Multi-Boson Interaction (MBI) 2021

EWK single and diboson production and aGCs of massive vector bosons

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	CMS		ATLAS		
	Z+2jets	$W^{\pm}W^{\pm}$ WZ WV ZZ	Z+2jets	$W^{\pm}W^{\pm}$ WZ VV	ZZ
	2016	Full Run II	Full Run II	2015+2016	Full Run II

Outline

CMS ANALYSES

- **VBF Z+ two jets** (EPJC 78 (2018) 589) - Electroweak production of two jets in association with a Z boson in proton–proton collisions at $\sqrt{s} = 13$ TeV
- **VBS $W^{\pm}W^{\pm}$ WZ** (PLB 809(2020) 135710) - Measurements of production cross sections of WZ and same-sign WW boson pairs in association with two jets in proton-proton collisions at $\sqrt{s} = 13$ TeV
- **VBS WV** (CMS-PAS-SMP-20-013) - Search for vector boson scattering at the LHC Run 2 with CMS data in the semi-leptonic lνqq final state
- **VBS ZZ** (PLB 812 (2020) 135992) - Evidence for electroweak production of four charged leptons and two jets in proton-proton collisions at $\sqrt{s} = 13$ TeV

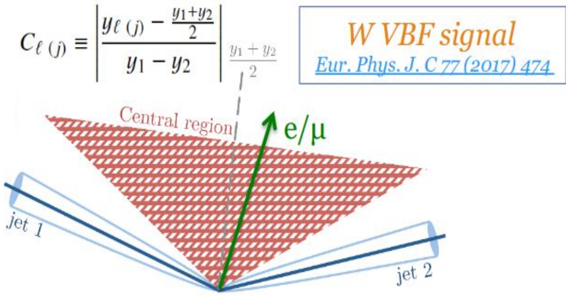
ATLAS ANALYSES

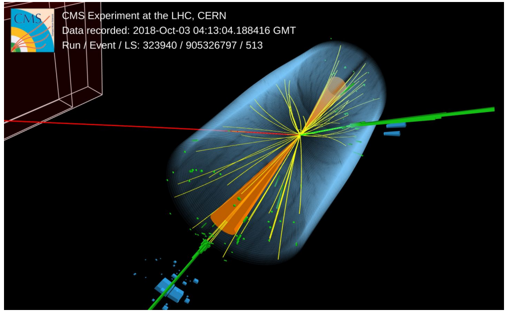
- **VBF Z+ two jets** (Eur. Phys. J. C 81 (2021) 163) - Differential cross-section measurements for the electroweak production of dijets in association withaZboson in proton–proton collisions at ATLAS
- **VBS $W^{\pm}W^{\pm}$** (Phys. Rev. Lett. 123 (2019) 161801) - Observation of electroweak production of a same-sign W boson pair in association with two jets in pp collisions at $\sqrt{s}$=13 TeV with the ATLAS detector
- **VBS WZ** (Phys. Lett. B 793 (2019) 469) - 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
- **VBS VV** (Phys. Rev. D 100, 032007 (2019)) - Search for electroweak diboson production in association with a high-mass dijet system in semileptonic final states in pp collisions at $\sqrt{s}$=13 TeV with the ATLAS detector
- **VBS ZZ** (2004.10612) - Observation of electroweak production of two jets and a Z-boson pair with the ATLAS detector at the LHC

A big thanks to Guillelmo(CMS) and Monica(ATLAS)!

Higgs Boson lone player responsible for Electroweak Symmetry Breaking ?

- Measurements of **vector boson fusion (VBF) and vector boson scattering (VBS) processes** → Key processes to test SM EW sector and to experimentally probe nature of EWSB
  - VBF with Z/W is a ‘standard candle’ for the other fusion processes at LHC (e.g. Higgs production)
  - VBS production cross-section can be used to probe how Higgs unitarizes the scattering amplitude
- **VBF and VBS topology**
  - Two high energy hadronic jets (large dijet mass) in forward and backward regions
  - Hadronic activity suppressed inside rapidity gap due to absence of colour flow between interacting partons
- **Experimental Analysis**
  - Select EW V/VV events
  - Estimate non-EW V/VV backgrounds
    - Combination of simulation and data driven techniques
  - Measurements
    - Inclusive and Differential Cross section Measurements
    - Search for anomalous Gauge Couplings



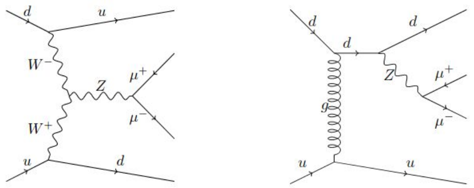


CMS VBF Z+2jets 2016 dataset: Overview

Published in EPJC

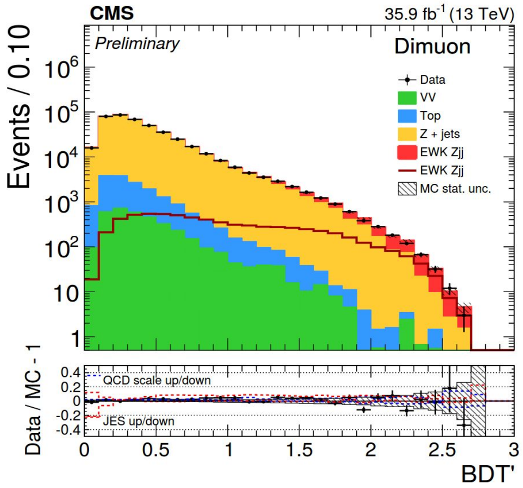
EPJC 78 (2018) 589

- The EWK Z+2jets process - Important SM benchmark to measure
  - Cross check and validate other VBF productions
- VBF Z process :
  - Central Z decay associated with energetic forward-backward jets
  - Large invariant dijet mass and large η separation between the tagging jets
- Pure EWK process :
  - Suppressed color flow between the quark-jets using QGL discriminator
  - Low hadronic activity in the central part of the detector
- Background Estimation
  - DY(major background)
    - MVA is used to discriminate signal & background
    - Independently in the di-electron and di-muon channels
  - Other backgrounds (top, WW, ZZ, WZ, ttbar)
    - Estimated from simulation
- Study of hadronic activity in tag-jet rapidity gap
  - Good agreement between data and QCD predictions

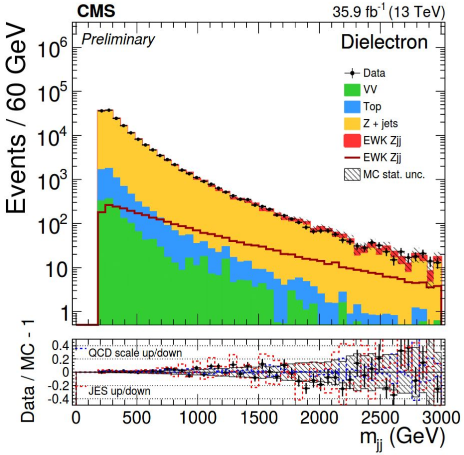


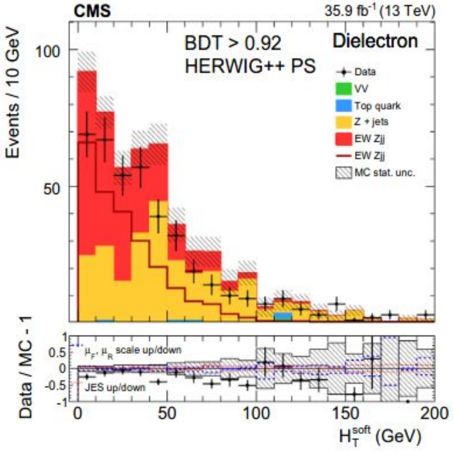
VBF EWK production

DY background



CMS Z+2jets: Results





Signal Strength

dielectron:	$\mu = 0.96 \pm 0.06\,(\text{stat}) \pm 0.13\,(\text{syst}) = 0.96 \pm 0.14\,(\text{total}),$
dimuon:	$\mu = 0.97 \pm 0.04\,(\text{stat}) \pm 0.11\,(\text{syst}) = 0.97 \pm 0.12\,(\text{total}),$
combined:	$\mu = 0.98 \pm 0.04\,(\text{stat}) \pm 0.10\,(\text{syst}) = 0.98 \pm 0.11\,(\text{total}),$

Signal is defined in the kinematic region with m_{ll}>50 GeV, p_T^j>25 GeV, m_{jj}>120 GeV and $|\eta_l|$<2.4

YIELDS

Sample	Initial		BDT > 0.92	
	ee	$\mu\mu$	ee	$\mu\mu$
WW	62 ± 16	116 ± 22	–	–
WZ	914 ± 38	2151 ± 63	1.6 ± 1.6	1.8 ± 1.8
ZZ	522 ± 17	1324 ± 29	1.8 ± 1.1	2.7 ± 1.3
$t\bar{t}$	5363 ± 48	12938 ± 81	7.1 ± 1.9	7.1 ± 1.9
Single top quark	269 ± 18	723 ± 31	–	–
W + jets	34 ± 5	36 ± 5	–	–
DY Zjj	152750 ± 510	394640 ± 880	273 ± 20	493 ± 31
Total backgrounds	159890 ± 510	411890 ± 890	283 ± 29	505 ± 43
EW Zjj signal	2833 ± 10	6665 ± 16	194.9 ± 2.6	379.7 ± 3.9
Data	163640	422499	418	892

Fiducial Cross section Measurements

dielectron: $\sigma(\text{EW}\ \ell\ell jj) = 521 \pm 34\,(\text{stat}) \pm 68\,(\text{syst})\,\text{fb} = 521 \pm 76\,(\text{total})\,\text{fb}.$

dimuon: $\sigma(\text{EW}\ \ell\ell jj) = 524 \pm 23\,(\text{stat}) \pm 61\,(\text{syst})\,\text{fb} = 524 \pm 65\,(\text{total})\,\text{fb}.$

combined: $\sigma(\text{EW}\ \ell\ell jj) = 534 \pm 20\,(\text{stat}) \pm 57\,(\text{syst})\,\text{fb} = 534 \pm 60\,(\text{total})\,\text{fb},$

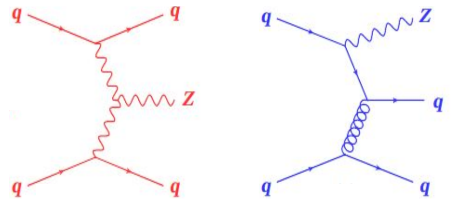
In agreement with SM prediction: $\sigma_{LO}(\text{EW}\ \ell\ell jj) = 543 \pm 24\,\text{fb}$

ATLAS Z+2jets full Run II dataset: Overview

- Differential Cross section measurement
  - Observables : m_{jj}, $|\Delta y_{jj}|$, $\Delta\phi_{jj}$, and p_T^{ll}
  - Both the EW and EW+QCD cross sections are extracted for several different phase spaces
- Determine which event generator predictions can be used reliably in analyses that seek to exploit VBF and VBS at the LHC
  - Theoretical predictions calculated using Powheg+Pythia8, Herwig7+Vbfnlo and Sherpa2.2
- Background Estimation
  - Data-driven method used to constrain both the shape and normalisation of the strong Zjj background
    - Data split into four regions by imposing criteria on Z centrality ξ_Z [*] and multiplicity of jets in the rapidity interval between the leading and subleading jets, N^{gap}_{jets}
  - EW Zjj event yield is measured in the EW-enhanced SR using a binned maximum-likelihood fit

Published in EPJC

Eur. Phys. J. C 81 (2021) 163



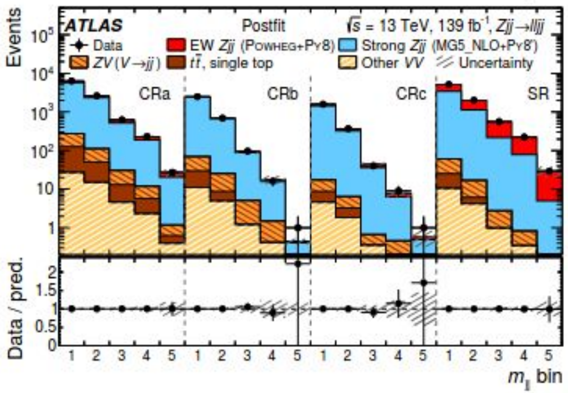
EWK production | QCD background

Event Selection

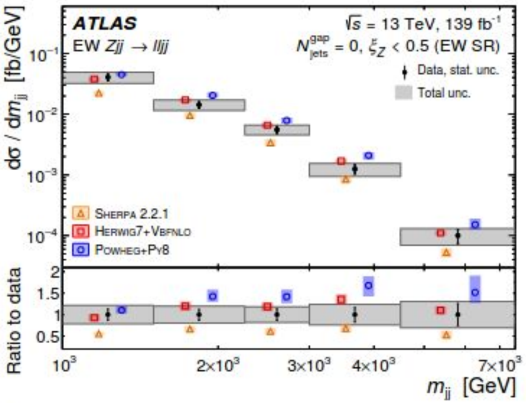
Dressed muons	$p_T > 25$ GeV and $|\eta| < 2.4$
Dressed electrons	$p_T > 25$ GeV and $|\eta| < 2.47$ (excluding $1.37 < |\eta| < 1.52$)
Jets	$p_T > 25$ GeV and $|y| < 4.4$
VBF topology	$N_\ell = 2$ (same flavour, opposite charge), $m_{\ell\ell} \in (81, 101)$ GeV $\Delta R_{min}(\ell_1, j) > 0.4$, $\Delta R_{min}(\ell_2, j) > 0.4$ $N_{jets} \geq 2$, $p_T^{j1} > 85$ GeV, $p_T^{j2} > 80$ GeV $p_{T,\ell\ell} > 20$ GeV, $p_T^{bal} < 0.15$ $m_{jj} > 1000$ GeV, $|\Delta y_{jj}| > 2$, $\xi_Z < 1$
CRa	VBF topology $\oplus$ $N^{gap}_{jets} \geq 1$ and $\xi_Z < 0.5$
CRb	VBF topology $\oplus$ $N^{gap}_{jets} \geq 1$ and $\xi_Z > 0.5$
CRc	VBF topology $\oplus$ $N^{gap}_{jets} = 0$ and $\xi_Z > 0.5$
SR	VBF topology $\oplus$ $N^{gap}_{jets} = 0$ and $\xi_Z < 0.5$

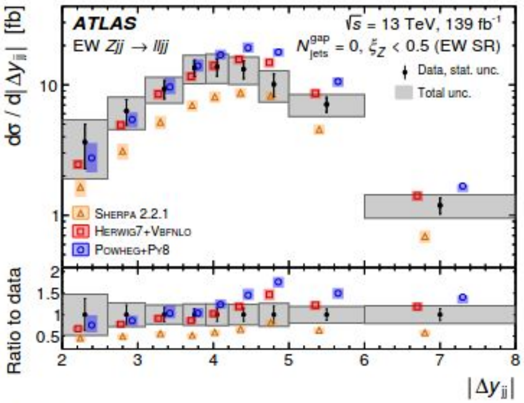
* $\xi_Z = |y_{\ell\ell} - 0.5(y_{j1} + y_{j2})| / |\Delta y_{jj}|$

ATLAS Z+2jets: Results

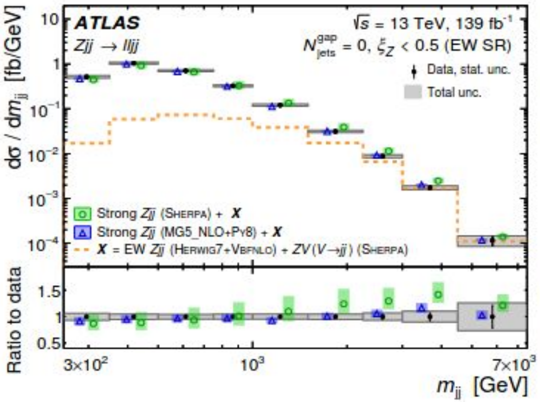


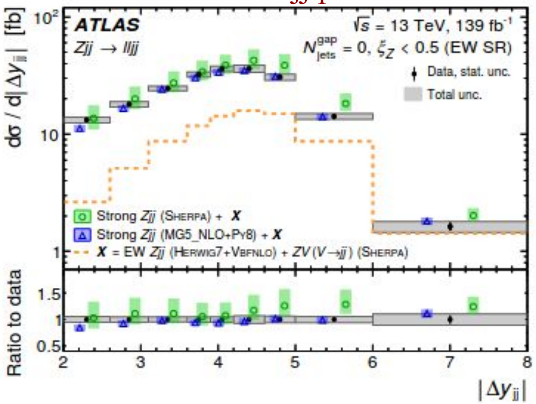
Differential cross-sections for EW Zjj production





Differential cross-sections in the SR for inclusive Zjj production





Fiducial Cross section Measurements

Calculated by integrating the differential cross-section as a function of m_{jj}

$$\sigma_{EW} = 37.4 \pm 3.5\,(\text{stat}) \pm 5.5\,(\text{syst})\ \text{fb}.$$

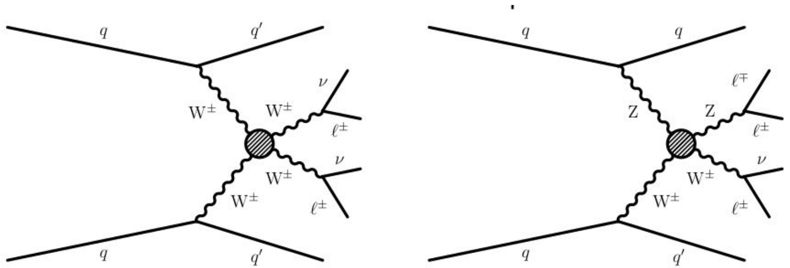
excellent agreement with the theoretical prediction from

HERWIG7+VBFNLO, $39.5 \pm 3.4\,(\text{scale}) \pm 1.2\,(\text{PDF})$ fb.

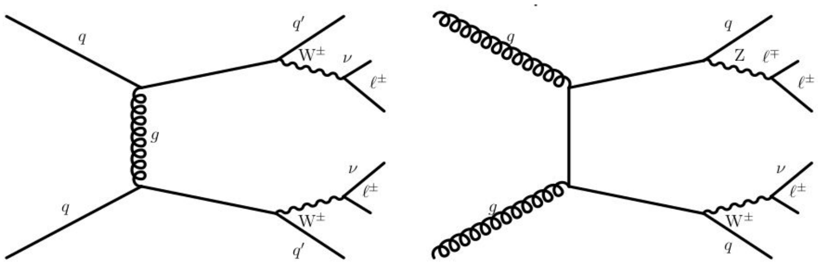
- **Why $W^\pm W^\pm jj$?**
  - EW production dominant over QCD-induced
  - Distinct same-sign (SS) lepton state with low background
- **Why WZjj ?**
  - Sensitive to charged resonances or couplings
  - Clean signature but higher background compared to $W^\pm W^\pm$

★ CMS - First simultaneous $W^\pm W^\pm jj$ & WZjj analyses using fully leptonic final states (exploiting full Run II data) *Published in Phys. Lett. B*

PLB 809(2020) 135710



EWK production



QCD production

CMS $W^{\pm}W^{\pm}$ & WZ: Event Selection & Background Estimation

EVENT SELECTION IN SIGNAL REGIONS

Variable	SSWW	WZ
leptons	2 SS, $P_T > 25/20$ GeV	1 OS pair + 1, $P_T > 25/10/20$ GeV
$\lvert m_{\ell\ell} - m_Z \rvert$	> 15 GeV for ee	< 15 GeV
$m_{\ell\ell}$	> 20 GeV	-
$m_{\ell\ell\ell}$	-	>100GeV
p_T^j	> 50GeV	> 50GeV
p_T^{miss}	> 30 GeV	> 30 GeV
Anti b-tagging	applied	applied
tau veto	applied	applied
$\max(z^*_\ell)$	<0.75	<1.0
m_{jj}	> 500GeV	> 500GeV
$\lvert \Delta\eta_{jj} \rvert$	> 2.5	> 2.5

$z^*_\ell = \lvert \eta_\ell - (\eta_{j1} + \eta_{j2})/2 \rvert / \lvert \Delta\eta_{jj} \rvert$

BACKGROUND ESTIMATION :

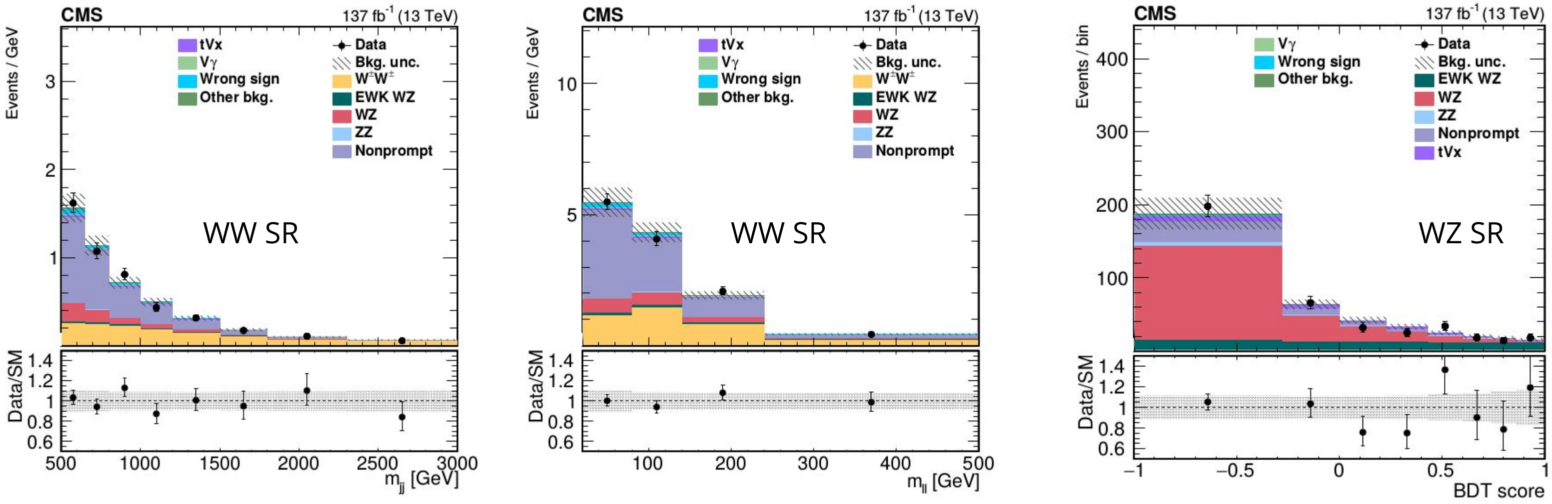
- ➔ Backgrounds estimated from simulation marked with [*] have **normalization assessed from data,** others are normalized to the best theoretical cross section prediction
- ➔ In all cases where simulation is used, events are reweighted to correct for the pileup, lepton and trigger efficiencies to agree with the data distribution

- WW SR is dominated by the EW signal process after the kinematic selection
- WZ SR is dominated by QCD WZ events after the kinematic selection
- **MultiVariate Analysis for WZ** → enhance WZ EWK production w.r.t large WZ QCD production
- Overall good separation between EWK signal and background

BACKGROUNDS

Category	Estimation
Non Prompt	From Data-Driven technique - from fake rates and "Tight+Loose" "Loose+Loose" data events
Wrong sign	From charge mis-ID scale factors and simulated opposite sign events
QCD WZ[*], ZZ[*], tZq[*], WW QCD, WW DPS, VVV	From simulation

CMS $W^{\pm}W^{\pm}$ & WZ: Results



Simultaneously fitting signal yields in WW & WZ signal regions as well as background yields in control regions (Non prompt, WZb(tZq) and ZZ), to assess normalization from data

YIELDS

Process	$W^{\pm}W^{\pm}$ SR		WZ SR	
	Pre-fit	Post-fit	Pre-fit	Post-fit
Total SM	535 ± 60	522 ± 49	216 ± 12	229 ± 23
Data	524		229	

UNCERTAINTIES

Source of uncertainty	$W^{\pm}W^{\pm}$ (%)	WZ (%)
Total systematic uncertainty	5.7	7.9
Statistical uncertainty	8.9	22
Total uncertainty	11	23

CMS $W^{\pm}W^{\pm}$ & WZ: Results

Published in Phys. Lett. B

[PLB 809(2020) 135710]

Inclusive Fiducial Cross section Measurements

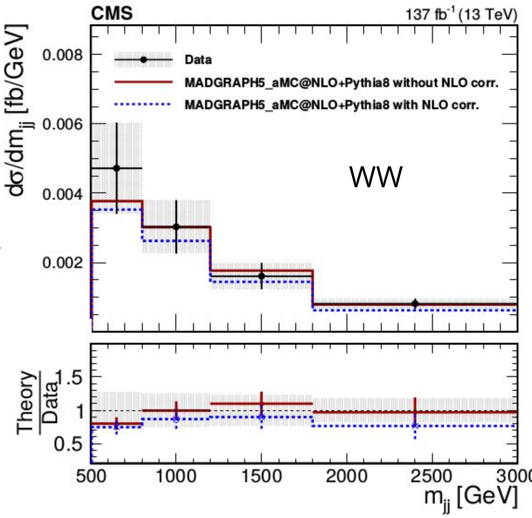
Process	$\sigma\,\mathcal{B}$ (fb)	Theoretical prediction without NLO corrections (fb)	Theoretical prediction with NLO corrections (fb)
EW $W^{\pm}W^{\pm}$	3.98 ± 0.45 $0.37\,(\text{stat}) \pm 0.25\,(\text{syst})$	3.93 ± 0.57	3.31 ± 0.47
EW+QCD $W^{\pm}W^{\pm}$	4.42 ± 0.47 $0.39\,(\text{stat}) \pm 0.25\,(\text{syst})$	4.34 ± 0.69	3.72 ± 0.59
EW WZ	1.81 ± 0.41 $0.39\,(\text{stat}) \pm 0.14\,(\text{syst})$	1.41 ± 0.21	1.24 ± 0.18
EW+QCD WZ	4.97 ± 0.46 $0.40\,(\text{stat}) \pm 0.23\,(\text{syst})$	4.54 ± 0.90	4.36 ± 0.88
QCD WZ	3.15 ± 0.49 $0.45\,(\text{stat}) \pm 0.18\,(\text{syst})$	3.12 ± 0.70	3.12 ± 0.70

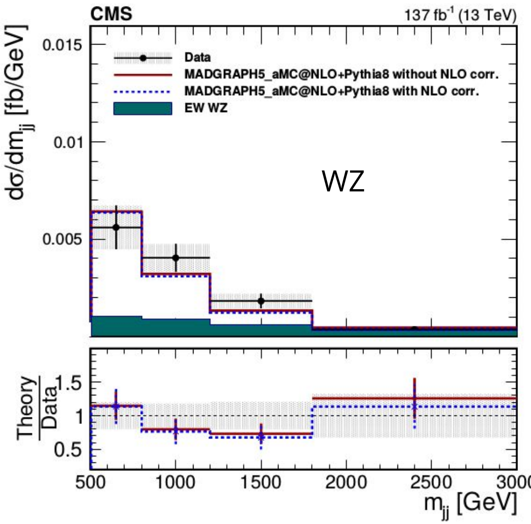
Significance Obs(Exp)

EWK WZ : 6.8 (5.3) σ

EWK WW : >> 5 σ

Absolute and normalized - WW (EWK+QCD) differential cross section measurements on m_{jj} (left plot), m_{ll} & p_T^{max} and WZ (EWK+QCD) differential cross section measurements on m_{jj} (right plot)





ATLAS $W^{\pm}W^{\pm}$ VBS 2015+2016 dataset: Results

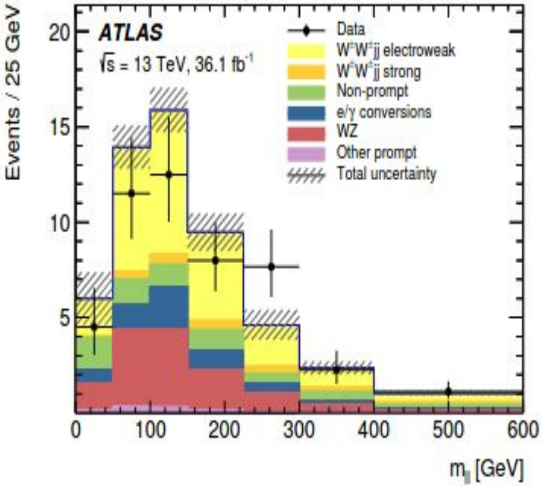
Published in PRL

Phys. Rev. Lett. 123 (2019) 161801

- Inclusive Cross section Measurement
- Kinematic selection cuts and background estimation - almost same as CMS analysis

YIELDS

	e^+e^+	e^-e^-	$e^+\mu^+$	$e^-\mu^-$	$\mu^+\mu^+$	$\mu^-\mu^-$	Combined
WZ	1.48 ± 0.32	1.09 ± 0.27	11.6 ± 1.9	7.9 ± 1.4	5.0 ± 0.7	3.4 ± 0.6	30 ± 4
Non-prompt	2.2 ± 1.1	1.2 ± 0.6	5.9 ± 2.5	4.7 ± 1.6	0.56 ± 0.05	0.68 ± 0.13	15 ± 5
e/γ conversions	1.6 ± 0.4	1.6 ± 0.4	6.3 ± 1.6	4.3 ± 1.1	—	—	13.9 ± 2.9
Other prompt	0.16 ± 0.04	0.14 ± 0.04	0.90 ± 0.20	0.63 ± 0.14	0.39 ± 0.09	0.22 ± 0.05	2.4 ± 0.5
$W^{\pm}W^{\pm}jj$ strong	0.35 ± 0.13	0.15 ± 0.05	2.9 ± 1.0	1.2 ± 0.4	1.8 ± 0.6	0.76 ± 0.25	7.2 ± 2.3
Expected background	5.8 ± 1.4	4.1 ± 1.1	28 ± 4	18.8 ± 2.6	7.7 ± 0.9	5.1 ± 0.6	69 ± 7
$W^{\pm}W^{\pm}jj$ electroweak	5.6 ± 1.0	2.2 ± 0.4	24 ± 5	9.4 ± 1.8	13.4 ± 2.5	5.1 ± 1.0	60 ± 11
Data	10	4	44	28	25	11	122



Significance

EWK WW : 6.5 σ (obs.)

Inclusive Fiducial Cross section Measurements

$$\sigma^{\text{fid.}} = 2.89^{+0.51}_{-0.48}\,(\text{stat.})\,^{+0.24}_{-0.22}\,(\text{exp. syst.})\,^{+0.14}_{-0.16}\,(\text{mod. syst.})\,^{+0.08}_{-0.06}\,(\text{lumi.})\text{ fb},$$

★ 2015 dataset contributes about 10% to the total dataset

ATLAS WZ VBS 2015+2016 dataset: Results

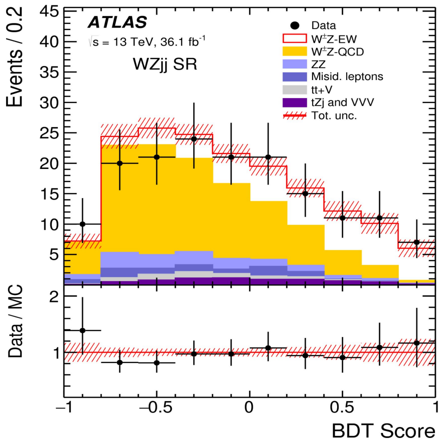
Published in PLB

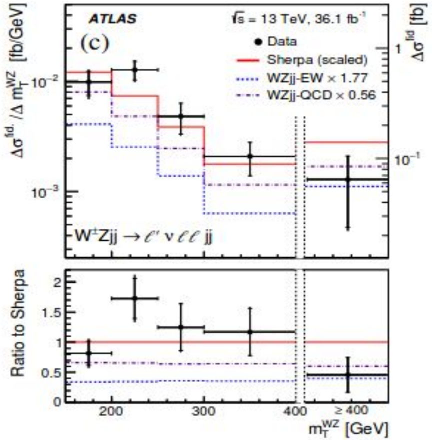
[Phys. Lett. B 793 (2019) 469]

- Inclusive and Differential Cross section Measurements
- Kinematic selection cuts and background estimation - almost same as CMS analysis
  - BDT score in the WZ SR is used to extract the significance of the EW WZ signal and to measure its fiducial cross-section via a maximum likelihood fit

YIELDS

	SR	
Data	161	
Total predicted	167	± 11
$WZjj$–EW (signal)	44	± 11
$WZjj$–QCD	91	± 10
Misid. leptons	7.8	± 3.2
$ZZjj$–QCD	11.1	± 2.8
tZj	6.2	± 1.1
$t\bar{t}+V$	4.7	± 1.0
$ZZjj$–EW	1.80	± 0.45
VVV	0.59	± 0.15





Significance Obs(Exp)

EWK WZ : 5.3 (3.2)σ

Inclusive Fiducial Cross section Measurements

EW

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

LO

$$\sigma^{\text{fid., MadGraph}}_{WZjj\text{–EW}} = 0.366 \pm 0.004\,(\text{stat.})\ \text{fb}$$

EW+ QCD

$$\sigma^{\text{fid.}}_{W^{\pm}Zjj} = 1.68 \pm 0.16\,(\text{stat.}) \pm 0.12\,(\text{exp. syst.}) \pm 0.13\,(\text{mod. syst.}) \pm 0.044\,(\text{lumi.})\ \text{fb}, \quad = 1.68 \pm 0.25\ \text{fb},$$

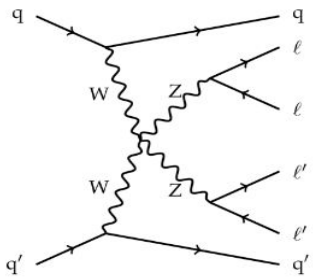
$$\sigma^{\text{fid., Sherpa}}_{W^{\pm}Zjj} = 2.15 \pm 0.01\,(\text{stat.}) \pm 0.05\,(\text{PDF})\,^{+0.65}_{-0.44}\,(\text{scale})\ \text{fb}.$$

CMS ZZ VBS Full Run II : Overview

Published in PLB

PLB 812 (2020) 135992

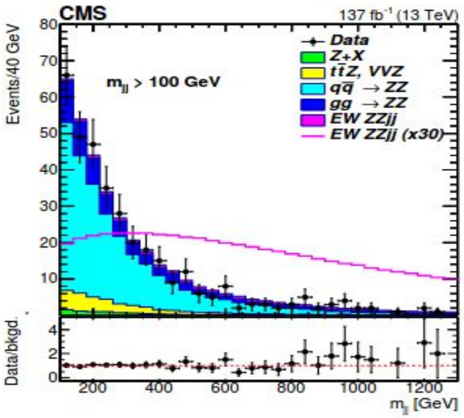
- Measurement of EW ZZjj production using 4ℓ events
  - Really clean, fully reconstructable final state
  - Small instrumental background
- Challenges
  - Small cross-section
  - Large QCD induced background
- Background Estimation
  - Irreducible Backgrounds
    - QCD ZZ , ttZ , VVZ → From MC
  - Reducible Backgrounds (Z+X)
    - Z+jets , tt+jets , WZ+jets → Data Driven
- Making use of a matrix-element discriminant (K_D) to enhance EW production
  - BDT was also studied - gave consistent results
- Define three regions to measure EW production
  - ZZjj inclusive
  - VBS-enriched loose
  - VBS-enriched tight

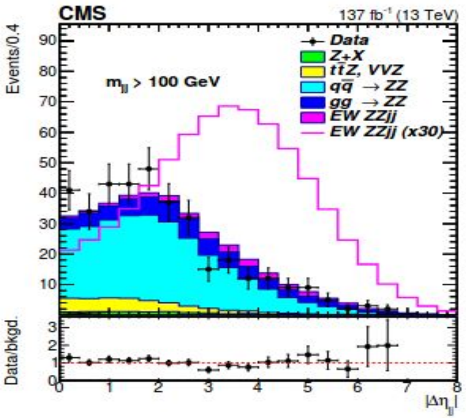


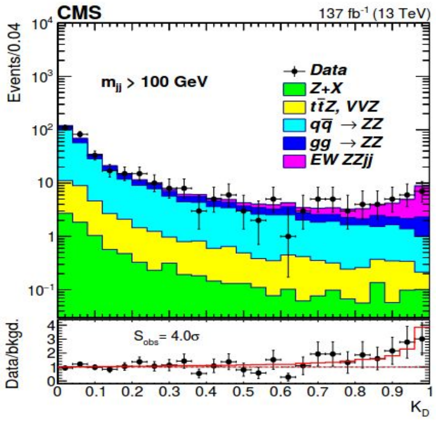
EWK production

Object	Selection
	ZZjj inclusive
Leptons	$p_T(\ell_1) > 20$ GeV $p_T(\ell_2) > 10$ GeV $p_T(\ell) > 5$ GeV $\|\eta(\ell)\| < 2.5$ (γ with $\Delta R(\ell,\gamma) < 0.1$ added to ℓ 4-vector)
Z and ZZ	$60 < m(\ell\ell) < 120$ GeV $m(4\ell) > 180$ GeV
Jets	at least 2 $p_T(j) > 30$ GeV $\|\eta(j)\| < 4.7$ $m_{jj} > 100$ GeV $\Delta R(\ell, j) > 0.4$ for each ℓ, j
	VBS-enriched (loose)
Jets	ZZjj inclusive + $\|\Delta\eta(jj)\| > 2.4$ $m_{jj} > 400$ GeV
	VBS-enriched (tight)
Jets	ZZjj inclusive + $\|\Delta\eta(jj)\| > 5$ $m_{jj} > 400$ GeV

CMS ZZ: Results







Inclusive Fiducial Cross section Measurements

	Perturbative order	SM σ (fb)	Measured σ (fb)
		ZZjj inclusive	
EW	LO	0.275 ± 0.021	$0.33^{+0.11}_{-0.10}$ (stat)$^{+0.04}_{-0.03}$ (syst)
	NLO QCD	0.278 ± 0.017	
	NLO EW	$0.242^{+0.015}_{-0.013}$	
EW+QCD		5.35 ± 0.51	$5.29^{+0.31}_{-0.30}$ (stat) $\pm$ 0.47 (syst)
		VBS-enriched (loose)	
EW	LO	0.186 ± 0.015	$0.180^{+0.070}_{-0.060}$ (stat)$^{+0.021}_{-0.012}$ (syst)
	NLO QCD	0.197 ± 0.013	
EW+QCD		1.21 ± 0.09	$1.00^{+0.12}_{-0.11}$ (stat) $\pm$ 0.07 (syst)
		VBS-enriched (tight)	
EW	LO	0.104 ± 0.008	$0.09^{+0.04}_{-0.03}$ (stat) $\pm$ 0.02 (syst)
	NLO QCD	0.108 ± 0.007	
EW+QCD		0.221 ± 0.014	$0.20^{+0.05}_{-0.04}$ (stat) $\pm$ 0.02 (syst)

Significance		Obs. (exp.)
EWK ZZ	:	4.0 (3.5) σ

ATLAS ZZ Full Run II: Overview

Submitted to Nature

arXiv:2004.10612

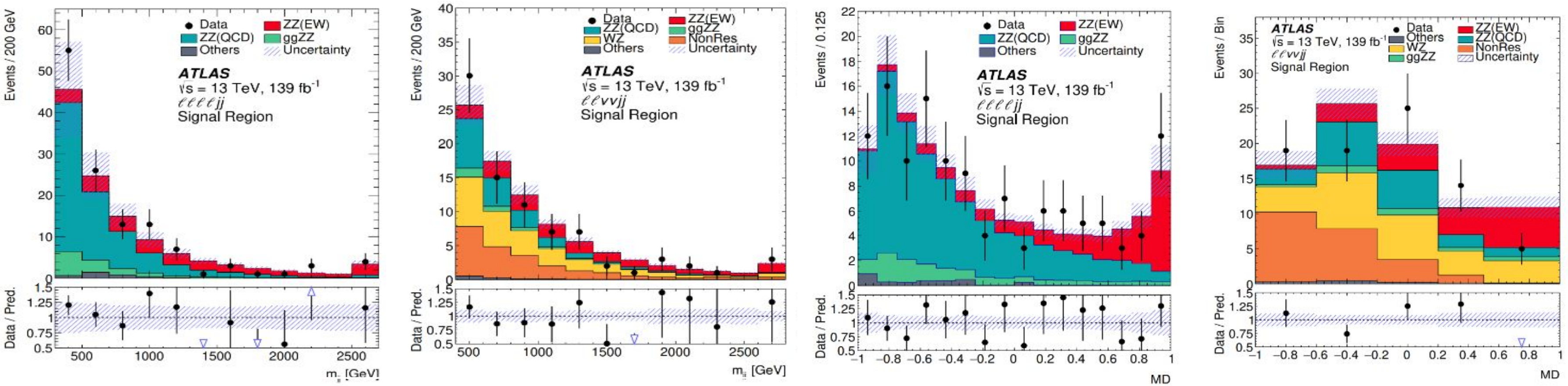
- Two ZZ decay channels: ZZ→4ℓ and ZZ→ℓℓνν
- 4ℓ channel: Small background contribution (~3%) from reducible backgrounds
  - QCD ZZjj: Large irreducible background. EW/QCD is ~20% level overall, MVA is needed
    - Estimated from simulation. Simulation is normalized to data in a EW-suppressed CR
  - Small backgrounds: Z+jets, top, WZjj
    - Data-driven: estimated using a fake-factor method
  - Minor backgrounds: triboson, ttV
    - Estimated from simulation
- ℓℓνν channel: More complicated backgrounds
  - WZjj
    - Constrained by a dedicated 3ℓ WZ CR
  - WWjj, top (non-resonant-ℓℓ backgrounds)
    - Estimated with events in dedicated $e\mu$ data CR
  - Z+jets
    - Largely suppressed with tight cut on the MET-significance[*]

Object Selection

	$\ell\ell\ell\ell jj$	$\ell\ell\nu\nu jj$
Electrons	$p_T > 7$ 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	$p_T > 7$ 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	$p_T > 7$ GeV, $\lvert\eta\rvert < 2.5$
Jets	$p_T > 30$ (40) GeV for $\lvert\eta\rvert < 2.4$ ($2.4 < \lvert\eta\rvert < 4.5$)	$p_T > 60$ (40) GeV for the leading (sub-leading) jet
ZZ selection	$p_T > 20, 20, 10$ 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	$p_T > 30$ (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_T^{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 $\Delta y(jj) > 2$

[*]MET significance is used to distinguish missing transverse energy arising from undetectable particles to object mis-reconstruction, finite detector resolution, or detector noise

ATLAS ZZ: Results



EW and QCD Signal strength from fitting, and the EW ZZjj production significant

	μ_{EW}	$\mu_{QCD}^{\ell\ell\ell\ell jj}$	Significance Obs. (Exp.)
$\ell\ell\ell\ell jj$	1.5 ± 0.4	0.95 ± 0.22	$5.5\ (3.9)\ \sigma$
$\ell\ell\nu\nu jj$	0.7 ± 0.7	–	$1.2\ (1.8)\ \sigma$
Combined	1.35 ± 0.34	0.96 ± 0.22	$5.5\ (4.3)\ \sigma$

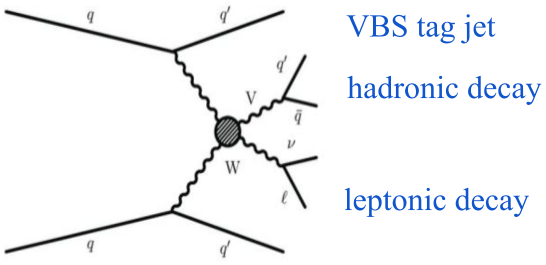
μ_{EW} is POI, μ_{QCD} (4ℓ channel) is used as a free parameter in the fit to constrain QCD normalization

Inclusive Fiducial Cross section Measurements

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

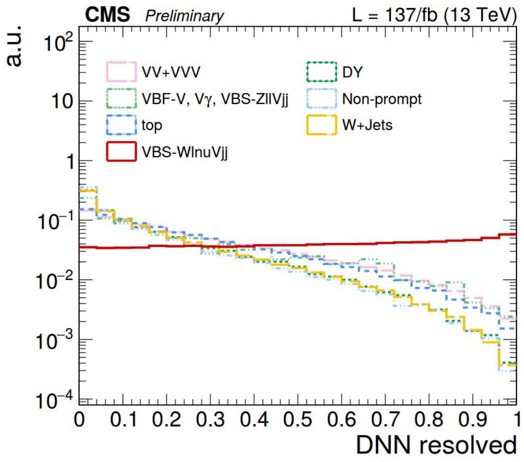
CMS-PAS-SMP-20-013

- First evidence of VBS in the semileptonic channel at LHC!
  - Purely EW process at LO with 6 fermions in final state
  - One V boson decay leptonically and other hadronically
  - Jets from initial scattering partons used to tag the VBS topology
  - Both resolved and boosted decay regimes of hadronic V bosons are combined in the analysis



EWK production

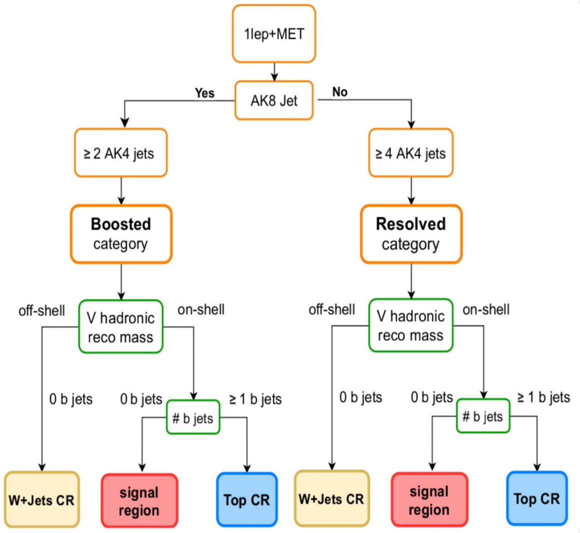
- DNN models are trained for resolved and boosted category to separate signal and backgrounds
  - DNN architecture 4 layers of 64(32) nodes for resolved(boosted) category models
  - 14 input variables
  - Trained with Adam optimizer[*], dropouts and L2 weights regularization to avoid overtraining.



[*] Ref. 1

CMS WV semileptonic: Analysis Strategy & Bkgd Estimation

Analysis cut flow and categories

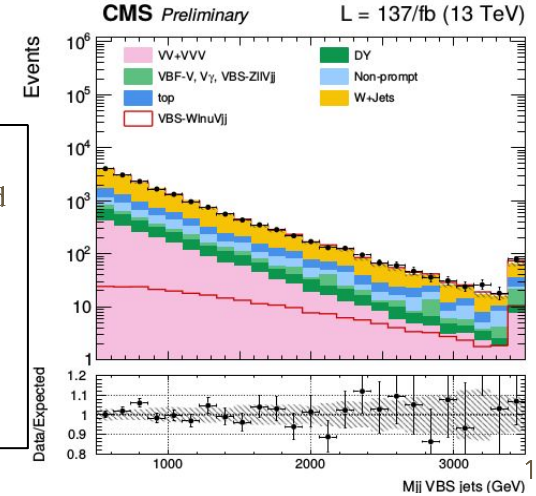


Combined likelihood ratio fit performed on the DNN distributions in the SR and measuring the W+jets and top contributions in the dedicated CRs

Background Estimation

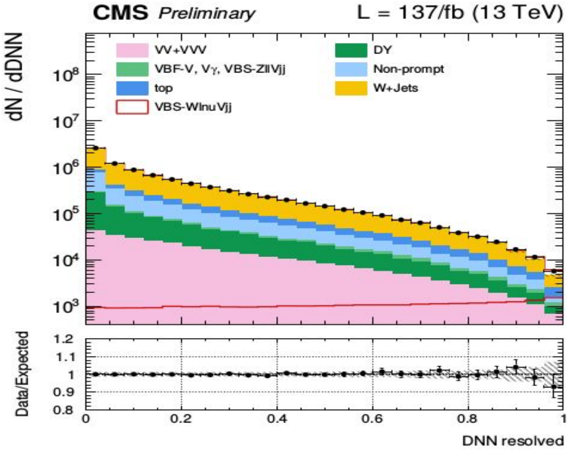
- QCD multijet background
  - From Data-driven
- W+jets and Top
  - From Simulation but data-driven technique is applied to improve the modelling
- Minor backgrounds contribution, e.g. DY, VBF-V, VVV, Vγ processes
  - From Simulation

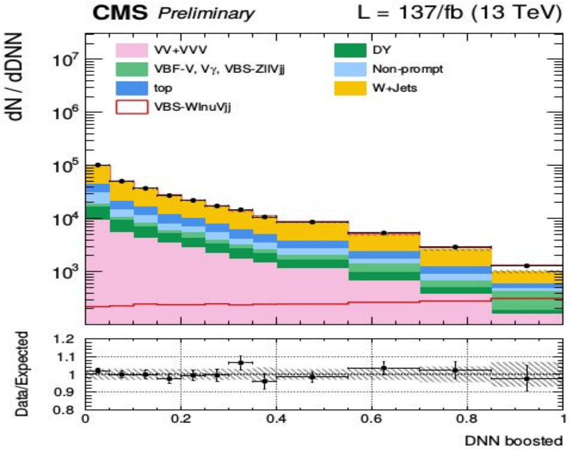
- Postfit distributions of VBS tag jet invariant mass in the boosted category
- One of most important observables for the signal extraction, as evaluated using the SHAP[*] explanation techniques on the DNN models

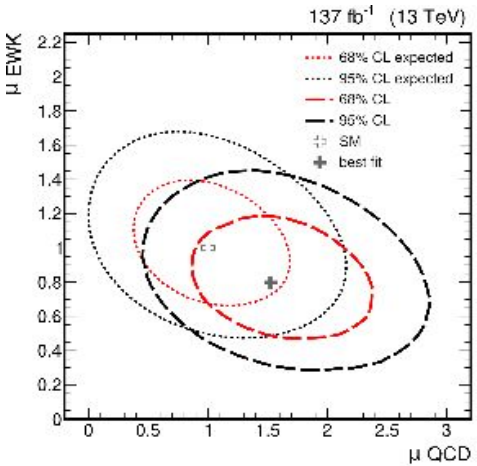


[*] Ref. 1 Ref. 2

CMS WV semileptonic: Results







Signal Strength

$$\mu_{EW} = \sigma^{obs}/\sigma^{SM} = 0.85^{+0.24}_{-0.20} = 0.85^{+0.21}_{-0.17}(\text{syst})\ ^{+0.12}_{-0.12}(\text{stat}),$$
$$\mu_{EW+QCD} = \sigma^{obs}/\sigma^{SM} = 0.98^{+0.20}_{-0.17} = 0.98^{+0.19}_{-0.16}(\text{syst})\ ^{+0.07}_{-0.07}(\text{stat})$$

Fiducial Cross section Measurements

EW 1.9 ± 0.5 pb, $2.23^{+0.08}_{-0.11}(\text{scale})\ ^{+0.05}_{-0.05}(\text{pdf})$ pb expected.

EW+QCD $16.6^{+3.4}_{-2.9}$ pb, $16.9^{+2.9}_{-2.1}(\text{scale})\ ^{+0.5}_{-0.5}(\text{pdf})$ expected.

Significance Obs(Exp)
EWK WV : 4.4(5.1)σ

ATLAS VV VBS 2015+2016 dataset: Overview

Published in PRD

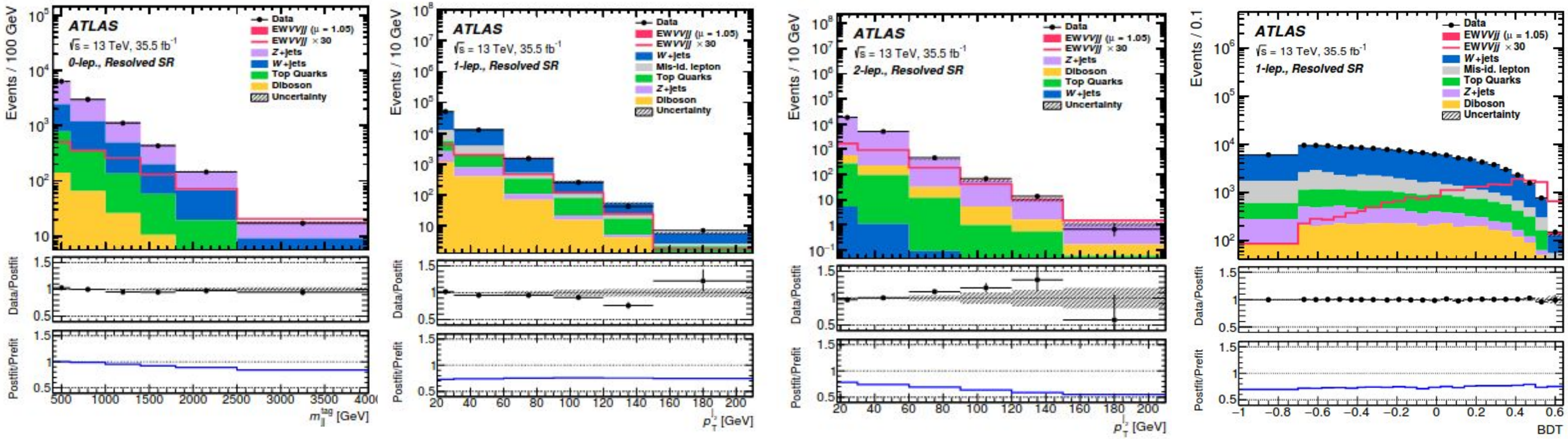
Phys. Rev. D 100, 032007 (2019)

- Three final states
  - ZV→ννqq, WV→ℓνqq and ZV→ℓℓqq
  - Events are categorized into the 0, 1 and 2 lepton channels
  - Two different reconstruction techniques are considered : resolved and merged (as in CMS)
- Background Estimation
  - Estimated using a combination of MC and data-driven techniques
  - 1-lepton channel
    - W+ jets and ttbar production(dominant)
  - 2-lepton channel
    - Z+ jets production(dominant)
  - 0-lepton channel
    - All backgrounds contribute significantly
    - Multijet -smaller background
- Single-top and QCD-induced diboson production - small background for all three lepton channels
- MVA is used
  - BDTs input variables are chosen in order to maximize the separation between signal and background
  - good agreement between data and simulation

Event Selection

Selection	0-lepton	1-lepton	2-lepton
Trigger	E_T^{miss} triggers	Single-electron triggers Single-muon or E_T^{miss} triggers	Single-lepton triggers
Leptons	0 'loose' leptons with $p_T > 7$ GeV	1 'tight' lepton with $p_T > 27$ GeV 0 'loose' leptons with $p_T > 7$ GeV	2 'loose' leptons with $p_T > 20$ GeV ≥ 1 lepton with $p_T > 28$ GeV
E_T^{miss}	> 200 GeV	> 80 GeV	–
$m_{\ell\ell}$	–	–	$83 < m_{ee} < 99$ GeV $(-0.0117 \times p_T^{\mu\mu} + 85.63\text{ GeV}) < m_{\mu\mu} < (0.0185 \times p_T^{\mu\mu} + 94\text{ GeV})$
Small-*R* jets	$p_T > 20$ GeV if $\|\eta\| < 2.5$, and $p_T > 30$ GeV if $2.5 < \|\eta\| < 4.5$		
Large-*R* jets	$p_T > 200$ GeV, $\|\eta\| < 2$		
$V_{had} \to J$ $V_{had} \to jj$	V boson tagging, $\min(\|m_J - m_W\|, \|m_J - m_Z\|)$ $64 < m_{jj} < 106$ GeV, jj pair with $\min(\|m_{jj} - m_W\|, \|m_{jj} - m_Z\|)$, leading jet with $p_T > 40$ GeV		
Tagging-jets	$j \notin V_{had}$, not b-tagged, $\Delta R(J, j) > 1.4$ $\eta_{tag,j_1} \cdot \eta_{tag,j_2} < 0$, $m_{jj}^{tag} > 400$ GeV, $p_T > 30$ GeV		
Num. of b-jets	–	0	–
Multijet removal	$p_T^{miss} > 50$ GeV $\Delta\phi(\vec{E}_T^{miss}, \vec{p}_T^{miss}) < \pi/2$ $\min[\Delta\phi(\vec{E}_T^{miss}, \text{small-}R\text{ jet})] > \pi/6$ $\Delta\phi(\vec{E}_T^{miss}, V_{had}) > \pi/9$	–	–

ATLAS VV VBS: Results



Signal Strength

$$\mu^{obs}_{EW\,VVjj} = 1.05 \pm 0.20(\text{stat.})^{+0.37}_{-0.34}(\text{syst.})$$

Significance Obs(Exp)

EWK VV : 2.7(2.5)σ

Fiducial Cross section Measurements

Fiducial phase space	Predicted $\sigma^{\text{fid,SM}}_{\text{EW}\,VVjj}$ [fb]	Measured $\sigma^{\text{fid,obs}}_{\text{EW}\,VVjj}$ [fb]
Merged	11.4 ± 0.7 (theo.)	12.7 ± 3.8 (stat.) $^{+4.8}_{-4.2}$ (syst.)
Resolved	31.6 ± 1.8 (theo.)	26.5 ± 8.2 (stat.) $^{+17.4}_{-17.1}$ (syst.)
Inclusive	43.0 ± 2.4 (theo.)	45.1 ± 8.6 (stat.) $^{+15.9}_{-14.6}$ (syst.)

Searches for Anomalous Couplings

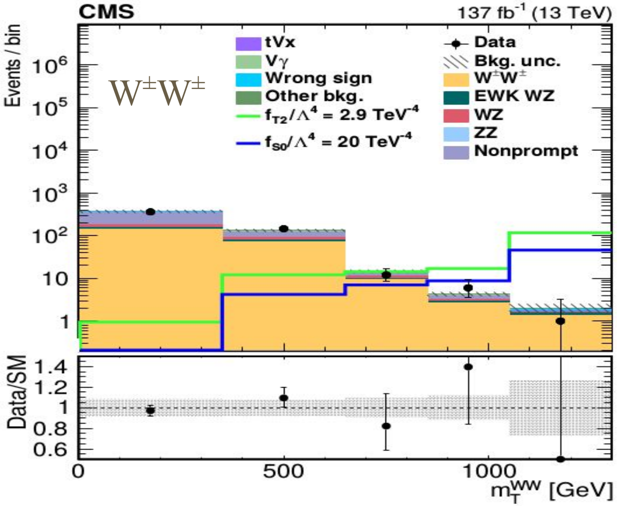
- ★ Limits on Anomalous Trilinear and Quartic Gauge Couplings associated with dimension-six and dimension-eight operators are given in the framework of an Effective Field Theory (EFT)

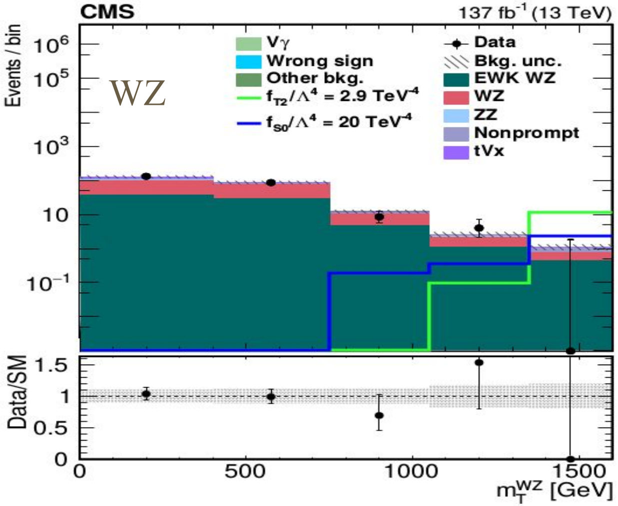
- ★ Covered in more detail in Saptaparna's talk tomorrow - Searches for New Physics in multi-boson events using both anomalous coupling and effective field theory approaches

- ★ SMP-19-012(CMS $W^{\pm}W^{\pm}$ & WZ): Highlight of this aQGC analysis - "Clipping method"

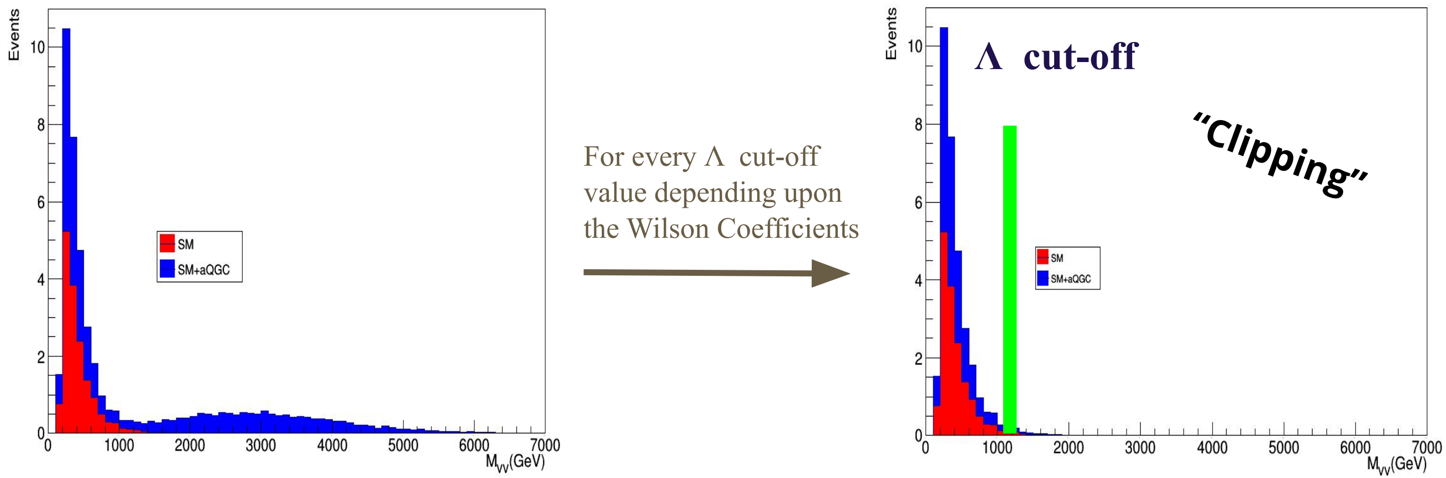
CMS aQGCs: Overview ($W^{\pm}W^{\pm}$ & WZ VBS Full Run II)

- Extensions of the Standard Model induce coupling modifications that can be parameterized in terms of the Effective Field Theory (EFT) approach.
- In this analysis, limits on **aQGCs** are set via EFT approach. Dimension-8 operators that can modify VVjj production through aQGCs are considered; one at a time
- Fitted regions and bins: different from SM analysis due to sensitivity and statistics





CMS aQGCs: Clipping Technique



- Measured signal is in general a sum of $M_{VV} < \Lambda$(unitarity limit) and $M_{VV} > \Lambda$. The only way to correctly use EFT is to make sure the region $M_{VV} > \Lambda$ does not significantly contribute
- Most conservative estimate = "clip" the generated aQGC distribution: take only SM contribution above Λ. This is the practical equivalent of not using data above Λ
- The technique is known as "Clipping", and essentially means using EFT only in the region it is valid
  - Implementation of "Clipping" in CMS Results
  - For aqgc simulation, events violating unitarity (vary with operator values) are rejected ~ max 80%(WW) & max 50%(WZ). Data & SM processes are not affected

CMS aQGCs: Results

$W^{\pm}W^{\pm}$ & WZ without considering unitarity bounds

	Observed ($W^{\pm}W^{\pm}$) (TeV^{-4})	Expected ($W^{\pm}W^{\pm}$) (TeV^{-4})	Observed (WZ) (TeV^{-4})	Expected (WZ) (TeV^{-4})	Observed (TeV^{-4})	Expected (TeV^{-4})
f_{T0}/Λ^4	[-0.28, 0.31]	[-0.36, 0.39]	[-0.62, 0.65]	[-0.82, 0.85]	[-0.25, 0.28]	[-0.35, 0.37]
f_{T1}/Λ^4	[-0.12, 0.15]	[-0.16, 0.19]	[-0.37, 0.41]	[-0.49, 0.55]	[-0.12, 0.14]	[-0.16, 0.19]
f_{T2}/Λ^4	[-0.38, 0.50]	[-0.50, 0.63]	[-1.0 , 1.3]	[-1.4, 1.7]	[-0.35, 0.48]	[-0.49, 0.63]
f_{M0}/Λ^4	[-3.0, 3.2]	[-3.7, 3.8]	[-5.8, 5.8]	[-7.6, 7.6]	[-2.7, 2.9]	[-3.6, 3.7]
f_{M1}/Λ^4	[-4.7, 4.7]	[-5.4, 5.8]	[-8.2, 8.3]	[-11, 11]	[-4.1, 4.2]	[-5.2, 5.5]
f_{M6}/Λ^4	[-6.0, 6.5]	[-7.5, 7.6]	[-12, 12]	[-15, 15]	[-5.4, 5.8]	[-7.2, 7.3]
f_{M7}/Λ^4	[-6.7, 7.0]	[-8.3, 8.1]	[-10, 10]	[-14, 14]	[-5.7, 6.0]	[-7.8, 7.6]
f_{S0}/Λ^4	[-6.0, 6.4]	[-6.0, 6.2]	[-19, 19]	[-24, 24]	[-5.7, 6.1]	[-5.9, 6.2]
f_{S1}/Λ^4	[-18, 19]	[-18, 19]	[-30, 30]	[-38, 39]	[-16, 17]	[-18, 18]

$W^{\pm}W^{\pm}$ & WZ with considering unitarity bounds

	Observed ($W^{\pm}W^{\pm}$) (TeV^{-4})	Expected ($W^{\pm}W^{\pm}$) (TeV^{-4})	Observed (WZ) (TeV^{-4})	Expected (WZ) (TeV^{-4})	Observed (TeV^{-4})	Expected (TeV^{-4})
f_{T0}/Λ^4	[-1.5, 2.3]	[-2.1, 2.7]	[-1.6, 1.9]	[-2.0, 2.2]	[-1.1, 1.6]	[-1.6, 2.0]
f_{T1}/Λ^4	[-0.81, 1.2]	[-0.98, 1.4]	[-1.3, 1.5]	[-1.6, 1.8]	[-0.69, 0.97]	[-0.94, 1.3]
f_{T2}/Λ^4	[-2.1, 4.4]	[-2.7, 5.3]	[-2.7, 3.4]	[-4.4, 5.5]	[-1.6, 3.1]	[-2.3, 3.8]
f_{M0}/Λ^4	[-13, 16]	[-19, 18]	[-16, 16]	[-19, 19]	[-11, 12]	[-15, 15]
f_{M1}/Λ^4	[-20, 19]	[-22, 25]	[-19, 20]	[-23, 24]	[-15, 14]	[-18, 20]
f_{M6}/Λ^4	[-27, 32]	[-37, 37]	[-34, 33]	[-39, 39]	[-22, 25]	[-31, 30]
f_{M7}/Λ^4	[-22, 24]	[-27, 25]	[-22, 22]	[-28, 28]	[-16, 18]	[-22, 21]
f_{S0}/Λ^4	[-35, 36]	[-31, 31]	[-83, 85]	[-88, 91]	[-34, 35]	[-31, 31]
f_{S1}/Λ^4	[-100, 120]	[-100, 110]	[-110, 110]	[-120, 130]	[-86, 99]	[-91, 97]

Summary

- CMS and ATLAS results on EWK single and diboson productions are presented
  - Inclusive fiducial cross section measurements in all channels
  - First Measurement of WV EW cross sections
  - First Differential cross sections measurements of $W^{\pm}W^{\pm}$ jj & WZjj processes on several distributions
  - The first observation of the EW ZZjj production with the ATLAS experiment
- Limits on dim-8 Wilson coefficients are set for anomalous quartic gauge couplings within the EFT validity for the first time

BACK UP

Z+2jets:Fiducial Definitions

CMS

The signal is defined in the kinematic region with dilepton invariant mass m_{ll}>50 GeV, parton transverse momentum p_T^j>25 GeV, diparton invariant mass m_{jj}>120 GeV and $|\eta|$<2.4

ATLAS

Dressed muons	$p_T > 25$ GeV and $\|\eta\| < 2.4$
Dressed electrons	$p_T > 25$ GeV and $\|\eta\| < 2.47$ (excluding $1.37 < \|\eta\| < 1.52$)
Jets	$p_T > 25$ GeV and $\|y\| < 4.4$
VBF topology	$N_\ell = 2$ (same flavour, opposite charge), $m_{\ell\ell} \in (81, 101)$ GeV $\Delta R_{\min}(\ell_1, j) > 0.4,\ \Delta R_{\min}(\ell_2, j) > 0.4$ $N_{\text{jets}} \geq 2,\ p_T^{j1} > 85$ GeV, $p_T^{j2} > 80$ GeV $p_{T,\ell\ell} > 20$ GeV, $p_T^{\text{bal}} < 0.15$ $m_{jj} > 1000$ GeV, $\|\Delta y_{jj}\| > 2,\ \xi_Z < 1$
CRa	VBF topology $\oplus N_{\text{jets}}^{\text{gap}} \geq 1$ and $\xi_Z < 0.5$
CRb	VBF topology $\oplus N_{\text{jets}}^{\text{gap}} \geq 1$ and $\xi_Z > 0.5$
CRc	VBF topology $\oplus N_{\text{jets}}^{\text{gap}} = 0$ and $\xi_Z > 0.5$
SR	VBF topology $\oplus N_{\text{jets}}^{\text{gap}} = 0$ and $\xi_Z < 0.5$

$W^{\pm}W^{\pm}$ & WZ VBS: Fiducial Definitions

CMS

- $W^{\pm}W^{\pm}$ fiducial region
  - Two same-sign leptons with a transverse momentum p_T>20 GeV, $|\eta|$<2.5 and m_{ll}>20 GeV
  - Two jets with p_T>50 GeV, m_{jj}>500 GeV, $|\eta|$<4.7 and a pseudo-rapidity difference$|\Delta\eta_{jj}|$>2.5
- WZ fiducial region
  - Three leptons with p_T>20 GeV,$|\eta|$<2.5, and opposite charge same-flavor lepton pair with $|m_{ll}$- $m_Z|$<15 GeV
  - Two jets with p_T>50 GeV, m_{jj}>500 GeV, $|\eta|$<4.7 and a pseudo-rapidity difference$|\Delta\eta_{jj}|$>2.5

ATLAS

- $W^{\pm}W^{\pm}$ fiducial region
  - Two same-sign leptons with a transverse momentum p_T>27 GeV and $|\eta|$<2.5
  - Two jets, one with p_T>65 GeV and another with p_T>35 GeV. The two highest-p_T jets must have an invariant mass m_{jj}>500 GeV and a rapidity difference$|\Delta y_{jj}|$>2
- WZ fiducial region
  - Leptons from Z decay should have p_T>25 GeV & lepton from W p_T>20 GeV, $|\eta|$<2.5, and opposite charge same-flavor lepton pair with $|m_{ll}$- $m_Z|$<10 GeV
  - Two jets with p_T>40 GeV and $|\eta|$<4.5

ZZ full Run II : Fiducial Definitions

CMS

Particle type	Selection
	ZZjj inclusive
Leptons	$p_T(\ell_1) > 20\,\text{GeV}$ $p_T(\ell_2) > 10\,\text{GeV}$ $p_T(\ell) > 5\,\text{GeV}$ $\lvert\eta(\ell)\rvert < 2.5$
Z and ZZ	$60 < m(\ell\ell) < 120\,\text{GeV}$ $m(4\ell) > 180\,\text{GeV}$
Jets	at least 2 $p_T(\text{j}) > 30\,\text{GeV}$ $\lvert\eta(\text{j})\rvert < 4.7$ $m_{\text{jj}} > 100\,\text{GeV}$ $\Delta R(\ell,\text{j}) > 0.4$ for each ℓ,j
	VBS-enriched (loose)
Jets	ZZjj inclusive + $\lvert\Delta\eta_{\text{jj}}\rvert > 2.4$ $m_{\text{jj}} > 400\,\text{GeV}$
	VBS-enriched (tight)
Jets	ZZjj inclusive + $\lvert\Delta\eta_{\text{jj}}\rvert > 2.4$ $m_{\text{jj}} > 1\,\text{TeV}$

ATLAS

- Fiducial regions are defined closely following the detector-level event selections, except
- 4ℓ channel:
  - Z window loose to [60, 120] GeV (is [66, 116] GeV for detector-level). This is to reduce migration effect and keep compatibility with the CMS publication
- $\ell\ell vv$ channel:
  - Lepton eta cuts harmonized to 2.5 for both electrons and muons
  - Generator level MET > 130 GeV instead of MET significance (difficult to define at truth level)

VV VBS: Fiducial Definitions

CMS

- WV fiducial region
  - At parton level requiring all partons to have p_T>10 GeV and at least one pair of outgoing quarks with invariant mass m_{qq} >100 GeV

ATLAS

Table 4: Fiducial phase-space definitions used for the measurement of electroweak $VVjj$ production.

Object selection		
Leptons		$p_T > 7$ GeV, $\lvert\eta\rvert < 2.5$
Small-R jets		$p_T > 20$ GeV if $\lvert\eta\rvert < 2.5$, and $p_T > 30$ GeV if $2.5 < \lvert\eta\rvert < 4.5$
Large-R jets		$p_T > 200$ GeV, $\lvert\eta\rvert < 2.0$
Event selection		
Leptonic V selection	0-lepton	Zero leptons, $p_T^{\nu\nu} > 200$ GeV
	1-lepton	One lepton with $p_T > 27$ GeV, $p_T^{\nu} > 80$ GeV
	2-lepton	Two leptons, with leading (subleading) lepton $p_T > 28$ (20) GeV $83 < m_{\ell\ell} < 99$ GeV
Hadronic V selection	Merged	One large-R jet, min($\lvert m_J - m_W\rvert, \lvert m_J - m_Z\rvert$) $64 < m_J < 106$ GeV
	Resolved	Two small-R jets, min($\lvert m_{jj} - m_W\rvert, \lvert m_{jj} - m_Z\rvert$) $p_T^{j_1}$ >40 GeV, $p_T^{j_2}$ >20 GeV $64 < m_{jj} < 106$ GeV
Tagging-jets		Two small-R non-b jets, $\eta_{\mathrm{tag},j_1} \cdot \eta_{\mathrm{tag},j_2} < 0$, highest m_{jj}^{tag} $m_{jj}^{\mathrm{tag}} > 400$ GeV, $p_T^{\mathrm{tag},j_{1,2}} > 30$ GeV
Number of b-jets	0-lepton	–
	1-lepton	0
	2-lepton	–

CMS MVA for WZ

- **Multivariate analysis** → enhance WZ EWK production w.r.t large WZ QCD production
- 13 Input variables retained ; BDT Gradient chosen from ROC curve

	Variable	Definition
jj variables	m_{jj}	Mass of the leading and trailing jets system
	$\lvert\Delta\eta_{\mathrm{jj}}\rvert$	Absolute difference in rapidity of the leading and trailing jets
	$\Delta\phi_{\mathrm{jj}}$	Absolute difference in azimuthal angles of the leading and trailing jets
	$p_{\mathrm{T}}^{\mathrm{j1}}$	p_{T} of the leading jet
	$p_{\mathrm{T}}^{\mathrm{j2}}$	p_{T} of the trailing jet
	η^{j1}	Pseudorapidity of the leading jet
VV variable	$\lvert\eta^{\mathrm{W}} - \eta^{\mathrm{Z}}\rvert$	Absolute difference between the rapidities of the Z boson and the charged lepton from the decay of the W boson
V-j mix variables	$z^*_{\ell_i} (i = 1-3)$	Zeppenfeld variable of the three selected leptons
	$z^*_{3\ell}$	Zeppenfeld variable of the vector sum of the three leptons
	$\Delta R_{\mathrm{j1,Z}}$	ΔR between the leading jet and the Z boson
	$\lvert\vec{p_{\mathrm{T}}}^{\mathrm{tot}}\rvert / \sum_i p_{\mathrm{T}}^i$	Transverse component of the vector sum of the bosons and tagging jets momenta, normalized to their scalar p_{T} sum

◆ **Overall good separation between EWK WZ and QCD WZ**

Note: Larger set of discriminating observables studied but variables improving sensitivity & showing some S/B separation retained.

CMS $W^{\pm}W^{\pm}$ & WZ VBS : Non-Prompt Estimation

- Fake rate ε_{fake}
  - Defined as the efficiency for fakeable objects to pass full lepton selection
  - Measured in a QCD-enriched sample with real lepton subtraction
  - η and p_T dependence
- Extrapolate the background yields
  - from "tight+loose" and "loose+loose" data events in "SR"
  - by weighted

"tight+loose": $$w_i = \frac{\epsilon_{\text{fake}}(p_{\text{Ti}}, \eta_i)}{1 - \epsilon_{\text{fake}}(p_{\text{Ti}}, \eta_i)}$$

"loose+loose": $$\left(w_{ij} = \frac{\epsilon_{\text{fake}}(p_{\text{Ti}}, \eta_i)}{1 - \epsilon_{\text{fake}}(p_{\text{Ti}}, \eta_i)} \times \frac{\epsilon_{\text{fake}}(p_{\text{Tj}}, \eta_j)}{1 - \epsilon_{\text{fake}}(p_{\text{Tj}}, \eta_j)}\right)$$

  - and with real lepton from simulation subtraction

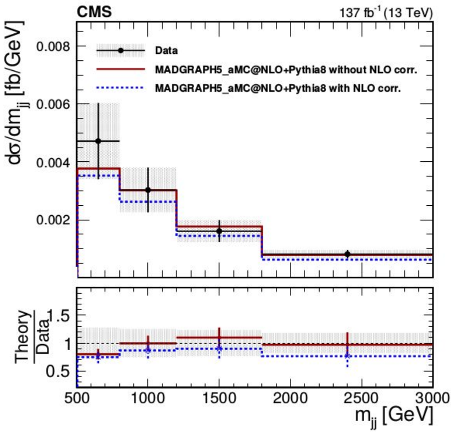
$$N^{non-prompt} = \left(\sum_i w_i^{data} - \sum_i w_i^{MC} - \sum_{i,j} w_{ij}^{data} + \sum_{i,j} w_{ij}^{MC}\right) N_{tt/tl}$$

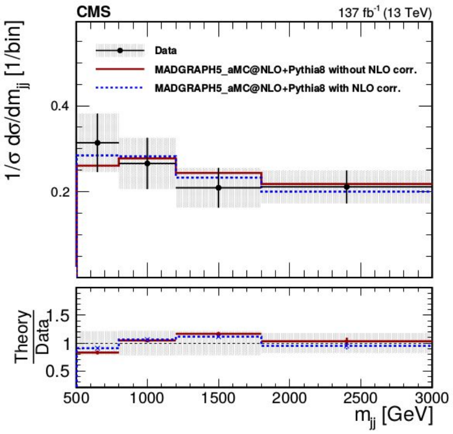
CMS $W^{\pm}W^{\pm}$ & WZ VBS: Analysis Strategy & Yields

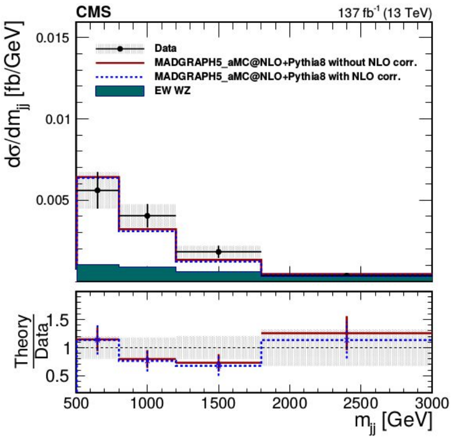
Process	$W^{\pm}W^{\pm}$ SR		WZ SR	
	Pre-fit	Post-fit	Pre-fit	Post-fit
EW $W^{\pm}W^{\pm}$	209 ± 22	210 ± 26	—	—
QCD $W^{\pm}W^{\pm}$	13.6 ± 2.3	13.7 ± 2.2	—	—
Interference $W^{\pm}W^{\pm}$	8.4 ± 2.3	8.7 ± 2.3	—	—
EW WZ	14.1 ± 1.7	17.8 ± 3.9	54.3 ± 5.7	69 ± 15
QCD WZ	42.9 ± 4.7	42.7 ± 7.4	117.9 ± 6.8	117 ± 17
Interference WZ	0.3 ± 0.1	0.3 ± 0.2	2.2 ± 0.6	2.7 ± 1.0
ZZ	0.7 ± 0.1	0.7 ± 0.2	6.1 ± 0.4	6.0 ± 1.8
Nonprompt	211 ± 55	193 ± 40	14.6 ± 7.6	14.4 ± 6.7
tVx	9.0 ± 3.1	7.4 ± 2.2	15.1 ± 1.9	14.3 ± 2.8
$W\gamma$	7.8 ± 2.0	9.1 ± 2.9	1.1 ± 0.5	1.1 ± 0.4
Wrong-sign	13.5 ± 7.1	13.9 ± 6.5	1.6 ± 0.7	1.7 ± 0.7
Other background	5.0 ± 2.4	5.2 ± 2.1	3.3 ± 0.7	3.3 ± 0.7
Total SM	535 ± 60	522 ± 49	216 ± 12	229 ± 23
Data	524		229	

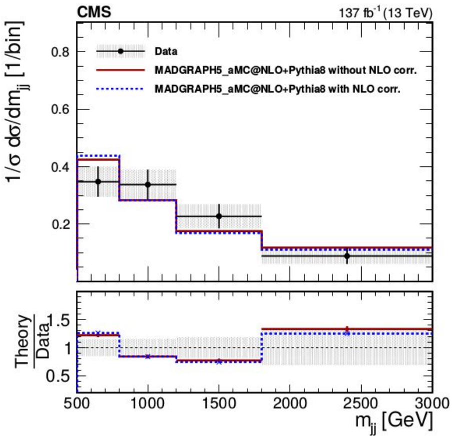
Source of uncertainty	$W^{\pm}W^{\pm}$ (%)	WZ (%)
Integrated luminosity	1.5	1.6
Lepton measurement	1.8	2.9
Jet energy scale and resolution	1.5	4.3
Pileup	0.1	0.4
b tagging	1.0	1.0
Nonprompt rate	3.5	1.4
Trigger	1.1	1.1
Limited MC sample size	2.6	3.7
Theory	1.9	3.8
Total systematic uncertainty	5.7	7.9
Statistical uncertainty	8.9	22
Total uncertainty	11	23

- Absolute and normalized - WW (EWK+QCD) differential cross section measurements on m_{jj} (shown below), m_{ll} & p_T^{max} and WZ (EWK+QCD) differential cross section measurements on m_{jj} (shown below)





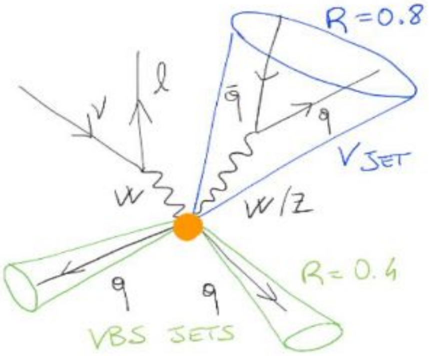




CMS WV Full Run II : Jet Categories

Boosted category

- **1 FatJet** (anti-kt R=0.8 jet) from **hadronic decay of W/Z boson** with P_T > 200 GeV
    - τ_{21} variables used for ID
- At least 2 jets (anti-kt R=0.4) with P_T > 30 GeV tagged as **VBS jets** looking for the max invariant mass pair.



Resolved category

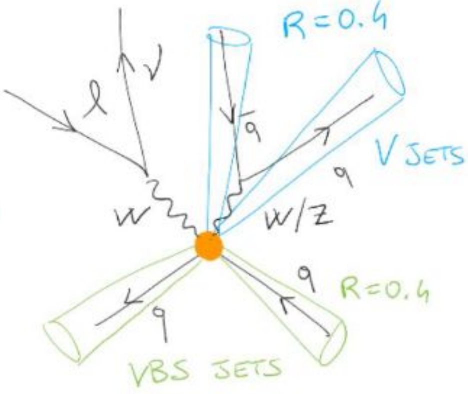
- At least 4 jets (anti-kt R=0.4) with P_T > 30 GeV.

  2 jets → **resolved** hadronic decay of W/Z boson

  2 jets → scattered initial partons (**VBS jets**)

Tagging order:

1. VBS tag jets: maximum invariant mass pair
2. V hadronic: pair with invariant mass near W/Z mass



WV Full Run II : Signal Selections

	Signal region	Top control region	W+jets control region
Resolved category	Ele $p_T >$ 30 GeV (2016), 35 GeV (2017, 2018) Muon $p_T >$ 30 GeV PuppiMET > 30 GeV Leading VBS jet $p_T >$ 50 GeV trailing VBS jet and Vjets $p_T >$ 30 GeV $\Delta\eta_{VBS} > 2.5$, $M_{jj\ VBS} > 500$ GeV Leptonic $M^T_W < 185$ GeV **bVeto with Loose** DeepCSV WP **V had p_T < 200 GeV** **65 GeV < Mjj Vhad < 105 GeV**	Ele $p_T >$ 30 GeV (2016), 35 GeV (2017, 2018) Muon $p_T >$ 30 GeV PuppiMET > 30 GeV Leading VBS jet $p_T >$ 50 GeV trailing VBS jet and Vjets $p_T >$ 30 GeV $\Delta\eta_{VBS} > 2.5$, $M_{jj\ VBS} > 500$ GeV Leptonic $M^T_W < 185$ GeV **bTag with Tight** DeepCSV WP **V had p_T < 200 GeV** **65 GeV < Mjj Vhad < 105 GeV**	Ele $p_T >$ 30 GeV (2016), 35 GeV (2017, 2018) Muon $p_T >$ 30 GeV PuppiMET > 30 GeV Leading VBS jet $p_T >$ 50 GeV trailing VBS jet and Vjets $p_T >$ 30 GeV $\Delta\eta_{VBS} > 2.5$, $M_{jj\ VBS} > 500$ GeV Leptonic $M^T_W < 185$ GeV **bVeto with Loose** DeepCSV WP **V had p_T < 200 GeV** **40 < Mjj Vhad < 65 GeV, Mjj Vhad > 105 GeV**
Boosted category	Ele $p_T >$ 30 GeV (2016), 35 GeV (2017, 2018) Muon $p_T >$ 30 GeV PuppiMET > 30 GeV Leading VBS jet $p_T >$ 50 GeV trailing VBS jet $p_T >$ 30 GeV $\Delta\eta_{VBS} > 2.5$, $M_{jj\ VBS} > 500$ GeV Leptonic $M^T_W < 185$ GeV **bVeto with Loose** DeepCSV WP **V had p_T > 200 GeV** **70 GeV < Mjj Vhad < 115 GeV**	Ele $p_T >$ 30 GeV (2016), 35 GeV (2017, 2018) Muon $p_T >$ 30 GeV PuppiMET > 30 GeV Leading VBS jet $p_T >$ 50 GeV trailing VBS jet $p_T >$ 30 GeV $\Delta\eta_{VBS} > 2.5$, $M_{jj\ VBS} > 500$ GeV Leptonic $M^T_W < 185$ GeV **bTag with Tight** DeepCSV WP **V had p_T > 200 GeV** **70 GeV < Mjj Vhad < 115 GeV**	Ele $p_T >$ 30 GeV (2016), 35 GeV (2017, 2018) Muon $p_T >$ 30 GeV PuppiMET > 30 GeV Leading VBS jet $p_T >$ 50 GeV trailing VBS jet $p_T >$ 30 GeV $\Delta\eta_{VBS} > 2.5$, $M_{jj\ VBS} > 500$ GeV Leptonic $M^T_W < 185$ GeV **bVeto with Loose** DeepCSV WP **V had p_T > 200 GeV** **40 GeV < Mjj Vhad < 70 GeV** **115 GeV < Mjj Vhad < 250 GeV**

WV Full Run II : DNN input variables

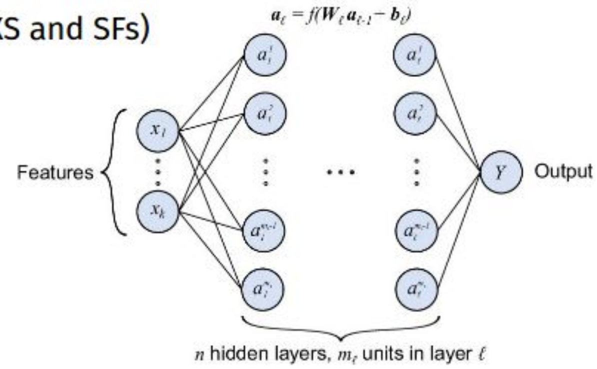
Studied the ranking of the DNN input variables with the SHapley Additive exPlanations (SHAP) method (presented also at CMS ML forum indico

Table 1: Variables used as input of the DNN for the resolved and boosted models. The Zeppenfeld variable of a particle X is defined as $Z_X = \frac{\eta^X - \bar{\eta}^{VBS}}{\Delta\eta^{VBS}}$, where $\bar{\eta}^{VBS}$ is the mean η of VBS tag-jets, while the centrality [6, 49] is $C_{VW} = \min(\Delta\eta_-, \Delta\eta_+)$, with $\Delta\eta_+ = \max(\eta^{VBS}) - \max(\eta^{V_{had}}, \eta^W)$ and $\Delta\eta_- = \min(\eta^{VBS}) - \min(\eta^{V_{had}}, \eta^W)$. The η^W is built assuming the W-mass from the lepton and p_T^{miss} kinematics.

Variable	Resolved	Boosted
Lepton pseudorapidity	✓	✓
Lepton transverse momentum	✓	✓
Zeppenfeld variable for the lepton	✓	✓
Number of jets with $p_T > 30$ GeV	✓	✓
VBS leading tag-jet p_T	-	✓
VBS trailing tag-jet p_T	✓	✓
Pseudorapidity interval between VBS tag-jets	✓	✓
Quark Gluon discriminator of the highest p_T jet of the VBS tag-jets	✓	✓
Azimuthal angle distance between VBS tag-jets	✓	✓
Invariant mass of the VBS tag-jets pair	✓	✓
p_T of jets from V_{had}	✓	-
Pseudorapidity difference between V_{had} jets	✓	-
Quark Gluon discriminator of the V_{had} jets	✓	-
V_{had} p_T	-	✓
Invariant mass of the V_{had}	✓	✓
Zeppenfeld variable for the V_{had}	-	✓
V_{had} centrality	-	✓

WV Full Run II : DNN for signal extraction

- Basic approach: **all Backgrounds** vs **Signal** (events weighted by XS and SFs)
- Training performed on events in **signal region**
- **Trained 2 different** models:
  - for **boosted** and **resolved** categories
  - joining all the years datasets
- Carefully checked and avoided **overtraining**



Boosted

- DNN fully connected (64-32-32-32 nodes)
- 13 inputs (see next slide)
- Regularization: Batch normalization and L2 norm weights normalization
- 416k background, 50k signal samples

Resolved

- DNN fully connected (64-64-64-64 nodes)
- 16 inputs (see next slide)
- Regularization: Batch normalization and L2 norm weights normalization
- 1.7 M background, 220k signal samples

MVA for ZZ

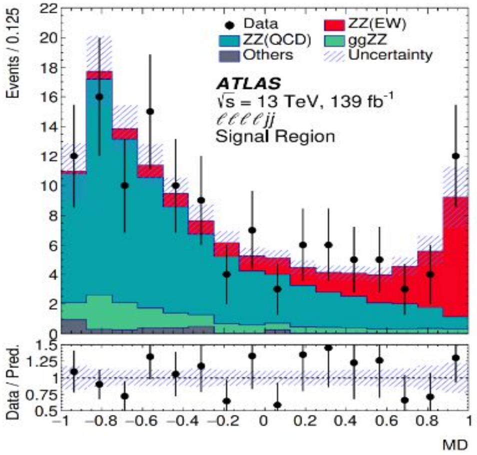
- MVA Analysis to extract EW ZZjj signal
- Gradient boosted decision tree (BDTG) is used in both channels
    - In the 4ℓjj channel, twelve input variables are used
        - The jet-related information provides the greatest sensitivity
    - In the $\ell\ell\nu\nu$ channel, thirteen input variables are used
        - Both the jet-related dilepton-related variables are important

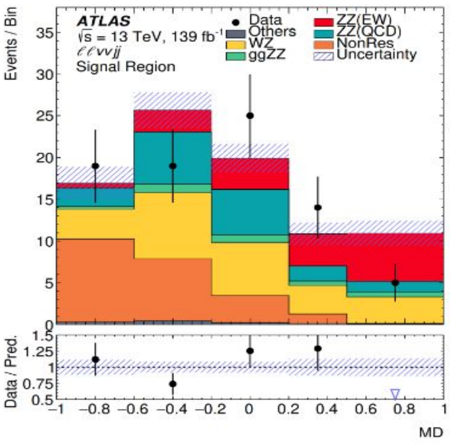
◆ **Overall good separation between EWK ZZ and QCD ZZ**

Rank	$llll$	$ll\nu\nu$
1	m_{jj}	$\Delta\eta(ll)$
2	leading p_T^j	m_{ll}
3	subleading p_T^j	$\Delta\phi(ll)$
4	$p_T(ZZjj)/h_T(ZZjj)$	m_{jj}
5	$Y(j1) \times Y(j2)$	MET significance
6	$\lvert\Delta Y(jj)\rvert$	$\Delta Y(jj)$
7	Y_{Z2}^*	$Y(j1) \times Y(j2)$
8	Y_{Z1}^*	h_T
9	p_T^{4l}	$\Delta R(ll)$
10	m_{4l}	subleading p_T^j
11	p_T^{Z1}	MET
12	p_T^{l3}	subleading p_T^l
13	-	leading p_T^l

ATLAS ZZ: Results

- MVA Analysis to extract EW ZZjj signal
- 4ℓ channel trained in SR using EW vs QCD events
- $\ell\ell\nu\nu$ channel trained in SR using EW vs all backgrounds
- BDT score is used as final discriminator for fitting
    - 3 regions are used in fitting: 4ℓ SR, 4ℓ QCD CR, $\ell\ell\nu\nu$ SR
    - μ_{EW} is POI, μ_{QCD} (4ℓ channel) is used as a free parameter in the fit to constrain QCD normalization





VV 2015+2016 : Cross-section Measurements

Table 4: Fiducial phase-space definitions used for the measurement of electroweak $VVjj$ production.

Object selection		
Leptons		$p_T > 7$ GeV, $\|\eta\| < 2.5$
Small-R jets		$p_T > 20$ GeV if $\|\eta\| < 2.5$, and $p_T > 30$ GeV if $2.5 < \|\eta\| < 4.5$
Large-R jets		$p_T > 200$ GeV, $\|\eta\| < 2.0$
Event selection		
Leptonic V selection	0-lepton	Zero leptons, $p_T^{\nu\nu} > 200$ GeV
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	2-lepton	Two leptons, with leading (subleading) lepton $p_T > 28$ (20) GeV $83 < m_{\ell\ell} < 99$ GeV
Hadronic V selection	Merged	One large-R jet, $\min(\|m_J - m_W\|, \|m_J - m_Z\|)$ $64 < m_J < 106$ GeV
	Resolved	Two small-R jets, $\min(\|m_{jj} - m_W\|, \|m_{jj} - m_Z\|)$ $p_T^{j_1} > 40$ GeV, $p_T^{j_2} > 20$ GeV $64 < m_{jj} < 106$ GeV
Tagging-jets		Two small-R non-b jets, $\eta_{\mathrm{tag},j_1} \cdot \eta_{\mathrm{tag},j_2} < 0$, highest m_{jj}^{tag} $m_{jj}^{\mathrm{tag}} > 400$ GeV, $p_T^{\mathrm{tag},j_{1,2}} > 30$ GeV
Number of b-jets	0-lepton	–
	1-lepton	0
	2-lepton	–

VV 2015+2016 : MVA

Table 2: Variables used for the BDT discriminant in the merged analysis category of each lepton channel.

Variable	0-lepton	1-lepton	2-lepton
m_{jj}^{tag}	✓	–	✓
$\Delta\eta_{jj}^{\text{tag}}$	–	–	✓
$p_{\text{T}}^{\text{tag},j_2}$	✓	✓	✓
m_J	✓	–	–
$D_2^{(\beta=1)}$	✓	–	✓
$E_{\text{T}}^{\text{miss}}$	✓	–	–
$\Delta\phi(\vec{E}_{\text{T}}^{\text{miss}}, J)$	✓	–	–
η_ℓ	–	✓	–
$n_{j,\text{track}}$	✓	–	–
ζ_V	–	✓	✓
m_{VV}	–	–	✓
p_{T}^{VV}	–	–	✓
m_{VVjj}	–	✓	–
p_{T}^{VVjj}	–	–	✓
w^{tag,j_1}	✓	–	–
w^{tag,j_2}	✓	–	–

VV 2015+2016 : MVA

Table 3: Variables used for the BDT discriminant in the resolved analysis category of each lepton channel analysis.

Variable	0-lepton	1-lepton	2-lepton
m_{jj}^{tag}	✓	–	✓
$\Delta\eta_{jj}^{\text{tag}}$	–	–	✓
$p_{\text{T}}^{\text{tag},j_1}$	✓	✓	–
$p_{\text{T}}^{\text{tag},j_2}$	✓	✓	✓
$\Delta\eta_{jj}$	✓	✓	✓
$p_{\text{T}}^{j_1}$	✓	–	–
$p_{\text{T}}^{j_2}$	✓	✓	✓
w^{j_1}	✓	✓	✓
w^{j_2}	✓	✓	✓
$n_{\text{tracks}}^{j_1}$	–	✓	✓
$n_{\text{tracks}}^{j_2}$	–	✓	✓
w^{tag,j_1}	✓	✓	✓
w^{tag,j_2}	✓	✓	✓
$n_{\text{tracks}}^{\text{tag},j_1}$	–	✓	✓
$n_{\text{tracks}}^{\text{tag},j_2}$	–	✓	✓
$n_{j,\text{track}}$	✓	–	✓
$n_{j,\text{extr}}$	✓	–	–
$E_{\text{T}}^{\text{miss}}$	✓	–	–
η_{ℓ}	–	✓	–
$\Delta R(\ell,\nu)$	–	✓	–
ζ_V	–	✓	✓
m_{VV}	–	–	✓
m_{VVjj}	–	✓	–

CMS aQGCs: Unitarity Issue

- It is well known that EFT amplitudes grow with M_{VV} and this growth is unphysical above a certain scale Λ; this sets the limit of validity of EFT approach
- FACT: pure EFT does not provide any predictions for $M_{VV} > \Lambda$, dictated by the requirement of unitarity
- Measured signal is in general a sum of $M_{VV} < \Lambda$ and $M_{VV} > \Lambda$. The only way to correctly use EFT is to make sure the region $M_{VV} > \Lambda$ does not significantly contribute
- Only the most conservative limits are guaranteed to be true
    - Most conservative estimate = "clip" the generated aQGC distribution: take only SM contribution above Λ. This is the practical equivalent of not using data above Λ [*]

The **EFT-controlled** part of the signal is given by:

$$D_i^{model} = \underbrace{\int_{2M_W}^{\Lambda} \frac{d\sigma}{dM}|_{model} dM}_{\text{EFT in its range of validity}} + \underbrace{\int_{\Lambda}^{M_{max}} \frac{d\sigma}{dM}|_{SM} dM}_{\text{Only SM contribution}}$$

- The technique is known as "Clipping", and essentially means using EFT only in the region it is valid!
- **Implementation** of "Clipping" in CMS Results

[*] Eur. Phys. J. C (2018) 78: 403 Eur. Phys. J. C 80, 181 (2020)