Evidence for VBF in Z production at the LHC

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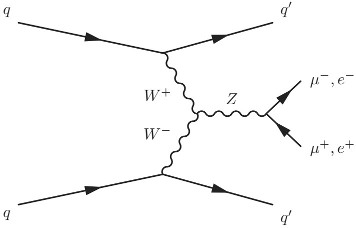
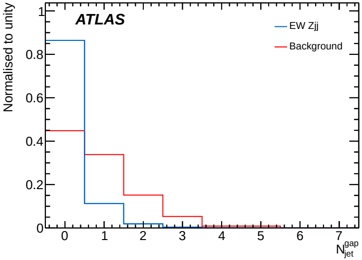
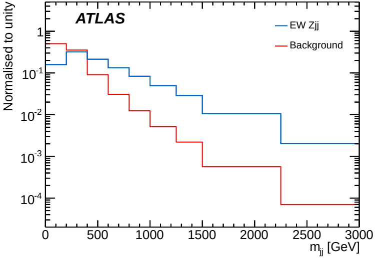
Main signal features

- colourless exchange of vector bosons
- jets tend to be produced at large rapidities with sizeable transverse momentum and together they balance the Z boson



- results in **two forward jets with large dijet invariant mass** and **no additional jets in the rapidity interval** between them





ATLAS Collaboration, JHEP 04 (2014) 031

Strategy

- select events requiring a Z candidate with tight invariant mass cut and at least two high-p_{T} jets
- use jet multiplicity in rapidity interval between leading two jets to construct signal-enhanced ($N_{\mathrm{jet}}^{\mathrm{gap}} = 0$) and signal-suppressed ($N_{\mathrm{jet}}^{\mathrm{gap}} \geq 1$) regions
- use signal-suppressed control region to **constrain shape of the background model**
- extract electroweak Zjj component in signal-enhanced search region using two-component template **fit to dijet invariant mass spectrum**

region	yield for N_{EW}
$m_{jj} > 250$ GeV	1657^{+134}_{-132} (fit) ± 40 (MC)
$m_{jj} > 1$ TeV	333^{+27}_{-26} (fit) ± 8 (MC)

- convert signal yields into fiducial cross sections and **correct back to particle level** using a correction factor ($\mathcal{C}_{\mathrm{EW}}$)

Selection

object	search	control
leptons	$\lvert\eta^{\ell}\rvert < 2.47$, $p_T^{\ell} > 25$ GeV	
dilepton pair	81 GeV $\leq m_{\ell\ell} \leq$ 101 GeV $p_T^{\ell\ell} > 20$ GeV	
jets	$\lvert y^{j}\rvert < 4.4$, $\Delta R_{j,\ell} \geq 0.3$ $p_T^{j_1} > 55$ GeV, $p_T^{j_2} > 45$ GeV	
dijet system	$m_{jj} > 250$ GeV	
interval jets	$N_{\text{jets}}^{\text{gap}} = 0$	$N_{\text{jets}}^{\text{gap}} \geq 1$
Zjj system	$p_T^{\text{balance}} < 0.15$	$p_T^{\text{balance,3}} < 0.15$

where

$$(\Delta R_{j,\ell})^2 = (\Delta\phi_{j,\ell})^2 + (\Delta\eta_{j,\ell})^2$$

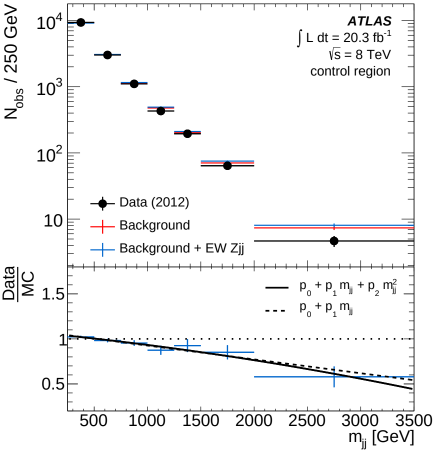
and

$$p_T^{\text{balance}} = \frac{\left|\vec{p}_T^{\,\ell_1} + \vec{p}_T^{\,\ell_2} + \vec{p}_T^{\,j_1} + \vec{p}_T^{\,j_2}\right|}{\left|\vec{p}_T^{\,\ell_1}\right| + \left|\vec{p}_T^{\,\ell_2}\right| + \left|\vec{p}_T^{\,j_1}\right| + \left|\vec{p}_T^{\,j_2}\right|}$$

Control region constraint

- fit of data-to-MC ratio in **control region used to constrain shape of background model in search region**
- get strong *Zjj* modelling directly from data
- **constrains systematics** on background model
- theory uncertainties $> 30\,\%$ and experimental uncertainties $> 20\,\%$ if background shape not constrained

dijet invariant mass in control region



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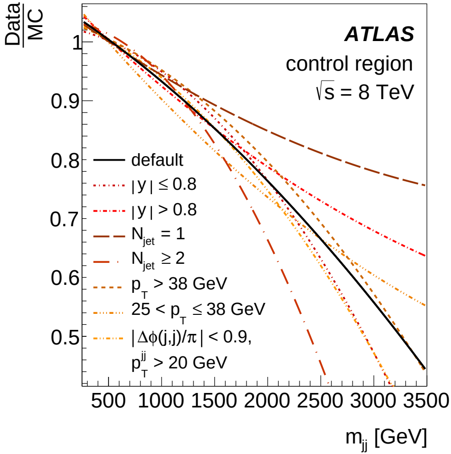
Choice of control region

- nominal control region split into 6 different subregions probing additional jet activity in rapidity interval between leading jets:
  - nominal control region split based on rapidity of in-gap jet
  - nominal control region split based on p_{T} of in-gap jet
  - nominal control region split based on number of in-gap jets
- MPI-suppressed subregion:
  - nominal control region with dijet $p_{\mathrm{T}}^{jj} > 20\,\mathrm{GeV}$ and $|\Delta\phi(j,j)| < 0.9\pi$



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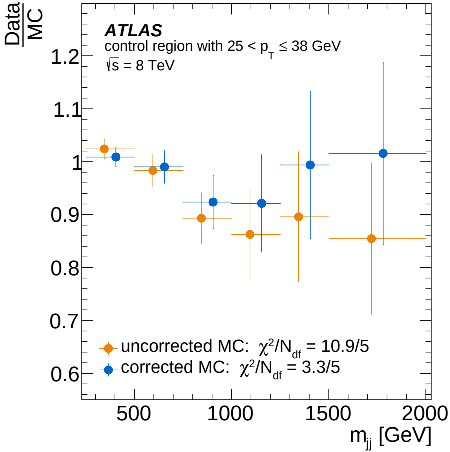
- **consistent signal yield with maximum 5 % spread** between subregions, i.e. within statistical uncertainty of extrapolation ($\sim 10\,\%$)

Proof of principle

- extrapolation procedure examined by correcting subregions with constraints derived in complementary subregion, e.g.
  - split nominal control region based on p_T of in-gap jet
  - correct one subregion with constraint derived in the other subregion
- in all cases, **corrected simulation describes data better than uncorrected simulation**



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Systematic uncertainties

Source	ΔN_{EW}		$\Delta \mathcal{C}_{\mathrm{EW}}$	
	Electrons	Muons	Electrons	Muons
Lepton systematics	—	—	±3.2 %	±2.5 %
Control region statistics	±8.9 %	±11.2 %	—	—
Jet-energy scale	±5.6 %		$^{+2.7}_{-3.4}$ %	
Jet-energy resolution	±0.4 %		±0.8 %	
Pileup jet modelling	±0.3 %		±0.3 %	
Jet-vertex fraction	±1.1 %		$^{+0.4}_{-1.0}$ %	
Signal modelling	±8.9 %		$^{+0.6}_{-1.0}$ %	
Background modelling	±7.5 %		—	
Signal/background interference	±6.2 %		—	
Parton distribution function	$^{+1.5}_{-3.9}$ %		±0.1 %	

EXPERIMENTAL

THEORY

Search region ($m_{jj} > 250$ GeV)

- Measurement:

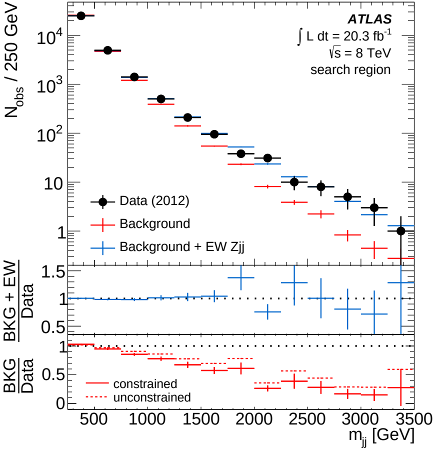
$$54.7 \begin{cases} \pm 4.6 & \text{(stats)} \\ {}^{+9.8}_{-10.4} & \text{(syst)} \\ \pm 1.5 & \text{(lumi)} \end{cases} \text{ fb}$$

- Standard Model prediction:

$$46.1 \begin{cases} \pm 0.2 & \text{(stats)} \\ {}^{+0.3}_{-0.2} & \text{(scale)} \\ \pm 0.8 & \text{(PDF)} \\ \pm 0.5 & \text{(model)} \end{cases} \text{ fb}$$

(using Powheg)

dijet invariant mass in search region



ATLAS Collaboration, JHEP 04 (2014) 031

Search region with $m_{jj} > 1$ TeV

- Measurement:

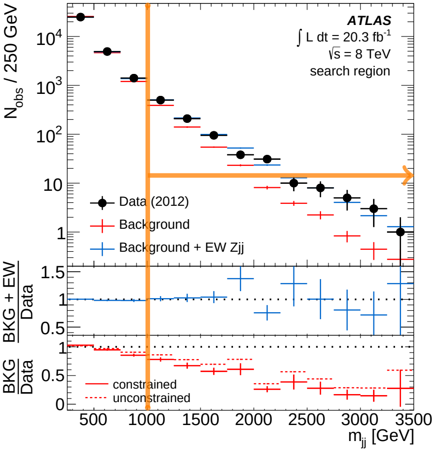
$$10.7 \begin{cases} \pm 0.9 & \text{(stats)} \\ \pm 1.9 & \text{(syst)} \\ \pm 0.3 & \text{(lumi)} \end{cases} \text{fb}$$

- Standard Model prediction:

$$9.38 \begin{cases} \pm 0.05 & \text{(stats)} \\ ^{+0.15}_{-0.24} & \text{(scale)} \\ \pm 0.24 & \text{(PDF)} \\ \pm 0.09 & \text{(model)} \end{cases} \text{fb}$$

(using `Powheg`)

dijet invariant mass in search region



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Limits on aTGCs

- observation of EW Zjj offers completely complementary test of anomalous triple gauge couplings
  - two gauge bosons in VBF diagram enter WWZ vertex with space-like momentum ($Q^2 < 0$)
- aTGC limits obtained from counting number of events with $m_{jj} > 1$ TeV in search phase space
- limits presented with and without form factor unitarisation:

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

- first ever limits at a hadron collider that use VBF diagram

Summary

ATLAS Collaboration, *Measurement of the electroweak production of dijets in association with a Z-boson and distributions sensitive to vector boson fusion in proton-proton collisions at $\sqrt{s} = 8$ TeV using the ATLAS detector*, JHEP 04 (2014) 031, arXiv:1401.7610

- measurement of electroweak *Zjj* production in two fiducial regions
    - first observation with significance beyond 5σ-level of a process involving a VBF diagram
- measurements in excellent agreement with theoretical predictions
- results also used to set limits on anomalous triple gauge couplings
- measurement of inclusive *Zjj* cross sections and differential distributions in five fiducial regions with varying sensitivity to electroweak component