Observation of ZZ production via Vector Boson Scattering in ATLAS

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Introduction

- Vector Boson Scattering (VBS) has captured our interest lately
  - Direct relation to EWSB and the Higgs mechanism
  - Ability to explore New Physics

- VBS $ZZjj \rightarrow \ell\ell\ell\ell jj$ is one of the rarest processes with signal cross section $\sim 0.1\, fb$
  - However, truly valuable channel due to its purity and ability to fully reconstruct the final state

- Results compatible to SM have been published by both ATLAS and CMS with measurements on the VBS ZZ channel
  - During Run-II, ATLAS managed to collect 139 $fb^{-1}$ of data
    - Proton-proton collisions with a center-of-mass energy 13TeV
  - Limited number of events in this channel does not allow remarkable results (yet)
    - Significant potential for future analyses
Signature characteristics of VBS interactions:

1. Two forward jets,
2. the production of VV in the central region and
3. suppressed hadronic activity between jets due to absence of color flow,
4. a purely EW contribution to VVjj

...something to take advantage of in order to achieve a good S/N ratio

Current study examined both $\ell\ell\ell\ell jj$ and $\ell\ell vvjj$ channels.
Use of two final states

Each of the final states is characterized by different pros/cons.

**lllljj**
- Chosen as the main channel
- Very clean
  - main background QCD ZZjj
- Fully reconstructible
  - Accurate lepton calibration favors this channel
- depends on our insight into jets

**llvvjj**
- Expected to have worse sensitivity
  - However, used as cross-check
- Suffers from a lot of background
  - QCD ZZjj, WZ, WW, top, Z+jet…
- Better BR but with more phase space restrictions
- Depends both on jet and MET understanding
- More sensitive to BSM in high mass/pT
Monte Carlo generation

- **Sherpa**, GG2VV and Madgraph (aMC@NLO) used to simulate events at tree level.
  - Follow-up decays and hadronization done with Madspin, Pythia 8, POWHEG-BOX and Sherpa’s internal showering tool
  - No NLO EW ZZjj estimations are included in this analysis

- Different samples generated for signal (EW ZZjj) and background (QCD qqZZjj, ggZZjj)

- Interference between QCD and EW has also been simulated
  - Proved to have insignificantly low contribution (smaller than statistical uncertainty of data) and was treated as a systematic (modelling) uncertainty.

- Decay to electrons or muons via τ-leptons is considered as signal but with negligible contribution
Background studies

Main background Sources:

- Events with the **same final state**
- Misidentified leptons

In order to constrain background:

- **Kinematic cuts** that minimize reducible background (different final state)
  - Control and signal regions defined with loose but effective cuts
- **Multivariate Discriminants** (MD) to optimize even more signal segregation from reducible and irreducible (non-EW ZZjj) background
### Signal region definition (detector level)

|                | \( \ell \ell \ell \ell jj \)                              | \( \ell \nu \nu \ell jj \)                              |
|----------------|------------------------------------------------------------|------------------------------------------------------------|
| **Electrons**  | \( p_T > 7 \text{ GeV}, |\eta| < 2.47 \)   \( |d_0/\sigma_{d_0}| < 5 \) and \( |z_0 \times \sin \theta| < 0.5 \text{ mm} \) | \( p_T > 7 \text{ GeV}, |\eta| < 2.5 \)                                                      |
| **Muons**      | \( p_T > 7 \text{ GeV}, |\eta| < 2.7 \)   \( |d_0/\sigma_{d_0}| < 3 \) and \( |z_0 \times \sin \theta| < 0.5 \text{ mm} \) | \( p_T > 7 \text{ GeV}, |\eta| < 2.5 \)                                                      |
| **Jets**       | \( p_T > 30 \) (40) \text{ GeV for } |\eta| < 2.4 (2.4 < |\eta| < 4.5) \) | \( p_T > 60 \) (40) \text{ GeV for the leading (sub-leading) jet} |
| \( \mu \mu \ell \ell \) selection | \( p_T > 20, 20, 10 \text{ GeV for the leading, sub-leading and third leptons} \) | \( p_T > 30 \) (20) \text{ GeV for the leading (sub-leading) lepton} |
| Two OSSF lepton pairs with smallest \( |m_{\ell^+\ell^-} - m_Z| + |m_{\ell^+\ell^-} - m_Z| \) | One OSSF lepton pair and no third leptons | \( 80 < m_{\ell^+\ell^-} < 100 \text{ GeV} \) |
| \( \Delta R(\ell, \ell') > 0.2 \) |  | No b-tagged jets |
| \( 66 < m_{\ell^+\ell^-} < 116 \text{ GeV} \) |  | \( E_T^{\text{miss}} \)-significance > 12 |
| **Dijet selection** | \( m_{jj} > 300 \text{ GeV and } \Delta y(jj) > 2 \) | \( m_{jj} > 400 \text{ GeV and } \Delta y(jj) > 2 \) |

- Event selection, though effective, has loose cuts → room for machine learning
- Different selection criteria based on experimental features (e.g. detector efficiency)
- Suppressed pile-up contribution → deemed to have negligible effects
Main background in $\ell\ell\ell\ell jj$ channel

- Mostly suppressed by $m_{jj}$ and $\Delta\eta_{jj}$ cuts

- Centrality $\zeta$ used as another criterion to suppress this background
  - Centrality = position estimate of a Z-boson w.r.t. the rapidity span of the outgoing jets
  - Smaller values $\rightarrow$ cleaner SR

$$\zeta = \left| \eta - \bar{\eta}_{jj} \right| / \Delta\eta_{jj}$$

where

$$\bar{\eta}_{jj} = \frac{\eta_{j1} + \eta_{j2}}{2}$$
QCD $qqZZjj$ / $ggZZjj$

- BDT studies pointed the following as most important discriminatory variables between QCD and EW:

| Variable     | Value       |
|--------------|-------------|
| $m_{jj}$     | $\approx 500\text{GeV}$ |
| $\Delta\eta_{jj}$ | $\approx 2.9$ |
| $\zeta_{\text{leading }Z}$ | $\approx 1.03$ |
| $\zeta_{\text{subleading }Z}$ | $\approx 1.62$ |

- However, (as already mentioned) looser cuts have been set for event selection
  - MVA methods took over afterwards
Other Background Sources

**llvvjj**
- WZjj
  - Estimated with simulations
  - Corrected with a 3-lepton CR

- Non-resonant $ll$ contributions
  - WW, ttbar, Wt
  - Estimated yield with an e/μ-pair requirement in CR
  - Distribution shapes extracted from simulations

- Others:
  - Z+jets
    - Largely suppressed
    - Estimated with MET extrapolation
  - Triboson, ttV
    - Estimated with simulations

**lllljj**
- Fake background
  - Estimated yield via (data-driven) fake-factor and its shape via simulation
  - Great (>50%) uncertainty

- Triboson, ttV
  - Estimated with simulations
In order to determine modeling uncertainties the method used is described explicitly in arXiv:1510.03865

- Different simulation programs (Sherpa, Madgraph) have been used to evaluate PDF and scale theoretical uncertainties
  - Additional uncertainties introduced to capture shape differences between Sherpa and Madgraph

- Several detector-related statistical and systematic uncertainties have been included as well in the estimation of the total reconstruction uncertainty
  - Luminosity, pile-up conditions, electron/muon reconstruction/identification/isolation, jet JVT efficiency….
  - All these uncertainties are considered fully correlated

- Total reconstruction uncertainties range around 10% (30%) for EW (QCD)
  - At tree level $\mu_R$ and $\mu_F$ scale uncertainties were estimated approximately 6% (25%) for EW (QCD)
  - and PDF uncertainties at 0.5-1.5% by using different PDF scale variations for several PDF sets:
  - NNPDF30_nlo_as_0118, NNPDF30_nlo_as_0119, NNPDF30_nlo_as_0117, CT14nlo, MMHT2014nlo68clas118, PDF4LHC15_nlo_30_pdfas
Estimation of Uncertainties (PDF)
Estimation of Uncertainties ($\mu_R$, $\mu_F$)
Observations

- Reasonable agreement between data and prediction
  - For cross-section measurements the parameter of interest is the signal strength (ratio $\mu$ of fiducial measured cross-section to SM prediction)

- Simulation and data found to be compatible even for high $m_{jj}$ and $m_{ZZ}$

- Further discrimination between signal and background was boosted with MD in order to reach observation threshold

| Process       | $\ell\ell\ell\ell jj$ | $\ell\ell\nu\nu jj$ |
|---------------|-----------------------|----------------------|
| EW ZZjj       | $20.6 \pm 2.5$        | $12.3 \pm 0.7$       |
| QCD ZZjj      | $77 \pm 25$           | $17.2 \pm 3.5$       |
| QCD $ggZZjj$  | $13.1 \pm 4.4$        | $3.5 \pm 1.1$        |
| Non-resonant-$\ell\ell$ | $-$                  | $21.4 \pm 4.8$       |
| WZ            | $-$                   | $22.8 \pm 1.1$       |
| Others        | $3.2 \pm 2.1$         | $1.2 \pm 0.9$        |
| Total         | $114 \pm 26$          | $78.4 \pm 6.2$       |
| Data          | $127$                 | $82$                 |
Observations

- Statistical fit in three regions simultaneously: $lllljj$ CR, $lllljj$ SR and $llvvjj$ SR
- Used profile likelihood fit to test compatibility with SM.
  - As input BDT scores were used
  - All systematic uncertainties (detector and modeling) were treated as nuisance parameters
  - TRexFitter framework used. (Based on HistFitter (arXiv:1410.1280)
  - Obtained 5.5$\sigma$ combined observation significance (arXiv:2004.10612)
Ongoing studies

- Using the data from Run-II, current studies aim to extract the differential cross section for the ZZjj channel with unfolding techniques.

- Plan to use NLO estimations for QCD and EW.

- Plan to set limits on dim-8 aQGC operators using the EFT approach (see talk by Alexandros Marantis on aQGC studies).
  - Focus on field strength tensor operators ($\mathcal{L}_{T,0}$, $\mathcal{L}_{T,1}$, $\mathcal{L}_{T,2}$, $\mathcal{L}_{T,5}$, $\mathcal{L}_{T,6}$, $\mathcal{L}_{T,7}$, $\mathcal{L}_{T,8}$, $\mathcal{L}_{T,9}$).
Thank you