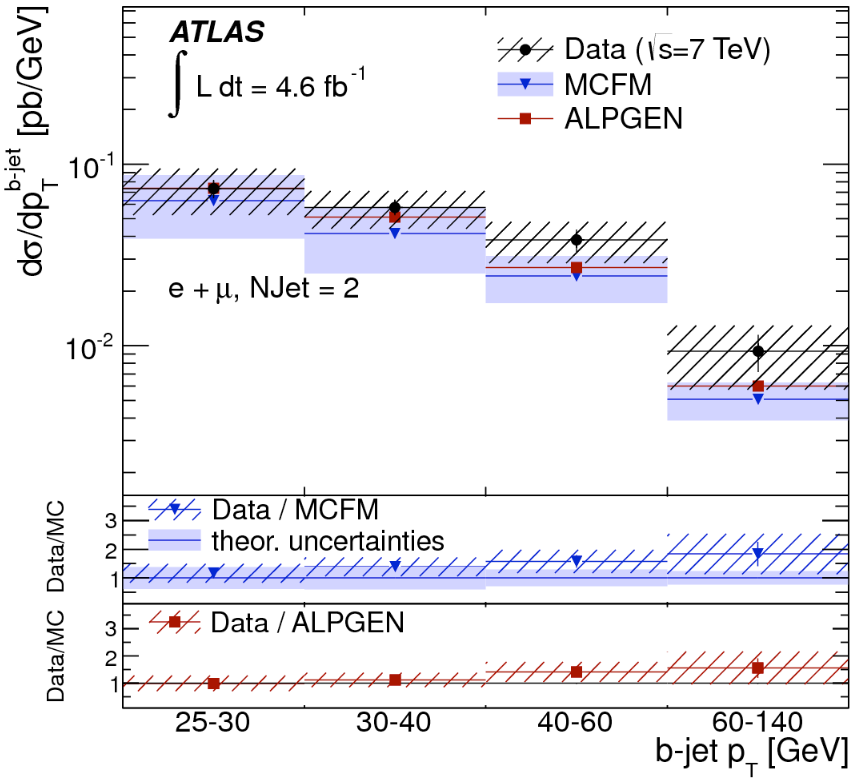
- 1+2 jet exclusive cross section: **7.1 ± 0.5 (stat.) ± 1.4 (syst.) pb**
- Measurement within 1.5 σ consistent with MCFM NLO prediction

W production in association with b jets (2)

One jet bin



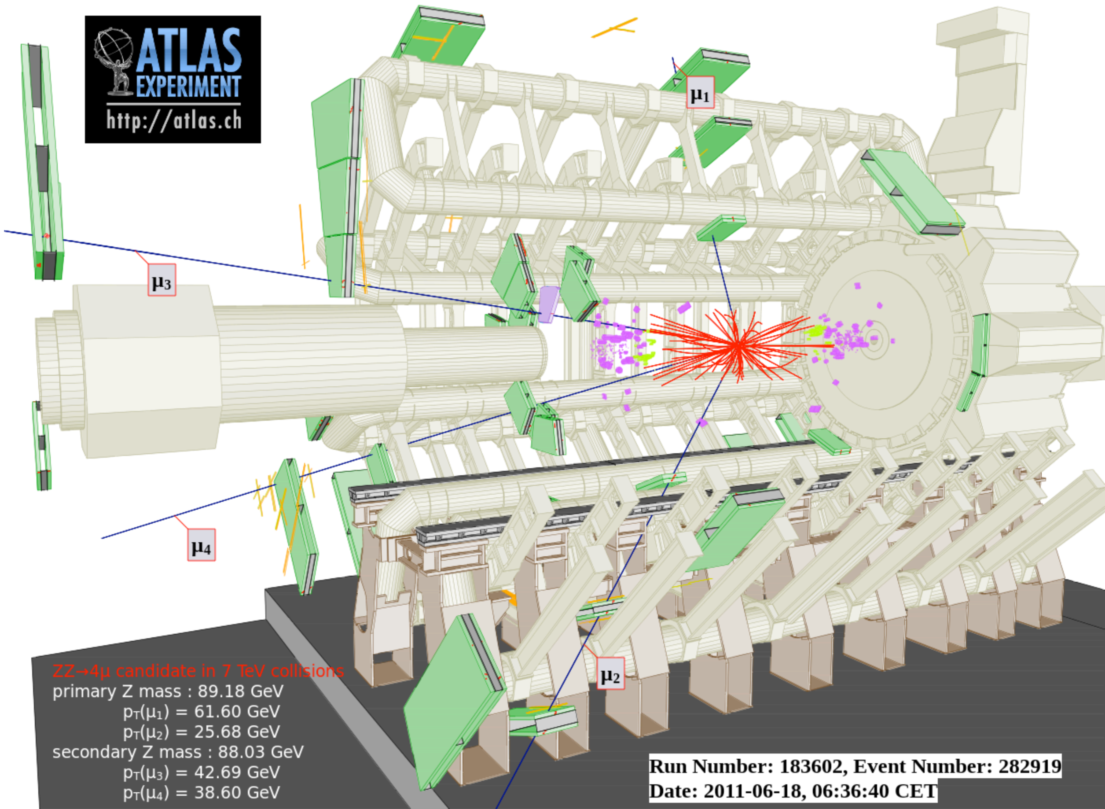
Two jet bin



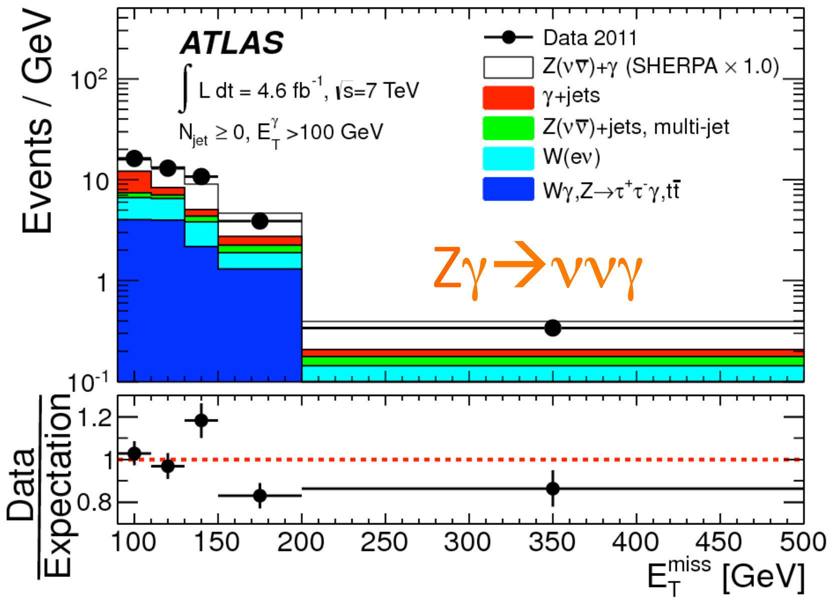
- **In the one jet bin**, the measurement is systematically higher than the MCFM prediction, but compatible within uncertainties
- **In the two jet bin**, the measurement is in agreement with the MCFM prediction within uncertainties

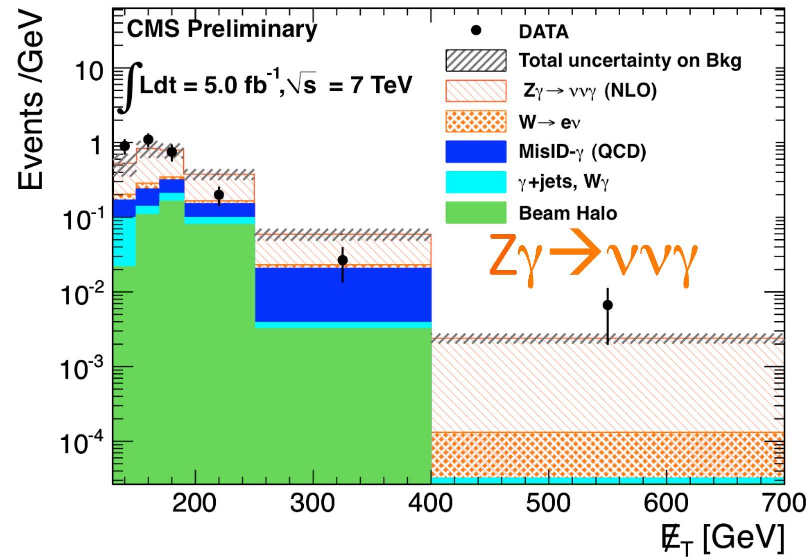
Diboson production

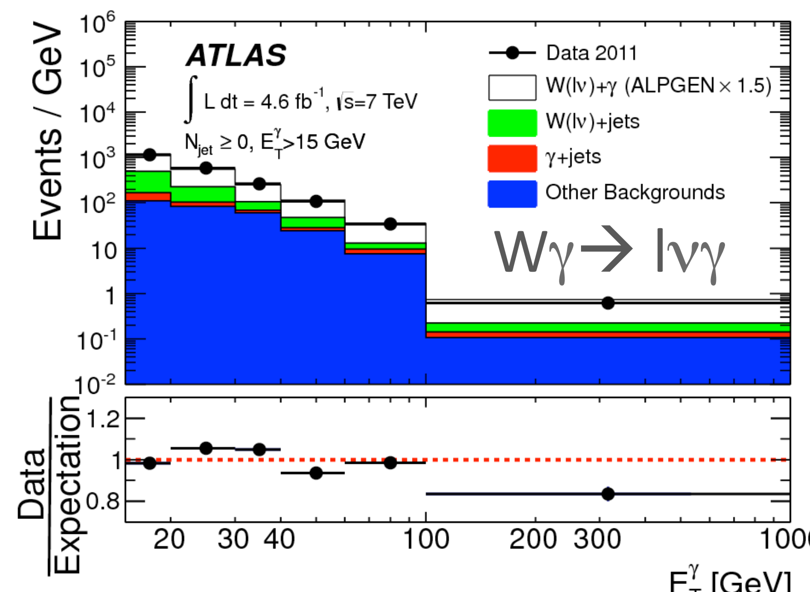
- **Fundamental test of Standard Model**
- **Probe for new physics**
  - Triple gauge couplings (TGC)
  - Resonances with diboson final states
- **Irreducible background for Higgs searches**



Wγ/Zγ production@ 7 TeV



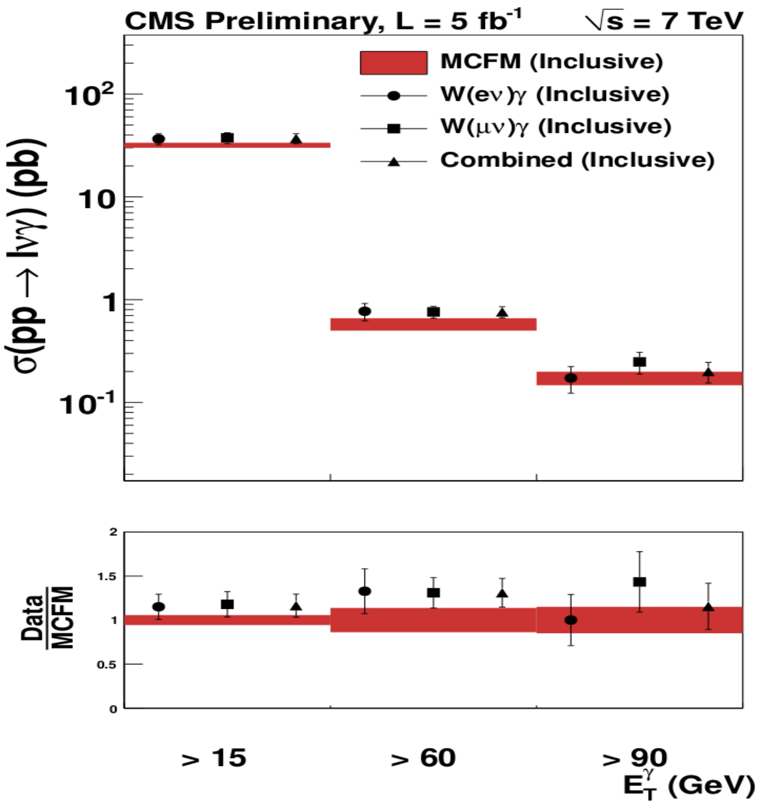




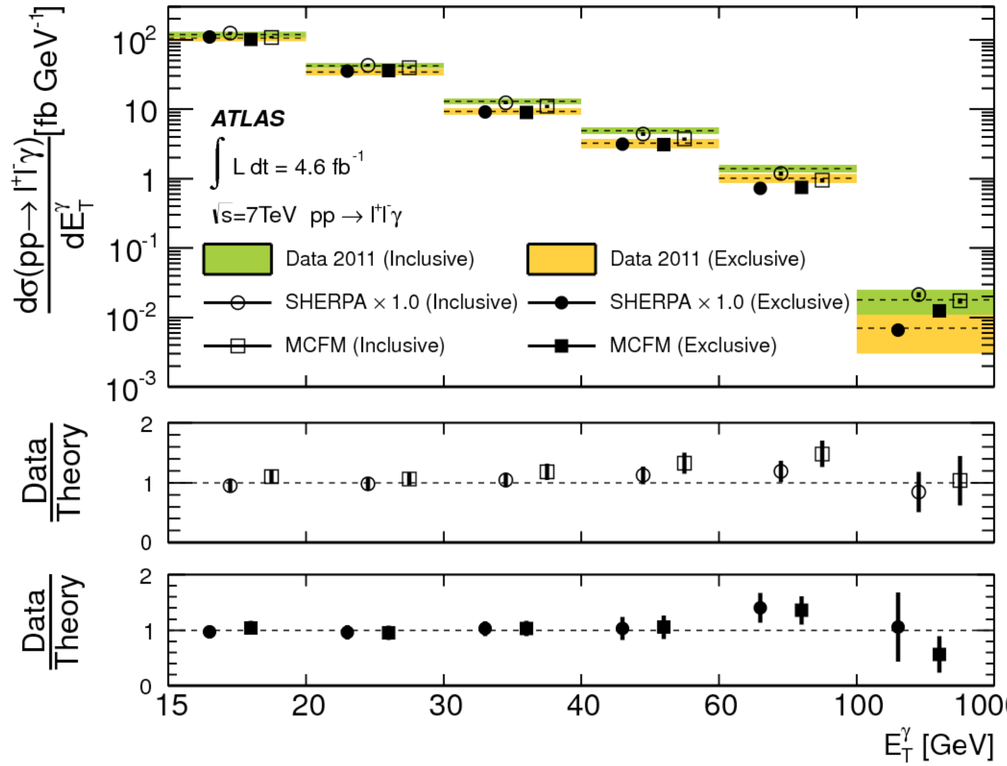
- **Analyses of lνγ, llγ and ννγ final states**
  - γ with high E_T
  - Large ΔR(l,γ) (suppress FSR)
  - Isolated lepton with high E_T
  - Missing energy if ννγ
  - $\Delta R(E_T^{miss}, \gamma)$ separation

Wγ/Zγ production @ 7 TeV

Wγ→ lνγ

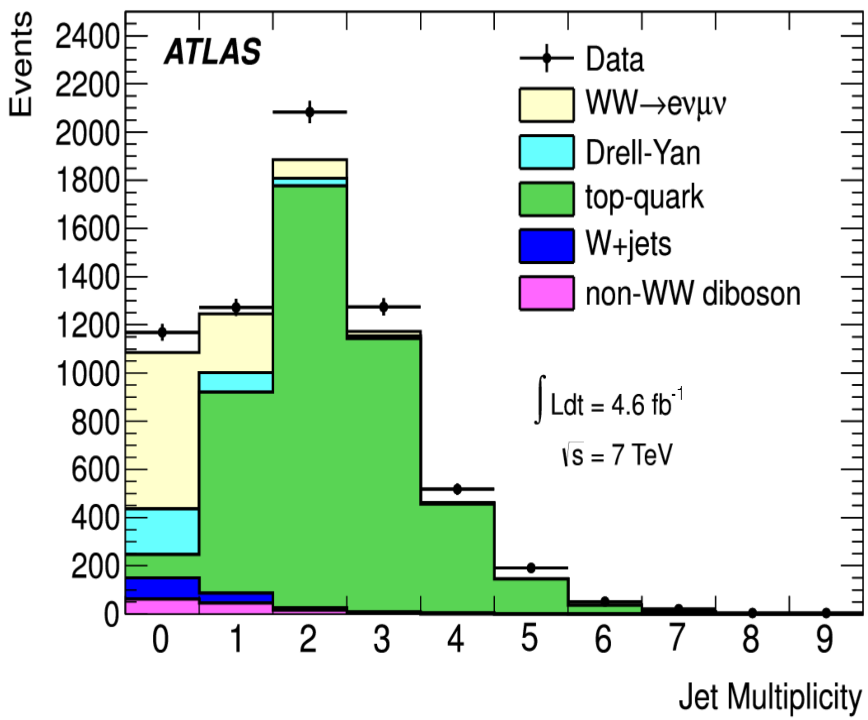


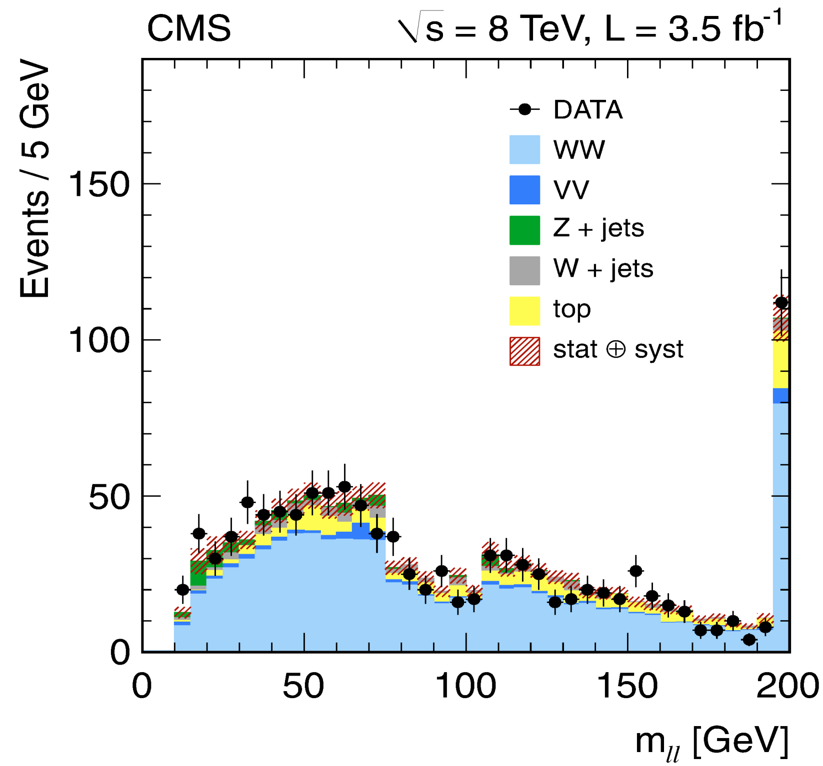
Zγ→ llγ



- Inclusive Wγ cross sections above theory (MCFM NLO)
- Fair agreement for Zγ

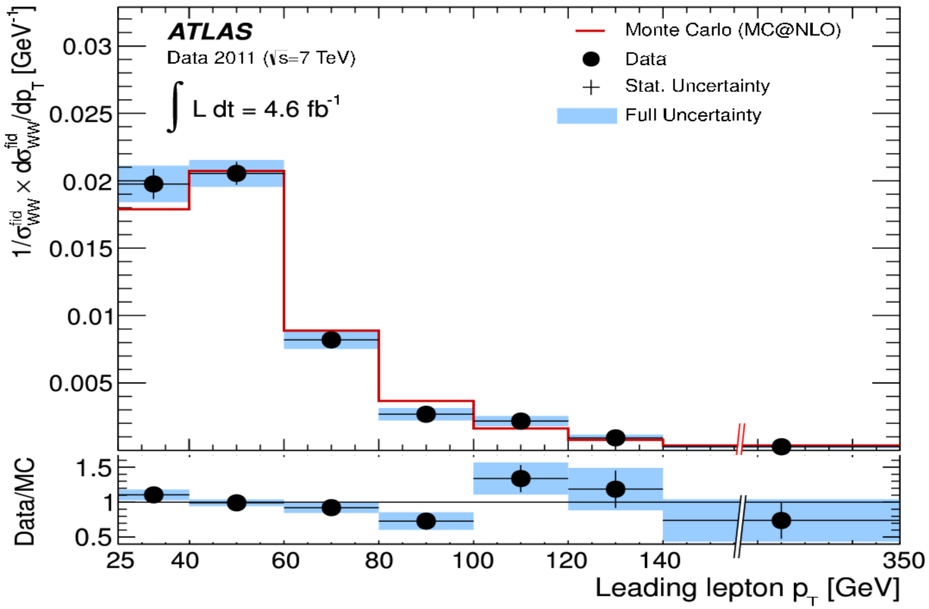
W W production @ 7-8 TeV





- **Signal** : dileptons (e and μ) and missing energy
- **Main backgrounds**:
  - Z → ll + fake missing Et → Z-veto in ee and μμ channels
  - W+jets (jet faking a lepton)
  - tW and tt → use only the 0-jet events

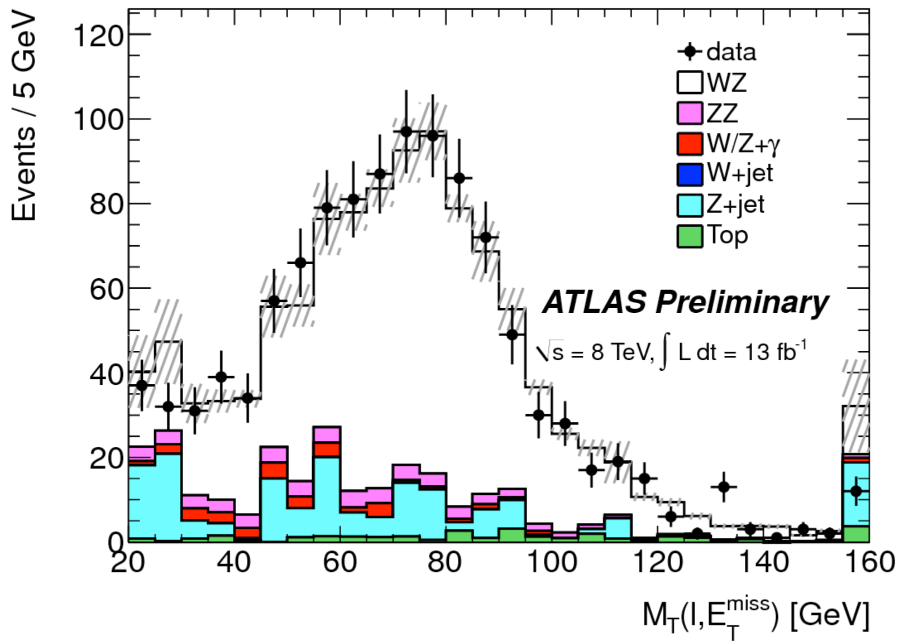
W W production@ 7-8 TeV

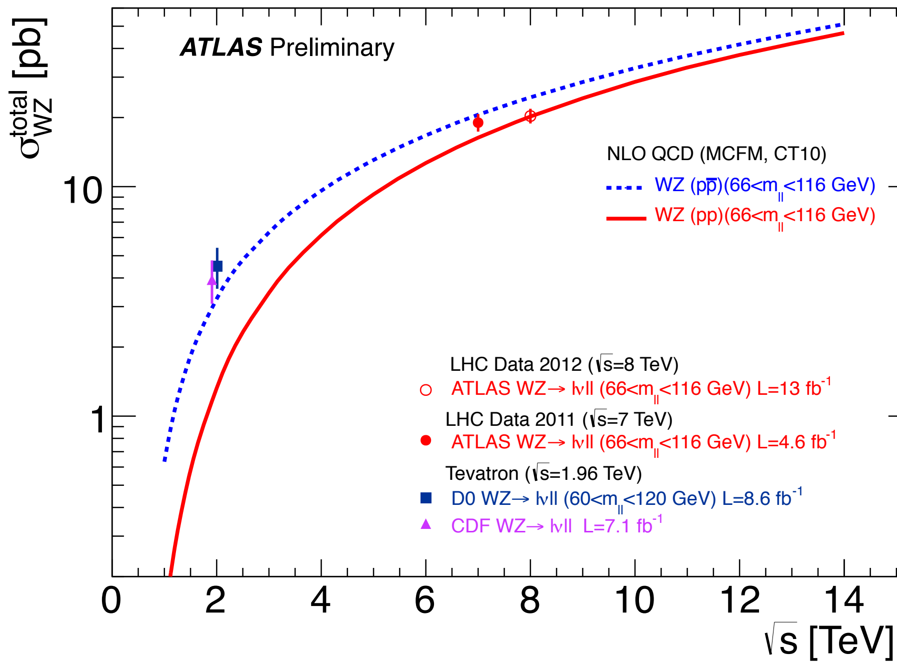


		Measured (pb)	MCFM NLO (pb)
ATLAS	7 TeV	51.9 ± 2.0 (stat) ± 3.9 (syst) ± 2.0 (lumi)	$44.7^{+2.1}_{-1.9}$
CMS	7 TeV	52.4 ± 2.0 (stat) ± 4.5 (syst) ± 1.2 (lumi)	47.0 ± 2.0
CMS	8 TeV	69.9 ± 2.8 (stat) ± 5.6 (syst) ± 3.1 (lumi)	$57.3^{+2.4}_{-1.6}$

- Measured cross sections slightly above theoretical predictions
- Higgs contribution of the order of 3% (not considered in this plot)

W Z production@ 8TeV

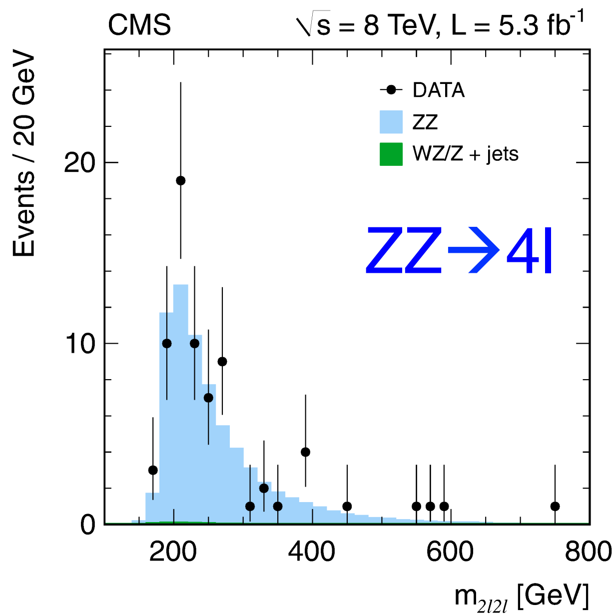


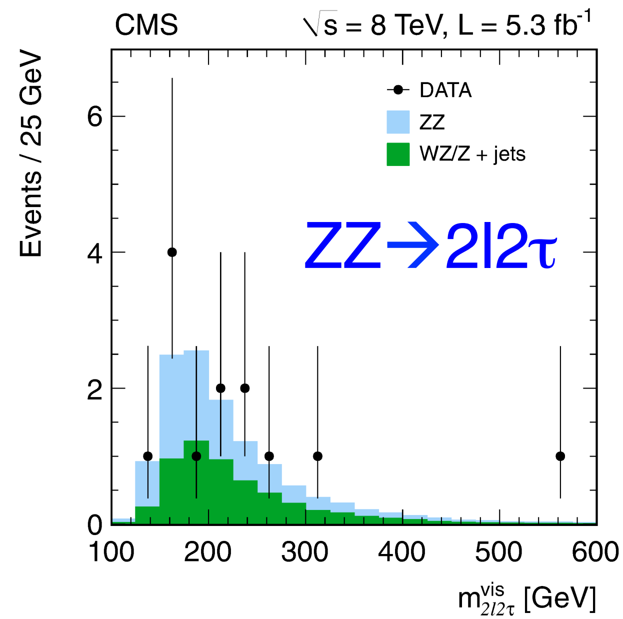


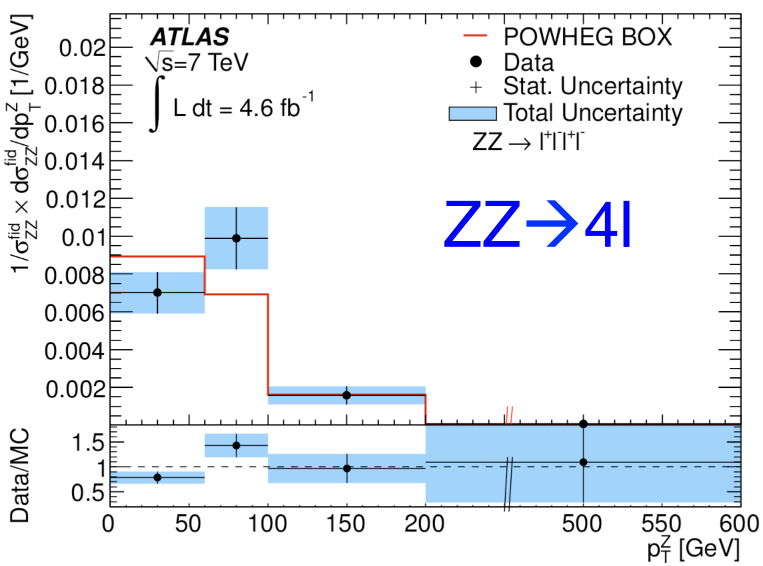
- **Signal** = tri-lepton (including one Z) and missing energy
- **Main backgrounds** : Z+jets, ttbar (jet faking a lepton), other dibosons

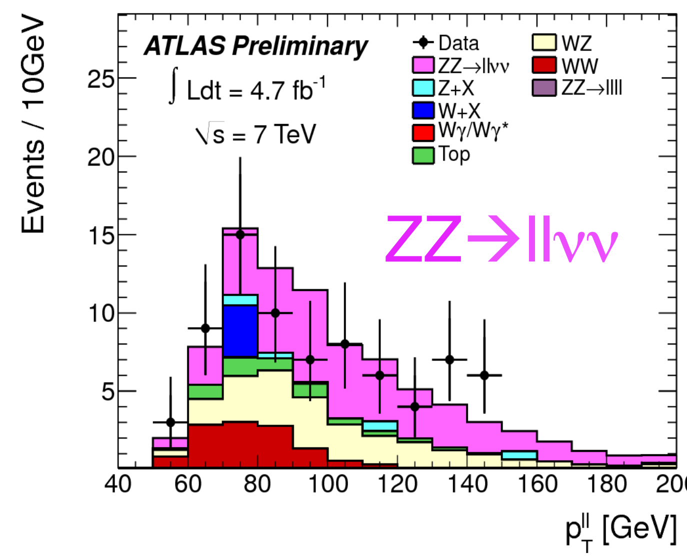
		Measured (pb)	**MCFM NLO (pb)**
ATLAS	7 TeV	19.0 ± 1.4 (stat) ± 0.8 (syst) ± 0.4 (lumi)	$17.6^{+1.1}_{-1.0}$
ATLAS	8TeV	20.3 ± 0.7(stat) ±1.1(syst) ±0.6(lumi)	20.3 ± 0.8
CMS	7 TeV	17.0 ± 2.4 (stat) ± 1.1 (syst) ± 1.0 (lumi)	17.5 ± 0.6

ZZ production@ 7-8 TeV

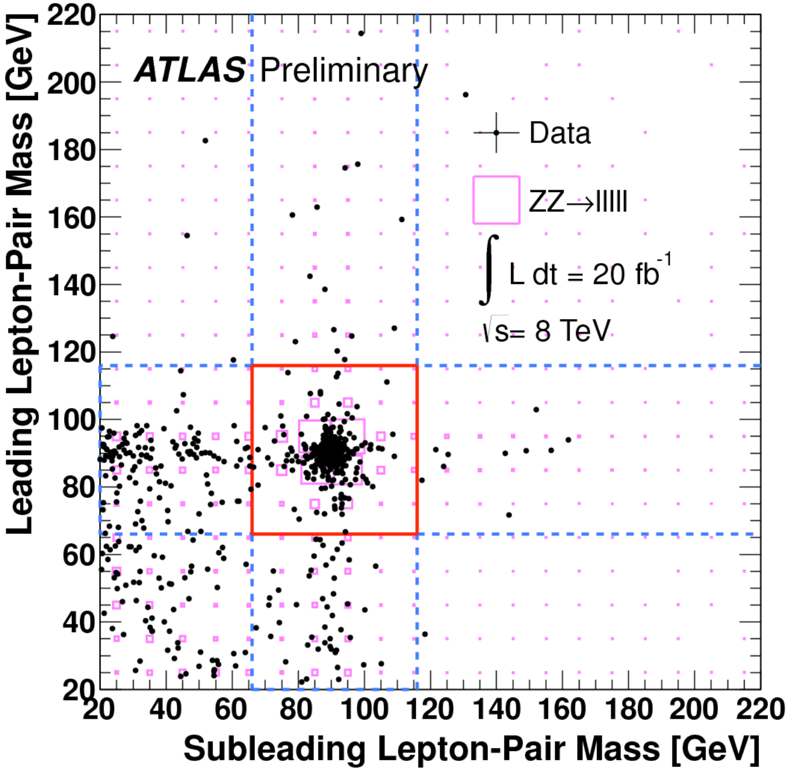


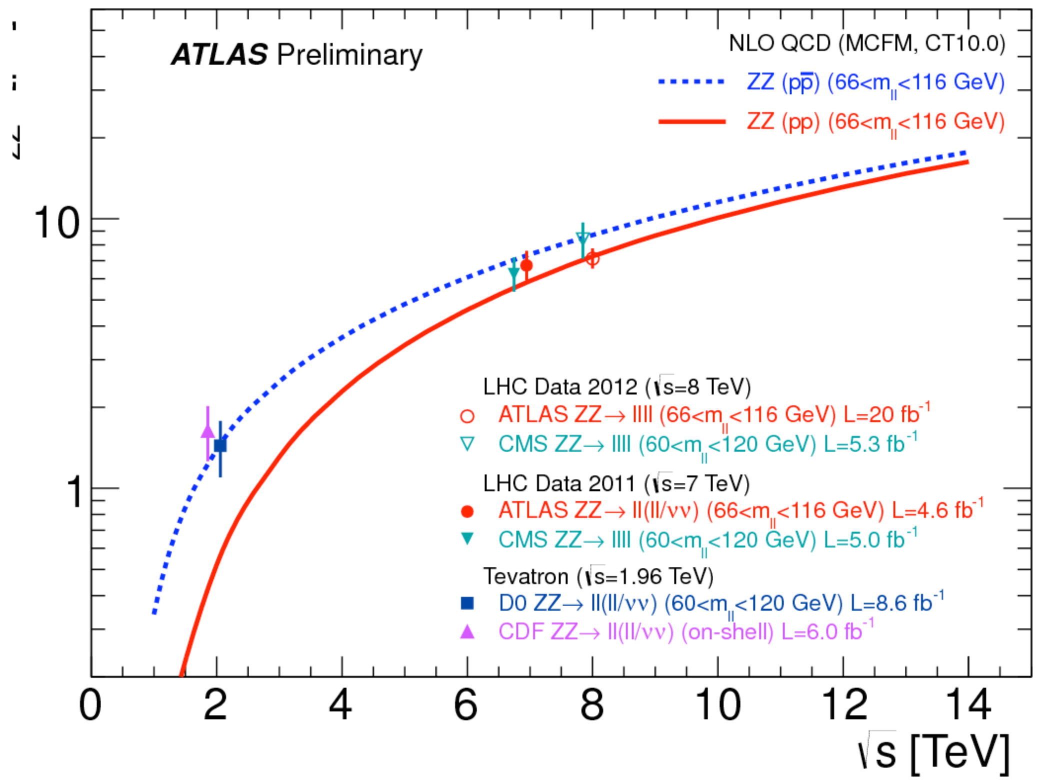






Z Z production@ 8TeV

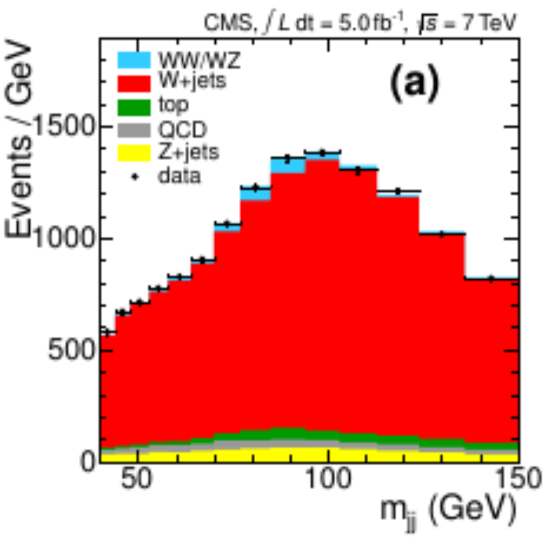


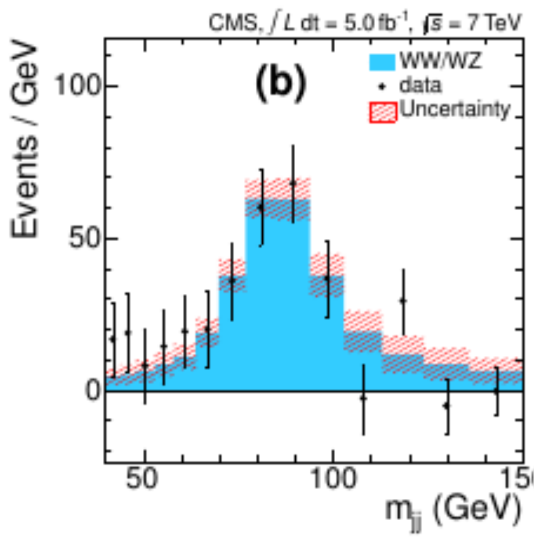


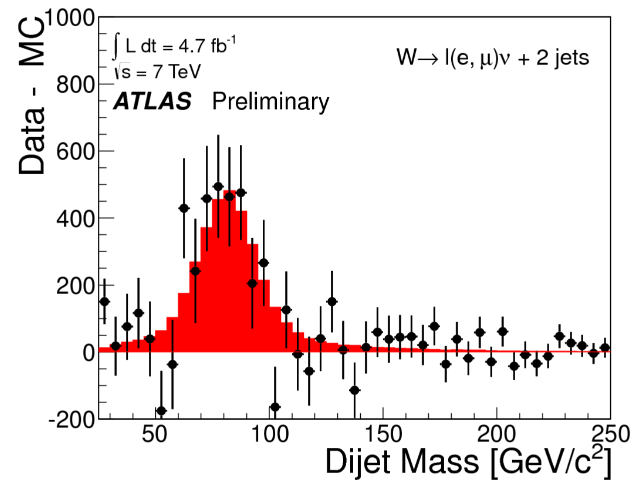
		Measured (pb)	MCFM NLO (pb)
ATLAS	7 TeV	7.2 ± 1.4 (stat) ± 0.8 (syst) ± 0.4 (lumi)	6.5 ± 0.3
CMS	7 TeV	6.2 ± 2.4 (stat) ± 1.1 (syst) ± 1.0 (lumi)	6.3 ± 0.4
ATLAS	8 TeV	7.1 ± 0.4 (stat) ± 0.3 (syst) ± 0.2 (lumi)	7.2 ± 0.3
CMS	8 TeV	8.4 ± 1.0 (stat) ± 0.7 (syst) ± 0.4 (lumi)	7.7 ± 0.4

Diboson with semi-leptonic decays@ 7TeV

- ATLAS and CMS have measured (WW+WZ)→lνjj
- Backgrounds: W/Z+jets
- **Major systematics**: Background estimation, jet scale/resolution

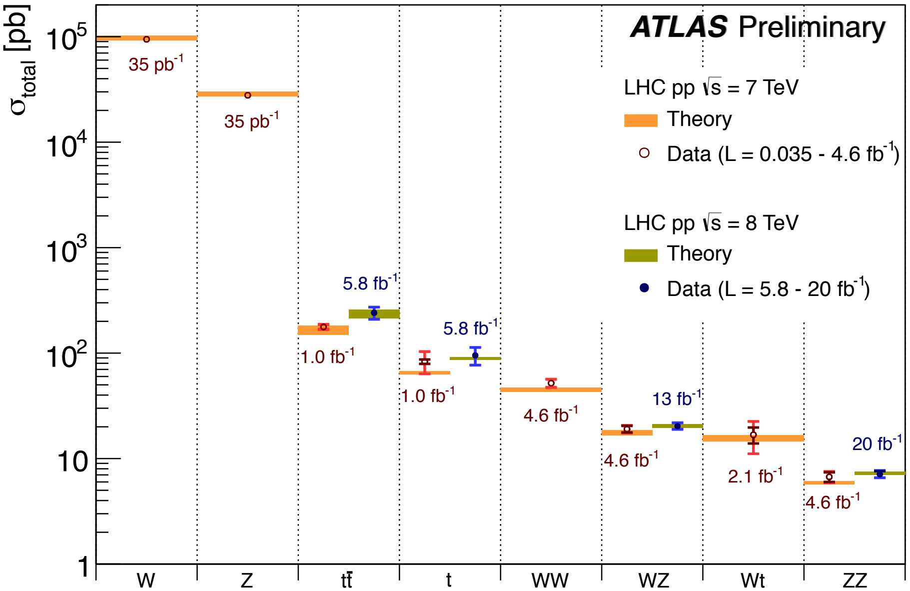




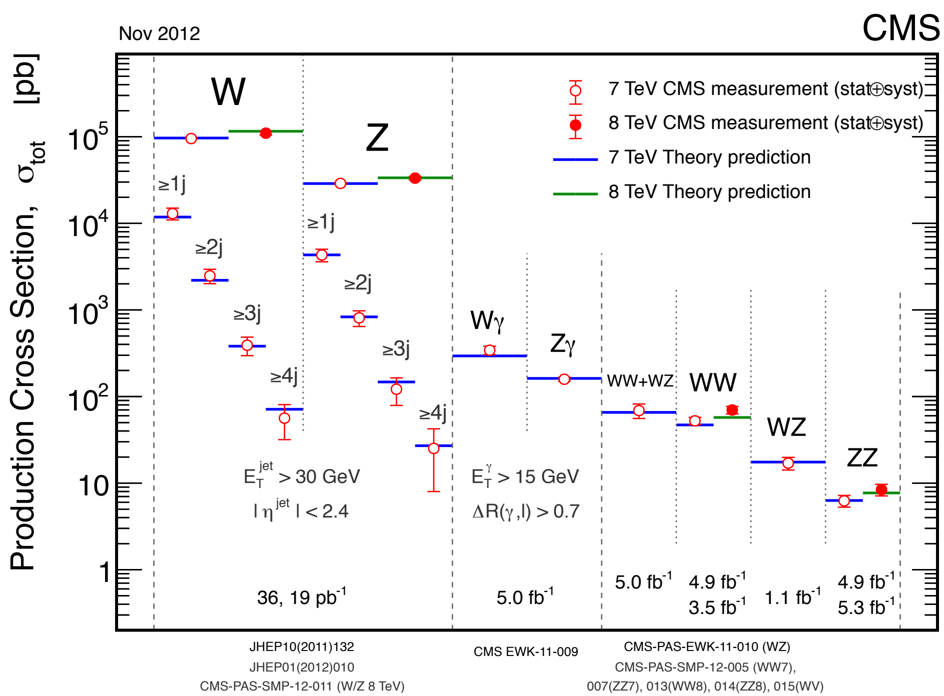


		Measured (pb)	MCFM NLO (pb)
CMS	7 TeV	68.9 ± 8.7 (stat) ± 9.7 (syst) ± 1.5 (lumi)	65.6 ± 2.2
ATLAS	7 TeV	72 ± 9 (stat) ± 15 (syst) ± 13 (MC stat)	63.4 ± 2.6

Summary on (di)boson cross sections

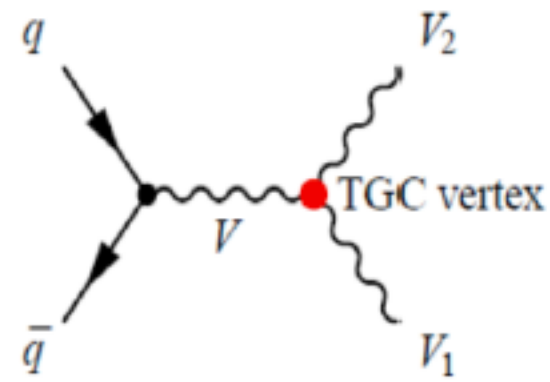


- **Theory includes :**
  - NNLO for single boson production
  - NLO for qq'→VV' (+ gg→VV' few%)

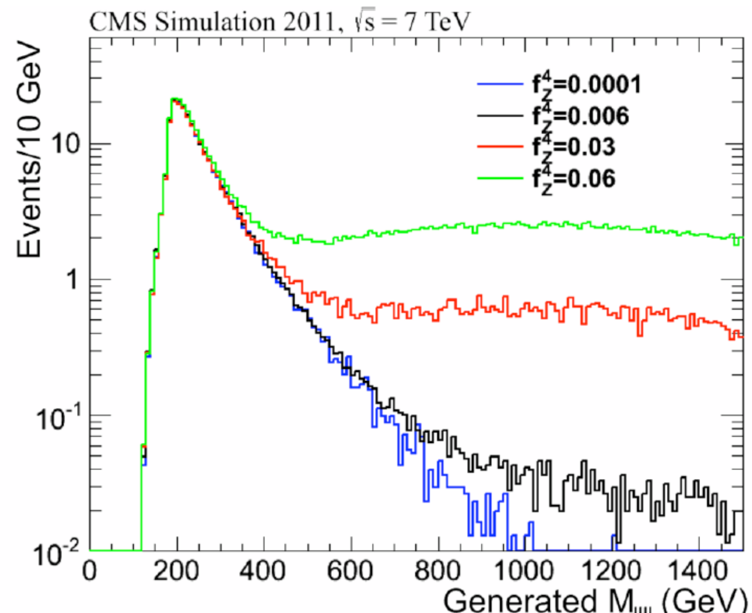


Anomalous Triple Gauge Coupling

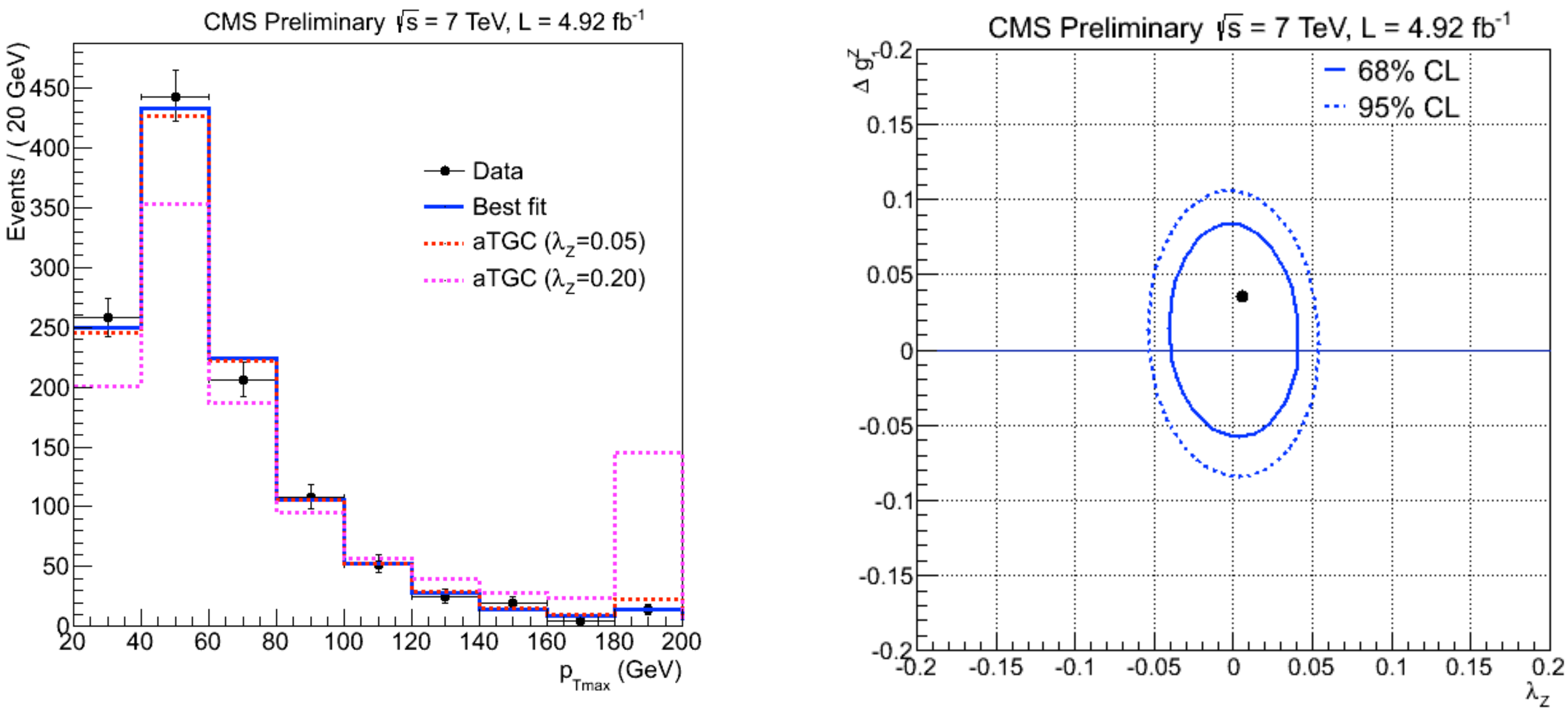
- Effect of aTGCs are modelled using an effective Lagrangian which depends on few parameters
- **Increase of cross section at high invariant mass and high transverse momentum**
- Neutral TGC are not allowed in the SM. In SM all parameters are 0, except g^V_1 and κ^V which are 1
- **Analysis on full 2011 dataset**



	Coupling	parameters	channel
Charged	$WW\gamma$	$\lambda_\gamma, \Delta\kappa_\gamma$	$WW, W\gamma$
	WWZ	$\lambda_Z, \Delta\kappa_Z, \Delta g^Z_1$	WW, WZ
Neutral	$ZZ\gamma$	h^Z_3, h^Z_4	$Z\gamma$
	$Z\gamma\gamma$	h^γ_3, h^γ_4	$Z\gamma$
	$Z\gamma Z$	f^Z_4, f^Z_5	ZZ
	ZZZ	f^γ_4, f^γ_5	ZZ



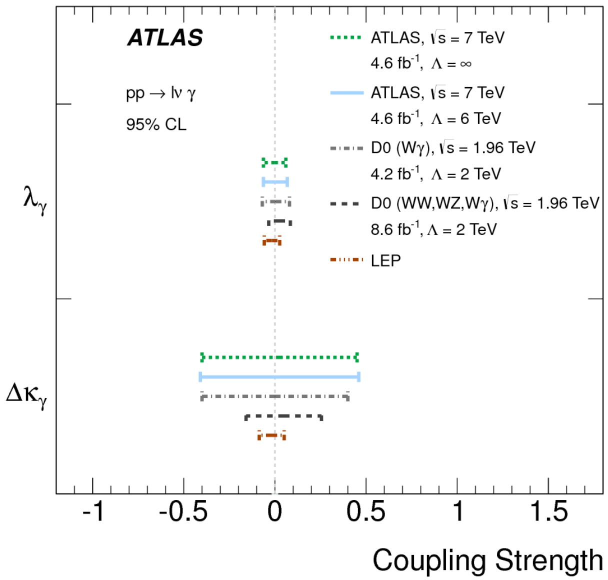
Anomalous triple gauge coupling : WWZ and WWγ



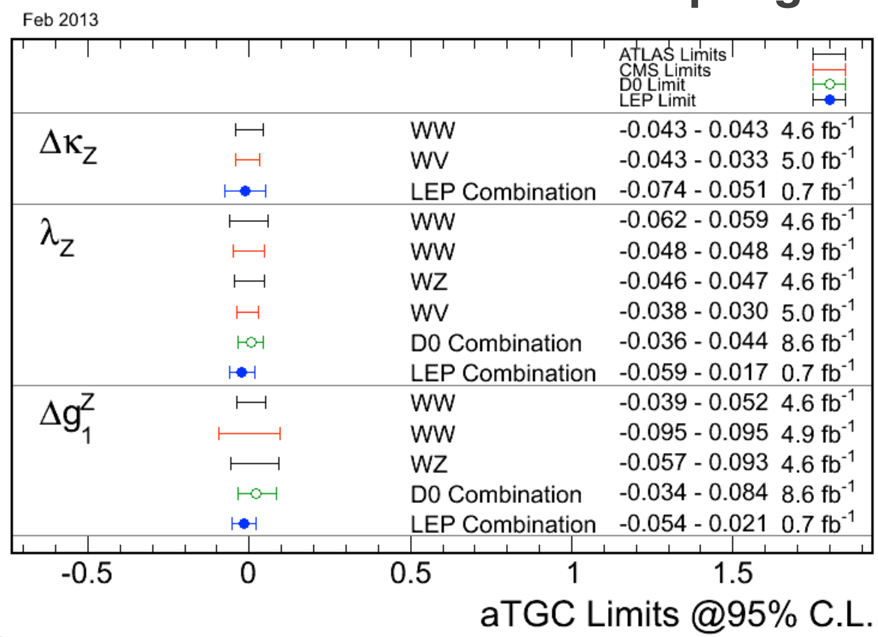
- Maximum likelihood fit performed for events in bin p_T^{lepton}
- **Statistics still limited** : so only one or two parameters left free during aTGC fits. The other ones are fixed to their SM value (=0)
- No sign of deviation from SM predictions

Charged Anomalous Triple Gauge Coupling Results

Limits on WWγ aTGC couplings



Limits on WWZ aTGC couplings



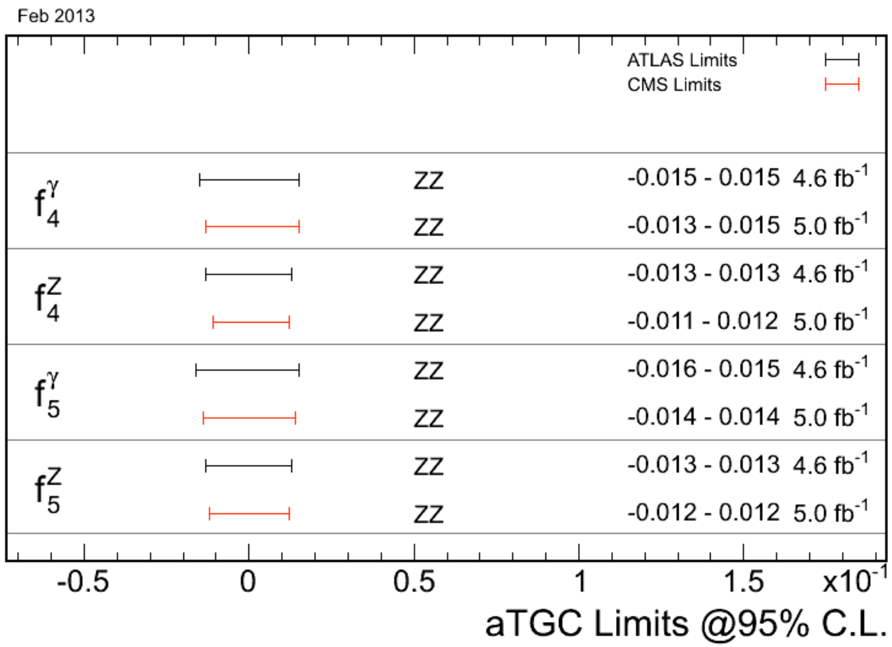
CMS Results

95% C.L.	$\Delta\kappa^{\gamma}$	λ	Δg_1^Z
$W\gamma \rightarrow l\nu\gamma$	[-0.38, 0.29]	[-0.05, 0.037]	-
$W^+W^- \rightarrow l\nu l\nu$	[-0.21, 0.22]	[-0.048, 0.048]	[-0.095, 0.095]
$W^+W^- + WZ \rightarrow l\nu jj$	[-0.111, 0.142]	[-0.038, 0.030]	-

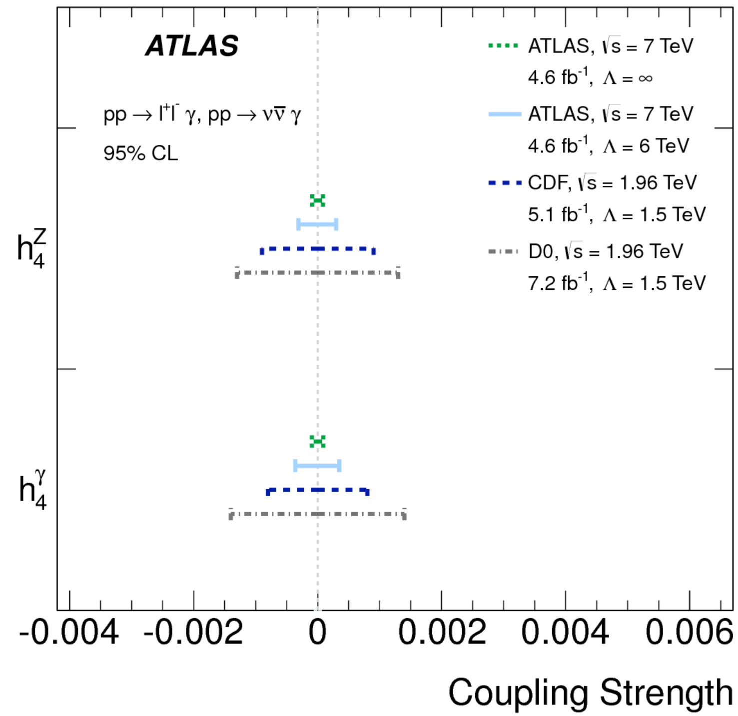
- No sign of deviation from SM predictions

Neutral Anomalous Triple Gauge Coupling Results

Limits on neutral aTGC ZZγ and ZZZ couplings



Limits on neutral aTGC Zγγ and ZZγ couplings



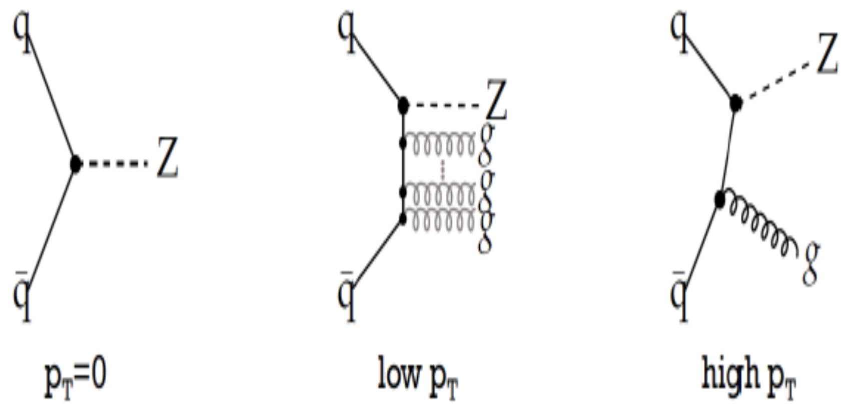
- **Limits surpassing Tevatron and LEP**
- Fully compatible with Standard Model

Conclusion

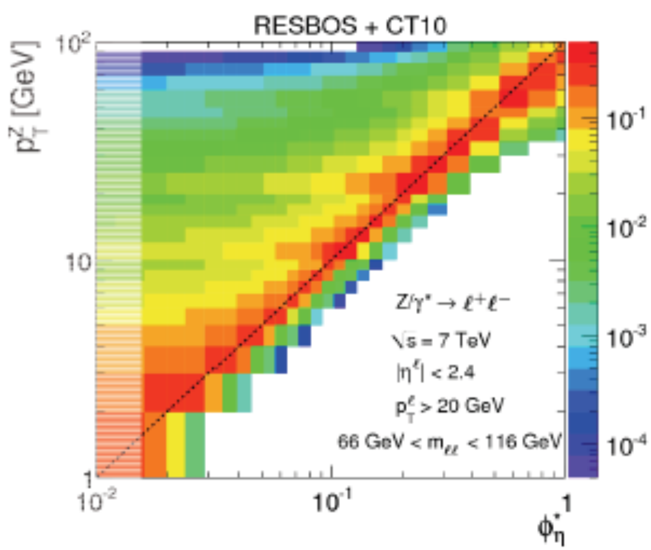
- **LHC program well underway:**
  - Precise test of the Standard Model at TeV scale
  - Significant contribution to PDFs
  - Stable ground for new physics searches
- **Agreement with theory across orders of magnitude is impressive**
- Cross section measurements have been performed in WW, WZ, $W\gamma$, $Z\gamma$ and ZZ channels
- Triple Gauge Coupling have been measured in all the channels and no deviations from SM were observed
- **Still most of the LHC data at 8 TeV to be analysed … more results with improved precision expected soon**

Backup

Z/γ* transverse momentum ($d\sigma/d\phi^*_\eta$(ll))



- High p_T: fixed order pQCD calculations (N)NLO, accurate
- Low p_T : soft gluon resum. techniques required (+ non perturb. form factors) or parton shower algorithms



Systematics (ee, μμ):

- QED FSR ~ 0.3 %
- MC stat. (0.1 – 0.2) %
- Tracking resolution (0.1 - 0.2) %
- Tracking bias ~ 0.1 %
- Unfolding ~ 0.1 %
- QCD background < 0.1%
- ID and reco efficiency < 0.05%
- EW background ~ 0.05%
- Pile-up < 0.05%
- Energy scale/smearing < 0.03%
- Z-vertex re-weighting (negligible)
- Trigger effciency (negligible)
- Charge mis-ID Z→ee (negligible)

Differential Z/γ* + jets cross section

$Z(\to ee)$	≥ 1 jet	≥ 2 jets	≥ 3 jets	≥ 4 jets	p_{T}^{jet} (30 – 500 GeV)
Electron reconstruction	2.8%	2.8%	2.8%	2.8%	2.6-2.9%
Jet energy scale, resolution	7.4%	10.1%	13%	17%	4.3-9.0%
Backgrounds	0.26%	0.34%	0.44%	0.50%	0.21-3.2%
Unfolding	0.22%	0.94%	1.2%	1.9%	1.4-6.8%
Total	7.9%	10.5%	13%	17%	5.5-12.0%

$Z(\to \mu\mu)$	≥ 1 jet	≥ 2 jets	≥ 3 jets	≥ 4 jets	p_{T}^{jet} (30 – 500 GeV)
Muon reconstruction	0.86 %	0.87 %	0.87 %	0.88 %	0.8 – 1.0%
Jet energy scale, resolution	7.5 %	9.9 %	13%	16%	3.2 – 8.7%
Backgrounds	0.093 %	0.20 %	0.41 %	0.66 %	0.1 – 1.9%
Unfolding	0.30 %	0.68 %	0.52 %	1.3 %	0.5 – 6.2%
Total	7.6 %	10.0 %	13 %	16 %	4.4-10.2%

- JES dominant component to total uncertainty

V+jets cross section measurement

<u>Uncertainties</u>

Statistics — Detector level (data)

JES, JER,
lepton reco & ID + triger

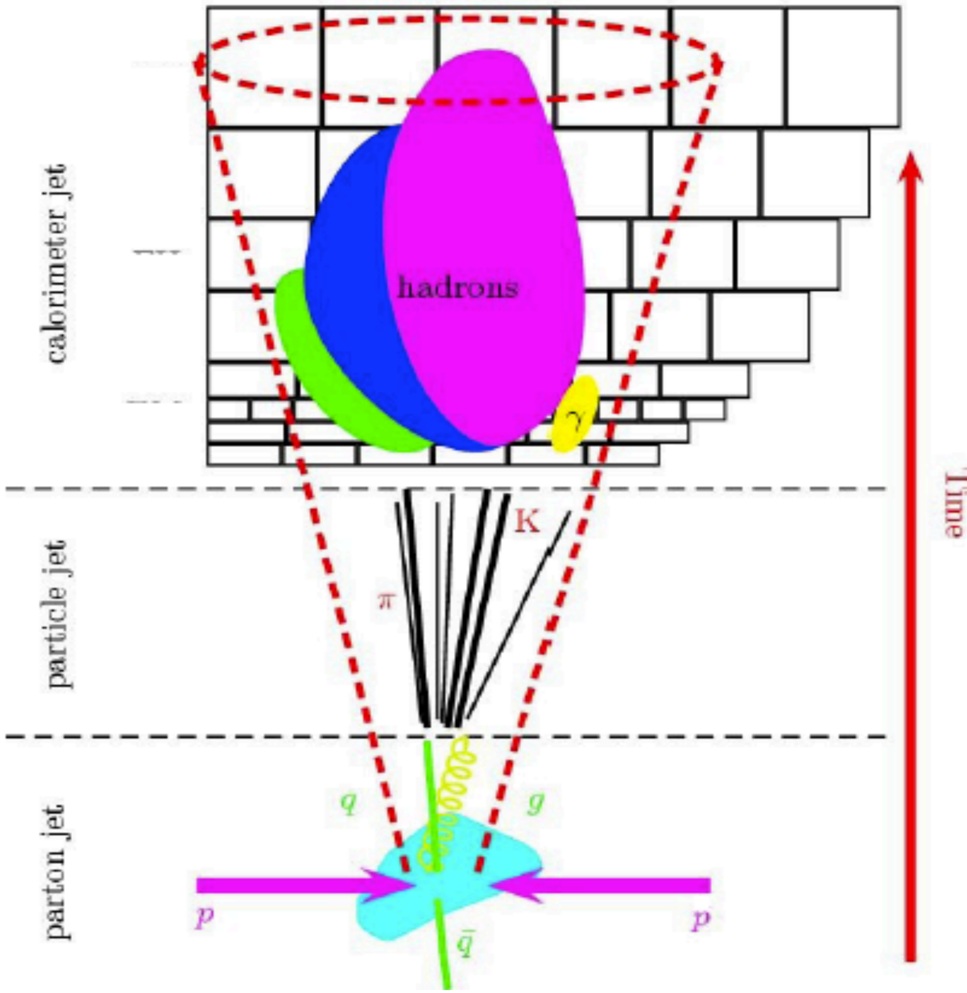
↓

Particle level

↑

Non-perturbative effects (UE, fragmentation)

PDF, α_s — Parton level (BH+Sherpa)



Detector Level → Bayes unfolding → **Hadron Level** ← UE/Fragm/QED ← BH+Sherpa

Hadron Level ← ME+PS

W+b inclusive results

Table 4. Measured fiducial $W+b$-jet cross-sections for one lepton flavor with statistical and systematic uncertainty and breakdown of relative systematic uncertainties per jet multiplicity, and combined across jet bins.

Fiducial cross section [pb]			
	1 jet	2 jet	1+2 jet
$\sigma_{W+b-\text{jet}}$	5.0	2.2	7.1
Statistical uncertainty	0.6	0.2	0.5
Systematic uncertainty	1.2	0.5	1.4
Breakdown of systematic uncertainty [%]			
Jet energy scale	15	15	15
Jet energy resolution	14	4	8
b-jet efficiency	6	4	5
c-jet efficiency	1	1	0
light-jet efficiency	1	3	2
ISR/FSR	4	8	3
MC modelling	8	4	6
Lepton resolution	1	1	0
Trigger efficiency	1	2	2
Lepton efficiency	1	2	1
$E_{\mathrm{T}}^{\mathrm{miss}}$ scale	3	6	2
$E_{\mathrm{T}}^{\mathrm{miss}}$ pile-up	2	2	2
b-jet template	3	5	4
c-jet template	4	2	3
light-jet template	0	0	0
Multijet template	2	2	2
Total syst. uncertainty	24	23	20

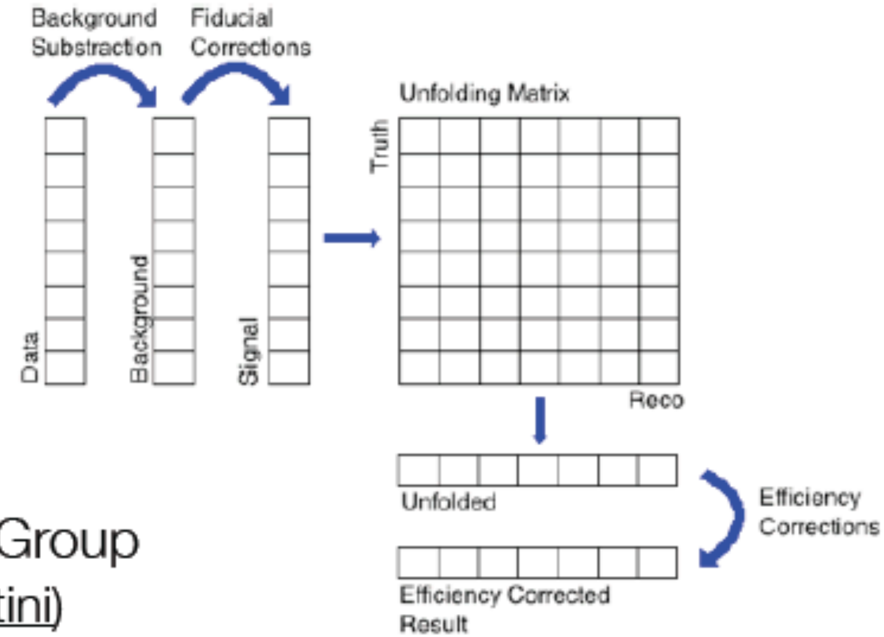
Unfolding - Methodology

Motivation

Determine **true value** of an observable

Measured value is distorted by detector's

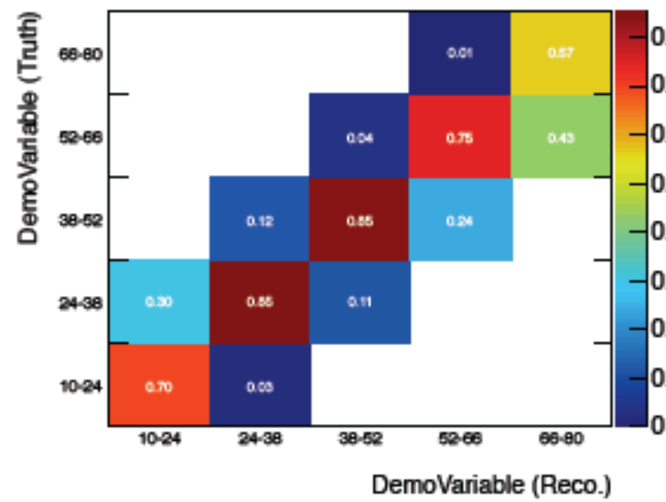
- limited acceptance
- imperfect efficiency
- finite resolution



Method

Common Framework among Electroweak Group

- use **iterative Bayesian unfolding** (d'Agostini)
- **normalized** unfolding within **fiducial region** only
- based on **RooUnfold** using **response matrix**



Published Results

Fractional, binned kinematic distributions

- $\Delta\sigma^{fid}(x)/\sigma^{fid}$

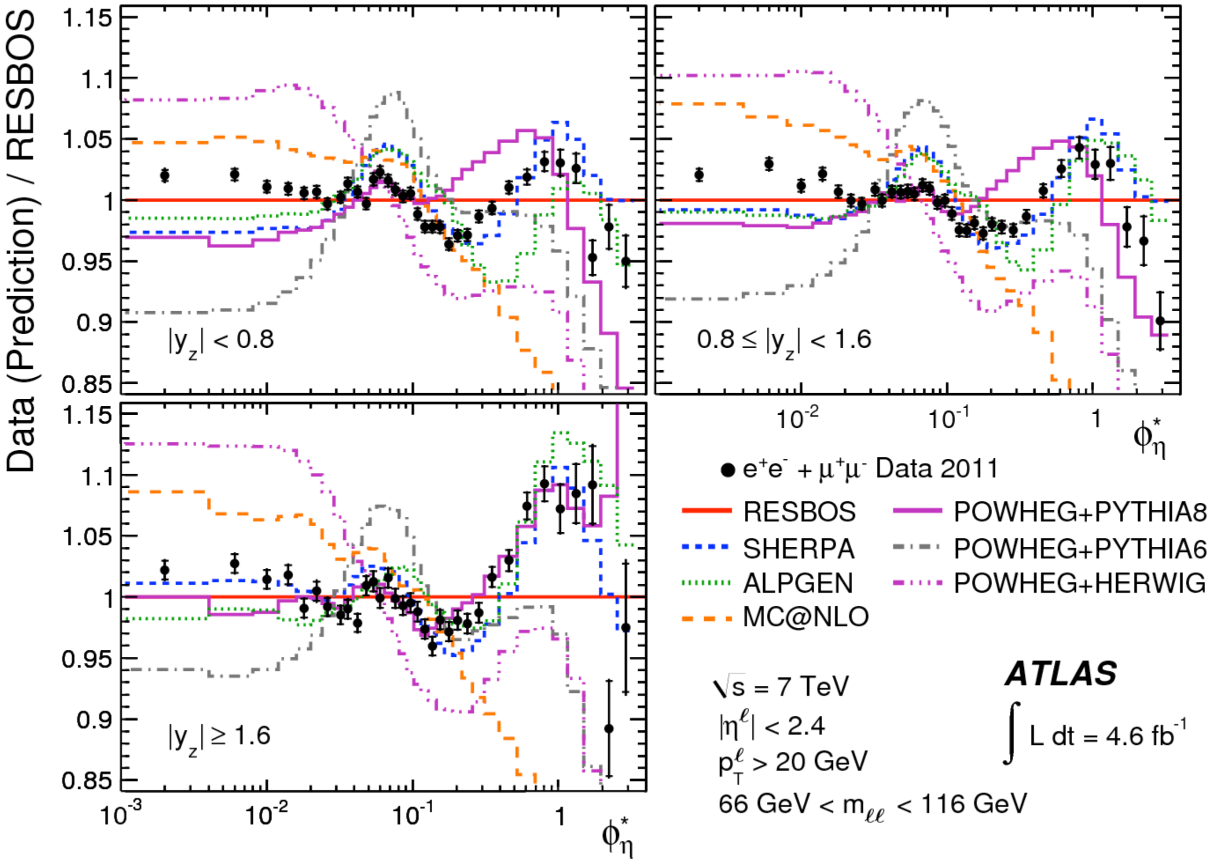
Full correlation matrices (on HEPDATA)

- combined stat, syst, background

Systematics uncertainties on diboson

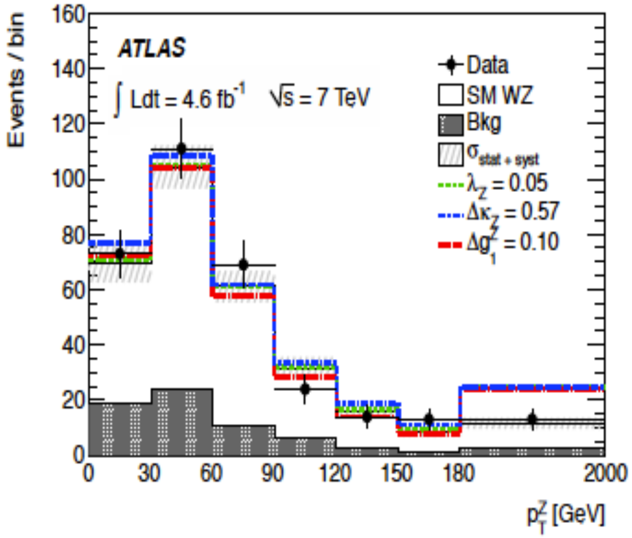
Channel	Main Uncertainties
$WW \rightarrow l\nu l\nu$	jet veto (3.6%)
$W(W/Z) \rightarrow l\nu qq$	jet energy scale (12%), W/Z+jets normalization (11%)
$WZ \rightarrow l\nu ll$	electron identification efficiency (3.5% for eee, 2.3% for eem) muon reconstruction efficiency (0.8% for $\mu\mu\mu$, 0.5% for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

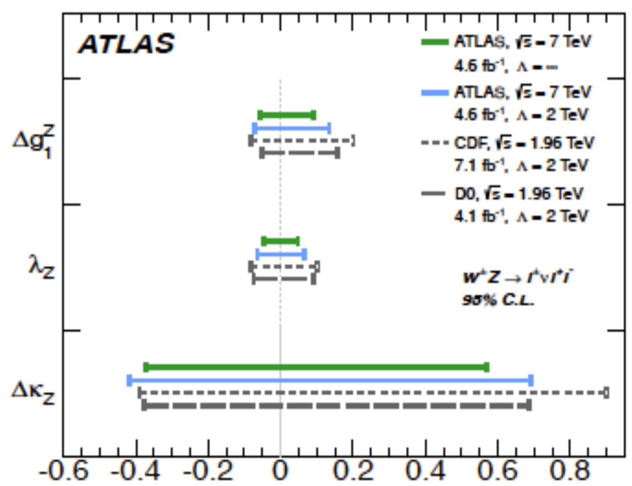
Z/γ* transverse momentum (dσ/dφ*$_\eta$(ll))

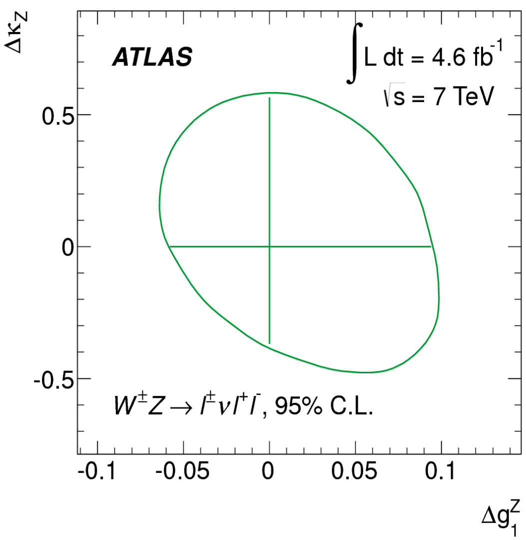


- SHERPA describes the data within 2%, better than RESBOS, for $\phi^*_\eta > 0.1$ (RESBOS still better for $\phi^*_\eta < 0.1$)
- POWHEG+Pythia8 describes the data within 5% over the full range
- MC@NLO+HERWIG does not properly describe the data for $\phi^*_\eta > 0.1$

Anomalous Triple Gauge Coupling : WWZ and WWγ

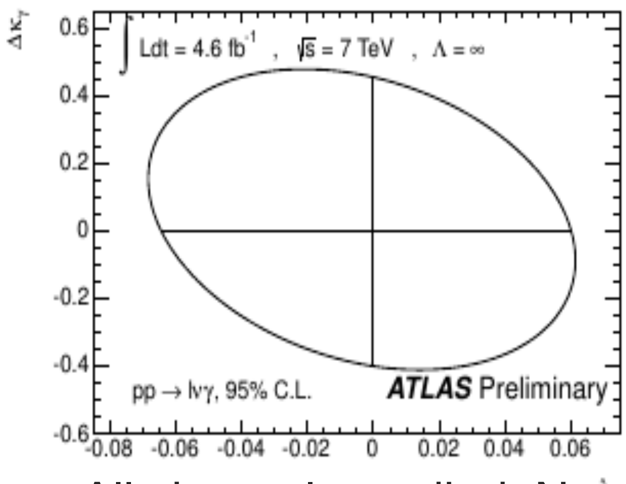


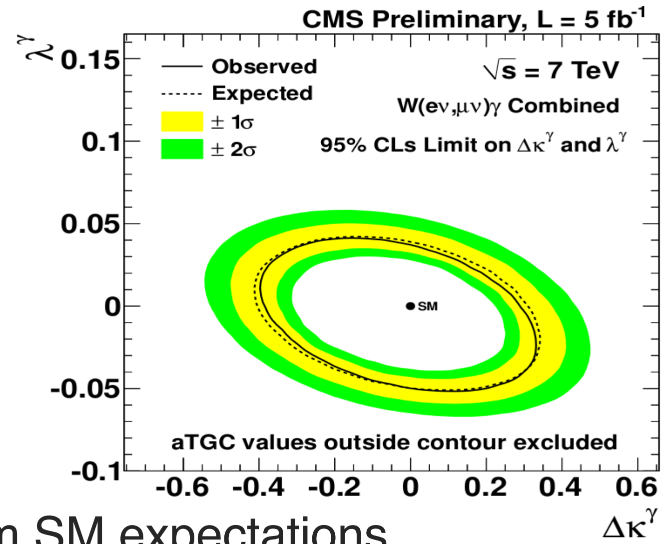




- Maximum likelihood fit performed for events in bin p_T^Z
- **Statistics still limited** : so only one or two parameters left free during aTGC fits. The other ones are fixed to their SM value (=0)
- No deviation from SM predictions observed

Summary of aTGC





- All channels studied. No deviations from SM expectations
- But sensitivity still low :
  - Channel with highest statistics Wγ give $\Delta\kappa_\gamma < 0.4$ and $\lambda_\gamma < 0.05$
  - while the « interesting » range is rather $\Delta\kappa_\gamma \sim 0.01$ and $\lambda_\gamma \sim 0.001$
- Expected improvements soon with the full 2012 stat to be analysed (23 fb-1) and combination of channels measuring the same couplings
- Need to run at 13 TeV (higher sensitivity with increasing s) and 100 fb-1 (2 to 3 years) to probe the « interesting » region