New VBS observations at the LHC

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on behalf of the ATLAS and CMS collaborations

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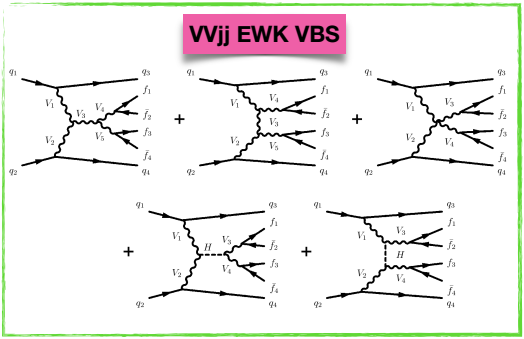
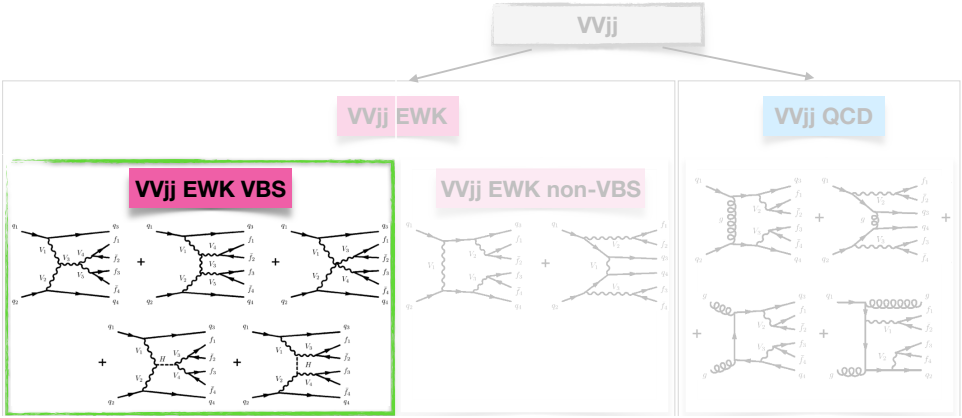
Motivation



Vector boson scattering (VBS) are rare processes predicted by the Standard Model.

- Unitarity at high energies requires the presence of the SM Higgs boson
  - VBS production probes the mechanism that restores the unitarity.
- VBS allows indirect search of New Physics by studying anomalous quartic gauge couplings (**aQGC**)

Introduction



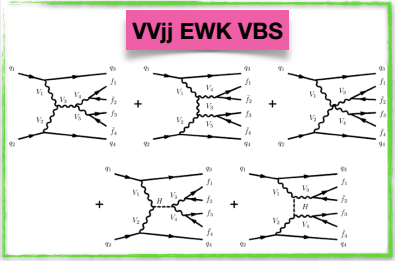
Experimentally we cannot access pure VBS diagrams and pure quartic couplings

Introduction

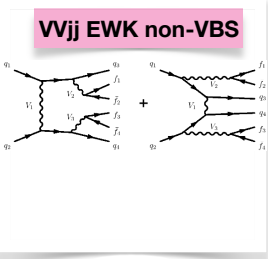
VVjj

VVjj EWK

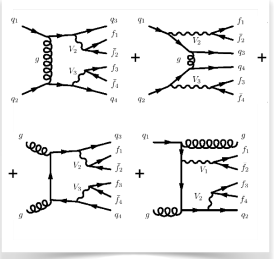
VVjj EWK VBS



VVjj EWK non-VBS



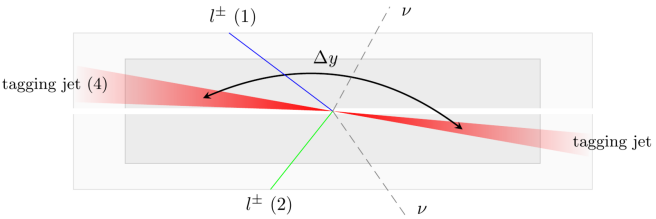
VVjj QCD

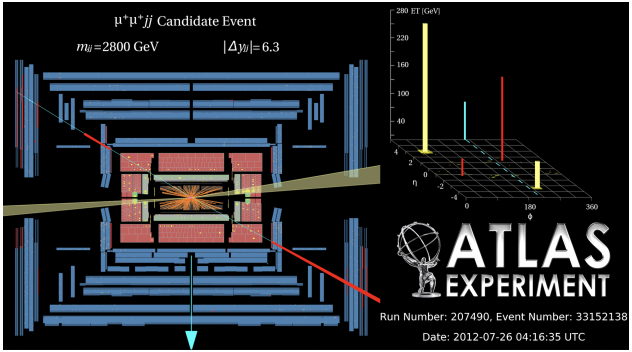


VVjj EWK VBS and **VVjj EWK non-VBS** components cannot be separated in a gauge invariant way, both treated as a **signal**

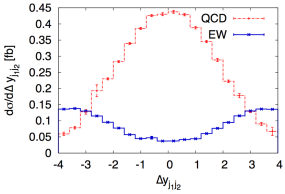
Background

VBS phenomenology





1. Two hadronic jets in forward and backward regions with very high energy: tagging jets
2. Absence of color flow between interacting partons: hadronic activity suppressed between the two jets.
3. Two bosons are produced ∼back-to-back.

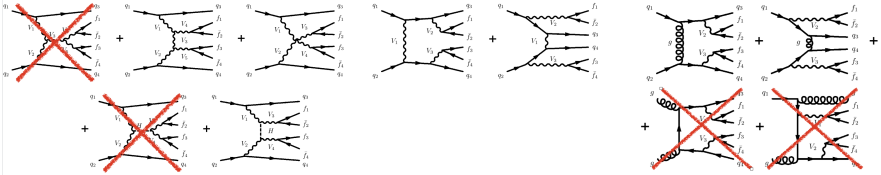


EWK VVjj production is distinguishable from QCD-induced component via kinematic variables

CMS: Phys. Rev. Lett. 120 (2018) 081801

ATLAS: ATLAS-CONF-2018-030

$W^{\pm}W^{\pm}jj$

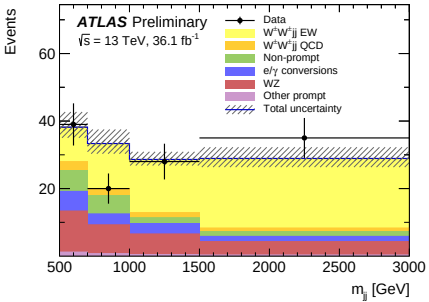


- $W^{\pm}W^{\pm}jj$ EWK: no s-channel
- $W^{\pm}W^{\pm}jj$ QCD: no gg-, nor qg-initiated diagrams

  $\rightarrow$ the largest EWK/QCD production ratio among VVjj processes
- Two same-sign leptons, MET, 2 tagging jets

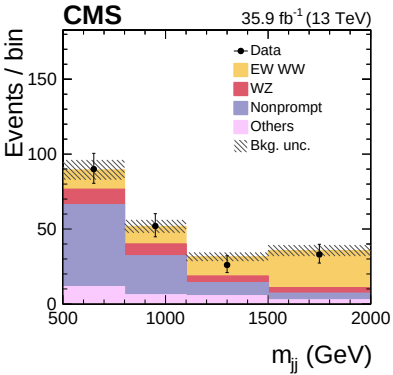
See talk of liqing Zhang for details of the ATLAS ssWW measurement

$W^{\pm}W^{\pm}jj$ signal extraction



Simultaneous likelihood fit of:

1. Signal region: m_{jj} spectrum split in 4 bins (for $m_{jj} > 500$ GeV), separately for 6 channels - $e^{\pm}e^{\pm}$, $e^{\pm}\mu^{\pm}$, $\mu^{\pm}\mu^{\pm}$
2. Control region enriched with *WZjj* (a single channel with one bin): the fit allows for normalization of this background.
3. Control region enriched with 'non-prompt': $200 < m_{jj} < 500$ GeV.



Simultaneous likelihood fit of:

1. Signal region: two-dimensional distributions (m_{jj}, $m_{\ell\ell}$).
2. Control region enriched with *WZjj* (a single channel, binned): m_{jj} spectrum, the fit allows for normalization of this background.

Results for $W^{\pm}W^{\pm}jj$

ATLAS:

Observed significance 6.9σ (4.6σ expected) SHERPA

$\mu_{EWK} = 1.45^{+0.25}_{-0.24}(\text{stat.})^{+0.13}_{-0.14}(\text{syst.})$

Measured fiducial cross-section:

$\sigma^{\text{fid}}_{\text{Data}} = 2.95 \pm 0.49(\text{stat.}) \pm 0.23(\text{syst.})$ fb

- $\sigma^{\text{fid}}_{\text{Data}}$ includes $W^{\pm}W^{\pm}jj$ EWK plus interference with $W^{\pm}W^{\pm}jj$ QCD
- $W^{\pm}W^{\pm}jj$ QCD subtracted as background

CMS:

Observed significance 5.5σ (5.7σ expected) MG_aMC@NLO

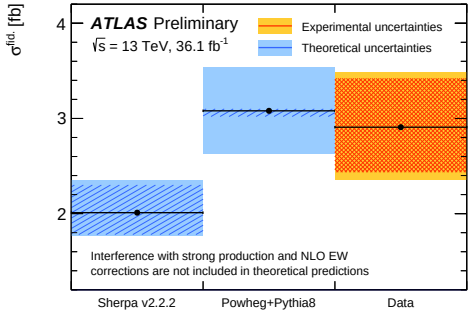
$\mu_{EWK} = 0.90 \pm 0.22$

Measured fiducial cross-section:

$\sigma^{\text{fid}}_{\text{Data}} = 3.83 \pm 0.66(\text{stat.}) \pm 0.35(\text{syst.})$ fb

Predicted LO cross-section (MadGraph):

$\sigma^{\text{fid}}_{\text{th}} = 4.25 \pm 0.27$ fb



CMS: CMS-PAS-SMP-18-001

ATLAS: ATLAS-CONF-2018-033

$W^{\pm}Zjj$

- 3 isolated leptons (e or μ), MET, 2 tagging jets
- Major background from WZ QCD production

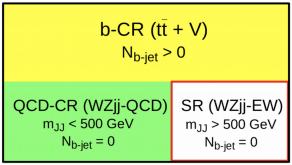
Details of the ATLAS analysis

- 15 discriminative variables are used as inputs for BDT training.

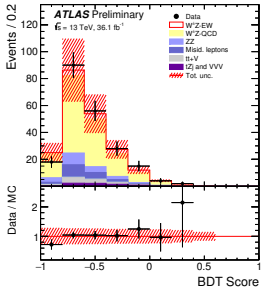
$\Delta y(\ell_W, Z)$	m_{jj}	η_W
ζ	$\Delta R(j1, Z)$	p_T^{j2}
$R_{p_T^{hard}}$	$\Delta\eta(j1, j2)$	p_T^{j1}
N_{jets}	p_T^W	m_T^{WZ}
$\Delta\phi(j1, j2)$	η_{j1}	p_T^Z

- Trained on MC to separate *WZjj*-EWK from all background.
- Background description of BDT score distribution and of all input variables is controlled in QCD CR.
- BDT score is used as SR template in the fit.

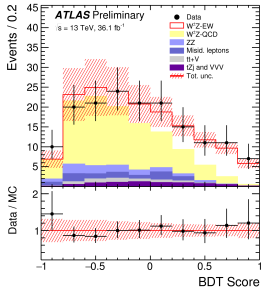
- Combined maximum-likelihood fit of SR + 3 CRs (WZ QCD, b-CR, ZZ)

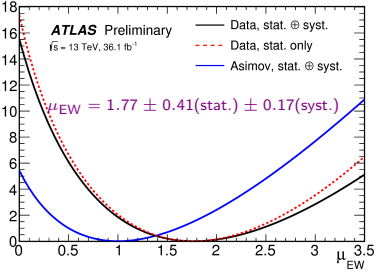


BDT score in QCD CR

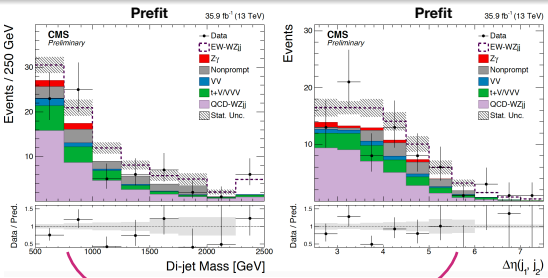


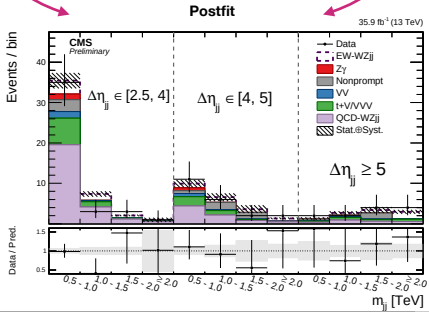
BDT score in SR





Details of the CMS analysis





- EWK contribution grows with increasing values of the dijet mass and $\Delta\eta_{jj}$: fit 2d distribution to extract *WZjj* EWK significance.

Target results:

- Extract signal strength of *WZjj* **EWK** production
- Measure *WZjj* **EWK+QCD** cross section in VBS-enhanced phase space
- Extrapolate results to **loose fiducial** regions for easier comparison with theory.

Results

ATLAS: SHERPA

Observed significance of *WZjj*-EWK **5.6**σ (3.3σ expected)

FIRST OBSERVATION OF THIS PROCESS!

$$\mu_{EWK} = 1.77 \pm 0.41(\text{stat.}) \pm 0.17(\text{syst.}) = 1.77 \pm 0.45$$
$$(\mu_{WZ-\text{QCD}} = 0.60 \pm 0.25,\ \mu_{t\bar{t}+V} = 1.18 \pm 0.19 \text{ and } \mu_{ZZ} = 1.34 \pm 0.29)$$

Measured fiducial CS of **EWK production**:
$\sigma^{\text{fid.,EW}}_{\text{meas.}} = 0.57^{+0.15}_{-0.14}\text{fb} = 0.57^{+0.14}_{-0.13}(\text{stat.})^{+0.05}_{-0.04}(\text{syst.})^{+0.04}_{-0.03}(\text{th.})\text{fb}$

Predictions (interference not included):
$\sigma^{\text{fid., EW th.}}_{\text{Sherpa}} = 0.321 \pm 0.002\,(\text{stat.}) \pm 0.005\,(\text{PDF})^{+0.027}_{-0.023}\,(\text{scale})\ \text{fb}$
$\sigma^{\text{fid., EW th.}}_{\text{MadGraph}} = 0.366 \pm 0.004\,(\text{stat.})\ \text{fb}$

CMS: MG_aMC@NLO

Observed significance of *WZjj*-EWK **1.9**σ (2.7σ expected)

$$\mu_{EWK} = 0.64^{+0.45}_{-0.37}$$

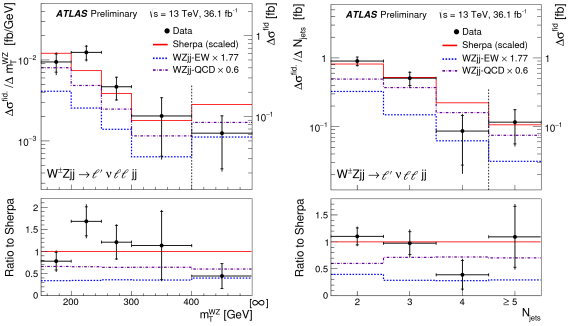
Measured fiducial CS of **EWK+QCD production** (tight fiducial region):

$$\sigma^{\text{fid}}_{\text{WZjj}} = 2.91^{+0.53}_{-0.49}\,(\text{stat})\ ^{+0.41}_{-0.34}\,(\text{syst}) = 2.91^{+0.67}_{-0.60}\ \text{fb}$$

Predictions:
$\sigma^{\text{fid., th.}}_{MG} = 3.27^{+0.39}_{-0.32}(\text{scale}) \pm 0.15(\text{PDF})\text{fb}$

Differential distributions

- Interesting kinematic distributions are unfolded from *WZjj*-EWK SR to fiducial PS.
  $\rightarrow$ first differential results in VVjj measurements
- Migration matrices are derived using *WZjj*-QCD and *WZjj*-EWK SHERPA2.2.2 samples.
- Two types of variables studied:
  - Variables sensitive to aQGCs: m_T^{WZ}, $\sum p_T^{\ell}$, $\Delta\phi(W,Z)$
  - Constraining variables for MC modeling: $N_{\text{jets}}(p_T > 40)$ GeV, $N_{\text{jets}}^{\text{gap}}(p_T > 25)$ GeV, m_{jj}, $\Delta\phi(j_1,j_2)$, $\Delta y(j_1,j_2)$



- Data is compared to total post-fit *WZjj* production.
- Measurements are dominated by statistical uncertainties.

ZZjj

Zγjj

More processes to explore…

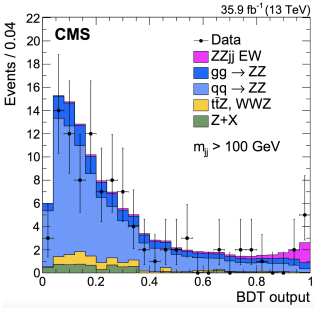
WVjj semileptonic

Wγjj

Searches of neutral VBS channels

ZZjj

CMS: PLB 774 (2017) 682, 35.9 fb^{-1} at 13 TeV



Observed (expected) of 2.7σ (1.6σ)

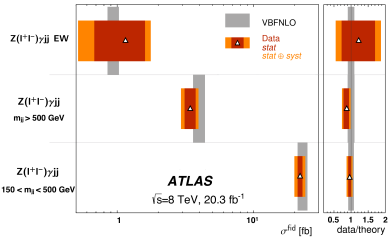
$\mu = \sigma_{obs}/\sigma_{th.} = 1.39\ ^{+0.72}_{-0.57}\ (stat)\ ^{+0.46}_{-0.31}\ (syst.)$

Zγjj

CMS: Phys. Lett. B 770 (2017) 380, 19.7 fb^{-1} at 8 TeV

ATLAS: JHEP07(2017)107, 20.2 fb^{-1} at 8 TeV

ATLAS: observed (expected) significance 2.0σ (1.8σ)



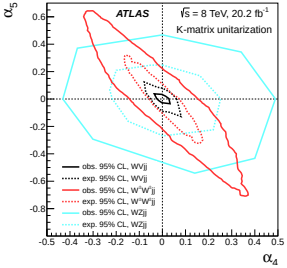
CMS: observed (expected) significance 3.0σ (2.1σ)

Searches of charged VBS channels

ATLAS: Phys. Rev. D 95 (2017) 032001, 20.2 fb^{-1} at 8 TeV

- $VVjj \to qq'\ell\nu jj$ ($V = W$ or Z)
- Main challenge: presence of large background from W+jets and $t\bar{t}$ events $\to$ leads to low signal-to-background ratio

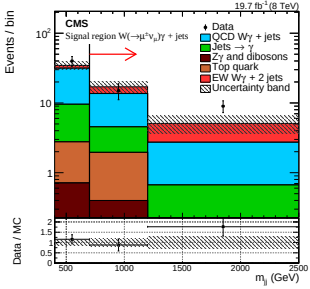
$\Rightarrow$ This channel is *not sensitive yet for CS measurement*, but is optimized for aQGC searches



WVjj semileptonic

CMS: JHEP 06 (2017) 106 , 19.7 fb^{-1} at 8 TeV

- Leptonic W decay: $(W\gamma)jj \to e/\mu\nu\gamma jj$
- One of the largest CS among VBS processes

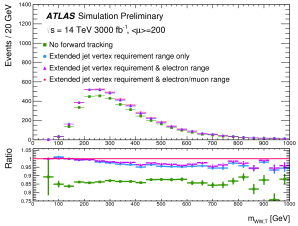


Items	EW measurement	EW+QCD measurement
Signal strength $\hat{\mu}_{sig}$	$1.78^{+0.98}_{-0.76}$	$0.99^{+0.21}_{-0.19}$
Observed (expected) significance	2.7 (1.5) standard deviations	7.7 (7.5) standard deviations
Theoretical cross section (fb)	6.1 ± 1.2 (scale) ± 0.2 (PDF)	23.5 ± 5.3 (scale) ± 0.8 (PDF)
Measured cross section (fb)	10.8 ± 4.1 (stat) ± 3.4 (syst) ± 0.3 (lumi)	23.2 ± 4.3 (stat) ± 1.7 (syst) ± 0.6 (lumi)

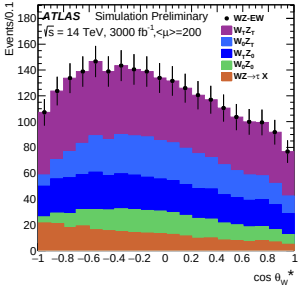
Wγjj

Prospects for HL-LHC

ATL-PHYS-PUB-2017-023



ATL-PHYS-PUB-2018-023



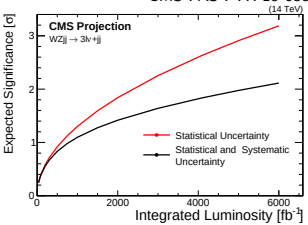
- Planned 3000 fb^{-1} of data after 10 years of operation

- Estimate impact of improved detectors geometries on VBS studies

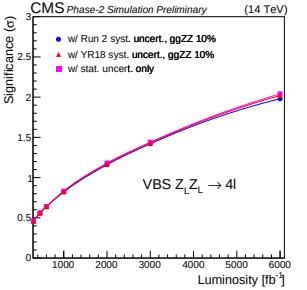
- One of the main focuses: searches for $V_L V_L \to V_L V_L$ production
  - $\to$ Improved analysis techniques are required
  - $\to$ For $Z_L Z_L \to Z_L Z_L$ **HE-LHC** option (15 ab^{-1} fb, $\sqrt{s} = 27$TeV) would bring 5σ sensitivity:

	significance	
	w/ syst. uncert.	w/o syst. uncert.
HL-LHC	1.4σ	1.4σ
HE-LHC	5.2σ	5.7σ

CMS-PAS-FTR-18-038



CMS-PAS-FTR-18-014



Summary

	$W^{\pm}W^{\pm}jj$ Best EW/QCD ratio	$W^{\pm}Zjj$	$WVjj$ semilept. access to aQGCs	$W\gamma jj$ Largest CS	$ZZjj$	$Z\gamma jj$
CMS	**13TeV**, 8TeV 5.5σ obs. (5.7σ exp.)	13TeV 1.9σ obs. (2.7σ exp.)	-	8TeV 2.7σ obs. (1.5σ exp.)	13TeV, 8TeV 2.7σ obs. (1.6σ exp.)	8TeV 3.0σ obs. (2.1 exp.)
ATLAS	**13TeV**, 8TeV 6.9σ obs. (4.6σ exp.)	**13TeV**, 8TeV 5.6σ obs. (3.3σ exp.)	8TeV	-	-	8TeV 2.0σ obs. (1.8 exp.)

- Observation of $W^{\pm}W^{\pm}jj$ and $WZjj$ EWK production with partial Run2 data (2015+2016).
- Cross sections are measured in fiducial regions for both pure **EWK** and **EWK+QCD** production: both give a useful input for theorists.
- First differential cross section results are reported.
- *Interpretation* of the data in terms of *aQGCs*, no sign of new physics so far...
- More results to come with full Run2 data
- And even more improvements are expected at HL-LHC

Backup slides

Phase space definitions for $W^{\pm}W^{\pm}jj$ measurements

ATLAS:

Fiducial phase space
Two same-sign leptons ($\ell = e$ and/or μ):
$p_T^{\ell} > 27$ GeV
$\lvert\eta^{\ell}\rvert < 2.5$
$m_{\ell\ell} > 20$ GeV
$\Delta R_{\ell\ell} > 0.3$
$p_T^{\nu\nu} > 30$ GeV
At least two jets:
$p_T^{j,\text{lead}} > 65$ GeV, $p_T^{j,\text{sub-lead}} > 35$ GeV
$\lvert\eta^{j}\rvert < 4.5$
$m_{jj} > 500$ GeV
$\lvert\Delta y_{jj}\rvert > 2$
$\Delta R_{\ell j} > 0.3$

*leptons are "dressed" with photons inside a cone of $\Delta R = 0.1$

CMS:

Fiducial phase space
Two same-sign leptons ($\ell = e$ and/or μ):
$p_T^{\ell} > 20$ GeV
$\lvert\eta^{\ell}\rvert < 2.5$
At least two jets:
$p_T^{j} > 30$ GeV
$\lvert\eta^{j}\rvert < 5.0$
$m_{jj} > 500$ GeV
$\lvert\Delta\eta_{jj}\rvert > 2.5$
$\Delta R_{\ell j}$

Phase space definitions for *WZjj* measurements

ATLAS:

Variable	Fiducial VBS
Lepton $\lvert\eta\rvert$	< 2.5
p_T of ℓ_Z, p_T of ℓ_W [GeV]	> 15, > 20
m_Z range [GeV]	$\lvert m_Z - m_Z^{\mathrm{PDG}}\rvert < 10$
m_{T}^W [GeV]	> 30
$\Delta R(\ell_Z^-, \ell_Z^+)$, $\Delta R(\ell_Z, \ell_W)$	> 0.2, > 0.3
p_T two leading jets [GeV]	> 40
$\lvert\eta_j\rvert$ two leading jets	< 4.5
Jet multiplicity	≥ 2
$\eta_{j1} \cdot \eta_{j1}$	< 0
m_{jj} [GeV]	> 500
$\Delta R(j, \ell)$	> 0.3
$N_{b-\mathrm{quark}}$	$= 0$

CMS:

	Tight Fiducial	Loose Fiducial
$p_{\mathrm{T}}(\ell_{Z,1})$ [GeV]	> 25	> 20
$p_{\mathrm{T}}(\ell_{Z,2})$ [GeV]	> 15	> 20
$p_{\mathrm{T}}(\ell_{\mathrm{W}})$ [GeV]	> 20	> 20
$\lvert\eta(\mu)\rvert$	< 2.5	< 2.5
$\lvert\eta(e)\rvert$	< 2.5	< 2.5
$\lvert m_{\mathrm{Z}} - m_{\mathrm{Z}}^{\mathrm{PDG}}\rvert$ [GeV]	< 15	< 15
$m_{3\ell}$ [GeV]	> 100	> 100
$m_{\ell\ell}$ [GeV]	> 4	> 4
$p_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	-	-
$\lvert\eta(\mathrm{j})\rvert$	< 4.7	< 4.7
$p_{\mathrm{T}}(\mathrm{j})$ [GeV]	> 50	> 30
$\lvert\Delta R(\mathrm{j}, \ell)\rvert$	> 0.4	> 0.4
n_{j}	≥ 2	≥ 2
$p_{\mathrm{T}}(\mathrm{b})$ [GeV]	-	-
$n_{\mathrm{b-jet}}$	-	-
m_{jj}	> 500	> 500
$\lvert\Delta\eta(\mathrm{j}_1, \mathrm{j}_2)\rvert$	> 2.5	> 2.5
$\lvert\eta_{3\ell} - \frac{1}{2}(\eta_{j_1} + \eta_{j_2})\rvert$	< 2.5	-

Systematic uncertainties for EWK *WZjj* measurement

ATLAS:

Source	Uncertainty [%]
$WZjj$-EW theory modelling	5.0
$WZjj$-QCD theory modelling	2.3
$WZjj$-EW and $WZjj$-QCD interference	1.9
Jets	6.7
Pileup	2.2
Electrons	1.6
Muons	0.7
b-tagging	0.3
MC statistics	2.1
Misid. lepton background	1.0
Other backgrounds	0.1
Luminosity	2.1

- Object-related systematics mostly coming from **jet reconstruction and calibration**.
- Theory-related sources come from:
  - QCD scale and PDF uncertainties for both WZjj-EW and WZjj-QCD
  - Signal modeling: MadGraph VS Sherpa2.2.2
  - *WZjj* QCD modeling: Powheg+Pythia VS Powheg+Herwig.
- Interference is included as a shape uncertainty on signal.

CMS:

Source of systematic uncertainty	Relative systematic uncertainty [%]	
	σ_{WZjj}	EW WZ Significance
Jet energy scale	+9.8/-9.2	7.5
Jet energy resolution	+1.1/-1.9	< 0.1
QCD WZ modeling	-	0.9
Other background theory	+2.5/-2.2	0.2
Nonprompt normalization	+2.1/-2.4	1.1
Nonprompt stat.	+6.1/-5.8	6.2
Lepton energy scale and eff.	+3.5/-2.7	< 0.1
b-tagging	+1.7/-1.9	< 0.1
Luminosity	+3.1/-3.4	< 0.1

- Object-related systematics is dominated by **jet energy measurements** and **nonprompt estimation**.
- Theory-related uncertainties:
  - QCD scale and PDF uncertainties
  - Signal modeling: no additional uncertainty - signal predictions are within scale and PDF uncertainties.
  - *WZjj* QCD modeling: compare predictions of the MLM and FxFx merged samples, and LO+up to 3j with NLO+ up to 1j samples.
- Interference is included as a shape uncertainty on signal.