Observation of electroweak production of two jets in association with a Z-boson pair with ATLAS

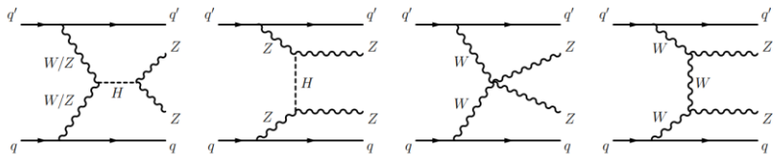
Abstract

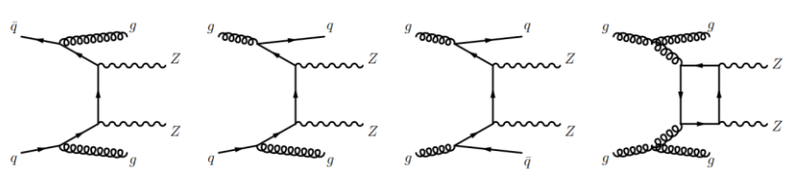
The study shows the observation of electroweak production of two jets in association with a Z-boson pair using $139\ fb^{-1}$ of pp collision data at $\sqrt{s} = 13$ TeV collected by the ATLAS detector at the LHC. Two different final states originating from the decays of the Z boson pair, one containing four charged leptons, and the other two charged leptons and two neutrinos, are considered. A significant deviation from the background-only hypothesis is observed, which corresponds to a statistical significance of 5.5 σ. The observed excess is compatible with the electroweak production of two jets in association with a Z-boson pair. In addition, cross-sections for inclusive production of ZZ plus two jets, as well as the observed signal strength of the EW production, are reported.

Introduction

At the LHC, Vector Boson Scattering (VBS) is typically produced as two vector bosons radiated from initial-state quarks and then scattering into another pair of vector bosons.

- VBS is a key process to probe the electroweak symmetry breaking (EWSB).
- VBS is sensitive to new physics.
- The detector signature of VBS contains decay products of the pair of outgoing bosons and a pair of hadronic jets.
- Typical diagrams for production of $ZZjj$, including the relevant EW VBS diagrams (first row) and QCD diagrams (second row):

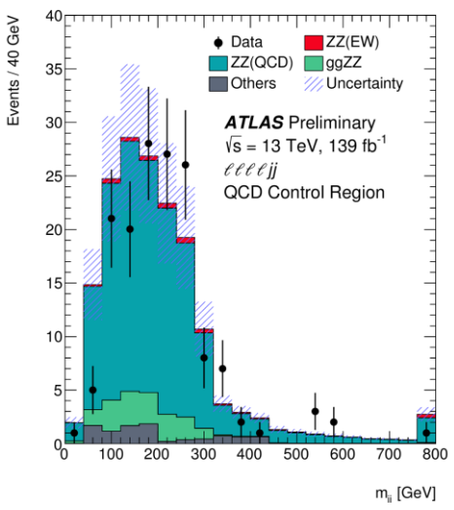


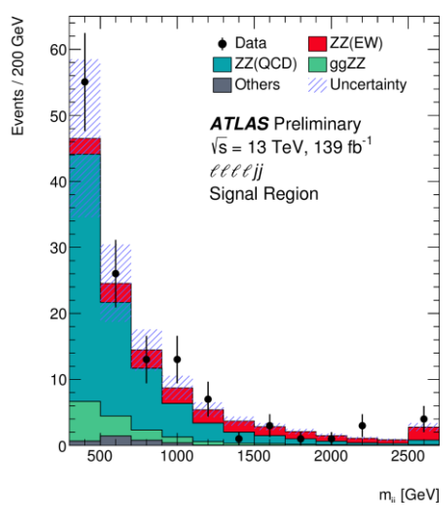


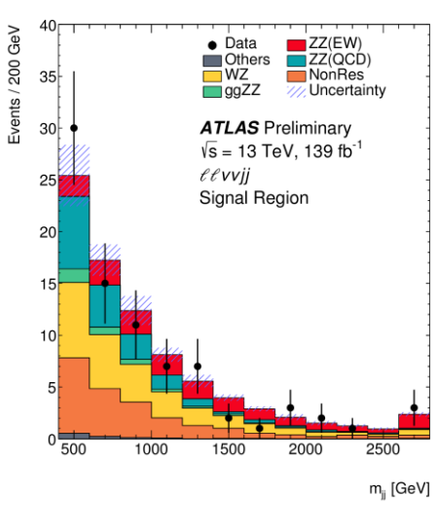
Event Selection

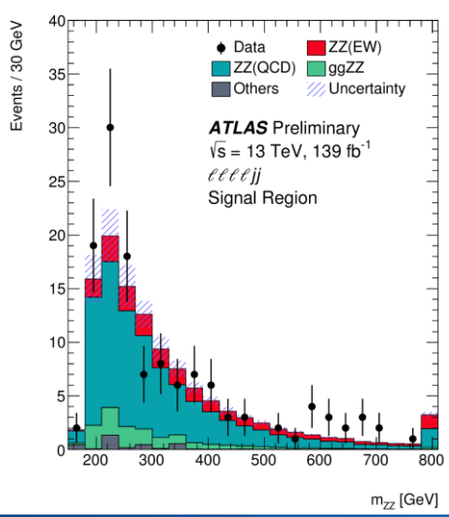
- Large invariant mass and rapidity separation of two jets in the forward and backward region to enhance VBS contributions, m_{jj} > 300 (400) GeV and $|\Delta y(jj)| > 2.0$ in $lllljj$ ($llvvjj$) channel.
- $llvvjj$ channel: one Z boson candidate reconstructed in dielectron and dimuon final state, including additional lepton veto, b veto and large E_T^{miss}-significance requirements to suppress background.
- $lllljj$ channel: two Z boson candidates reconstructed in dielectron or dimuon final state.

Kinematic Distributions









Background Estimation

$lllljj$ channel:

- QCD CR: the normalization of QCD $ZZjj$ is constrained by a dedicated control region defined in data by reverting either m_{jj} or Δy(jj) requirements.
- Fake leptons: contribution from $Z + jets, t\bar{t}, WZ$ are estimated from data with the fake lepton method.

$llvvjj$ channel:

- QCD CR: QCD $ZZjj$ is estimated from simulation by reverting either the m_{jj} or $\Delta y(jj)$ requirements.
- $3l$ CR: constrain the normalization of WZ background by requiring three selected leptons and a looser event selection.
- $e\mu$ CR, use $\epsilon - \text{factor}$ to correct the reconstruction efficiency difference between electrons and muons for non-resonant di-lepton backgrounds ($t\bar{t}, WW$).
- $Z + jets$ CR: extrapolate the low E_T^{miss} –significance region distribution in data to the high E_T^{miss} –significance region using an exponential function for $Z + jets$ background.

Signal region yields:

Process	$\ell\ell\ell\ell jj$	$\ell\ell\nu\nu jj$
EW $ZZjj$	20.6 ± 2.5	12.3 ± 0.7
QCD $ZZjj$	77.4 ± 25.0	17.2 ± 3.5
QCD $ggZZjj$	13.1 ± 4.4	3.5 ± 1.1
Non-resonant-$\ell\ell$	-	21.4 ± 4.8
WZ	-	22.8 ± 1.1
Others	3.2 ± 2.1	1.2 ± 0.9
Total	114.3 ± 25.6	78.4 ± 6.2
Data	127	82

Results

Measurement of Fiducial Cross-sections

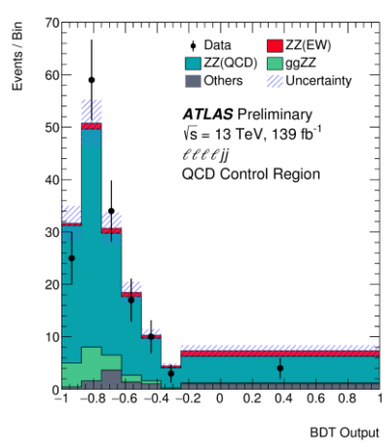
- $lllljj$ channel fiducial region: Z window loose to [60, 120] GeV (is [66, 116] GeV for detector level) to reduce migration effect.
- $llvvjj$ channel fiducial region: Truth E_T^{miss} > 130 GeV instead of E_T^{miss} –significance cut at detector level.
- Measured and predicted fiducial cross-section in both $lllljj$ and $llvvjj$ channel.

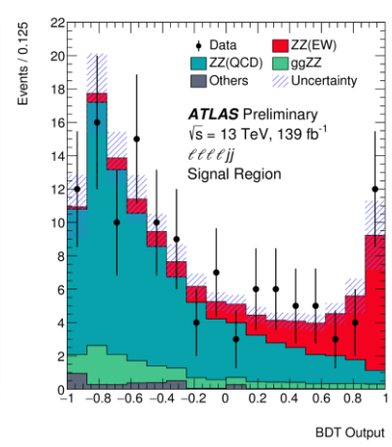
$$C - factor = \frac{N_{detector\ level}}{N_{F.V.truth}}, \sigma = \frac{N_{data} - N_{background}}{C \times L}$$

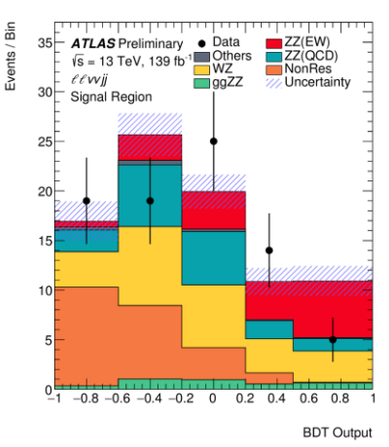
	Measured fiducial σ [fb]	Predicted fiducial σ [fb]
$\ell\ell\ell\ell jj$	$1.27 \pm 0.12(\text{stat}) \pm 0.02(\text{theo}) \pm 0.07(\text{exp}) \pm 0.01(\text{bkg}) \pm 0.03(\text{lumi})$	$1.14 \pm 0.04(\text{stat}) \pm 0.20(\text{theo})$
$\ell\ell\nu\nu jj$	$1.22 \pm 0.30(\text{stat}) \pm 0.04(\text{theo}) \pm 0.06(\text{exp}) \pm 0.16(\text{bkg}) \pm 0.03(\text{lumi})$	$1.07 \pm 0.01(\text{stat}) \pm 0.12(\text{theo})$

Search for Electroweak $ZZjj$

- To separate the EW $ZZjj$ processes from backgrounds, multivariate discriminants (MDs) based on the Gradient Boosted Decision Tree algorithm are trained for each channel in the signal region with kinematic variables.
- Highest ranking variable in BDT: m_{jj} (Δη(ll)) in $lllljj$ ($llvvjj$) channel.







- The MD distribution in both signal regions and QCD control region are used in statistical fit to extract the EW signal strength. The observed μ_{EW} and μ_{QCD}, as well as the observed and expected significance from the individual channels, and the combined fits can be shown as:

	μ_{EW}	$\mu_{\text{QCD}}^{\ell\ell\ell\ell jj}$	Significance Obs. (Exp.)
$\ell\ell\ell\ell jj$	1.54 ± 0.42	0.95 ± 0.22	5.48 (3.90) σ
$\ell\ell\nu\nu jj$	0.73 ± 0.65	-	1.15 (1.80) σ
Combined	1.35 ± 0.34	0.96 ± 0.22	5.52 (4.30) σ

The first observation of EW ZZjj production is an important milestone for studies of EW VVjj production and marks the start of the precision measurement program, which will utilize the collected EW VVjj events to strengthen the study of VBS and probe the nature of EWSB.

Shuzhou Zhang (University of Michigan)
on behalf of ATLAS Collaboration

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