Electroweak production of dijets in association with a Z boson in pp collisions at $\sqrt{s}$=13 TeV with the ATLAS detector

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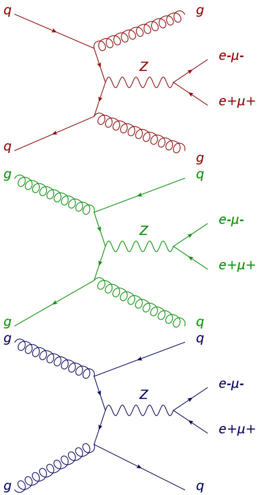
Introduction: Strongly produced Zjj

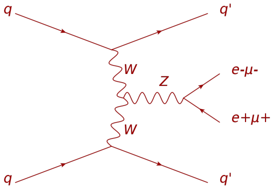
We are interested in the l^+l^-jj final state

- Z plus jets events at the LHC are predominantly produced via a **strong interaction** (qq, qg or gg fusion)
- In these QCD Zjj events, the incoming partons are **colour connected**
- We observe this experimentally as additional quarks/gluons emitted into the rapidity gap between the 2 leading jets, so called **gap jets**

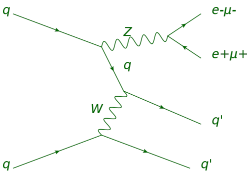


Introduction: Electroweak Zjj

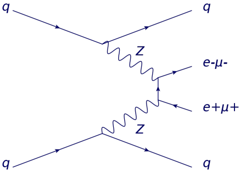
- EW Zjj includes all contributions to l^+l^-jj where there is a t-channel exchange of a W/Z boson
- Leading jets are **not colour connected**, less likely to have **gap jets**
- The VBF component of EW production is of interest because of the similarity to VBF higgs production
- VBF Z is also a probe for new physics via higher order corrections to the WWZ vertex, so called anomalous triple gauge couplings



Vector Boson Fusion (VBF)



Z-boson bremsstrahlung



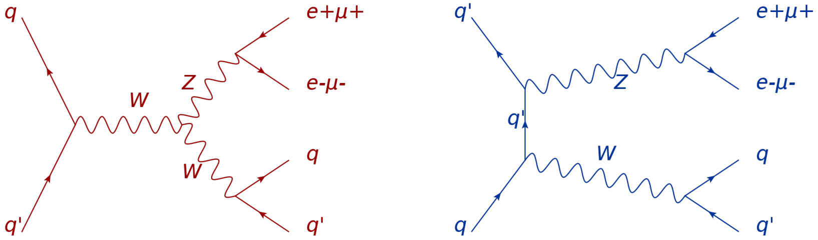
non-resonant l^+l^-jj

Introduction: Background processes (1)

QCD Zjj is the dominant process

Other backgrounds include:

- Semi-leptonic diboson decays (ZZ, WZ)



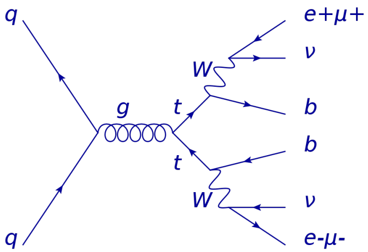
Have a Z boson but the leading jets come from a vector boson

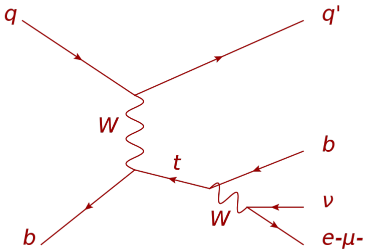
Introduction: Background processes (2)

QCD Zjj is the dominant process

Other backgrounds include:

- $t\bar{t}$, single top, multijet, WW and W+jets

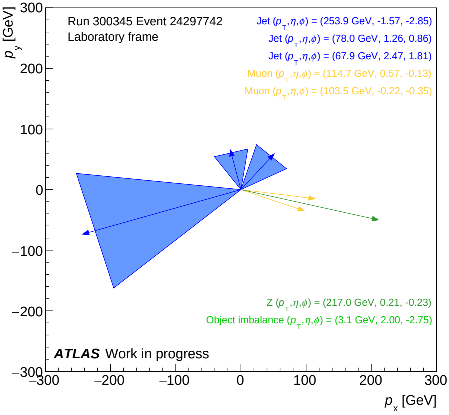


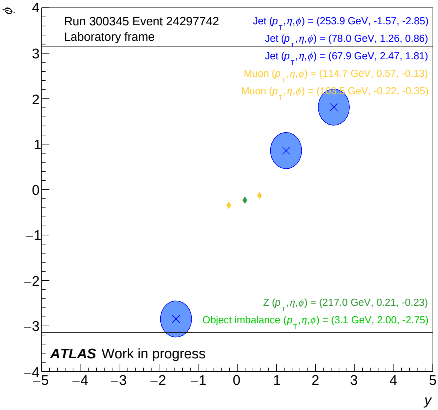


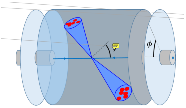
These background have no Z boson, a lepton pair is misidentified as a Z

Example event: Z plus 2 jets (QCD type)

A 13 TeV event with **1 gap jet**



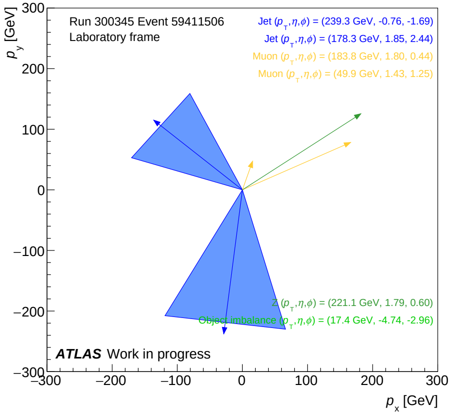


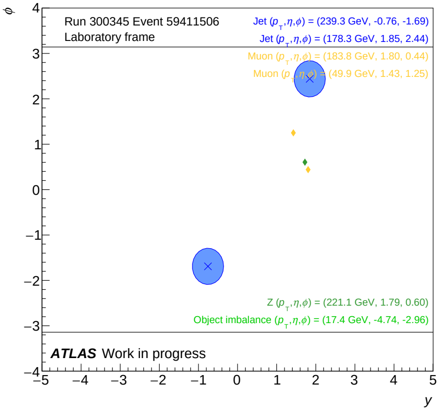


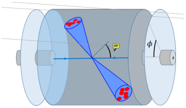
Rapidity: $y = \frac{1}{2} \ln \left(\frac{E + p_z}{E - p_z} \right)$

Example event: Z plus 2 jets (EW type)

A 13 TeV event with **no gap jets**







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Event selection: **search** region

Event requirements for the EW Zjj enhanced region:

1. **Z Candidate**: 2 opposite sign leptons with $81 \leq m_{ll} \leq 101$ GeV
    - Suppress background events that **don't contain a Z boson**

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3. **Jet pT**: one jet with $p_T > 55$ GeV and another with $p_T > 45$ GeV
4. **No gap jets**: no jets in the rapidity gap between the leading 2 jets
   - Preferentially enhance EW Zjj with respect to QCD Zjj

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5. **Dilepton pT**: $p_T^{ll} > 20$ GeV
6. **pT balance**: $p_T^{\mathrm{balance}} < 0.15$
   - Suppress events originating from pileup or multiple parton hard scatters

$$p_T^{\mathrm{balance}} = \frac{|\vec{p}_T^{\,l_1} + \vec{p}_T^{\,l_2} + \vec{p}_T^{\,j_1} + \vec{p}_T^{\,j_2}|}{|\vec{p}_T^{\,l_1}| + |\vec{p}_T^{\,l_2}| + |\vec{p}_T^{\,j_1}| + |\vec{p}_T^{\,j_2}|}$$

8 TeV analysis: Fiducial region composition

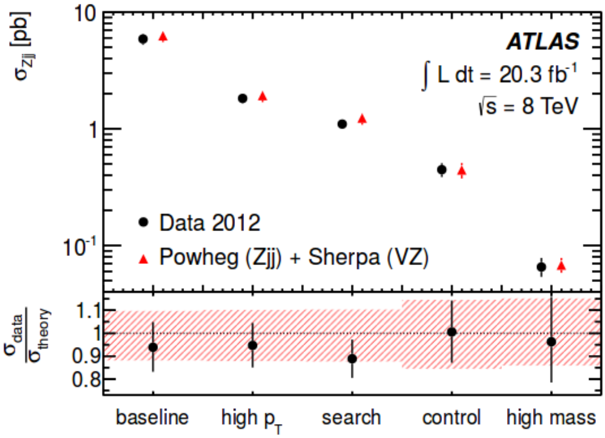
	Composition (%)				
Process	*baseline*	*high-p_T*	*search*	*control*	*high-mass*
Strong Zjj	95.8	94.0	94.7	96.0	85
Electroweak Zjj	1.1	2.1	4.0	1.4	12
WZ and ZZ	1.0	1.3	0.7	1.4	1
$t\bar{t}$	1.8	2.2	0.6	1.0	2
Single top	0.1	0.1	< 0.1	< 0.1	< 0.1
Multijet	0.1	0.2	< 0.1	0.2	< 0.1
WW, W+jets	< 0.1	< 0.1	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

The cuts described so far describe the **search** region

- $t\bar{t}$ is the largest background
- *Search* vs *Control* (no gap jets vs gap jets) gives a 2.6% enhancement to the EW Zjj component
- The *Search* region has significantly lower background contribution than the other EW Zjj enhancing regions

table: arXiv:1401.7610

8 TeV analysis: Inclusive cross sections



The inclusive Zjj cross sections measured in all 5 fiducial regions is in agreement with the MC prediction

figure: arXiv:1401.7610

8 TeV analysis: EW Zjj cross section extraction

- EW component of the cross section is extracted by fitting the **dijet invariant mass**(m_{jj}) distribution in the *search* region

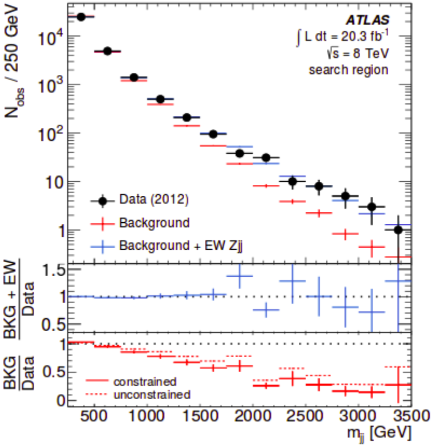


figure: arXiv:1401.7610

8 TeV analysis: EW Zjj cross section result

The fiducial cross sections in the electron and muon channels are

$$\sigma_{\mathrm{EW}}^{ee} = 67.2 \pm 6.9(\mathrm{stat})^{+12.7}_{-13.4}(\mathrm{syst}) \pm 1.9(\mathrm{lumi})\mathrm{fb}$$
$$\sigma_{\mathrm{EW}}^{\mu\mu} = 45.6 \pm 6.1(\mathrm{stat})^{+9.1}_{-9.6}(\mathrm{syst}) \pm 1.3(\mathrm{lumi})\mathrm{fb}$$

The consistency between the 2 channels is 1.7σ, combining them yields

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

which is in agreement with the MC prediction

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

Sufficient signal events were observed to exclude the background only hypothesis at 5σ significance

reference: arXiv:1401.7610

8 TeV analysis: anomalous triple gauge couplings (aTGCs)

The effective Lagrangian for aTCGs can be written:

$$\frac{\mathcal{L}}{g_{WWZ}} = i\left[g_{1,Z}\left(W^{\dagger}_{\mu\nu}W^{\mu}Z^{\nu} - W_{\mu\nu}W^{\dagger\mu}Z^{\nu}\right) + \kappa_Z W^{\dagger}_{\mu}W_{\nu}Z^{\mu\nu} + \frac{\lambda_Z}{m_W^2}W^{\dagger}_{\rho\mu}W^{\mu}_{\nu}Z^{\nu\rho}\right]$$

where the dimensionless coupling are $g_{1,Z} = 1$, $\kappa_Z = 1$ and $\lambda_Z = 0$ in the standard model

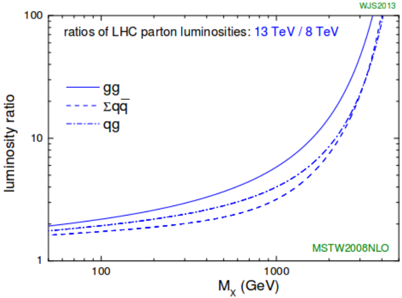
Looking at events in the high m_{jj} region, the 95% confidence intervals are obtained for the couplings

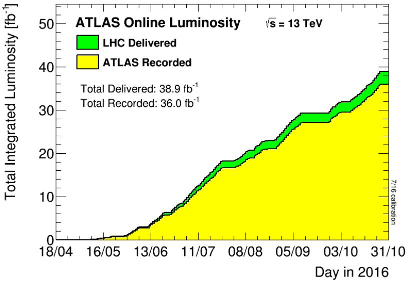
aTGC	$\Lambda = 6$ TeV (obs)	$\Lambda = 6$ TeV (exp)	$\Lambda = \infty$ (obs)	$\Lambda = \infty$ (exp)
$\Delta g_{1,Z}$	[−0.65, 0.33]	[−0.58, 0.27]	[−0.50, 0.26]	[−0.45, 0.22]
λ_Z	[−0.22, 0.19]	[−0.19, 0.16]	[−0.15, 0.13]	[−0.14, 0.11]

table: arXiv:1401.7610

13 TeV analysis

At $\sqrt{s}$=13 TeV the production rate of high dijet invariant mass events will increase due to the parton luminosity enhancement at high mass





The 2015 13 TeV dataset (3.2 fb^{-1}) is expected to contain as much statistics in the high dijet region as the 8 TeV analysis (20.3 fb^{-1})

The full 2016 dataset will effectively contain roughly 10 times the statistics as available in the 8 TeV analysis

left figure: http://www.hep.ph.ic.ac.uk/ wstirlin/plots/lhclumi7813_2013_v1.pdf
right figure: ATLAS public results

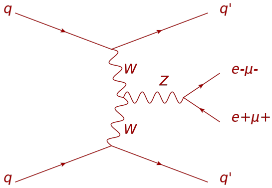
13 TeV analysis: Ongoing analyses

Currently there are 2 ongoing EW Zjj 13 TeV analyses:

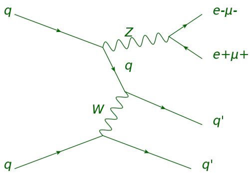
- 2015 data ($3.2\ \mathrm{fb}^{-1}$):
  - Will use the same fiducial regions defined by the 8 TeV analysis to provide a direct comparison
- 2016 data ($20.3\ \mathrm{fb}^{-1}$):
  - Will re-optimize the fiducial regions for 13 TeV
  - Increased statistics will be available in the high m_{jj} region where EW Zjj is most enhanced

Conclusions

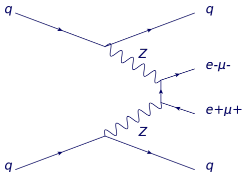
- The 8 TeV analysis provided the first 5σ observation of EW Zjj production at the LHC
- The 13 TeV dataset will contain significantly more statistics:
  - Compute differential cross sections (σ vs m_{jj}, σ vs $\Delta\phi_{jj}$)
  - More precise measurements of new physics effects in the ZWW vertex



Vector Boson Fusion (VBF)



Z-boson bremsstrahlung



non-resonant l^+l^-jj

Acknowledgements

University of Manchester
J. Crane, A. Pilkington
Carleton
A. Bellerive, D. Gillberg

Questions?

8 TeV analysis: Events predicted/observed

Table 5. The number of strong ($N_{\rm bkg}$) and electroweak ($N_{\rm EW}$) Zjj events as predicted by the MC simulation and obtained from a fit to the data. The number of events in data is also given. The first and second uncertainties on the fitted yields are due to statistical uncertainties in data and simulation, respectively. The first and second uncertainties in the MC prediction are the experimental and theoretical systematic uncertainties, respectively.

	Electron	Muon	Electron+muon
Data	14248	17938	32186
MC predicted $N_{\rm bkg}$	$13700 \pm 1200\,^{+1400}_{-1700}$	$18600 \pm 1500\,^{+1900}_{-2300}$	$32600 \pm 2600\,^{+3400}_{-4000}$
MC predicted $N_{\rm EW}$	$602 \pm 27 \pm 18$	$731 \pm 29 \pm 22$	$1333 \pm 50 \pm 40$
Fitted $N_{\rm bkg}$	$13351 \pm 144 \pm 29$	$17201 \pm 161 \pm 31$	$30530 \pm 216 \pm 40$
Fitted $N_{\rm EW}$	$897 \pm 92 \pm 27$	$737 \pm 98 \pm 28$	$1657 \pm 134 \pm 40$

table: arXiv:1401.7610

8 TeV analysis: Systematic uncertainties

Source	ΔN_{EW} Electrons	ΔN_{EW} Muons	$\Delta \mathcal{C}_{EW}$ Electrons	$\Delta \mathcal{C}_{EW}$ Muons
Lepton systematics	—	—	± 3.2 %	± 2.5%
Control region statistics	± 8.9 %	± 11.2 %	—	—
JES	± 5.6 %		$^{+2.7}_{-3.4}$ %	
JER	± 0.4 %		± 0.8 %	
Pileup jet modelling	± 0.3 %		± 0.3 %	
JVF	± 1.1 %		$^{+0.4}_{-1.0}$ %	
Signal modelling	± 8.9 %		$^{+0.6}_{-1.0}$ %	
Background modelling	± 7.5 %		—	
Signal/background interference	± 6.2 %		—	
PDF	$^{+1.5}_{-3.9}$ %		± 0.1 %	

table: arXiv:1401.7610

8 TeV analysis: fiducial regions

<table>
<tr><th>Object</th><th>baseline</th><th>high-mass</th><th>search</th><th>control</th><th>high-p_{T}</th></tr>
<tr><td>Leptons</td><td colspan="5">$|\eta^{\ell}| < 2.47$, $p_{\mathrm{T}}^{\ell} > 25$ GeV</td></tr>
<tr><td rowspan="2">Dilepton pair</td><td colspan="5">$81 \leq m_{\ell\ell} \leq 101$ GeV</td></tr>
<tr><td colspan="2">—</td><td colspan="2">$p_{\mathrm{T}}^{\ell\ell} > 20$ GeV</td><td>—</td></tr>
<tr><td rowspan="3">Jets</td><td colspan="5">$|y^{j}| < 4.4$, $\Delta R_{j,\ell} \geq 0.3$</td></tr>
<tr><td colspan="4">$p_{\mathrm{T}}^{j_1} > 55$ GeV</td><td>$p_{\mathrm{T}}^{j_1} > 85$ GeV</td></tr>
<tr><td colspan="4">$p_{\mathrm{T}}^{j_2} > 45$ GeV</td><td>$p_{\mathrm{T}}^{j_2} > 75$ GeV</td></tr>
<tr><td>Dijet system</td><td>—</td><td>$m_{jj} > 1$ TeV</td><td colspan="2">$m_{jj} > 250$ GeV</td><td>—</td></tr>
<tr><td>Interval jets</td><td colspan="2">—</td><td>$N_{\mathrm{jet}}^{\mathrm{gap}} = 0$</td><td>$N_{\mathrm{jet}}^{\mathrm{gap}} \geq 1$</td><td>—</td></tr>
<tr><td>Zjj system</td><td colspan="2">—</td><td>$p_{\mathrm{T}}^{\mathrm{balance}} < 0.15$</td><td>$p_{\mathrm{T}}^{\mathrm{balance,3}} < 0.15$</td><td>—</td></tr>
</table>

- *Control*: Suppress EW Zjj in favour of QCD Zjj (require gap jet(s))
- *high-mass* and high-pT: Enhance EW Zjj without pT balance or gap jet requirements
- *Baseline*: Inclusive, other control regions are a subset of *baseline*

table: arXiv:1401.7610

13 TeV analysis: Data size reduction

The derivation `STDM3` is used for all plus jets analyses, the full 2016 dataset `STDM3` derivation is >10 TB in size

The most inclusive fiducial region (*baseline*) excludes >99% of events, thus it is impractical to run over the full sized STDM3 derivations on the grid

Far better to slim/skim the data on the grid one time with a fast event loop algorithm that will remove events that won't pass the baseline analysis cuts