Recent Electroweak Results from ATLAS

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On behalf of the ATLAS Collaboration
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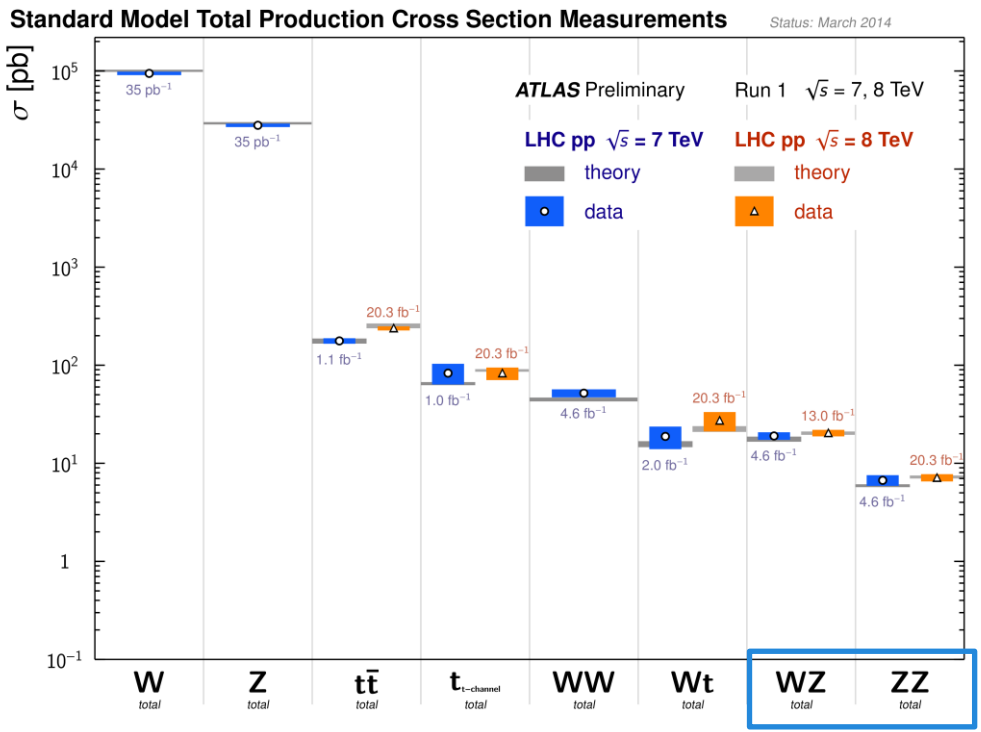
Motivation for Electroweak (Di)Boson Studies

- (Di)Boson production cross section measurement:
  - Test of SM electroweak theory and perturbative QCD at TeV scale
  - Irreducible background to Higgs ($WW, ZZ, Z\gamma$)
  - Sensitive to new particles decaying to dibosons
  - Small cross sections *O*(1-100 pb)
- Anomalous Gauge Couplings (aGC)
  - aGC modifies total cross sections and kinematics
  - An effective Lagrangian featuring such couplings can be constructed and tested

(Di)Boson Analysis Overview

- Leptonic decay channels
- Experimental signature:
  - isolated high p_T leptons
  - E_T^{miss} if ν present
  - Jets (for some study)
- Common backgrounds: Top, V+jets/γ, other diboson processes
  - Data driven used where possible
- Focus on summary of recent results using <u>8 TeV</u> datasets
  - 7 TeV in backup slides
  - Selections, major backgrounds, results



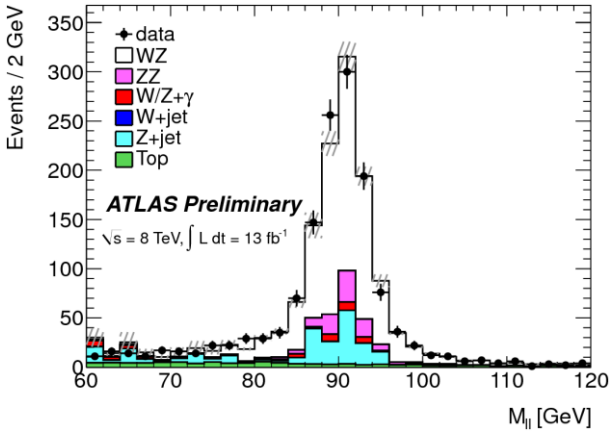
$WZ \rightarrow l\nu ll$

ATLAS-CONF-2013-021 (13 fb^{-1},8 TeV)

Main Selection Cuts:

- Z:
- 2 leptons, p_T > 10 GeV
- $|M_{ll} - M_Z|$ < 10 GeV
- W:
- 3rd lepton, p_T > 20 GeV
- E_T^{miss} > 25 GeV
- M_T > 20 GeV

Major backgrounds: Z+jets/γ, Top, ZZ



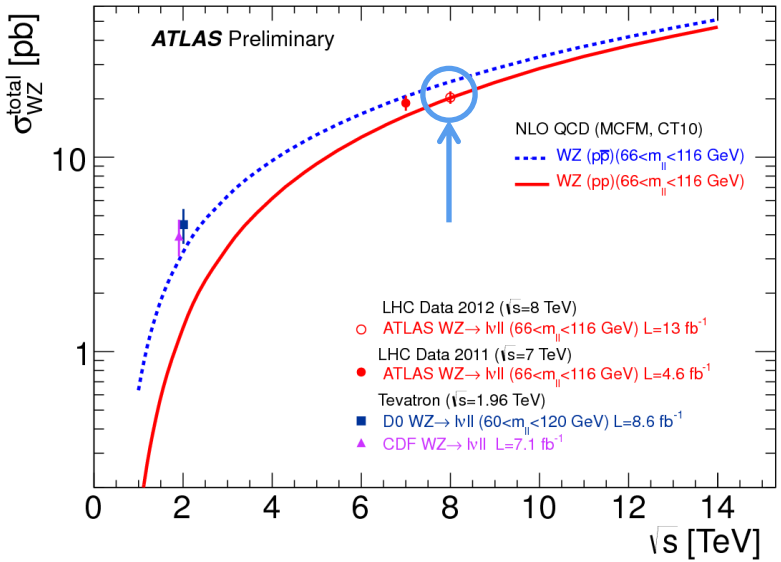
Main Systematics: Reco acceptance, BG, luminoisity

Measured total cross section:

$\sigma_{WZ} = 20.3^{+0.8}_{-0.7}(stat)^{+1.2}_{-1.1}(syst)^{+0.7}_{-0.6}(lumi)\ pb$

SM: $\sigma_{WZ}(NLO) = 20.3 \pm 0.8\ \ pb$

σ in common fiducial volume provided as well



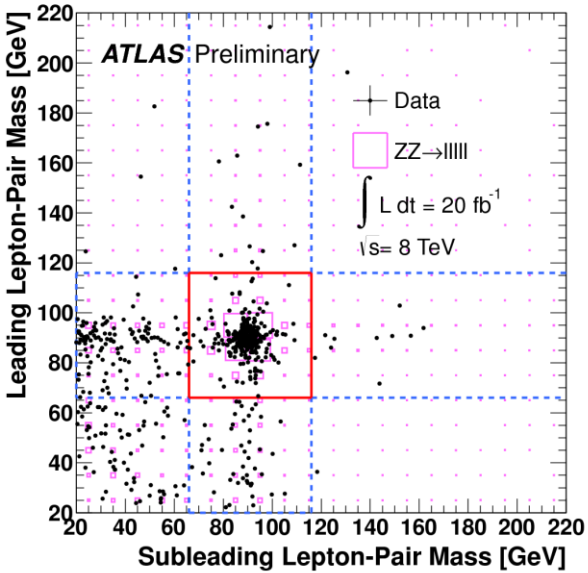
$ZZ \rightarrow llll$

ATLAS-CONF-2013-020 (20.3 fb^{-1},8 TeV)

Main Selection Cuts:

- 4 leptons, p_T > 7 GeV
- Trigger matched lepton: $p_T^{leading}$ > 25 GeV
- 66 GeV < M_{ll}< 116 GeV (each pair)

Major backgrounds: Z+jets/γ, Top, ZZ

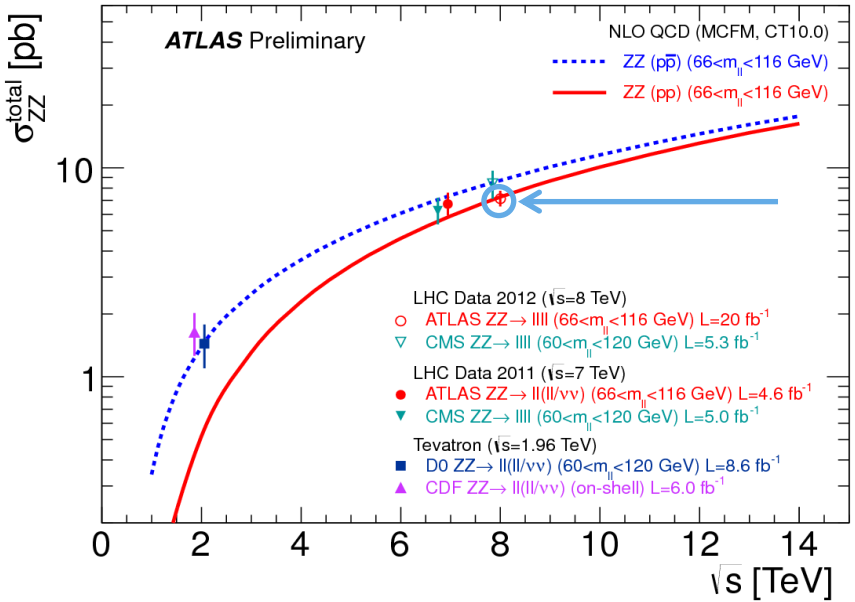


Measured total cross section:

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

SM: $\sigma_{WZ}(NLO) = 7.2^{+0.3}_{-0.2}\ pb$ (both Z's in mass window)

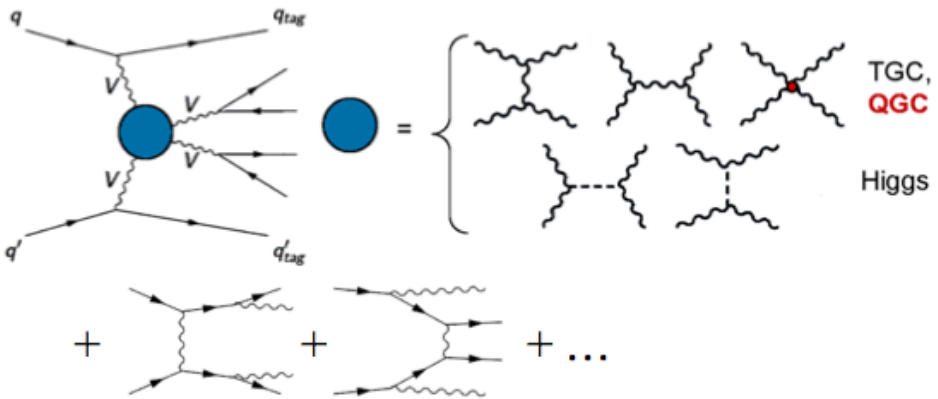
σ in common fid. vol. provided as well



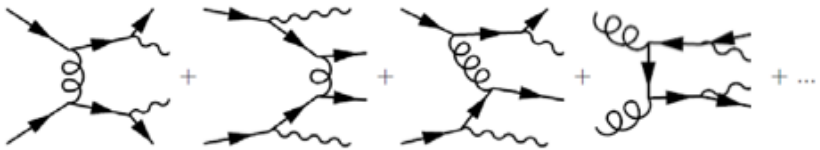
Vector Boson Scattering

$VV \to VV$ provides insight into EWSB mechanism, access to quartic couplings

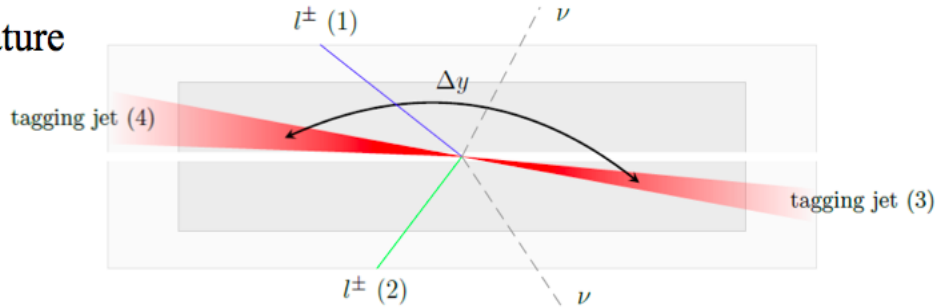
Electroweak $VVjj$ production:



Strong $VVjj$ production:



Experimental signature ($W^{\pm}W^{\pm}$ example):



* Same sign WW channel has the lowest QCD background.

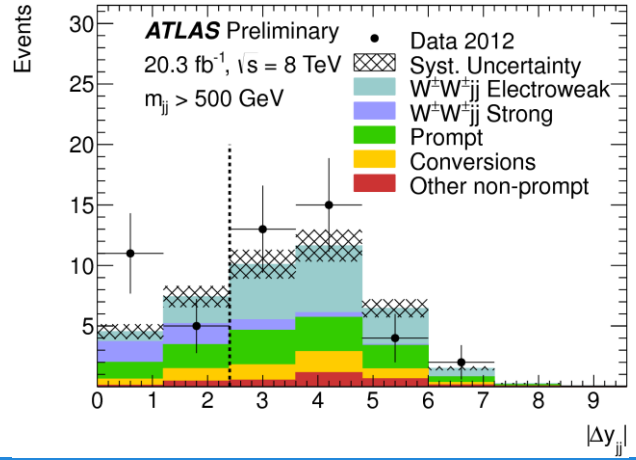
$W^{\pm}W^{\pm}jj \rightarrow l\nu l\nu jj$

ATLAS-CONF-2014-013 (20.3 fb^{-1},8 TeV)

Main Selection Cuts:

- 2 same-sign lepton, p_T > 25 GeV
- M_{ll}> 20 GeV
- $|M_{ee} - M_Z|$ > 10 GeV
- ≥ 2 jets, p_T > 30 GeV
- E_T^{miss} > 40 GeV, no b-jet
- M_{jj}> 500 GeV; $|\Delta y_{jj}|$ > 2.4(VBS region only)

Major backgrounds: prompt l (WZ/γ+jets), conversion (Wγ+jets), non-prompt l



Expected S/B: 0.9

Main Systematics: WZ/γ+jets, norm. theo. unc., JES

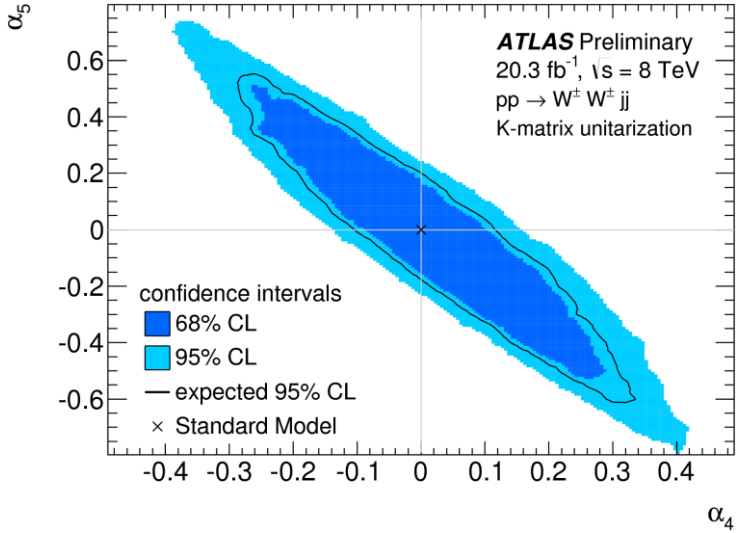
Measured EW fiducial cross section:

$\sigma^{EW}_{W^{\pm}W^{\pm}jj} = 1.3 \pm 0.4(stat) \pm 0.2(syst)\ \ fb$

SM: $\sigma^{EW}_{W^{\pm}W^{\pm}jj}(NLO) = 0.95 \pm 0.06\ \ fb$

1st evidence (3.6σ) for EW $W^{\pm}W^{\pm}jj$ production

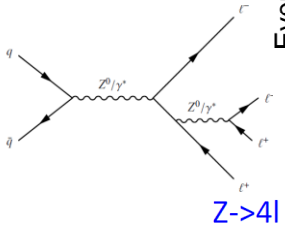
Access to WWWW vertex, set 1st limits on aQGC parameters α_4 & α_5

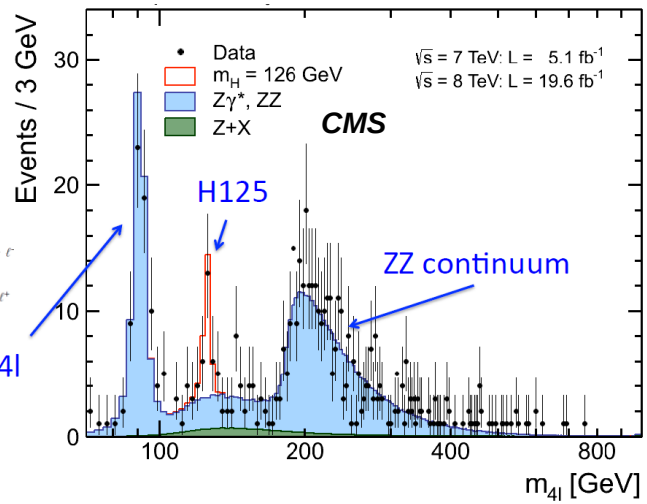


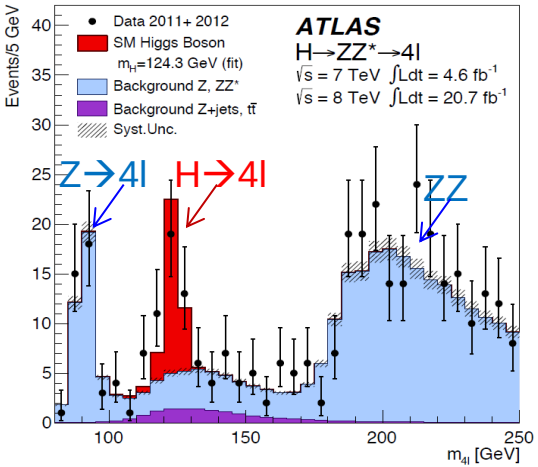
$Z \to 4l$

arXiv:1403.5657v1 (7 & 8 TeV)

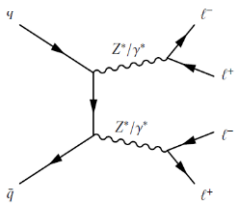
- The $Z \to 4l$ production was first observed at the LHC by both ATLAS and CMS along with the Higgs boson discovery in the $4l$ decay channel

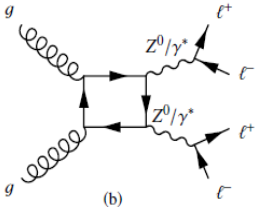






Non-resonant $Z \to 4l$ production:





$Z \rightarrow 4l$

arXiv:1403.5657v1 (7 & 8 TeV)

- Measurement approaches:
  - Measure inclusive $4l$ production cross-section at the Z resonance, i.e. the non-resonance $4l$ events are treated as *signal*

    → *cross section measurement will be less depending on theory interpretation*
  - In determination of $Z \rightarrow 4l$ decay branching fraction, the non-resonance $4l$ contribution is subtracted and the resonance $4l$ event yield is normalized by the $Z \rightarrow \mu\mu$ with the same dataset
- Experimental Challenges:
  - The $Z \rightarrow 4l$ process is dominant by low mass m_{34} and low p_T leptons (the p_T -ordered 4th leptons)
  - **Need to detect low p_T leptons**

$Z \rightarrow 4l$

arXiv:1403.5657v1 (7 & 8 TeV)

Main Selection Cuts:

- 4 leptons, p_T > 4/7 GeV (μ/e)
- $p_T^{leading}$ > 20, 15, 8/10 GeV
- M_{12}> 20 GeV, M_{34}> 5 GeV
- 4e,4μ: M_{ll}> 5 GeV
- 80 GeV < M_{4l}< 100 GeV

Major backgrounds: VV, Z+jets, Top

Measured total cross section (8 TeV, $M_{l^+l^-}$ > 5 GeV):

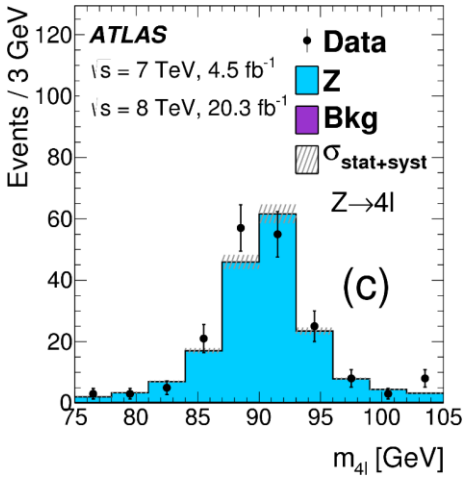
$\sigma_{Z\rightarrow 4l} = 107 \pm 9(stat) \pm 4(syst) \pm 3(lumi)\ \ fb$

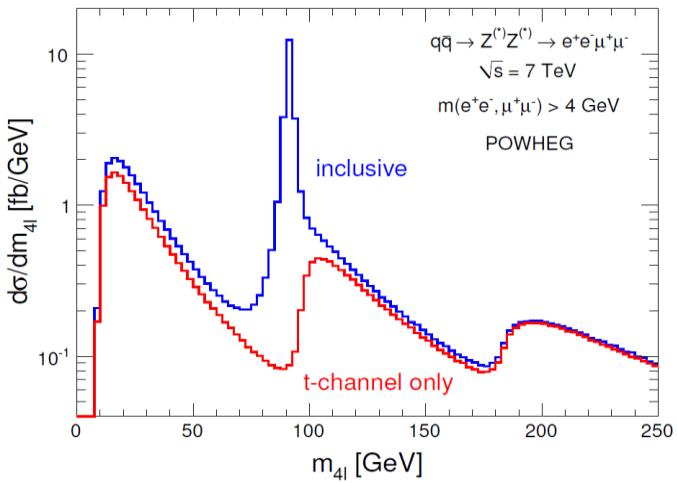
SM:$\sigma_{Z\rightarrow 4l}(NLO) = 104.8 \pm 2.5\ \ fb$

Measured branching fraction (7 & 8 TeV):

$\Gamma_{Z\rightarrow 4l}/\Gamma_Z = \left(3.20 \pm 0.25(stat) \pm 0.13(syst)\right) \times 10^{-6}$

SM prediction: $(3.33 \pm 0.01) \times 10^{-6}$



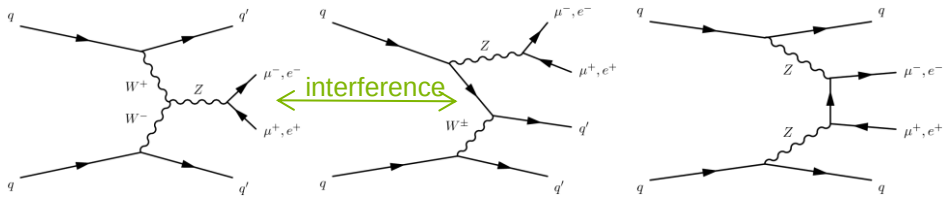


Zjj

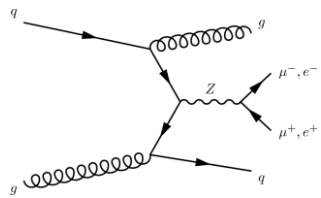
JHEP04(2014)031 (20.3 fb^{-1},8 TeV)

Zjj sets constraint on QCD modeling with VBF topology, sets limits on WWZ couplings

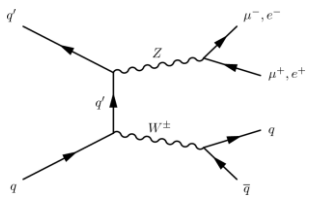
Electroweak Zjj production:



Strong Zjj production:



Diboson Zjj production:



5 fiducial regions: different sensitivity to EW Zjj

- Search: Optimize for EW Zjj
- Control: Suppress EW Zjj, evaluate strong Zjj
- Baseline: Most inclusive fiducial region
- High-mass: M_{jj} > 1 TeV
- High-p_T: $p_T^{j_1}/p_T^{j_2}$ > 85/75 GeV

The last 3 regions are chosen with looser selection to study inclusive Zjj production. The last 2 regions are useful to probe the impact of the EW Zjj

Major backgrounds: $t\bar{t}$

	Composition (%)				
Process	*baseline*	*high-p_T*	*search*	*control*	*high-mass*
Strong Zjj	95.8	94.0	94.7	96.0	85
Electroweak Zjj	1.1	2.1	4.0	1.4	12
WZ and ZZ	1.0	1.3	0.7	1.4	1
$t\bar{t}$	1.8	2.2	0.6	1.0	2
Single top	0.1	0.1	< 0.1	< 0.1	< 0.1
Multijet	0.1	0.2	< 0.1	0.2	< 0.1
WW, W+jets	< 0.1	< 0.1	< 0.1	< 1.1	< 0.1

Zjj

JHEP04(2014)031 (20.3 fb^{-1},8 TeV)

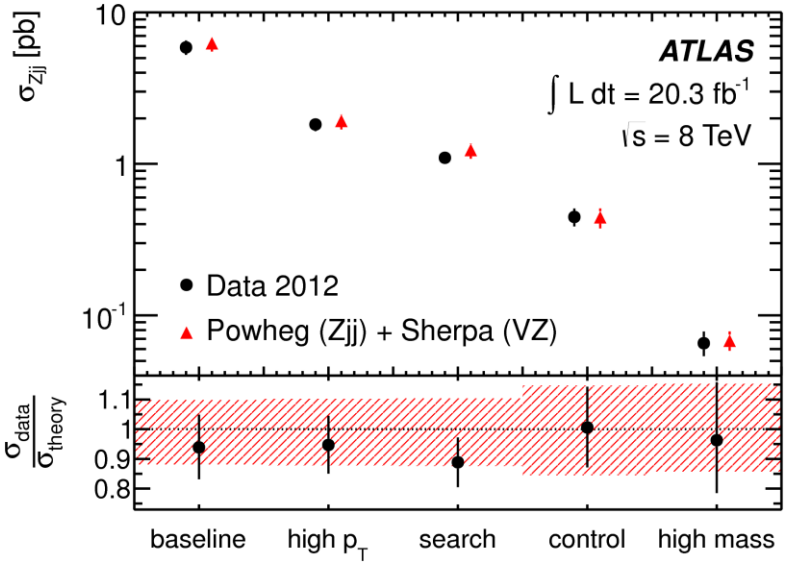
Main Selection Cuts:

$$p_{\mathrm{T}}^{\mathrm{balance}} = \frac{\left|\vec{p}_{\mathrm{T}}^{\ell_1} + \vec{p}_{\mathrm{T}}^{\ell_2} + \vec{p}_{\mathrm{T}}^{j_1} + \vec{p}_{\mathrm{T}}^{j_2}\right|}{\left|\vec{p}_{\mathrm{T}}^{\ell_1}\right| + \left|\vec{p}_{\mathrm{T}}^{\ell_2}\right| + \left|\vec{p}_{\mathrm{T}}^{j_1}\right| + \left|\vec{p}_{\mathrm{T}}^{j_2}\right|}$$

Object	*baseline*	*high-mass*	*search*	*control*	*high-p_{T}*
Leptons	$\lvert\eta^{\ell}\rvert < 2.47$, $p_{\mathrm{T}}^{\ell} > 25$ GeV				
Dilepton pair	$81 \le m_{\ell\ell} \le 101$ GeV				
	—		$p_{\mathrm{T}}^{\ell\ell} > 20$ GeV		—
Jets	$\lvert y^{j}\rvert < 4.4$, $\Delta R_{j,\ell} \ge 0.3$				
	$p_{\mathrm{T}}^{j_1} > 55$ GeV				$p_{\mathrm{T}}^{j_1} > 85$ GeV
	$p_{\mathrm{T}}^{j_2} > 45$ GeV				$p_{\mathrm{T}}^{j_2} > 75$ GeV
Dijet system	—	$m_{jj} > 1$ TeV	$m_{jj} > 250$ GeV		—
Interval jets	—		$N_{\mathrm{jet}}^{\mathrm{gap}} = 0$	$N_{\mathrm{jet}}^{\mathrm{gap}} \ge 1$	—
Zjj system	—		$p_{\mathrm{T}}^{\mathrm{balance}} < 0.15$	$p_{\mathrm{T}}^{\mathrm{balance,3}} < 0.15$	—

Main Systematics: JES, JER

Measured fiducial cross sections:



Zjj

JHEP04(2014)031 (20.3 fb^{-1},8 TeV)

Extracted EW Zjj cross sections (fit M_{jj} in *search* region):

$\sigma_{Zjj}^{EW} = 54.7 \pm 4.6(stat)^{+9.8}_{-10.4}(syst) \pm 1.5(lumi)\ fb$

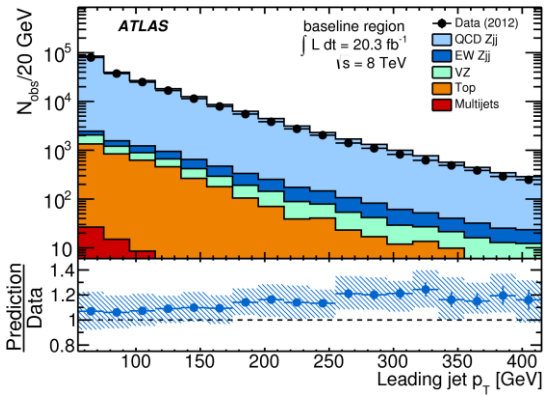
SM:$\sigma_{Zjj}^{EW}(NLO) = 46.1 \pm 0.2(stat)^{+0.3}_{-0.2}(scale) \pm 0.8(PDF) \pm 0.5(model)\ fb$

$\sigma_{Zjj}^{EW}(M_{jj} > 1\ TeV) = 10.7 \pm 0.9(stat) \pm 1.9(syst) \pm 0.3(lumi)\ fb$

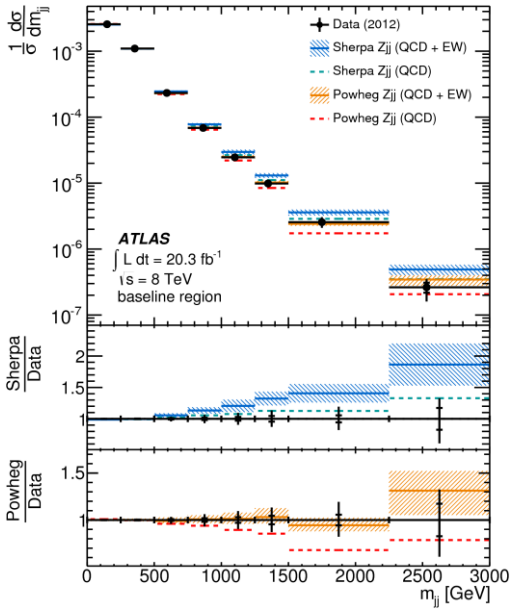
SM:$\sigma_{Zjj}^{EW}(NLO)(M_{jj} > 1\ TeV) = 9.38 \pm 0.05(stat)^{+0.15}_{-0.24}(scale) \pm 0.24(PDF) \pm 0.09(model)\ fb$

The background-only hypothesis is rejected at $> 5\sigma$ significance.

Main Systematics: JES, JER, sig. modeling, bkg Modeling, sig/bkg interference



aTGC	$\Lambda = 6$ TeV (obs)	$\Lambda = 6$ TeV (exp)	$\Lambda = \infty$ (obs)	$\Lambda = \infty$ (exp)
$\Delta g_{1,Z}$	$[-0.65, 0.33]$	$[-0.58, 0.27]$	$[-0.50, 0.26]$	$[-0.45, 0.22]$
λ_Z	$[-0.22, 0.19]$	$[-0.19, 0.16]$	$[-0.15, 0.13]$	$[-0.14, 0.11]$



Summary

- Cross sections:
  - Compatible with SM expectations
  - Differential cross section probe MC modelling
- aGCs:
  - Competitive limits obtained
- Plans:
  - 8 TeV publications in preparation for all VV
  - Working towards combination across channels (& experiments)
  - Need for coherent NLO+PS MC for all analyses; NNLO QCD, NLO EW
  - VBS/VBF cross sections will rise a lot with the increase in energy
  - 13/14 TeV data will allow measurements of new rare processes, probe NP

Backup

$W(l\nu)\gamma, Z(ll/\nu\nu)\gamma$

Phys. Rev. D 87, 112003 (2013) (4.6 fb^{-1},7 TeV)

Main Selection Cuts:

- Common:
- $\Delta R(l,\gamma)$ > 0.7 to surpress FSR photon
- 1 isolated photon, E_T^{γ} > 15 GeV
- $W\gamma(l\nu\gamma)$:
- 1 lepton, p_T > 25 GeV
- E_T^{miss} > 35 GeV, $M_T^{l\nu\gamma}$ > 40 GeV
- $|M_{e\gamma} - M_Z|$ > 15 GeV
- $Z\gamma(ll\gamma)$:
- 2 opposite charge lepton, M_{ll} > 40 GeV
- $Z\gamma(\nu\nu\gamma)$:
- E_T^{γ} > 100 GeV, E_T^{miss} > 90 GeV
- $\Delta\phi(E_T^{miss},\gamma)$ > 2.6, $\Delta\phi(E_T^{miss},jet)$ > 0.4

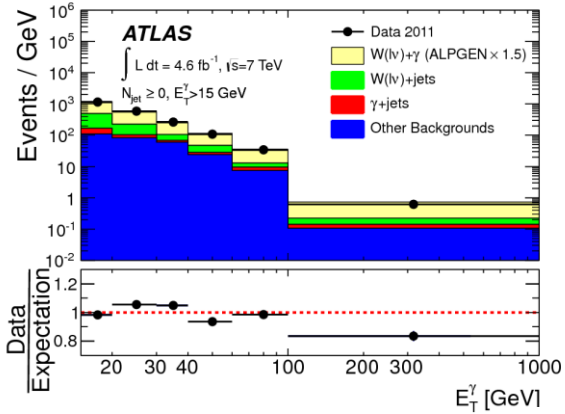
Major backgrounds: W+jets, γ+jets, Zll

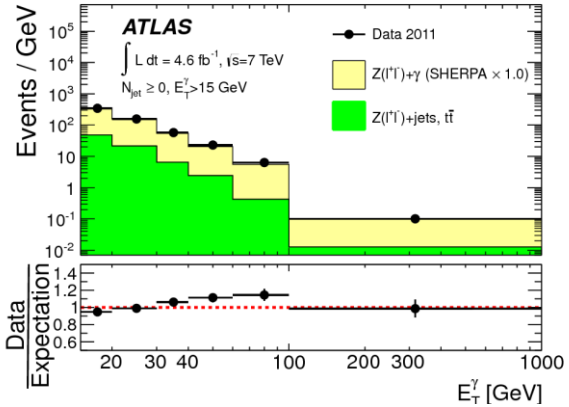
Measured total cross section:

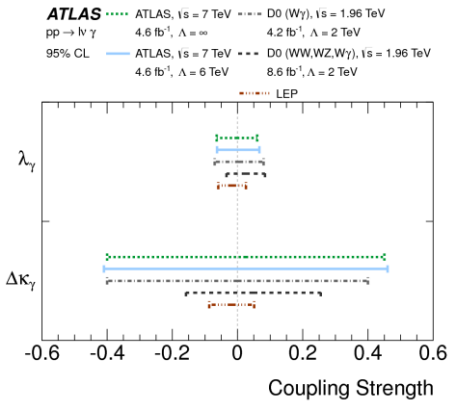
	$\sigma^{\text{ext-fid}}$[pb] Measurement	$\sigma^{\text{ext-fid}}$[pb] MCFM Prediction
	$N_{\text{jet}} \geq 0$	
$e\nu\gamma$	2.74 ± 0.05 (stat) ± 0.32 (syst) ± 0.14 (lumi)	1.96 ± 0.17
$\mu\nu\gamma$	2.80 ± 0.05 (stat) ± 0.37 (syst) ± 0.14 (lumi)	1.96 ± 0.17
$\ell\nu\gamma$	2.77 ± 0.03 (stat) ± 0.33 (syst) ± 0.14 (lumi)	1.96 ± 0.17
$e^+e^-\gamma$	1.30 ± 0.03 (stat) ± 0.13 (syst) ± 0.05 (lumi)	1.18 ± 0.05
$\mu^+\mu^-\gamma$	1.32 ± 0.03 (stat) ± 0.11 (syst) ± 0.05 (lumi)	1.18 ± 0.05
$\ell^+\ell^-\gamma$	1.31 ± 0.02 (stat) ± 0.11 (syst) ± 0.05 (lumi)	1.18 ± 0.05
$\nu\bar{\nu}\gamma$	0.133 ± 0.013 (stat) ± 0.020 (syst) ± 0.005 (lumi)	0.156 ± 0.012
	$N_{\text{jet}} = 0$	
$e\nu\gamma$	1.77 ± 0.04 (stat) ± 0.24 (syst) ± 0.08 (lumi)	1.39 ± 0.13
$\mu\nu\gamma$	1.74 ± 0.04 (stat) ± 0.22 (syst) ± 0.08 (lumi)	1.39 ± 0.13
$\ell\nu\gamma$	1.76 ± 0.03 (stat) ± 0.21 (syst) ± 0.08 (lumi)	1.39 ± 0.13
$e^+e^-\gamma$	1.07 ± 0.03 (stat) ± 0.12 (syst) ± 0.04 (lumi)	1.06 ± 0.05
$\mu^+\mu^-\gamma$	1.04 ± 0.03 (stat) ± 0.10 (syst) ± 0.04 (lumi)	1.06 ± 0.05
$\ell^+\ell^-\gamma$	1.05 ± 0.02 (stat) ± 0.10 (syst) ± 0.04 (lumi)	1.06 ± 0.05
$\nu\bar{\nu}\gamma$	0.116 ± 0.010 (stat) ± 0.013 (syst) ± 0.004 (lumi)	0.115 ± 0.009

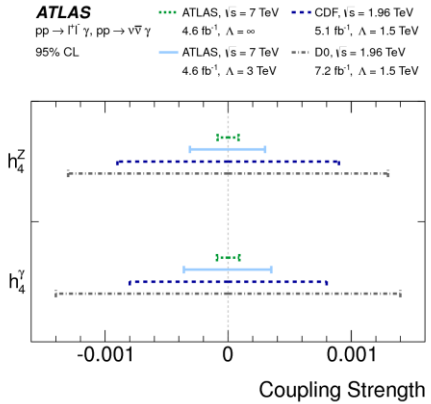
$W(l\nu)\gamma, Z(ll/\nu\nu)\gamma$

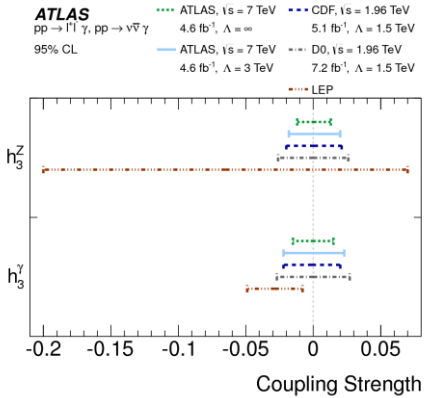
Phys. Rev. D 87, 112003 (2013) (4.6 fb^{-1},7 TeV)











$WW \rightarrow l\nu l\nu$

Phys. Rev. D 87, 112001(2013) (4.6 fb^{-1},7 TeV)

Main Selection Cuts:

- 2 isolated opposite sign leptons
- $p_T^{leading}/p_T^{sub-leading}$ > 25/20 GeV
- $|M_{ll} - M_Z|$ > 15/10 GeV (SF/OF)
- $E_{T,Rel}^{miss}$ > 45/25 GeV (SF/OF)
- JetVeto
- p_T^{ll} > 30 GeV

Major backgrounds: V+jets, Top, VV

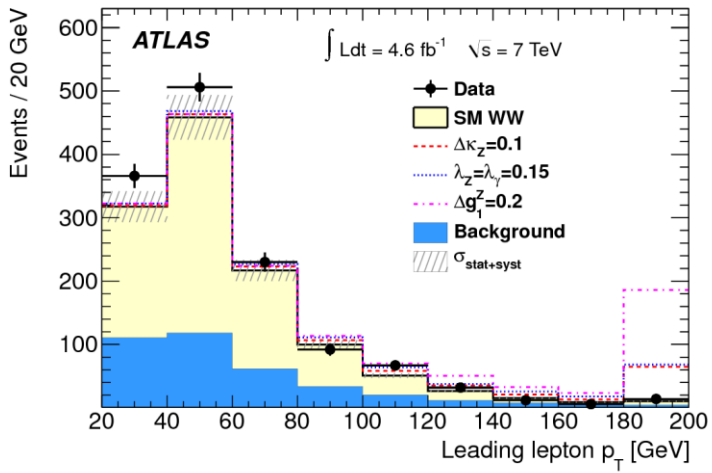
Expected S/B: 2.3

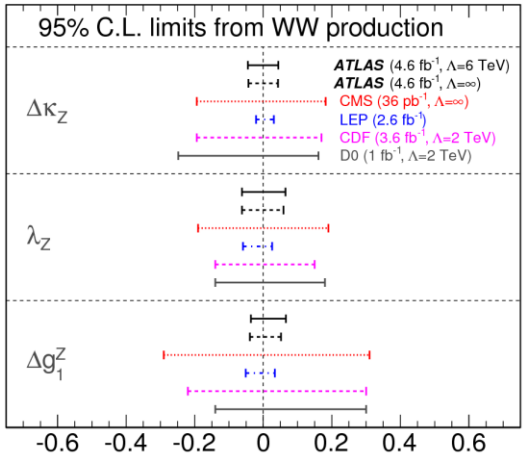
Main Systematics: Jet Veto Efficiency

Measured total cross section:

$\sigma_{WW} = 51.9 \pm 2.0(stat) \pm 3.9(syst) \pm 0.9(lumi)\ pb$

SM: $\sigma_{WW}(NLO) = 44.7^{+2.1}_{-1.9}\ pb$





$WW/WZ \rightarrow l\upsilon q\bar{q}'$

ATLAS-CONF-2012-157 (4.6 fb^{-1},7 TeV)

Main Selection Cuts: (electron)

- 1 lepton, p_T > 25 GeV
- 2 jets, $p_T^{leading}/p_T^{sub-leading}$ > 30/25 GeV
- E_T^{miss} > 30 GeV
- $M_T^{l\nu}$ > 40 GeV
- $\Delta\phi(E_T^{miss}, j^1)$ > 0.8, $\Delta R(j^1, j^2)$ > 0.7, $\Delta\eta(j^1, j^2)$ < 1.5

Expected S/B: 0.027

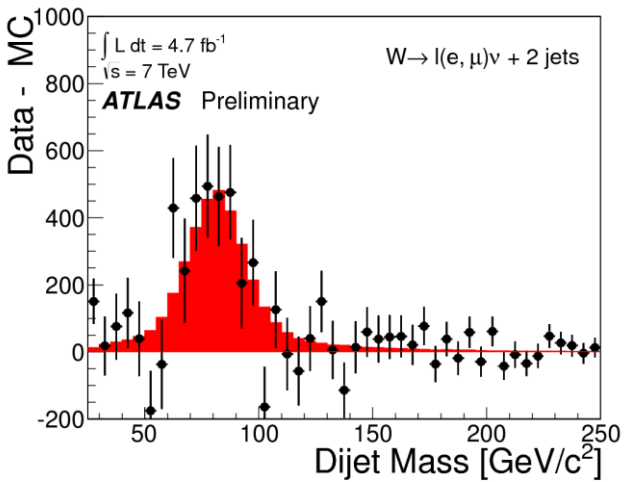
Major backgrounds: V+jets

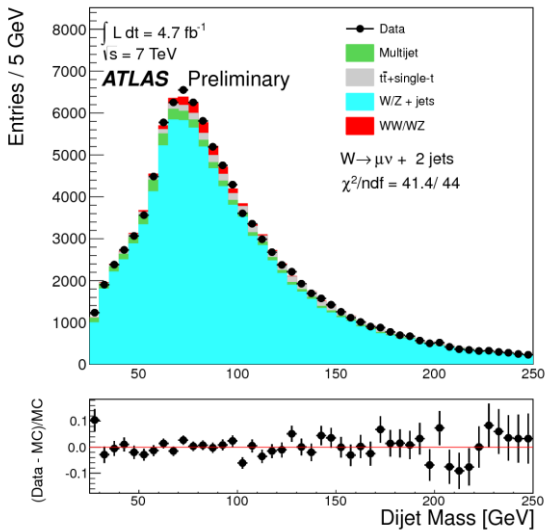
Main Systematics: MC stats, JES, W/Z+jets norm.

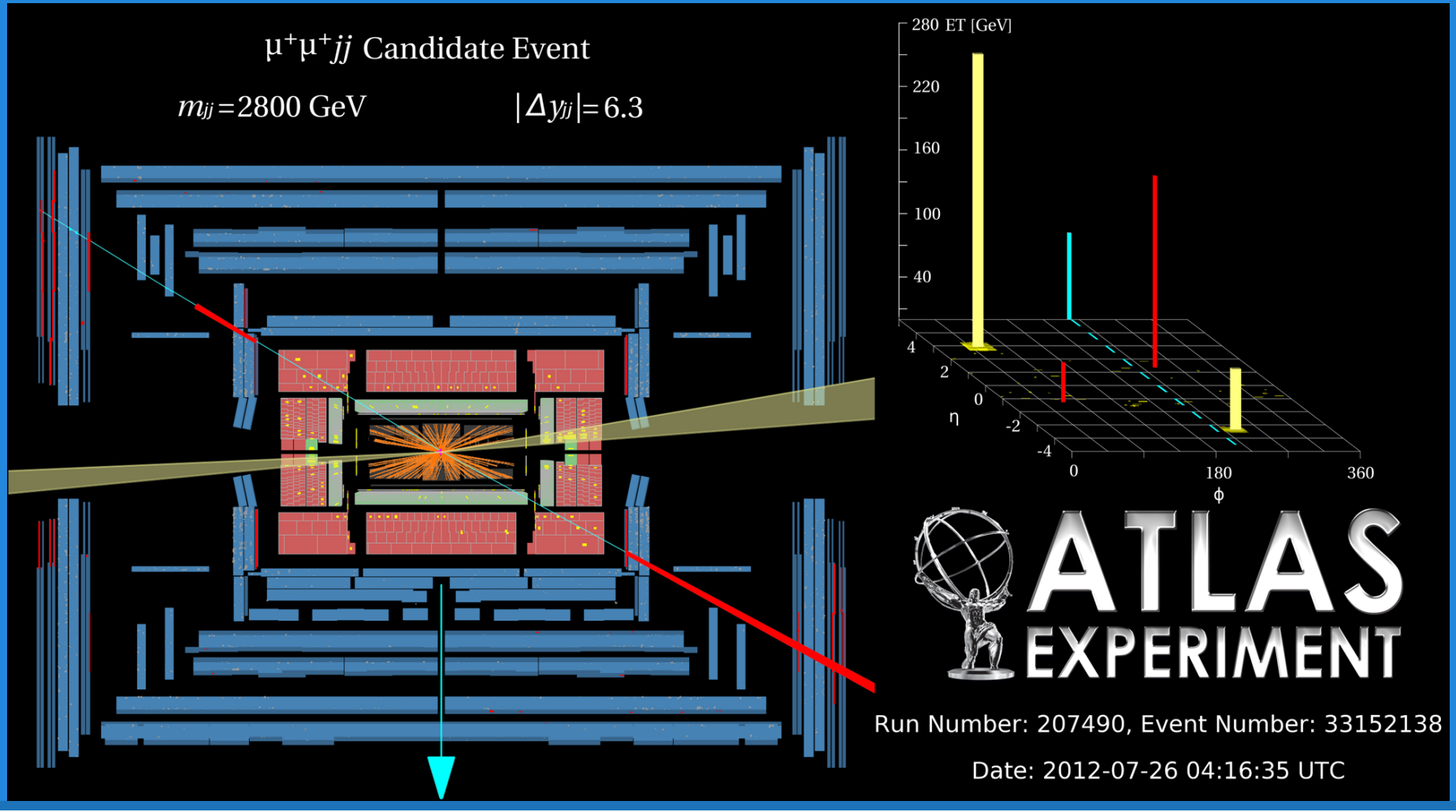
Measured total cross section:

$\sigma_{WW+WZ} = 72 \pm 9(stat) \pm 15(syst) \pm 13(MC\ stat.)\ pb$

SM: $\sigma_{WW+WZ}(NLO) = 63.4 \pm 2.6\ pb$







$WWjj \rightarrow l\nu l\nu jj$ Candidate Event Display

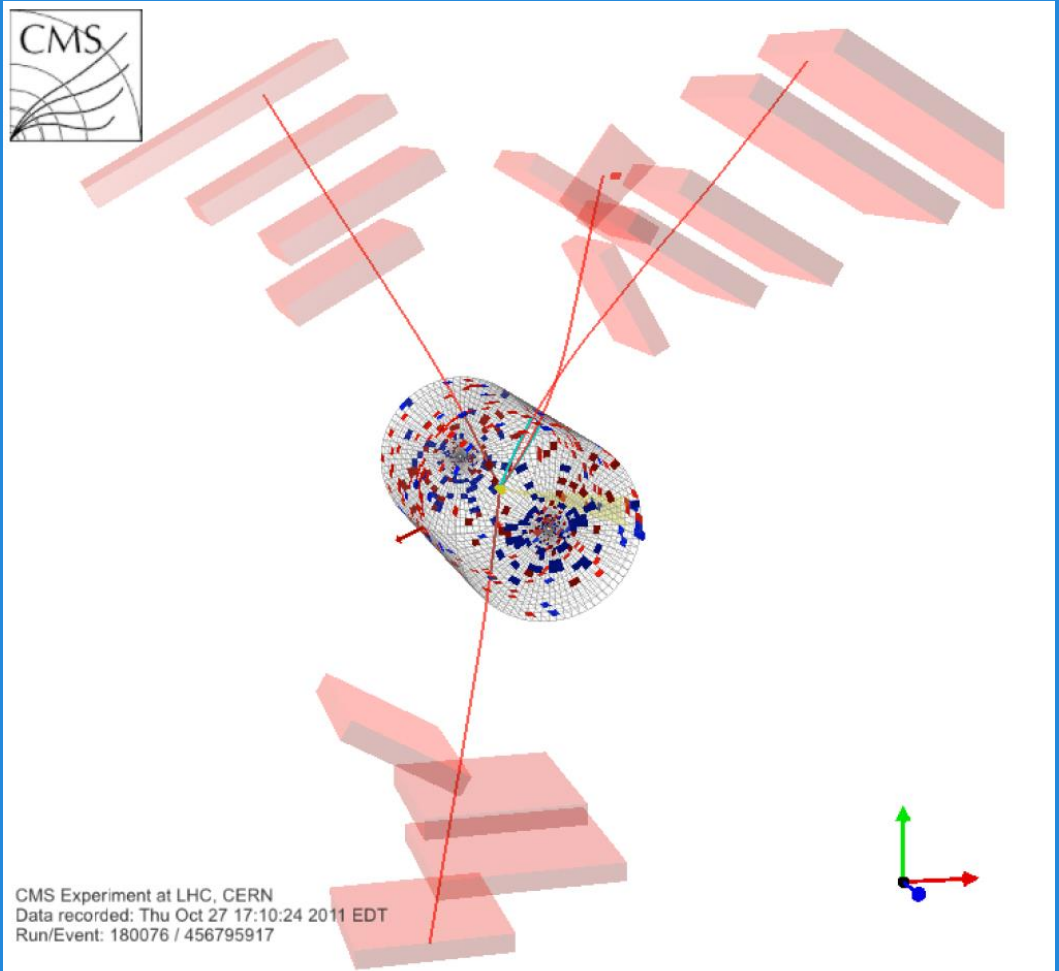


Figure 5: Event display of a typical event from the peak at the Z boson mass.

Z→ $4l$ Candidate Event Display