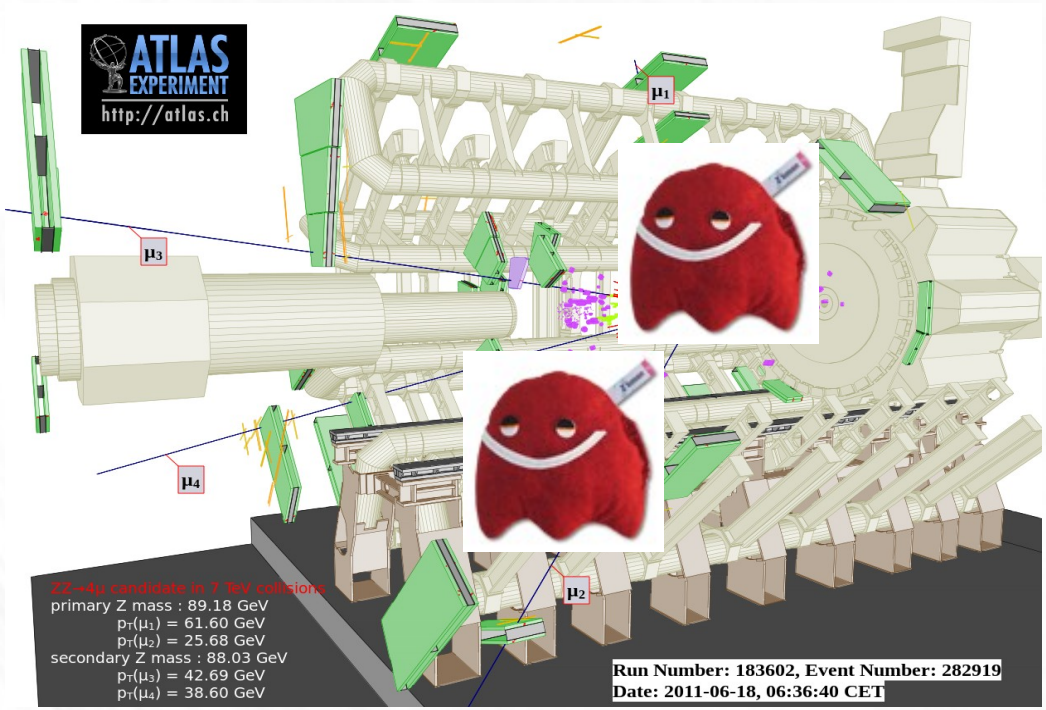
ATLAS measurements of multi-boson production

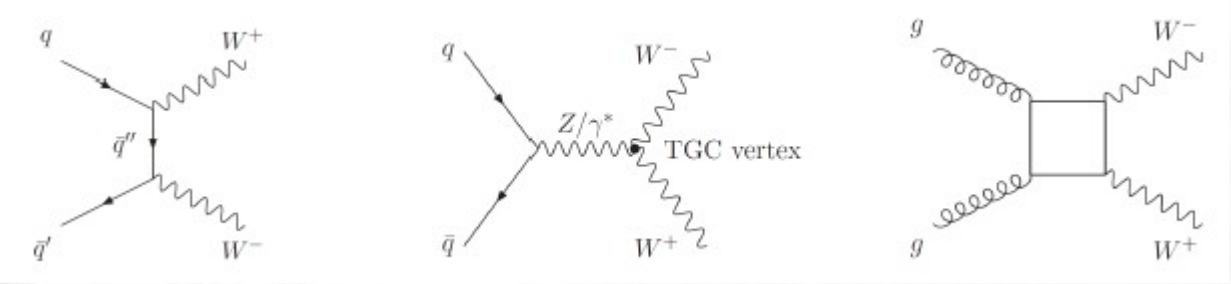


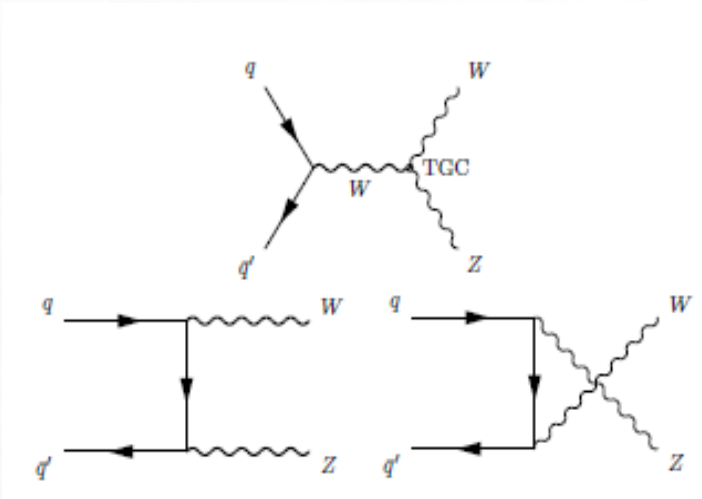
C. Hays, Oxford University
for the ATLAS Collaboration

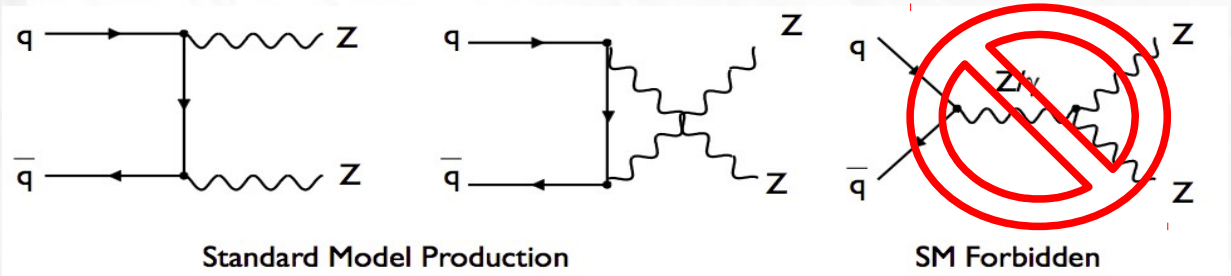
3 June 2014

Diboson production at the LHC

Probing gauge-boson self-couplings & interference with increasing precision

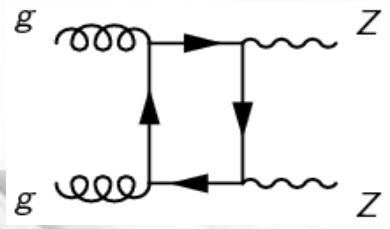




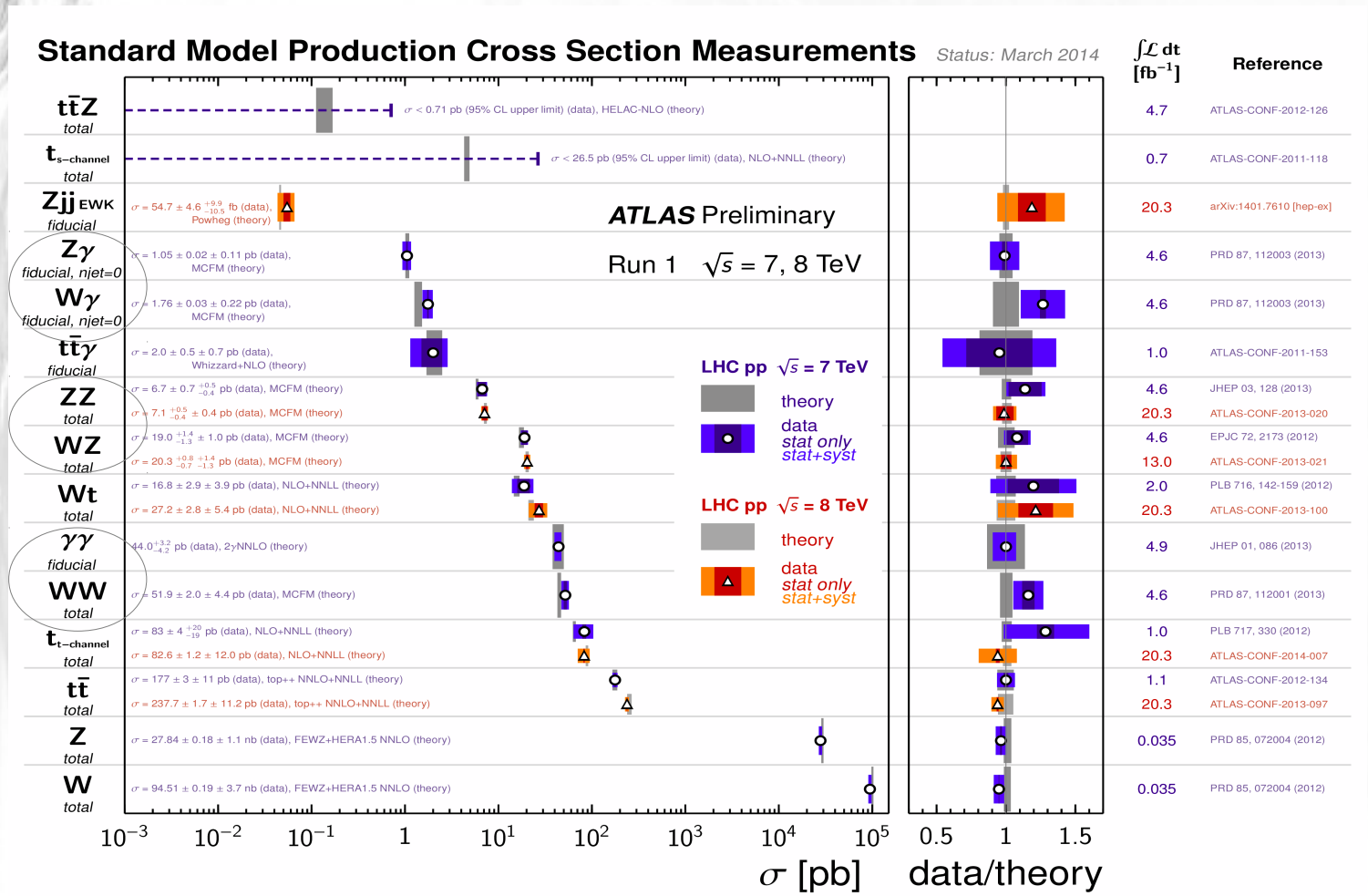


Measurements constrain modelling of backgrounds to Higgs measurements

Testing QCD calculations to increasing accuracy



Diboson measurements at ATLAS



$ZZ \rightarrow llll$: 7 & 8 TeV

$WZ \rightarrow l\nu ll$: 7 & 8 TeV

$WW \rightarrow l\nu l\nu, l\nu jj$: 7 TeV

$Z\gamma \rightarrow ll\gamma, \nu\nu\gamma$: 7 TeV

$W\gamma \rightarrow l\nu\gamma$: 7 TeV

$\gamma\gamma$: 7 TeV

(Also same-charge WW via vector-boson scattering: Simone Pagan Griso's talk)

Diboson measurement strategy

Measure cross section within a fiducial region

$$\sigma_{\text{fid}} = \frac{N_{\text{data}} - N_{\text{bg}}}{\mathcal{L} C_{WW}}$$

C_{WW}: ratio of measured to produced WW events in fiducial region

Extrapolate to total cross section

$$\sigma(pp \to WW) = \frac{N_{\text{data}} - N_{\text{bg}}}{A_{WW} C_{WW} \mathcal{L} \mathcal{B}}$$

A_{WW}: kinematic and geometric acceptance

B: branching ratio

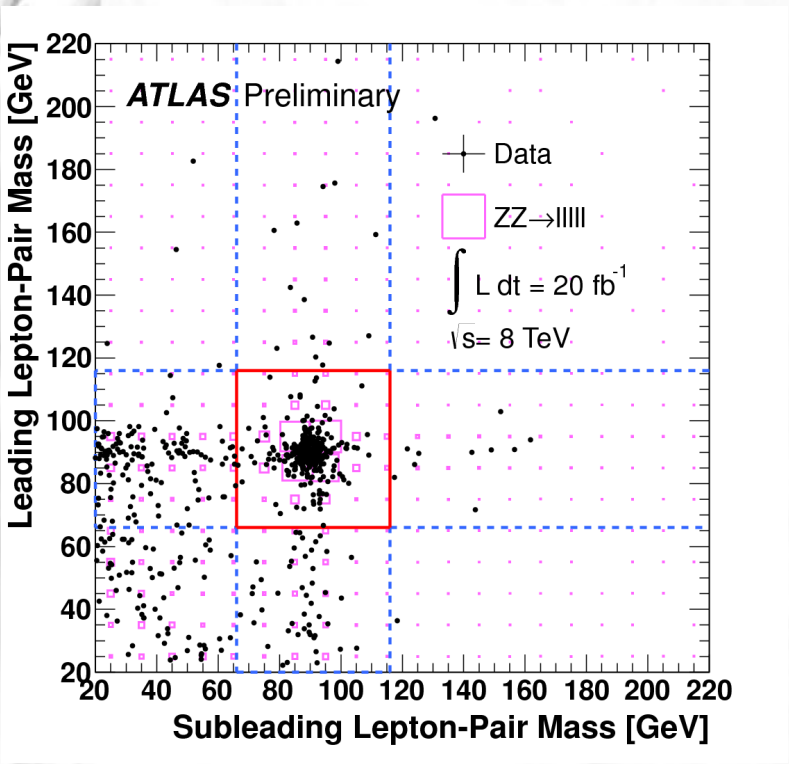
Study unfolded differential cross sections and probe high-Q^2 events for anomalous TGCs

$$\mathcal{L}_{WWV}/g_{WWV} = ig_1^V \left(W^\dagger_{\mu\nu} W^\mu V^\nu - W^\dagger_\mu V_\nu W^{\mu\nu}\right) + i\kappa_V W^\dagger_\mu W_\nu V^{\mu\nu} + \frac{i\lambda_V}{m_W^2} W^\dagger_{\lambda\mu} W^\mu_\nu V^{\nu\lambda}$$

SM: $g_1^V = \kappa_V = 1$; $\lambda_V = 0$

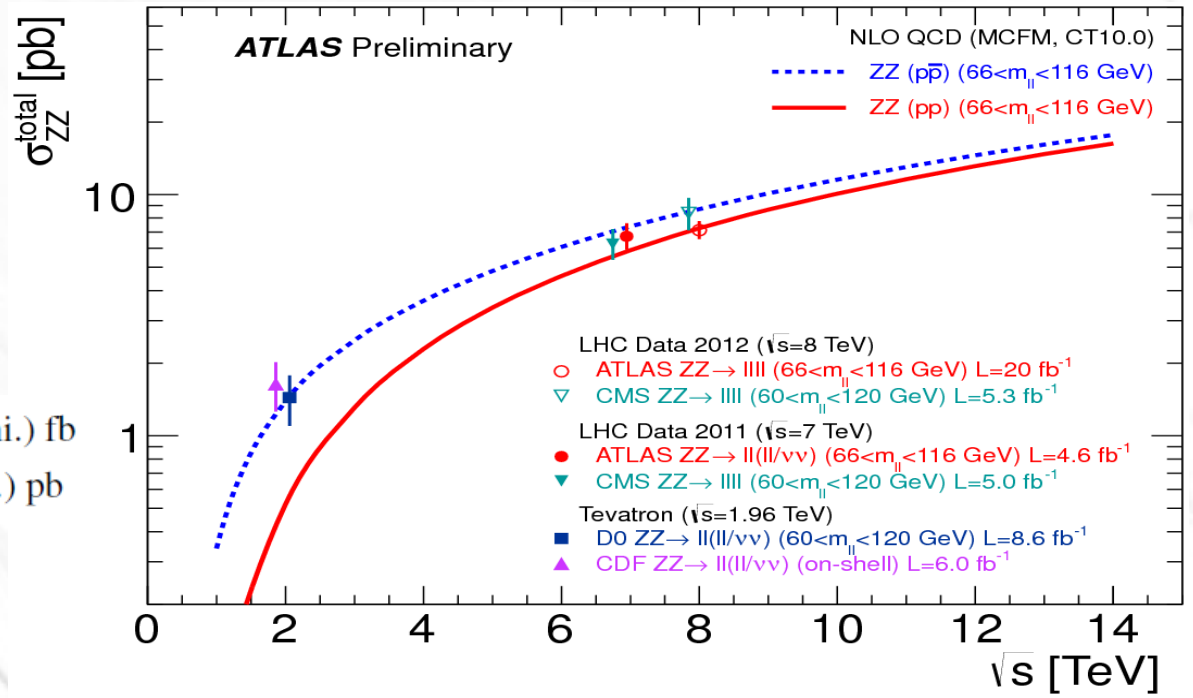
ZZ cross sections

Select events with four leptons with two $m_{ll} \sim m_Z$



>300 candidates, >90% purity

Final state	$e^+e^-e^+e^-$	$\mu^+\mu^-\mu^+\mu^-$	$e^+e^-\mu^+\mu^-$	$\ell^+\ell^-\ell'^+\ell'^-$
Observed	62	85	158	305
Signal (MC)	59.5±4.0	90.2±2.7	142.7±5.6	292.5±10.6
Background	10.0±1.8±1.4	1.1±1.4±0.5	9.3±2.1±3.1	20.4±2.9±5.0



$$\sigma^{\text{fid}}_{ZZ\to\ell^-\ell^+\ell'^-\ell'^+} = 20.7^{+1.3}_{-1.2}(\text{stat.}) \pm 0.8(\text{syst.}) \pm 0.6(\text{lumi.})\ \text{fb}$$

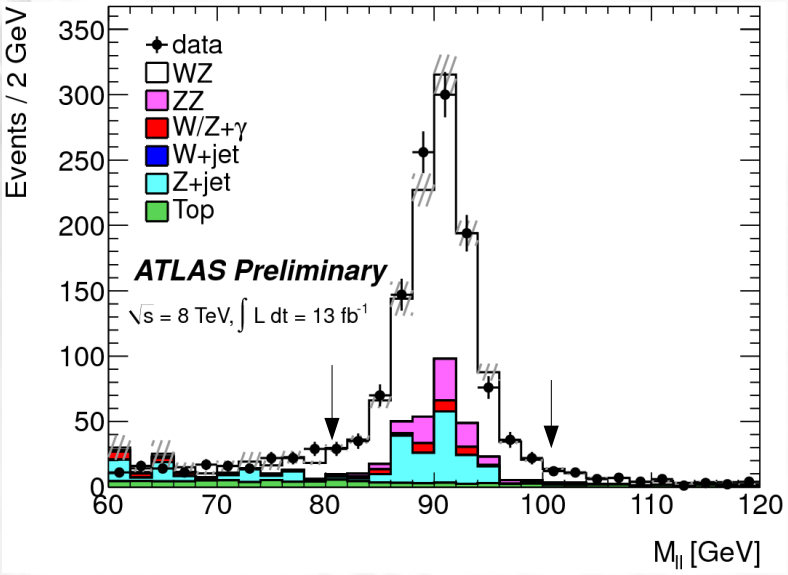
$$\sigma^{\text{tot}}_{ZZ} = 7.1^{+0.5}_{-0.4}(\text{stat.}) \pm 0.3(\text{syst.}) \pm 0.2(\text{lumi.})\ \text{pb}$$

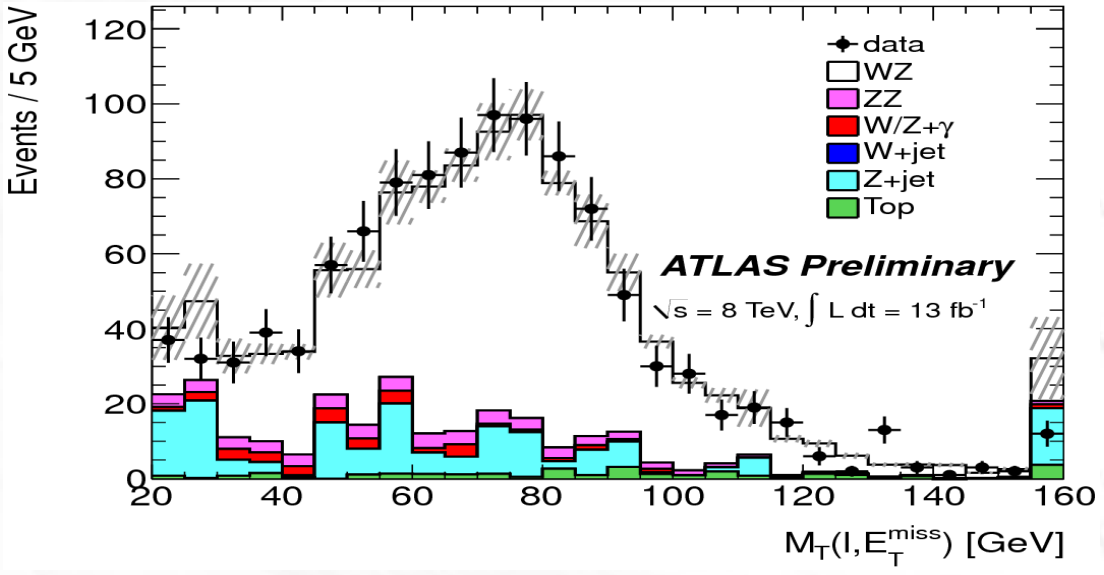
SM total cross section prediction:

$7.2^{+0.3}_{-0.2}$ pb

WZ cross sections

Select events with lepton pairs with mass ~ m_Z, an additional lepton, and large E_T^{miss}





Final State	*eee*	*eeμ*	*eμμ*	*μμμ*	Combined
Observed	192	270	298	334	1094
ZZ	10.3±0.6	14.7±0.8	12.8±0.7	18.8±1.0	56.6±1.6
Z + jets	37±3±11	33±4±10	57±4±11	47±5±14	188±8±24
Top		6.3±0.5±3.4		9.1±0.7±4.9	
$W/Z + \gamma$	13±3	1.3±0.6	17±3	–	32±5
Bkg (total)	60±4±11	55±4±10	87±5±11	75±5±14	277±9±24
Expected signal	144±12	199±16	200±16	276±21	819±34

ATLAS-CONF-2013-021

75% purity

>800 WZ events

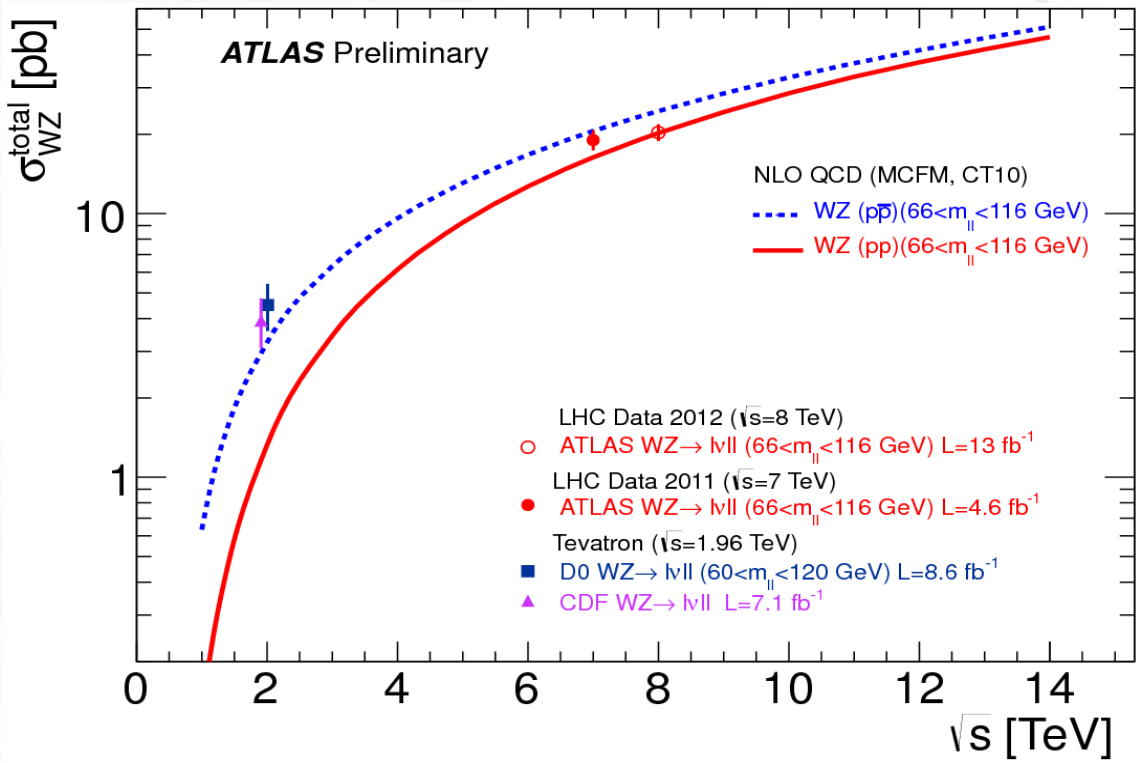
WZ cross sections

Channel	Cross Section [fb]
$\mu\mu\mu$	$23.3^{+1.7}_{-1.6}$(stat.) $^{+1.5}_{-1.5}$(syst.) $^{+0.7}_{-0.7}$(lumi.)
$e\mu\mu$	$26.2^{+2.2}_{-2.1}$(stat.) $^{+1.7}_{-1.7}$(syst.) $^{+0.9}_{-0.8}$(lumi.)
$ee\mu$	$26.8^{+2.1}_{-2.0}$(stat.) $^{+1.6}_{-1.6}$(syst.) $^{+0.8}_{-0.8}$(lumi.)
eee	$22.7^{+2.5}_{-2.3}$(stat.) $^{+2.3}_{-2.3}$(syst.) $^{+0.8}_{-0.7}$(lumi.)
Combined	$99.2^{+3.8}_{-3.0}$(stat.) $^{+5.1}_{-5.4}$(syst.) $^{+3.1}_{-3.0}$(lumi.)

SM fiducial cross section predictions:
24.8 ± 0.9 fb per channel
99.2 ± 3.6 fb sum over channels

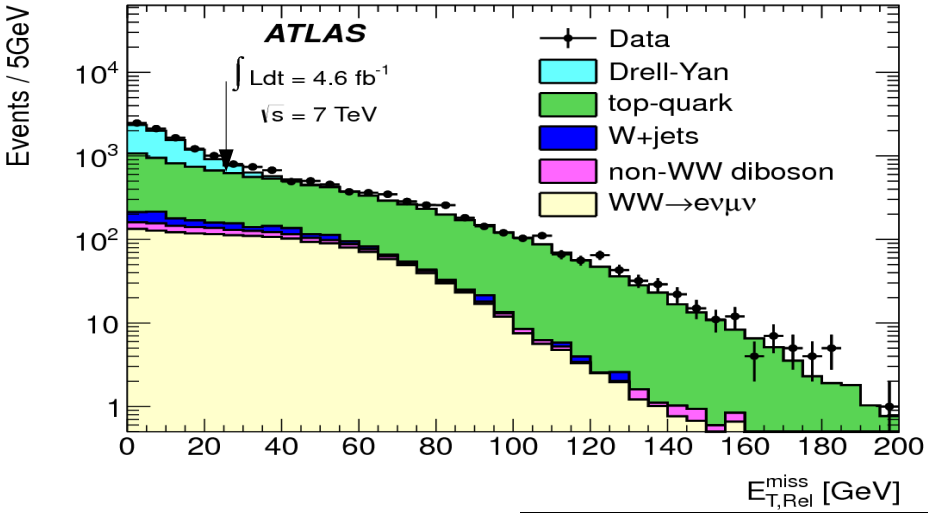
SM total cross section prediction:
20.3 ± 0.8 pb

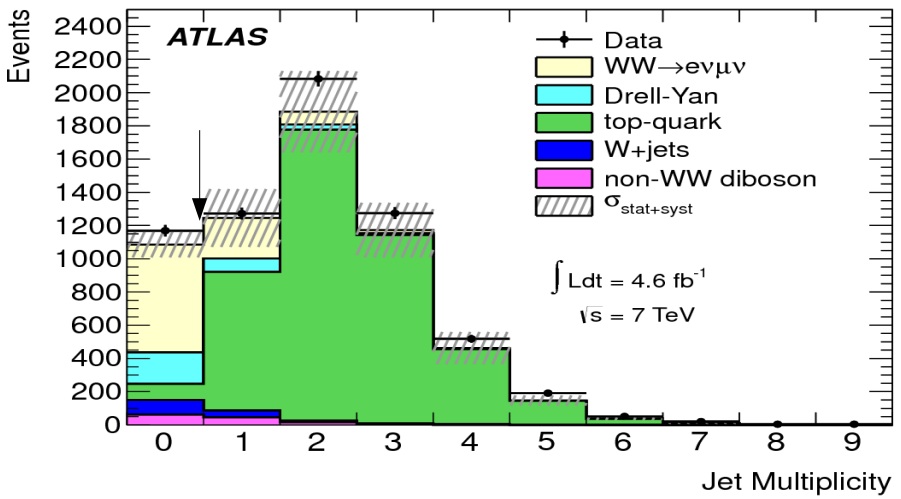
Channel	Cross Section [pb]
$\mu\mu\mu$	$19.1^{+1.4}_{-1.3}$(stat.) $^{+1.3}_{-1.3}$(syst.) $^{+0.6}_{-0.6}$(lumi.)
$e\mu\mu$	$21.4^{+1.9}_{-1.7}$(stat.) $^{+1.5}_{-1.5}$(syst.) $^{+0.7}_{-0.7}$(lumi.)
$ee\mu$	$21.9^{+1.8}_{-1.6}$(stat.) $^{+1.4}_{-1.4}$(syst.) $^{+0.7}_{-0.6}$(lumi.)
eee	$18.6^{+2.1}_{-1.9}$(stat.) $^{+1.9}_{-1.9}$(syst.) $^{+0.6}_{-0.6}$(lumi.)
Combined	$20.3^{+0.8}_{-0.7}$(stat.) $^{+1.2}_{-1.1}$(syst.) $^{+0.7}_{-0.6}$(lumi.)



WW cross sections

Select dilepton events with $m_{ll} \neq m_Z$, large $E_{T,Rel}^{miss}$ and no jets





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

PRD 87, 112001 (2013)

	ee	*μμ*	*eμ*	Combined
Data	174	330	821	1325
WW	100 ± 2 ± 9	186 ± 2 ± 15	538 ± 3 ± 45	824 ± 4 ± 69
Top	22 ± 12 ± 3	32 ± 14 ± 5	87 ± 23 ± 13	141 ± 30 ± 22
W + jets	21 ± 1 ± 11	7 ± 1 ± 3	70 ± 2 ± 31	98 ± 2 ± 43
Drell-Yan	12 ± 3 ± 3	34 ± 6 ± 10	5 ± 2 ± 1	51 ± 7 ± 12
Other dibosons	13 ± 1 ± 2	21 ± 1 ± 2	44 ± 2 ± 6	78 ± 2 ± 10
Total background	68 ± 12 ± 13	94 ± 15 ± 13	206 ± 24 ± 35	369 ± 31 ± 53
Total expected	169 ± 12 ± 16	280 ± 16 ± 20	744 ± 24 ± 57	1192 ± 31 ± 87

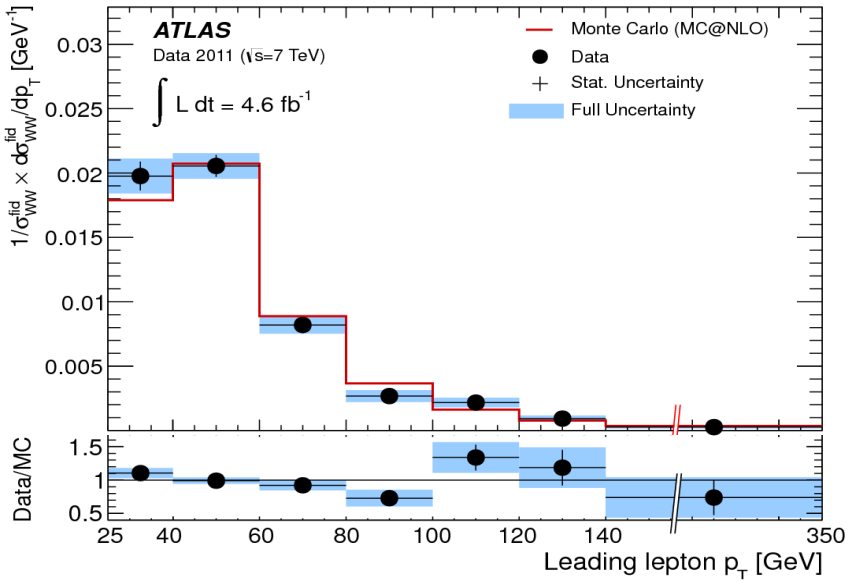
>800 WW events

70% purity

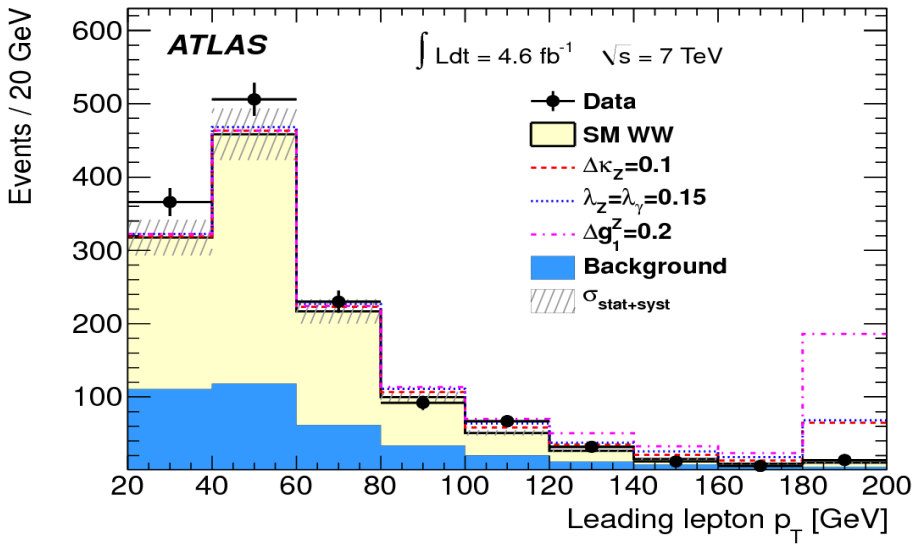
	Measured σ_{WW}^{fid} (fb)	Predicted σ_{WW}^{fid} (fb)	Measured σ_{WW} (pb)	Predicted σ_{WW} (pb)
ee	56.4 ± 6.8 ± 9.8 ± 2.2	54.6 ± 3.7	46.9 ± 5.7 ± 8.2 ± 1.8	$44.7^{+2.1}_{-1.9}$
μμ	73.9 ± 5.9 ± 6.9 ± 2.9	58.9 ± 4.0	56.7 ± 4.5 ± 5.5 ± 2.2	$44.7^{+2.1}_{-1.9}$
eμ	262.3 ± 12.3 ± 20.7 ± 10.2	231.4 ± 15.7	51.1 ± 2.4 ± 4.2 ± 2.0	$44.7^{+2.1}_{-1.9}$
Combined	···	···	51.9 ± 2.0 ± 3.9 ± 2.0	$44.7^{+2.1}_{-1.9}$

9% uncertainty on total cross section

WW differential cross section & aTGCs



Measure unfolded differential cross section of leading lepton p_T



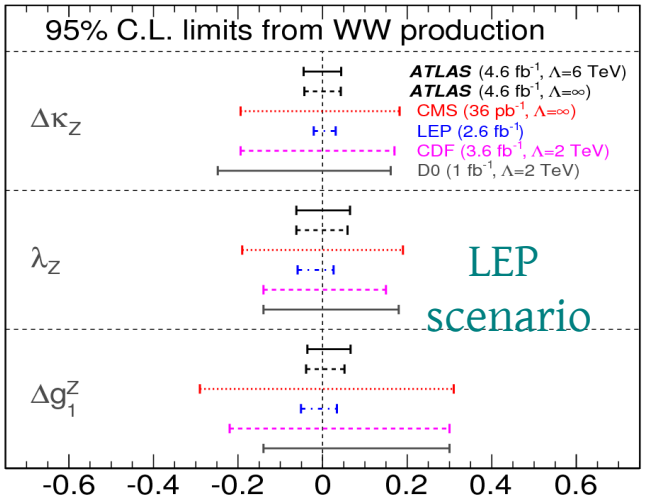
Probe anomalous couplings at high p_T

Set limits in three scenarios:

"LEP" ($\Delta\kappa_\gamma$ μ Δg_1^Z - $\Delta\kappa_Z$: 3 parameters)

"Equal Couplings" (WWZ = WWγ: 2 parameters)

"HISZ" (Δg_1^Z μ $\Delta\kappa_Z$ & $\Delta\kappa_\gamma$ μ $\Delta\kappa_Z$: 2 parameters)



$\lambda(s) = \lambda / (1 + s/\Lambda^2)^2$

$Z\gamma$ cross sections

Events with two leptons with high invariant mass, and a photon

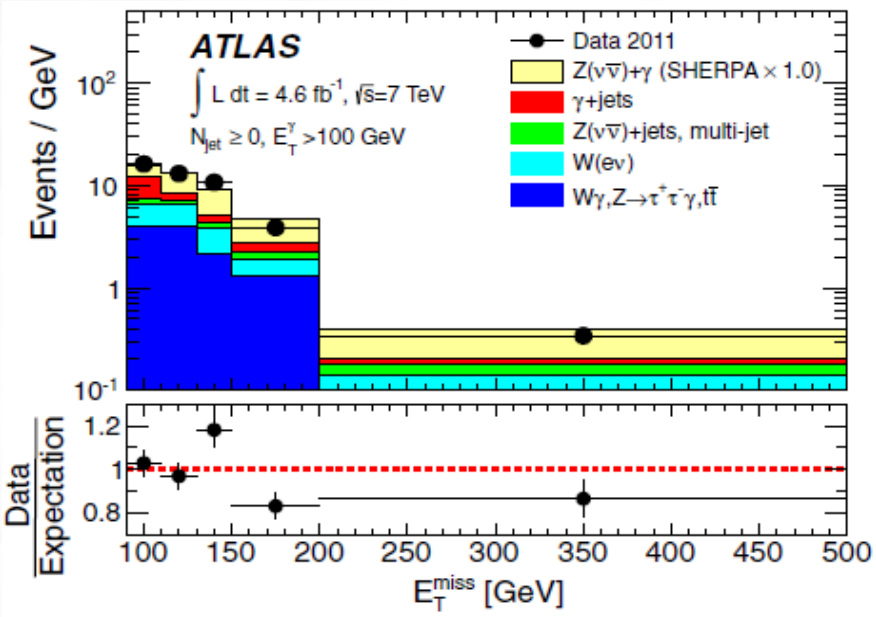
	$N_{jet} \geq 0$		$N_{jet} = 0$	
	$e^+e^-\gamma$	$\mu^+\mu^-\gamma$	$e^+e^-\gamma$	$\mu^+\mu^-\gamma$
$N^{obs}_{Z\gamma}$	1908	2756	1417	2032
$N^{BG}_{Z\gamma}$	$311 \pm 57 \pm 68$	$366 \pm 83 \pm 73$	$156 \pm 43 \pm 32$	$244 \pm 41 \pm 49$
$N^{sig}_{Z\gamma}$	$1600 \pm 71 \pm 68$	$2390 \pm 97 \pm 73$	$1260 \pm 56 \pm 32$	$1790 \pm 59 \pm 49$

PRD 87, 112003 (2013)

4000 Zγ events
85% purity

Events with no leptons, large E_T^{miss}, and a photon

	$\nu\bar{\nu}\gamma$ $N_{jet} \geq 0$	$\nu\bar{\nu}\gamma$ $N_{jet} = 0$
$N^{obs}_{Z\gamma}$	1094	662
$W(e\nu)$	$171 \pm 2 \pm 17$	$132 \pm 2 \pm 13$
$Z(\nu\bar{\nu})$ + jets, multijet	$70 \pm 13 \pm 14$	$29 \pm 5 \pm 3$
$W\gamma$	$238 \pm 12 \pm 37$	$104 \pm 9 \pm 24$
γ + jets	$168 \pm 20 \pm 42$	$26 \pm 7 \pm 11$
$Z(\tau^+\tau^-)\gamma$	$11.7 \pm 0.7 \pm 0.9$	$6.5 \pm 0.6 \pm 0.6$
$t\bar{t}$	$11 \pm 1.2 \pm 1.0$	$0.9 \pm 0.6 \pm 0.1$
$N^{sig}_{Z\gamma}$	$420 \pm 42 \pm 60$	$360 \pm 29 \pm 30$



>400 Zγ events
40% purity

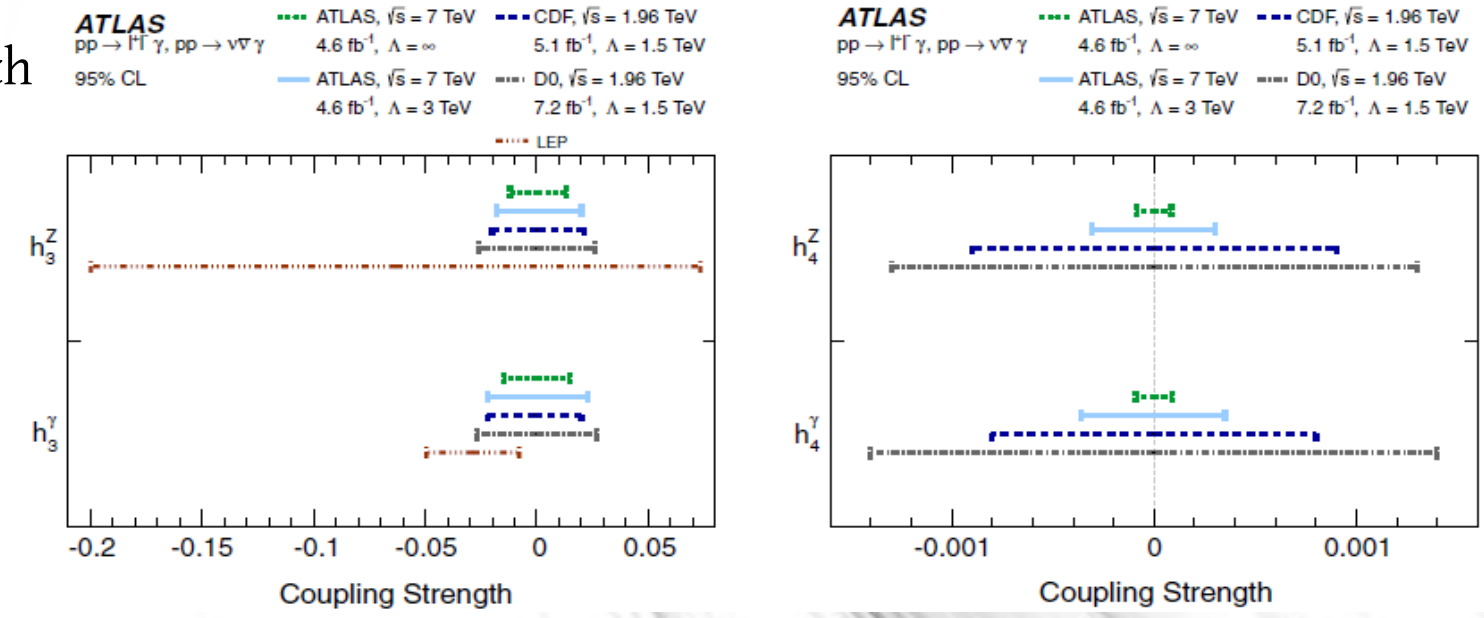
$Z\gamma$ cross sections & aTGCs

	$\sigma^{\text{ext-fid}}$[pb] Measurement	$\sigma^{\text{ext-fid}}$[pb] MCFM prediction
	$N_{\text{jet}} \geq 0$	
$e^+e^-\gamma$	$1.30 \pm 0.03(\text{stat}) \pm 0.13(\text{syst}) \pm 0.05(\text{lumi})$	1.18 ± 0.05
$\mu^+\mu^-\gamma$	$1.32 \pm 0.03(\text{stat}) \pm 0.11(\text{syst}) \pm 0.05(\text{lumi})$	1.18 ± 0.05
$\ell^+\ell^-\gamma$	$1.31 \pm 0.02(\text{stat}) \pm 0.11(\text{syst}) \pm 0.05(\text{lumi})$	1.18 ± 0.05
$\nu\bar{\nu}\gamma$	$0.133 \pm 0.013(\text{stat}) \pm 0.020(\text{syst}) \pm 0.005(\text{lumi})$	0.156 ± 0.012
	$N_{\text{jet}} = 0$	
$e^+e^-\gamma$	$1.07 \pm 0.03(\text{stat}) \pm 0.12(\text{syst}) \pm 0.04(\text{lumi})$	1.06 ± 0.05
$\mu^+\mu^-\gamma$	$1.04 \pm 0.03(\text{stat}) \pm 0.10(\text{syst}) \pm 0.04(\text{lumi})$	1.06 ± 0.05
$\ell^+\ell^-\gamma$	$1.05 \pm 0.02(\text{stat}) \pm 0.10(\text{syst}) \pm 0.04(\text{lumi})$	1.06 ± 0.05
$\nu\bar{\nu}\gamma$	$0.116 \pm 0.010(\text{stat}) \pm 0.013(\text{syst}) \pm 0.004(\text{lumi})$	0.115 ± 0.009

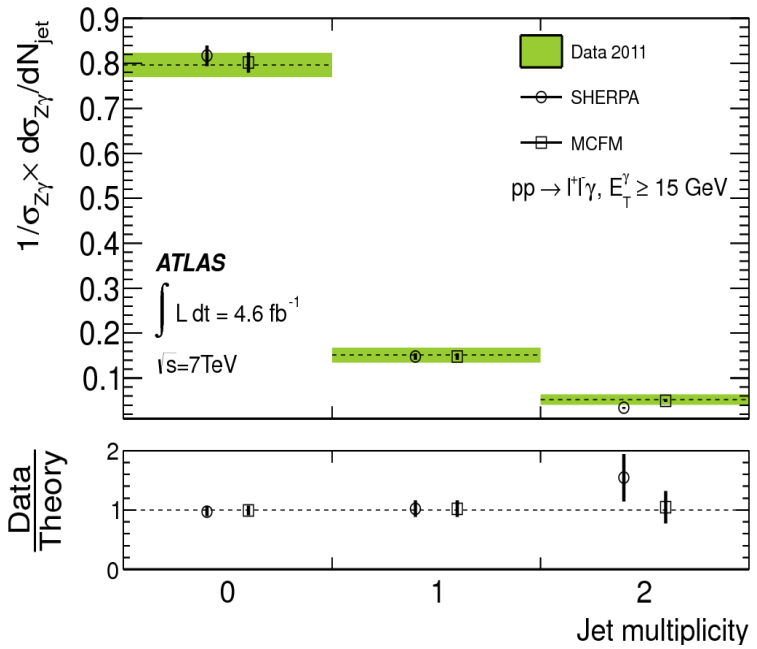
Probe aTGCs using events with E_T^{γ}>100 GeV

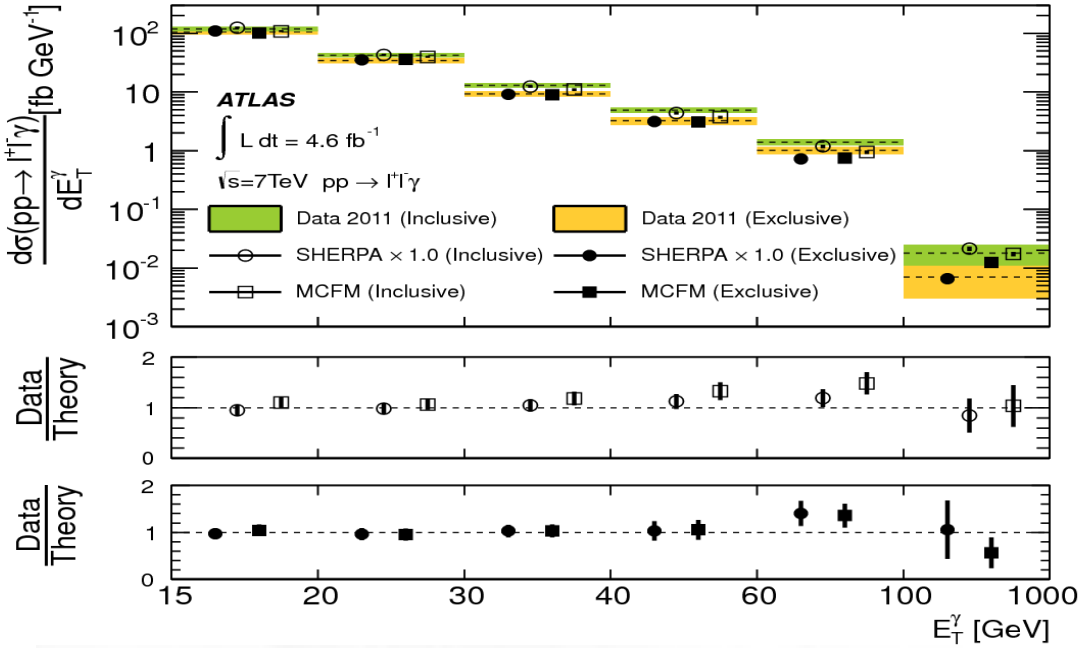
ZZγ vertex

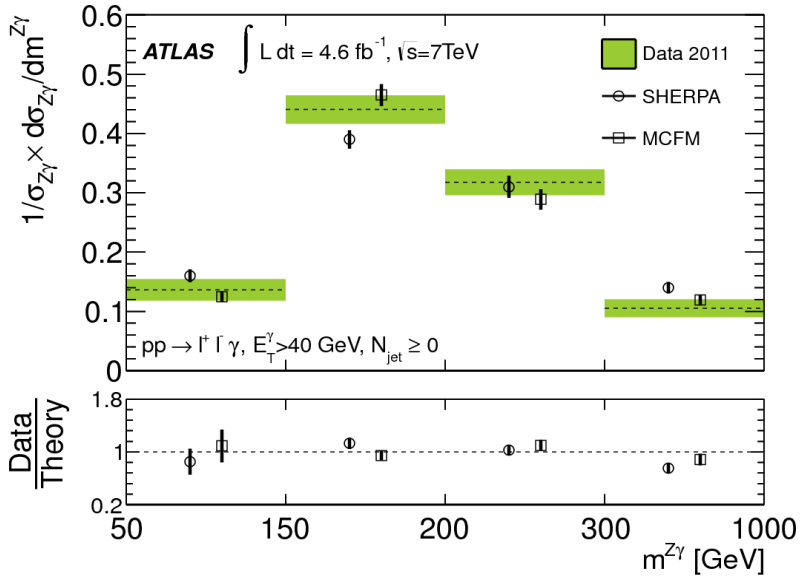
Zγγ vertex



$Z\gamma$ differential cross sections







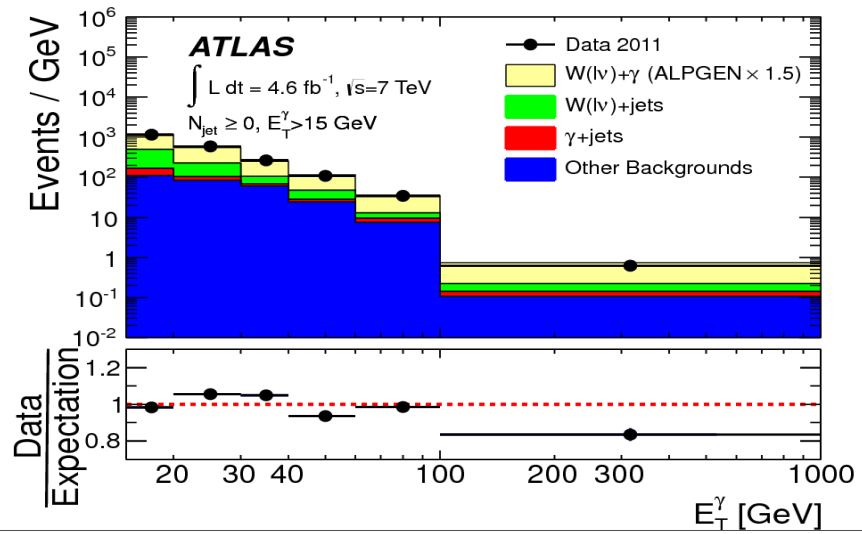
Presence of jets preferentially increases high E_T^γ

Sherpa normalized to data (inclusive in jets)

$m_{ll\gamma}$ general probe for new particles decaying to $Z\gamma$

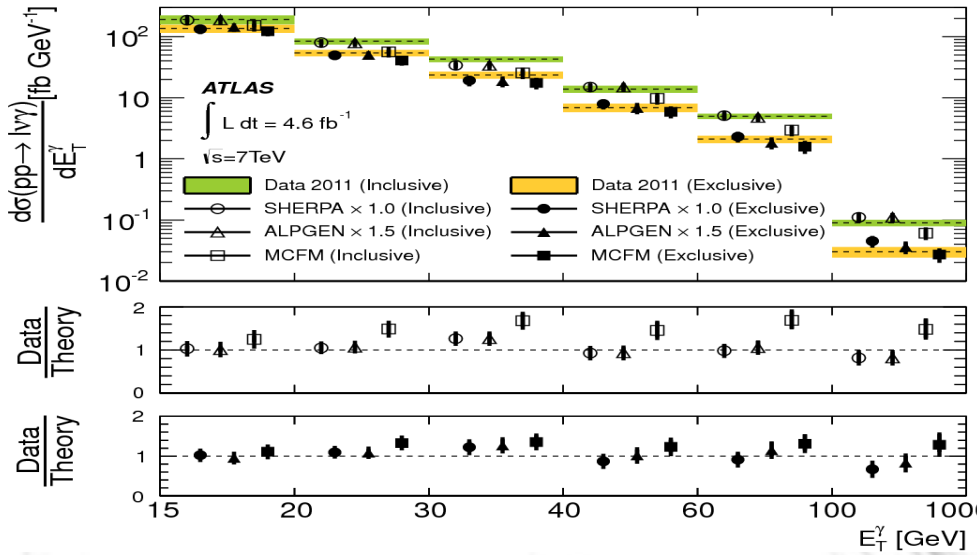
$W\gamma$ cross sections

Select events with a lepton, photon, and large E_T^{miss}



	$N_{jet} \geq 0$	
	$e\nu\gamma$	$\mu\nu\gamma$
$N_{W\gamma}^{obs}$	7399	10914
$W(\ell\nu)$ + jets	$1240 \pm 160 \pm 210$	$2560 \pm 270 \pm 580$
$Z(\ell^+\ell^-) + X$	$678 \pm 18 \pm 86$	$779 \pm 19 \pm 93$
γ + jets	$625 \pm 80 \pm 86$	$184 \pm 9 \pm 15$
$t\bar{t}$	$320 \pm 8 \pm 28$	$653 \pm 11 \pm 57$
Other background	$141 \pm 16 \pm 13$	$291 \pm 29 \pm 26$
$N_{W\gamma}^{sig}$	$4390 \pm 200 \pm 250$	$6440 \pm 300 \pm 590$

>10000 $W\gamma$ events, 60% purity

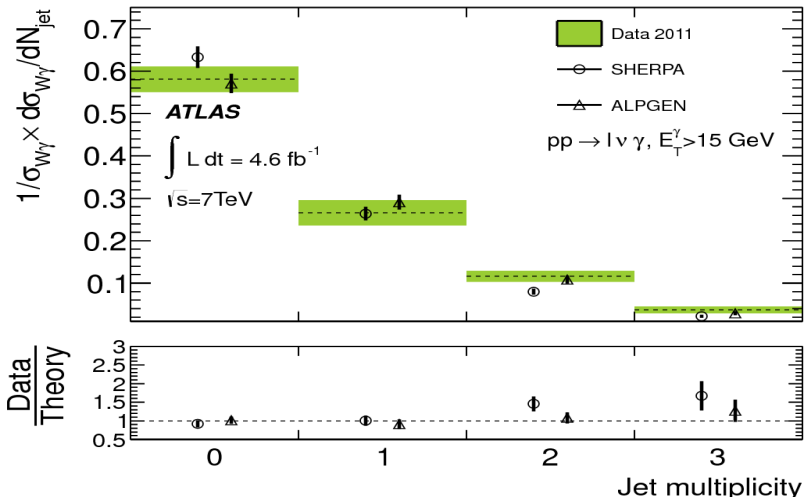


	$\sigma^{ext-fid}$[pb] Measurement	$\sigma^{ext-fid}$[pb] MCFM prediction
	$N_{jet} \geq 0$	
$e\nu\gamma$	$2.74 \pm 0.05(stat) \pm 0.32(syst) \pm 0.14(lumi)$	1.96 ± 0.17
$\mu\nu\gamma$	$2.80 \pm 0.05(stat) \pm 0.37(syst) \pm 0.14(lumi)$	1.96 ± 0.17
$\ell\nu\gamma$	$2.77 \pm 0.03(stat) \pm 0.33(syst) \pm 0.14(lumi)$	1.96 ± 0.17

Disagreement between fiducial measurement and NLO QCD due to missing photon radiation from quarks produced at higher orders in QCD

	$N_{jet} = 0$	
$e\nu\gamma$	$1.77 \pm 0.04(stat) \pm 0.24(syst) \pm 0.08(lumi)$	1.39 ± 0.13
$\mu\nu\gamma$	$1.74 \pm 0.04(stat) \pm 0.22(syst) \pm 0.08(lumi)$	1.39 ± 0.13
$\ell\nu\gamma$	$1.76 \pm 0.03(stat) \pm 0.21(syst) \pm 0.08(lumi)$	1.39 ± 0.13

$W\gamma$ differential cross sections



Jet multiplicity distribution agrees with Alpgen (Sherpa) generator producing up to five (three) additional partons

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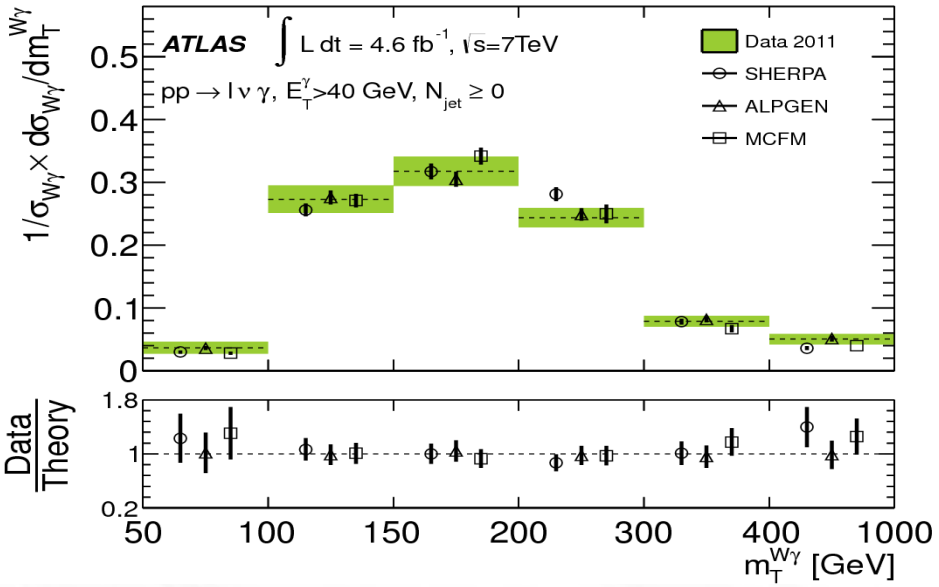
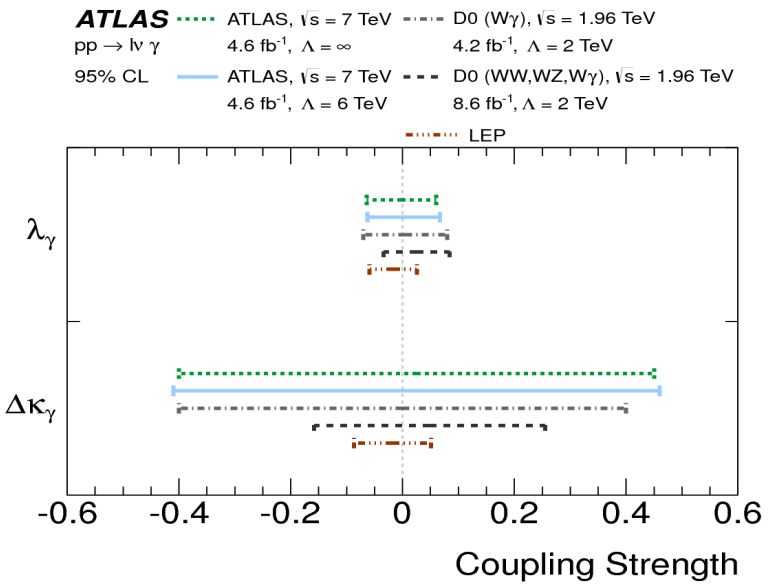
Transverse mass of Wγ system probes for new resonances decaying to Wγ





High E_T^{γ} probes for anomalous couplings

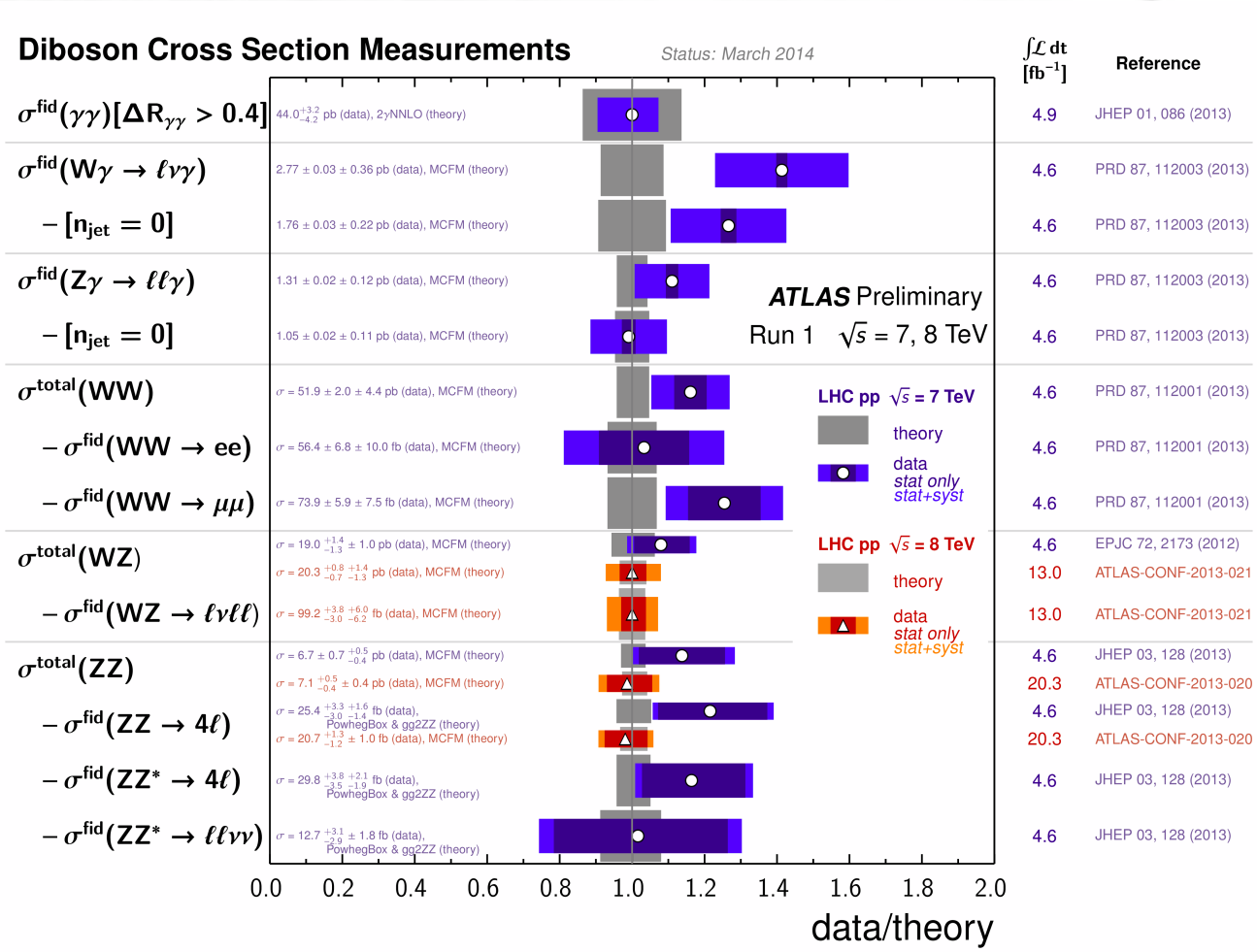
Summary

Diboson cross sections measured in 7 & 8 TeV data sets

Many measurements include unfolded differential cross sections

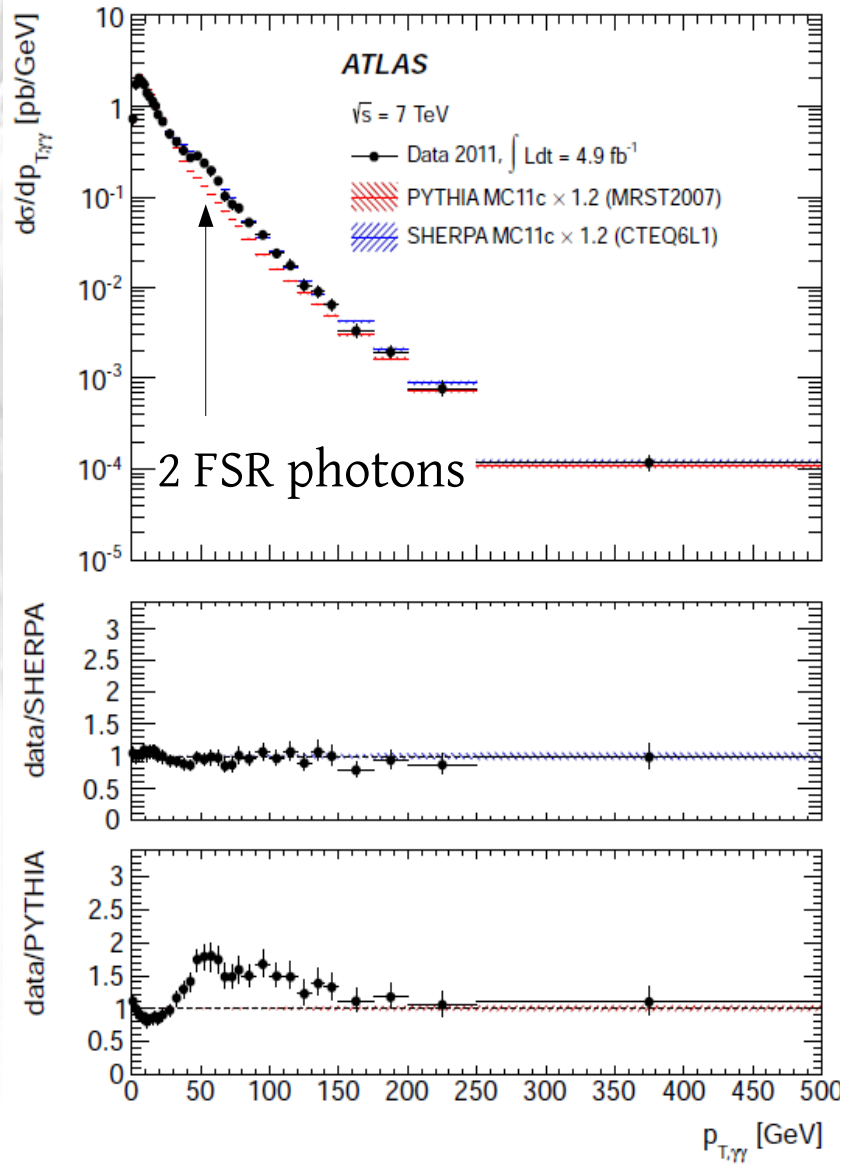
Anomalous-coupling limits set with 7 TeV data

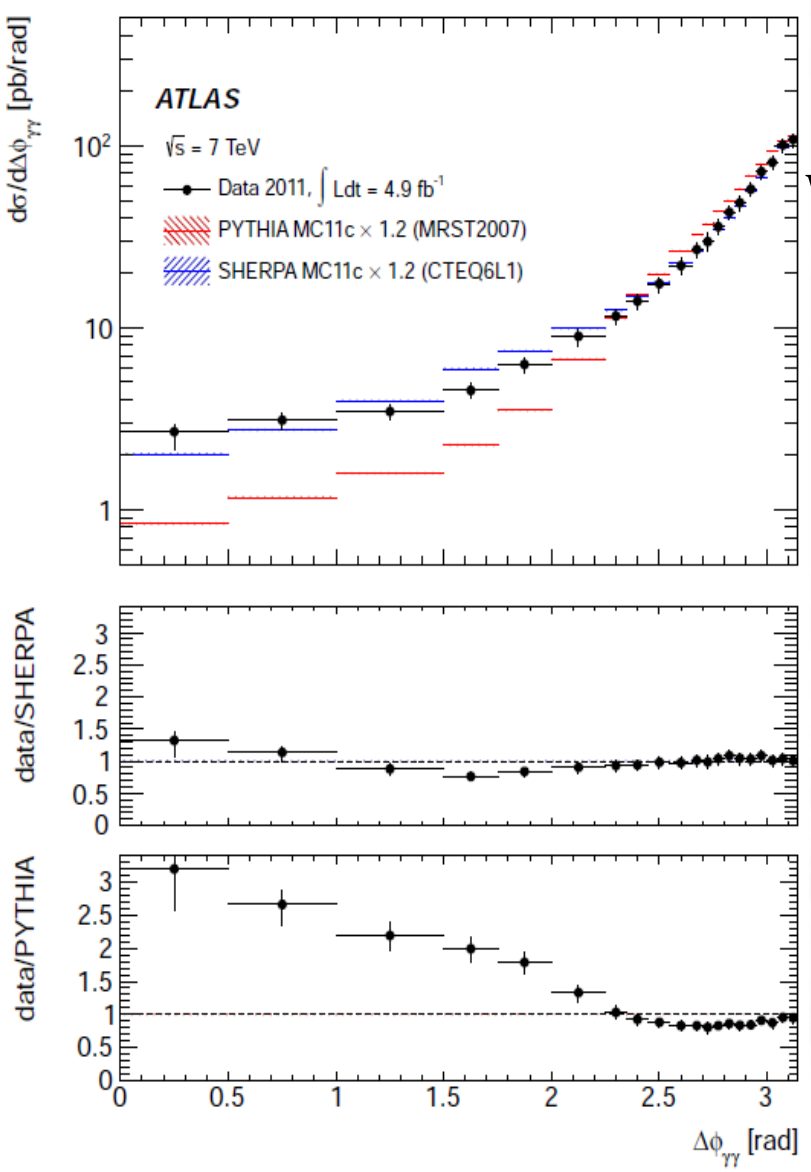
Increasing sensitivity to modelling of higher orders in QCD



Backup

Diphoton cross section





Select photons with E_T > 25, 22 GeV

Sherpa includes QED radiation from up to two additional partons

Also compare to fixed-order calculations DIPHOX and 2γNNLO