Observation of electroweak $W^{\pm}Z$ boson pair production in association with two jets in pp collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector and prospects for New Physics

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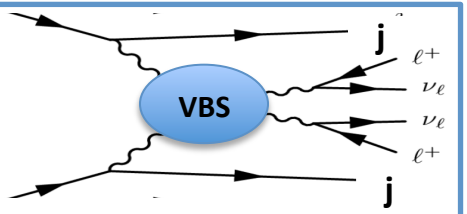
Overview

- Motivation: Vector Boson Scattering
- WZjj: Observation
  - Phys. Lett B 793 (2019) 469
- Future Prospects in Effective Field Theories

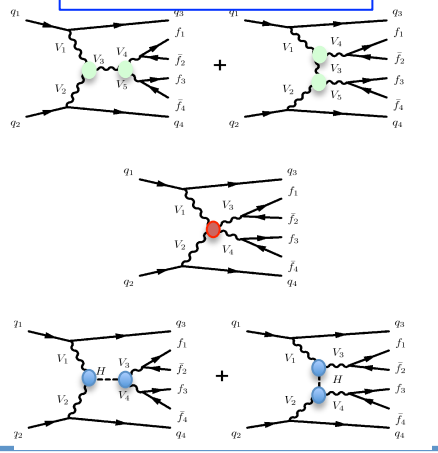
Vector Boson Scattering

- Vector Boson Scattering: interaction of two vector bosons radiated from the initial-state quarks, yielding a final state with two bosons and two jets, VVjj, in a purely electroweak process

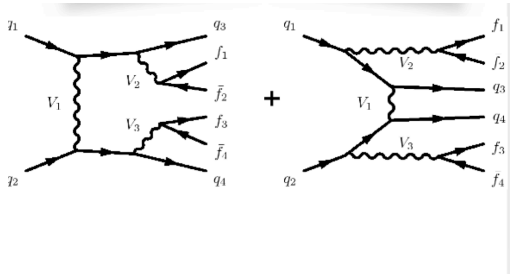


EWK production contains both VBS and non-VBS processes that cannot be dissociated

EWK VVjj VBS



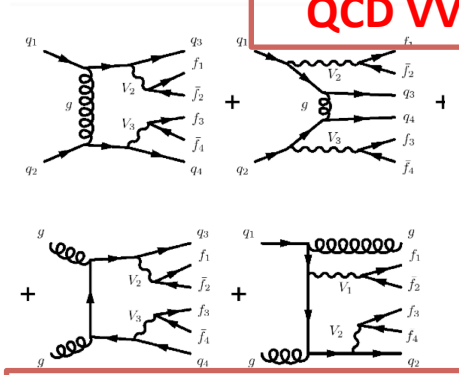
EWK VVjj non-VBS



EWK: QED<=6, QCD=0

Main background:
Diboson QCD production in association with two jets

QCD VVjj

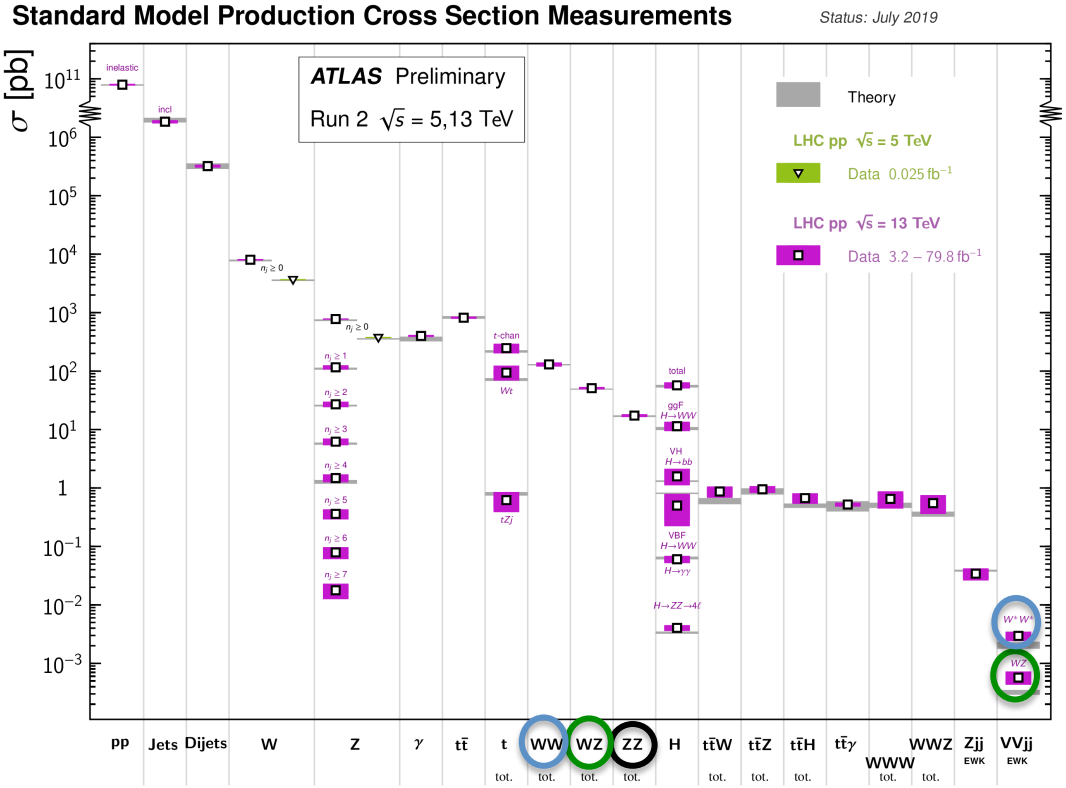


QCD: QCD=2, QED=4

Vector Boson Scattering: Motivation

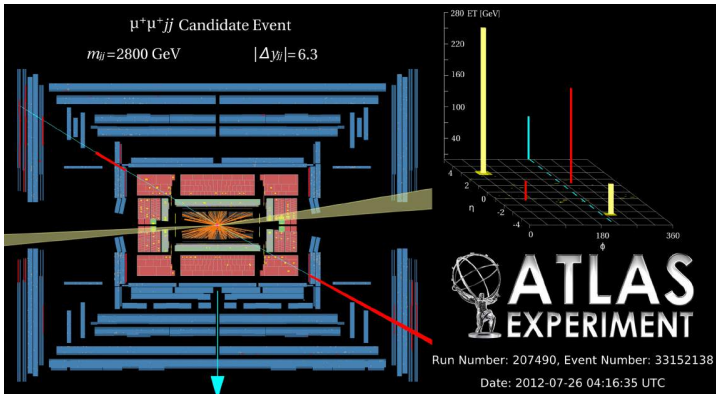
- Vector boson scattering (VBS) are rare processes predicted by the Standard Model.
- The Higgs mechanism ensures unitarity up to ~1 TeV
  - VBS production mechanism can restore unitarity at higher C.M energies, where Higgs mechanism fails

- VBS allows indirect searches of New Physics by studying anomalous quartic gauge couplings (aQGC)

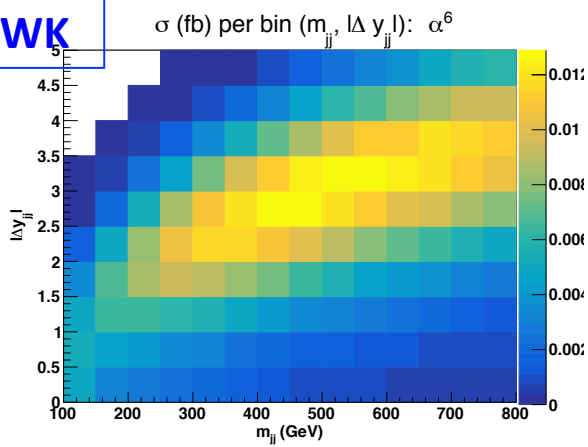


VBS phenomenology

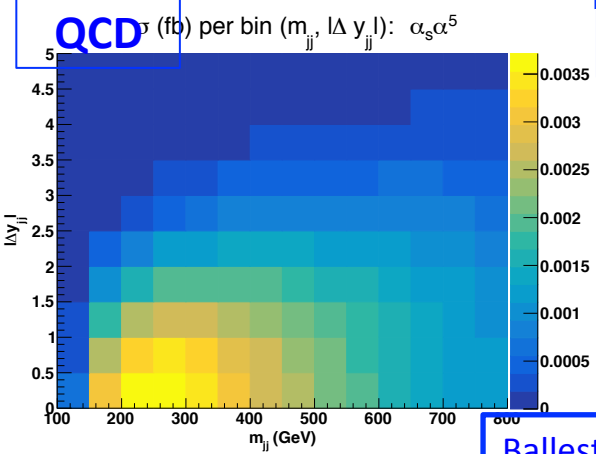
- VBS events at LHC have distinct event topology: VVjj
  - Two energetic jets with large di-jet mass (m_{jj}) and high rapidity separation
  - diboson system, centrally produced with respect to the two forward jets
- Separation from Background (QCD production)



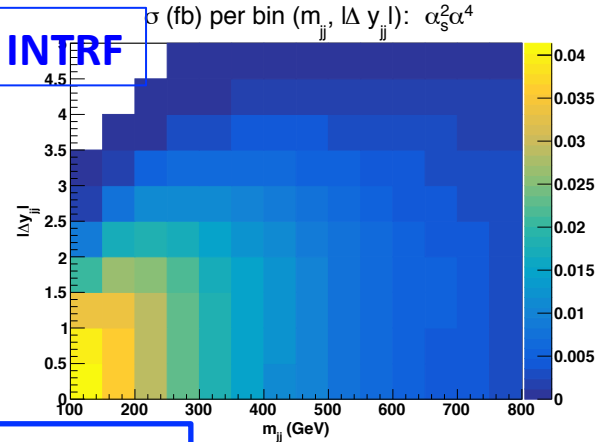
EWK



QCD



INTRF



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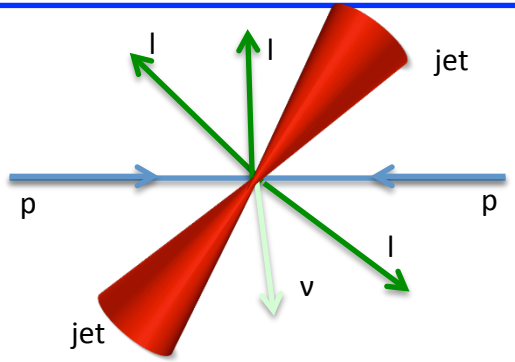
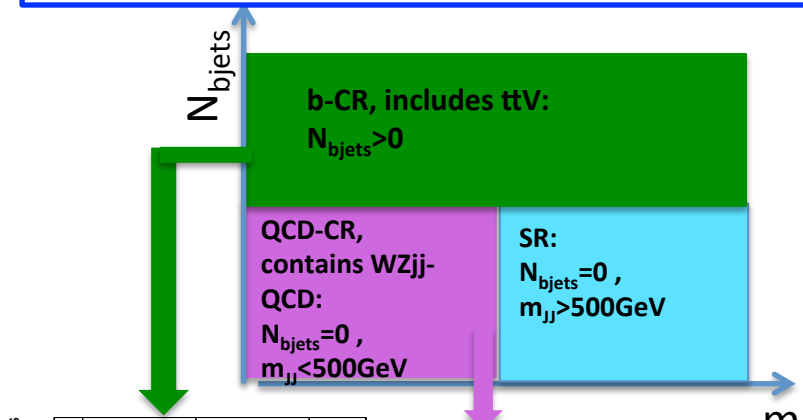
WZjj: Event Selection

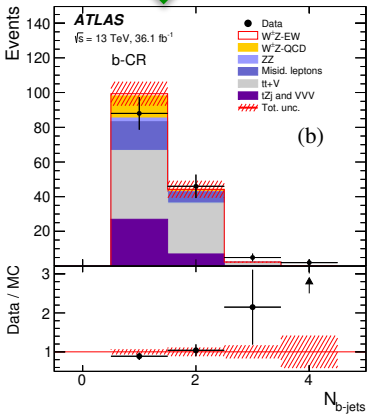


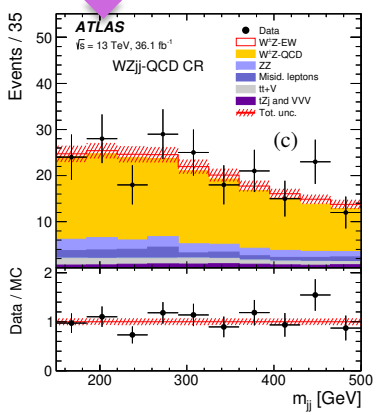
- Exactly 3 leptons:
  - $|\eta|<2.5$
  - $p_T^{l,Z}>15$GeV
  - $|M_z-M_z^{PDG}|<10$ GeV
  - $m_T^W>30$ GeV
- At least 2 jets:
  - $|\eta|<4.5$
  - opposite hemispheres
  - $p_T^j>40$GeV
  - $m_{jj}>150$ GeV

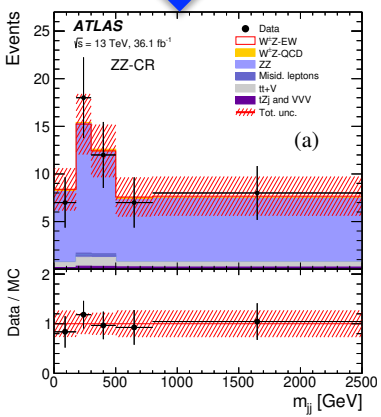
- Selection separated in 3 orthogonal regions



Additional CR to better constrain the ZZ background, requiring 4 leptons







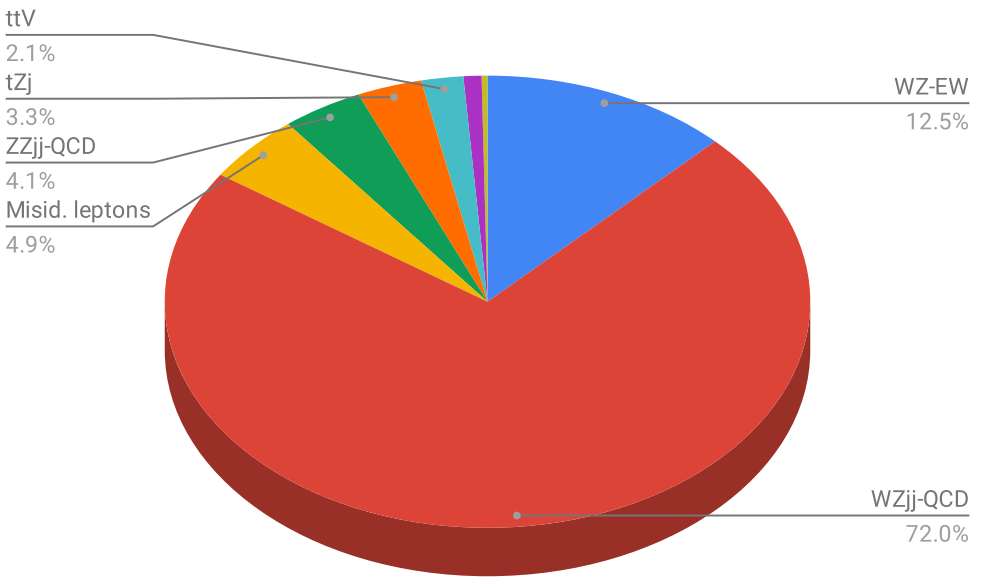
Background estimation

Irreducible Background

- WZjj-QCD, ZZjj, ttV: Use MC simulation and control regions to better constrain them
  - QCD: dominant background
  - ZZjj: second dominant background
- VVV, tZj: Use MC simulation to model them

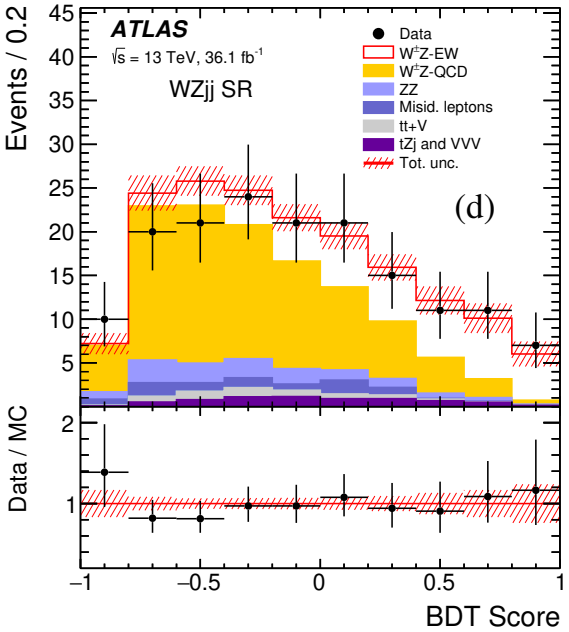
Reducible Background

- Z+j, Zγ, ttbar, Wt, WW: Data-driven method based on the inversion of a global matrix containing the efficiencies and the misidentification probabilities for prompt and fake leptons



Signal Extraction

- Given the small contribution of the WZjj-EWK to the signal,
- Multivariate discriminant is used to separate the signal from the backgrounds
- BDT trained in the signal region
- 15 variables chosen for their discrimination power between signal and all backgrounds



Cross section Measurement

- A maximum likelihood Simultaneous Fit is performed in the SR and 3 CRs
- Systematic uncertainties are taken into account as well as their correlations in the 4 fitted regions
- EWK-QCD interference is taken into account and treated as part of the signal
- Theory modelling: A global modelling uncertainty in the WZjj-EW signal template is estimated by comparing predictions of the BDT score distribution in the signal region from the Sherpa and MG MC event generators.
  - affects the shape of the BDT score distribution by at most 14% at large values of the BDT score.

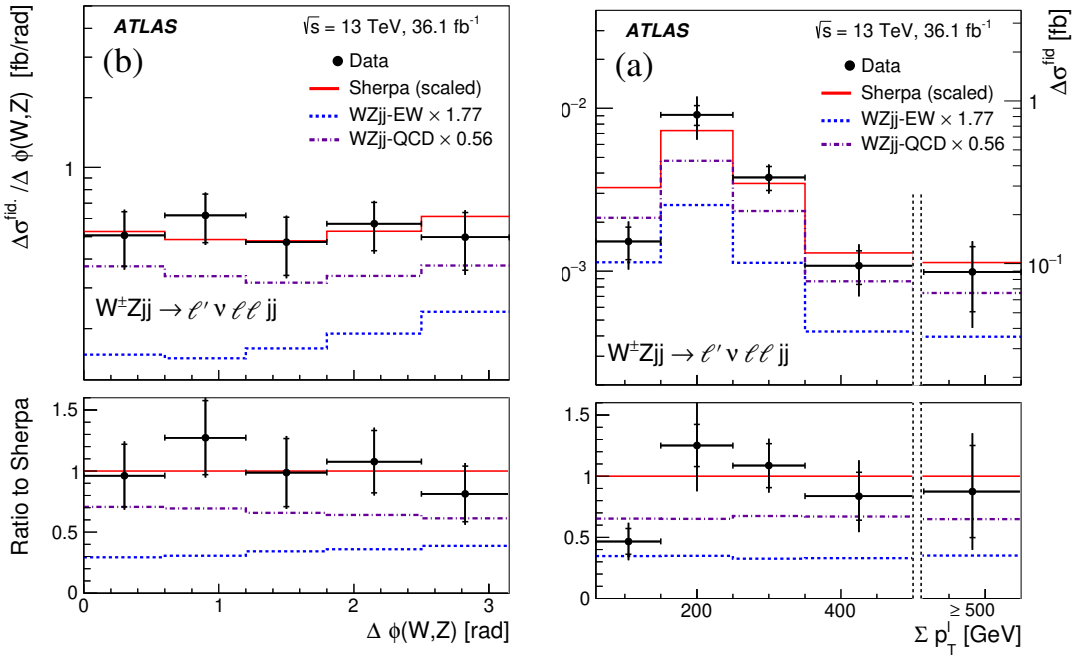
Source	Uncertainty [%]
$WZjj$–EW theory modelling	4.8
$WZjj$–QCD theory modelling	5.2
$WZjj$–EW and $WZjj$–QCD interference	1.9
Jets	6.6
Pile-up	2.2
Electrons	1.4
Muons	0.4
b-tagging	0.1
MC statistics	1.9
Misid. lepton background	0.9
Other backgrounds	0.8
Luminosity	2.1
Total Systematics	10.9

- The electroweak production of $W^{\pm}Z$ bosons in association with two jets is measured with observed significance of 5.3σ.

$$\sigma_{WZjj\text{–EW}} = 0.57\ ^{+0.14}_{-0.13}\,(\text{stat.})\ ^{+0.05}_{-0.04}\,(\text{exp. syst.})\ ^{+0.05}_{-0.04}\,(\text{mod. syst.})\ ^{+0.01}_{-0.01}\,(\text{lumi.})\ \text{fb}$$

Differential Cross Sections

- Events in the SR are also used to measure the WZjj differential production cross-section in the VBS fiducial phase space
- Data are unfolded using an Iterative Bayesian unfolding method
- Differential cross section measurements in variables sensitive to aQGCs for future studies: $m_T WZ$, $\Sigma p_T l$, $\Delta\Phi_{(W,Z)}$

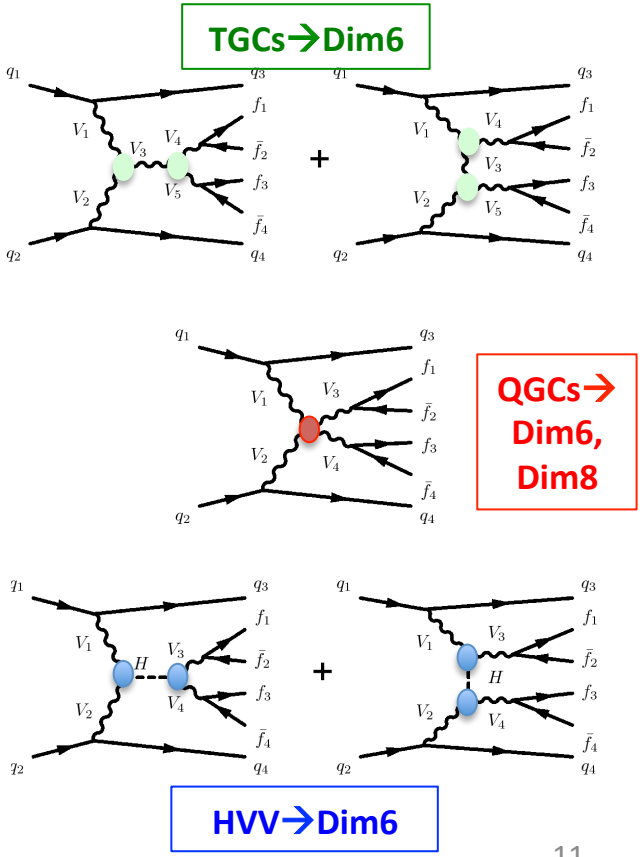


EFT Interpretations

- EFTs emerge as the tool to look for deviations from the standard model
- Unknown physics reachable at very high energies can be parametrized as extension of SM in an expansion in terms of Dim-6 (O_i) and Dim-8 (O_j)

$$L = L^{SM} + \sum_i \frac{c_i}{\Lambda^2} O_i + \sum_j \frac{c_j}{\Lambda^4} O_j$$

- aQGCs can be parametrized in terms of Dim-8 operators, by the assumption that the Dim-6 can already be constrained elsewhere
- Use EFT parameterization from [Eboli, Gonzales-Garcia model]
- Measurements of aQGC → constrain the following operators: f_{S0}/Λ^2, f_{S1}/Λ^2, f_{T0}/Λ^2, f_{T1}/Λ^2, f_{T2}/Λ^2, f_{M0}/Λ^2, f_{M1}/Λ^2
- Plan to reinterpret the existing data using EFT MC predictions of D8 operators



Conclusions

- Run II of the LHC provides access to the Vector Boson Scattering
- First observation of Electroweak WZjj production with 36fb^{-1}
- Fiducial cross section measurement and differential cross sections provided
- EFTs is the tool to look for BSM effects and WZjj serves as a good candidate for the search
- With the full Run II data, improved cross section sensitivity can be achieved
- Better limits in Effective Field theory operators are expected with higher statistic and after combining the results with other final states

Thank you for your attention!

Backup: WZjj selection

Inclusive selection

Electron object selection

Selection	Baseline selection	Z selection	W selection
$p_T > 5$ GeV	✓	✓	✓
Electron object quality	✓	✓	✓
$\lvert\eta^{\text{cluster}}\rvert < 2.47$, $\lvert\eta\rvert < 2.5$	✓	✓	✓
LooseLH+BLayer identification	✓	✓	✓
$\lvert d_0^{\text{BL}}/\sigma(d_0^{\text{BL}})\rvert < 5$	✓	✓	✓
$\lvert\Delta z_0^{\text{BL}}\sin\theta\rvert < 0.5$ mm	✓	✓	✓
LooseTrackOnly isolation	✓	✓	✓
e-to-μ and e-to-e overlap removal	✓	✓	✓
e-to-jets overlap removal		✓	✓
$p_T > 15$ GeV		✓	✓
Exclude $1.37 < \lvert\eta^{\text{cluster}}\rvert < 1.52$		✓	✓
MediumLH identification		✓	✓
Gradient isolation		✓	✓
$p_T > 20$ GeV			✓
TightLH identification			✓
Unambiguous author			✓

Muon object selection

Selection	Baseline selection	Z selection	W selection
$p_T > 5$ GeV	✓	✓	✓
$\lvert\eta\rvert < 2.7$	✓	✓	✓
Loose quality	✓	✓	✓
$\lvert d_0^{\text{BL}}/\sigma(d_0^{\text{BL}})\rvert < 3$ (*for* $\lvert\eta\rvert < 2.5$ *only*)	✓	✓	✓
$\lvert\Delta z_0^{\text{BL}}\sin\theta\rvert < 0.5$ mm (*for* $\lvert\eta\rvert < 2.5$ *only*)	✓	✓	✓
FixedCutLoose isolation	✓	✓	✓
μ-jet Overlap Removal		✓	✓
$p_T > 15$ GeV		✓	✓
$\lvert\eta\rvert < 2.5$		✓	✓
Medium quality		✓	✓
$p_T > 20$ GeV			✓
Tight quality			✓
Gradient isolation			✓

ZZ veto	Less than 4 baseline leptons
N leptons	Exactly three leptons passing the Z lepton selection
Leading lepton p_T	$p_T^{\text{lead}} > 25$ GeV (in 2015) or $p_T^{\text{lead}} > 27$ GeV (in 2016)
Z leptons	Two same flavor oppositely charged leptons passing Z lepton selection
Mass window	$\lvert M_{\ell\ell} - M_Z\rvert < 10$ GeV
W lepton	Remaining lepton passes W selection
W transverse mass	$m_T^W > 30$ GeV

VBS selection

***WZjj* Event selection**	
Jet multiplicity	≥ 2
p_T of two tagging jets	> 40 GeV
$\lvert\eta\rvert$ of two tagging jets	< 4.5
η of two tagging jets	opposite sign
m_{jj}	> 150 GeV
***WZjj* b-CR**	
$N_{b-\text{jet}}$	> 0
***WZjj* QCD-CR**	
$N_{b-\text{jet}}$	$= 0$
m_{jj}	< 500 GeV
***WZjj* SR**	
$N_{b-\text{jet}}$	$= 0$
m_{jj}	> 500 GeV

Backup: BDT input variables

- For the BDT, the classification is performed using 15 selected input variables, which can be classified in three categories:

Variables related to the kinematics of the tagging jets:

- m_{jj}
- N_{jets}
- p_T^{j1} p_T^{j2}
- η_{j1}
- $\Delta\eta(j1,j2)$
- $\Delta\varphi(j1,j2)$

Variables related to the kinematics of the vector bosons:

- $|y_{l,W}-y_{l,Z}|$
- p_T^W p_T^Z
- η_W
- m_T^{WZ}

Variables related to the kinematics of the vector bosons:

- $\Delta R(j1,Z)$
- R_{pT}^{hard}
- ζ_{lep}