Study of VBS ZZ production associating two jets with the ATLAS experiment

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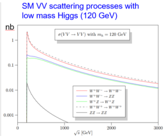
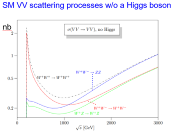
The VBS Processes at the LHC

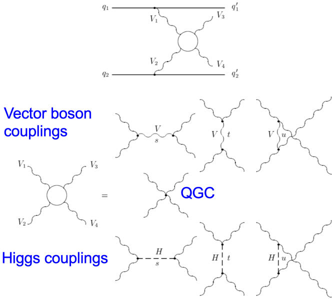
Vector Boson Scattering (VBS) is a key process to probe the mechanism of electroweak symmetry breaking, and close connection with the SM Higgs.





JHEP11(2008)010

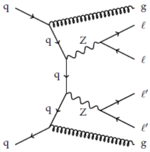
- Involving Quartic Gauge Couplings (QGCs) which is sensitive to new physics.



Phys. ReV. D 55, 7165-Published 1 June 1997

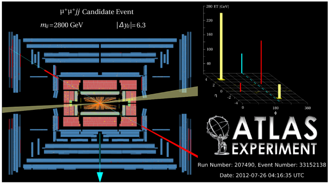
Experimental Signatures of VBS

- Two intermediate vector bosons radiated from two incoming quarks.
- Final state with two vector bosons plus two outgoing jets.
- In general, two "tag" jets in forward region with large rapidity separation and large invariant mass.
- EW VBS has relatively smaller cross-sections, suffer from irreducible QCD VV + 2jets events.



First evidence of these processes

Candidate VBS event from ssWW



Phys. Rev Lett. 113, 141803

Analysis in the ZZ Channels

- Measurement of inclusive ZZ+2j cross-section (QCD and electroweak production of ZZ+2j) in sensitive phase spaces for 4l and llvv.
- Observation of electroweak production of ZZ+2j, combining 4l and llvv.
- Data: full Run II data, 2015-2018, 139 fb^{-1}.
- Signal sample: MG.
- QCD background: Sherpa.

Analysis Strategy

- First step inclusive cross-section measurements with cut-based analysis.
- MVA (BDT)-based analysis is used then to extract the EW VBS ZZ signal from background.
- Interference between EW and QCD is treated as systematic on the EW VBS ZZ production measurement.

- Study of EW VV→ZZ (V=W, Z) processes is a good way to probe vector boson scattering. Analysis is optimized to the on-shell ZZ region so VBF H is minor.

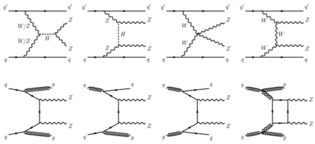


Figure 1: Typical diagrams for the production of $ZZjj$, including the relevant VBS diagrams (first row) and the QCD diagrams (second row).

Analysis Overview

ZZ$\rightarrow 4l$ channel:

- Very clean experimental signature, small background contribution (3%) from misidentified leptons (Z+jets, $t\bar{t}$, WZ).
- While extrapolating the EW VBS processes, the QCD 4ljj production becomes the major background. EW/QCD is around 20% level overall, MVA is needed

ZZ$\rightarrow 2l2\nu$ channel:

- Larger background compared to the 4l channel. Mostly from WZ,WW,$t\bar{t}$ and irreducible QCD ZZjj.
- EW/background is around 15% level, MVA is used as well to extrapolate EW VBS ZZ processes, but background components are more complicated than the 4l channel.

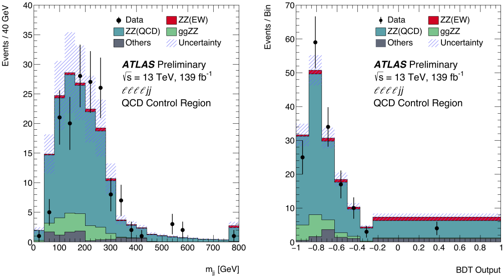
Object and Event Selection

	$\ell\ell\ell\ell jj$	$\ell\ell\nu\nu jj$
Electrons	$p_{\mathrm{T}} > 7$ GeV, $\lvert\eta\rvert < 2.47$ $\lvert d_0/\sigma_{d_0}\rvert < 5$ and $\lvert z_0 \times \sin\theta\rvert < 0.5$ mm	
Muons	$p_{\mathrm{T}} > 7$ GeV, $\lvert\eta\rvert < 2.7$ $\lvert d_0/\sigma_{d_0}\rvert < 3$ and $\lvert z_0 \times \sin\theta\rvert < 0.5$ mm	$p_{\mathrm{T}} > 7$ GeV, $\lvert\eta\rvert < 2.5$
Jets	$p_{\mathrm{T}} > 30$ (40) GeV for $\lvert\eta\rvert < 2.4$ ($2.4 < \lvert\eta\rvert < 4.5$)	$p_{\mathrm{T}} > 60$ (40) GeV for the leading (sub-leading) jet
ZZ selection	$p_{\mathrm{T}} > 20, 20, 10$ GeV for the leading, sub-leading and third leptons Two OSSF lepton pairs with smallest $\lvert m_{\ell^+\ell^-} - m_Z\rvert + \lvert m_{\ell'^+\ell'^-} - m_Z\rvert$ $m_{\ell^+\ell^-} > 10$ GeV for lepton pairs $\Delta R(\ell, \ell') > 0.2$ $66 < m_{\ell^+\ell^-} < 116$ GeV	$p_{\mathrm{T}} > 30$ (20) GeV for the leading (sub-leading) lepton One OSSF lepton pair and no third leptons $80 < m_{\ell^+\ell^-} < 100$ GeV No b-tagged jets $E_{\mathrm{T}}^{\mathrm{miss}}$ significance > 12
Dijet selection	Two most energetic jets with $y_{j_1} \times y_{j_2} < 0$ $m_{jj} > 300$ GeV and $\Delta y(jj) > 2$	$m_{jj} > 400$ GeV and $\Delta y(jj) > 2$

- Different quality and isolation requirements for two channels, due to different background level.
- Lepton favored overlap removal for 4l channel, where higher priority was given to leptons when overlapping with jets. Signal (background) yields increase by 19 (14)%.

Background Estimation-4l, QCD ZZjj

- Yield is constrained by dedicated QCD control region. QCD CR is defined by reverting m_{jj} or $\Delta\eta_{jj}$ cut to $m_{jj} < 300$ GeV or $|\Delta\eta_{jj}| < 2.0$.



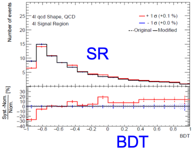
m_{jj} and BDT in QCD CR

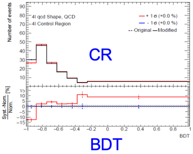
- Additional systematic uncertainties due to different generators and pile-up are also checked.

Background Estimation - 4l, QCD ZZjj, Additional Systematics

Modeling of the QCD ZZjj

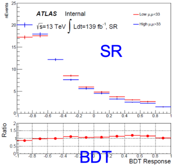
- The shape differences between different generators can not be covered by the standard QCD up/down systematics
- Additional shape systematic derived by comparing Sherpa with MG samples at truth level

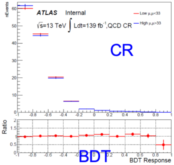




Check the pile-up modeling

- Have compared shape difference using low/high mu QCD MC events to cover the possible bias due to pile-up effect





Background Estimation - 4l, Fakes

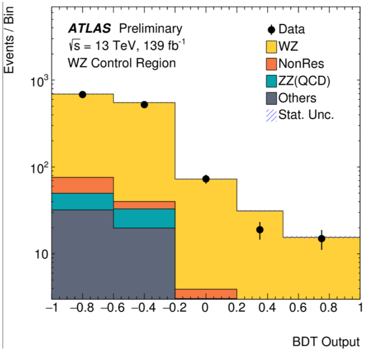
Fake factor method used, where different fake factors have been derived for Zjets and $t\bar{t}$ processes, from dedicated CRs.

- Z+jets: two tag leptons under Z mass. Counting additional good and bad leptons to calculate fake factor.
- $t\bar{t}$: two tag leptons ($e\mu$ flavor) with additional btagging, MET and m_T^W cuts to enhance $t\bar{t}$ purity. Counting additional good and bad leptons to calculate fake factor.
- Bad lepton is defined by reverting the lepton quality, isolation or impact parameters.
- 4ljj data CR defined with at least two good leptons.

Final estimation is 2.3$\pm$1.6. Systematic includes variations on those MC subtraction, bad lepton definitions, fake factor binning, data MC difference, statistical uncertainty on fake factor due to limited data events.

WZjj Background Estimation - $2l2\nu$

- Normalization constraint by dedicated 3l, WZ dominant CR, with looser 2jet selections.
- Derived normalization factor is 0.85.
- Shape is estimated using simulation.



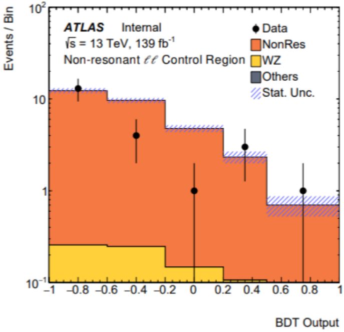
WW, top, Z$\rightarrow \tau\tau$ Background Estimation - $2l2\nu$

- Estimated with events in dedicated em data CR, following:

$$N^{Q,e\mu}_{SRee} = \frac{1}{2} \times \epsilon^{Q} \times N^{\mu\in Q,sub,bkg}_{e\mu CR}$$

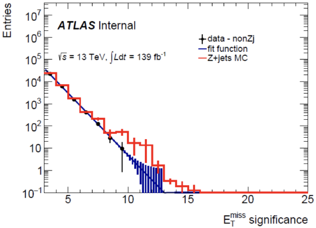
$$N^{Q,e\mu}_{SR\mu\mu} = \frac{1}{2} \times \frac{1}{\epsilon^{Q}} \times N^{e\in Q,sub,bkg}_{e\mu CR}$$

- e/m reconstruction and selection efficiency difference is taken care of by the epsilon factor (p_T, η dependent), calculated with data events from Z region.



Z+jets Background Estimation - $2l2\nu$

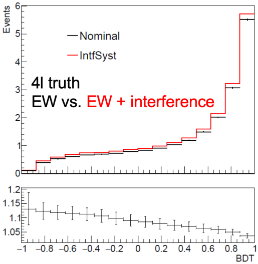
- Estimated by extrapolation (with Exponential function) from data events in low MET-significance region to high MET-significance region.
- Systematics include the MC and data-driven difference (dominant), different fitting functions, and different fitting range.



Final estimation: 0.3 + 1.5 – 0.3

Systematics on the EW VBS Signal

- Experimental systematics (based on CP recommendations).
- Theoretical (PDF, QCD scale, parton showering).
- Additional uncertainty due to the interference between EW and QCD processes, studied in truth level then convert to reconstruction level.
- Uncertainty due to interference:7(2)% in 4l ($2l2\nu$) channel. Difference mostly due to different m_{jj} cut between two channels



Summary of Signal and Background Yields

Process	$4l$ channel	$2l2\nu$ channel
EW $ZZjj$	20.6 ± 2.5	12.30 ± 0.65
QCD $ZZjj$	77 ± 25	17.2 ± 3.5
QCD gg$ZZjj$	13.1 ± 4.4	3.5 ± 1.1
Non-resonant-ll	-	21.4 ± 4.8
WZ	-	22.8 ± 1.1
Others	3.2 ± 2.1	1.15 ± 0.89
Total	114 ± 26	78.4 ± 6.2
Data	127	82

- Numbers shown in table are used to calculate the measured inclusive XS (pre-fit numbers).
- For minor backgrounds only the CP experimental systematics are included.

Inclusive Cross section Measurements

Cross sections are measured for the inclusive processes, in individual 4l and $2l2\nu$ channels in fiducial region.

- $4l$ channel fiducial region: Z window loose to [60, 120] GeV (is [66, 116] GeV for detector level) to reduce migration effect.
- $2l2\nu$ channel fiducial region: Lepton eta cuts harmonized to 2.5 for both electrons and muons. Truth MET $>$ 130 GeV instead of MET significance (difficult to define at truth level)

	Measured Fiducial σ [fb]	Predicted Fiducial σ [fb]
$\ell\ell\ell\ell jj$	1.27$\pm$0.12(stats)$\pm$0.02(theo)$\pm$0.07(exp)$\pm$0.01(bkg)$\pm$0.03(lumi)	1.14$\pm$0.04(stats)$\pm$0.20(theo)
$\ell\ell\ell\ell jj$	1.22$\pm$0.30(stats)$\pm$0.04(theo)$\pm$0.06(exp)$\pm$0.16(bkg)$\pm$0.03(lumi)	1.07$\pm$0.01(stats)$\pm$0.12(theo)

Uncertainties: statistic dominant.

MVA Analysis for EW Processes

- Gradient BDT is used in both channels.
- 4l channel trained in SR using EW vs. QCD events.
- $2l2\nu$ channel trained in SR using EW vs. all backgrounds except Zjets (due to minor contribution and large fraction of negative weight events).

Rank	$\ell\ell\nu\nu$ variables	$\ell\ell\ell\ell$ variables
1	$\Delta\eta(ll)$	m_{jj}
2	m_{ll}	leading p_T^j
3	$\Delta\phi(ll)$	subleading p_T^j
4	m_{jj}	$p_T(ZZjj)/H_T(ZZjj)$
5	$E_{\mathrm{T}}^{\mathrm{miss}} significance$	$Y(j1) \times Y(j2)$
6	$\Delta Y(jj)$	$\lvert\Delta Y(jj)\rvert$
7	$Y(j1) \times Y(j2)$	Y^*_{Z2}
8	HT	Y^*_{Z1}
9	$\Delta R(ll)$	p_T^{ZZ}
10	subleading p_T^j	m_{ZZ}
11	$E_{\mathrm{T}}^{\mathrm{miss}}$	p_T^{Z1}
12	subleading p_T^l	$p_T^{\ell 3}$
13	leading p_T^l	-

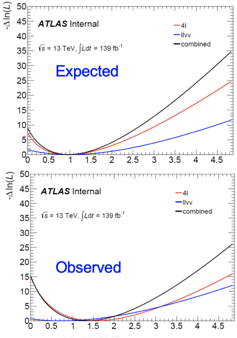
Table 48: Input variables for $\ell\ell\nu\nu$ and $\ell\ell\ell\ell$ channels.

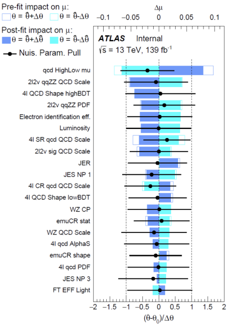
Input variables ordered by ranking

Statistical Fit for EW Processes

- BDT output is used as final discriminator for fitting.
- 3 regions enter the fit: 4l SR, 4l QCD CR and $2l2\nu$ SR.
- μ_{EW} as POI. μ_{QCD} (for 4l) also introduced as free parameter in the fit to constrain QCD normalization.

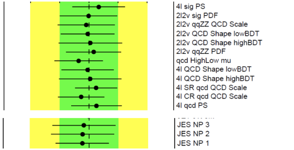
Fit Details





Observed (combined channel)

- ✓ Only the pulled ones shown here
- ✓ Full list in supporting note
- ✓ Pulls are understood as correlated to data-prediction differences in various bins.

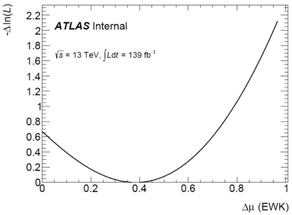


Result on EW Processes

	μ_{EW}	$\mu_{QCD}^{\ell\ell\ell\ell jj}$	Significance Obs. (Exp.)
$4l$	1.54 ± 0.42	0.95 ± 0.22	5.48(3.90) σ
$2l2\nu$	0.73 ± 0.65	-	1.15(1.80) σ
Combined	1.35 ± 0.34	0.96 ± 0.22	5.52(4.30) σ

- Cross section for EW processes (4l and $2l2\nu$) is derived ($\mu_{EW} \times \sigma_{SM}$) from combined fit, to be 0.82$\pm$0.21 fb (SM prediction0.61$\pm$0.03 fb), dominant by statistical uncertainty from data.

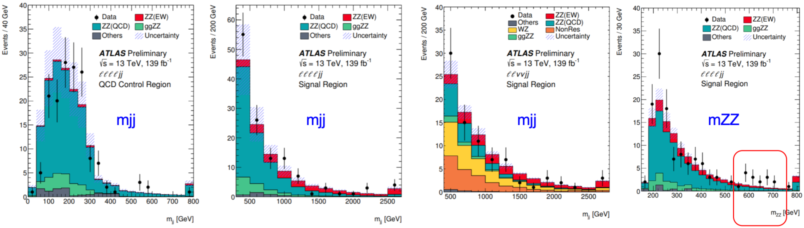
- Compatibility test: Two channels compatible within 1.2 σ.



$$\Delta\mu = \mu 4l - \mu_{2l2\nu}$$

Distribution: m_{jj} and m_{ZZ}

- Predictions have been scaled with (μ_{EW} and μ_{QCD}) from combined fit using BDT output.



Post-Fit BDT Distributions

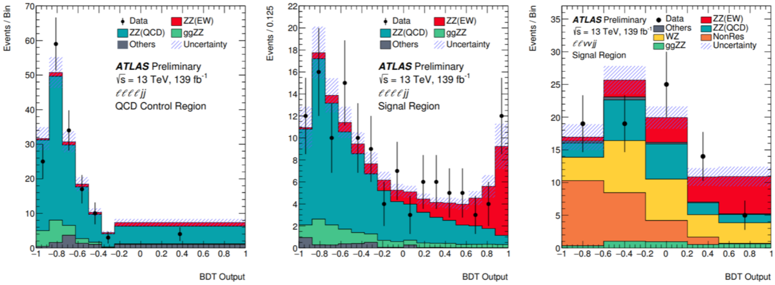


Figure 5: Observed and expected multivariate discriminant distributions after the statistical fit in the $\ell\ell\ell\ell jj$ QCD CR (left), and in the $\ell\ell\ell\ell jj$ (middle) and $\ell\ell\nu\nu jj$ (right) signal regions. The error bands include the experimental and theoretical uncertainties, as well as the uncertainties in μ_{EW} and $\mu_{\text{QCD}}^{\ell\ell\ell\ell jj}$. The error bars on the data points show the statistical uncertainty on data.

Summary

- Inclusive ZZ+2 jets cross section was measured.
- Observation of electroweak production of ZZ+2jet.
- This analysis completes observation of weak boson scattering.

Back Up

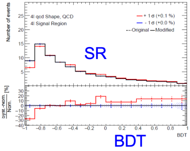
Samples Information

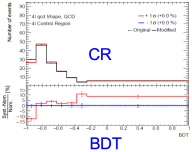
- Full Run 2 datasets

Process	Sample	Comments
EWK ZZjj	MG	Include VBF H (small contribution due to Z mass cuts)
QCD-qq ZZjj	Sherpa222	Compared with private MG sample at truth level for 4l channel
gg ZZjj	4l: Sherpa222 llvv: gg2VV	
Triboson, other diboson	Sherpa222	
Zjet	Sherpa221	
Top	Powheg, MG, aMC@NLO, Sherpa	

Modeling of the QCD ZZjj

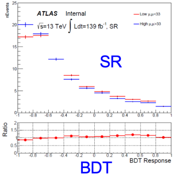
- The shape differences between different generators can not be covered by the standard QCD up/down systematics
- Additional shape systematic derived by comparing Sherpa with MG samples at truth level

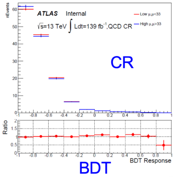




Check the pile-up modeling

- Have compared shape difference using low/high mu QCD MC events to cover the possible bias due to pile-up effect





QCD ZZjj Background Estimation-llvv

- Estimated from simulations.
- Experimental and theoretical systematics are included.
- Additional Sherpa vs. MG shape uncertainty is also included
  - Derived using 4l events at truth level in the eeμμ channel, but treat muon as neutrino