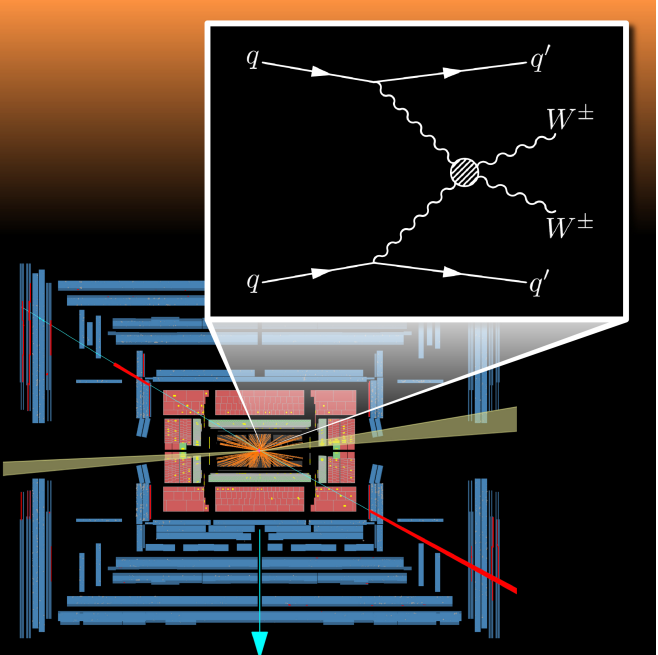


8 TeV Run-1 event display (Phys. Rev. Lett. 113, 141803)

Study of Vector Boson Scattering Processes with $W^{\pm}W^{\pm}jj$ and $W^{\pm}Zjj$ Final States at the ATLAS Detector

Stefanie Todt
On behalf of the ATLAS collaboration

TECHNISCHE UNIVERSITÄT DRESDEN

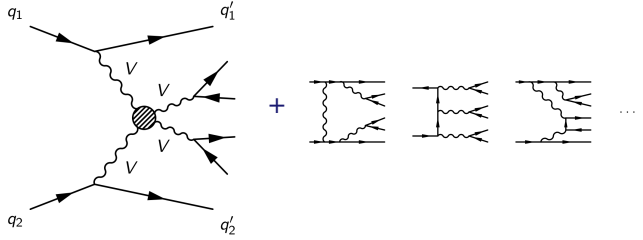
Corfu Summer Institute
Workshop on the Standard Model and Beyond
September 1, 2018

ATLAS EXPERIMENT

CERN

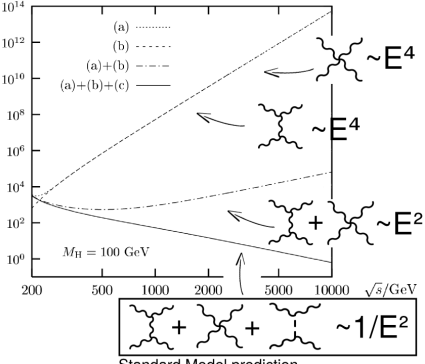
Vector boson scattering @ the LHC

SM-EWK diagrams: $\mathcal{O}(\alpha_{\mathrm{EW}}^6)$ @ LO - VBS-production + non-VBS production



[Denner, Hahn, 1997]

Cross section for longitudinal W^+W^- scattering.



Vector boson scattering includes:

- Triple and quartic gauge couplings, Higgs processes
  - ⇒ Probe of electroweak gauge theory in the SM
  - ⇒ Higgs restores unitarity at high energies in this process
  - ⇒ Complementary insight into EWSB w.r.t. to direct Higgs measurements

Overview of VBS measurements @ the LHC

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Status as of July 2018:

Channel	Final state	Observed (expected) significance	Recent measurements	Experimental Challenges
VBS $W^{\pm}W^{\pm}$	$l^{\pm}l^{\pm}\nu\nu$ jj	5.5 (5.7) σ	CMS @13 TeV	"golden channel": first observation of VBS in this channel, very good EW/QCD ratio, mostly experimental backgrounds
VBS $W^{\pm}Z$	$lll\nu$ jj	1.9 (1.0) σ	CMS @13 TeV	similar cross section as ssWW, but larger QCD backgrounds, reasonable reconstruction of final state (m_T^{WZ})
VBS ZZ	llll jj	2.7 (1.6) σ	CMS @13 TeV	very clean channel, reconstruction of final state, low background but small cross section
VBS $W^{\pm}V$	$l^{\pm}\nu$jj jj	only BSM interpretation @8 TeV		large backgrounds, but promising when looking for BSM effects in boosted topology
VBS $\gamma\gamma \rightarrow W^+W^-$	ll$\nu\nu$ jj	3.4 (2.8) σ	ATLAS & CMS @8 TeV	huge backgrounds (dileptonic ttbar), no sensitivity to BSM EWSB
VBS $W\gamma/Z\gamma$	l$\nu\gamma$ jj / ll$\nu\gamma$ jj	2.7 (1.5) σ / 3.0 (2.1) σ	CMS @8 TeV	higher statistics due to photon, but no sensitivity to BSM EWSB

Overview of VBS measurements @ the LHC

TECHNISCHE UNIVERSITÄT DRESDEN

Recent update:

Channel	Final state	Observed (expected) significance	Recent measurements	Experimental Challenges
VBS $W^{\pm}W^{\pm}$	$l^{\pm}l^{\pm}\nu\nu$ jj	5.5 (5.7) σ NEW	CMS @13 TeV ATLAS @13 TeV	"golden channel": first observation of VBS in this channel, very good EW/QCD ratio, mostly experimental backgrounds
VBS $W^{\pm}Z$	lllν jj	1.9 (1.0) σ NEW	CMS @13 TeV ATLAS @13 TeV	similar cross section as ssWW, but larger QCD backgrounds, reasonable reconstruction of final state (m_T^{WZ})
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VBS Wγ/Zγ	l$\nu\gamma$ jj / ll$\nu\gamma$ jj	2.7 (1.5) σ / 3.0 (2.1) σ	CMS @8 TeV	higher statistics due to photon, but no sensitivity to BSM EWSB

Today's focus:

- Measurement in fully leptonic final states in VBS $W^{\pm}W^{\pm}$jj and $W^{\pm}Z$jj with the ATLAS detector @13 TeV

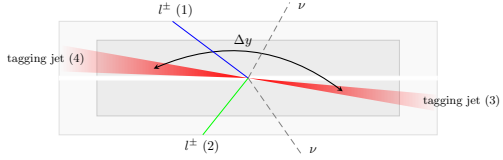
Measurement of electro-weak production in $W^{\pm}W^{\pm}jj$

Major backgrounds and experimental selection

ATLAS publication with Run-2 data (2015+2016, $\sqrt{s} = 13\,\text{TeV}$, $36.1\,\text{fb}^{-1}$): ATLAS-CONF-2018-030

Fiducial selection:

Cut	2 leptons	jet_1	jet_2	$\nu\nu$-system
$W^{\pm}W^{\pm}jj$ final state	same-charge (e or μ)	anti-k_T ($R = 0.4$)		
$p_T >$	27 GeV	65 GeV	35 GeV	30 GeV
$\lvert\eta\rvert <$	2.5	4.5	4.5	
	$m_{ll} > 20\,\text{GeV}$			
VBS selection	$m_{jj} > 500\,\text{GeV}$, $\Delta y_{jj} > 2.0$			



Main background contributions:

1. Processes with two real prompt same-charge leptons:
   ⇒ Mainly $W^{\pm}Z$ +jets
2. Experimental backgrounds:
   ⇒ Processes with non-prompt (“fake”) leptons from mis-identified jets, or leptons from hadron decays
   ⇒ Processes with electron charge mis-identification

⇒ Suppression via additional experimental cuts:

- Third lepton veto ($p_T^{l_3} > 6\,\text{GeV}$)
- Tight reconstruction and isolation requirements on lepton candidates
- B-jet veto
- Z veto in ee channel ($|m_{ee} - m_Z| > 15\,\text{GeV}$)

Measurement of electro-weak production in $W^{\pm}W^{\pm}jj$

Background estimate methods and event yields in signal region

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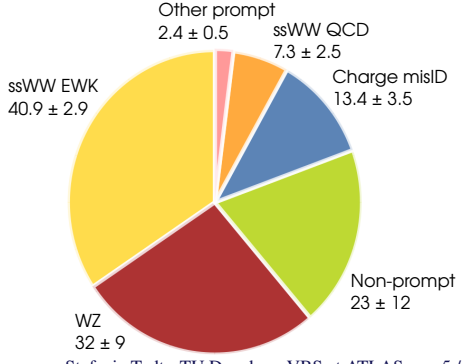
Derived from data | Monte-Carlo modelled

- $W^{\pm}Z$ +jets: Shape MC modelled and normalised from data in tri-lepton control region
  $\Rightarrow$ Reduction of uncertainties (dominantly theoretical pQCD scale uncertainties) to 8%

- Non-prompt leptons estimate:
  Scale factor from di-jet control region
  $\Rightarrow$ Dominant experimental uncertainty (40-90%)

- Electron charge mis-identification and $\gamma \rightarrow$ e conversions probability and background estimate:
  From $Z \rightarrow ee$ enriched region

- Other irreducible backgrounds
  ($W^{\pm}W^{\pm}jj$ QCD, ZZ+jets, VVV, $t\bar{t}V$)



Event yields in combined channel in signal region before the fit:

Total expected:	118.9 ± 15.3 events
Data:	122 events

Measurement of electro-weak production in $W^{\pm}W^{\pm}jj$

Sensitivity estimate

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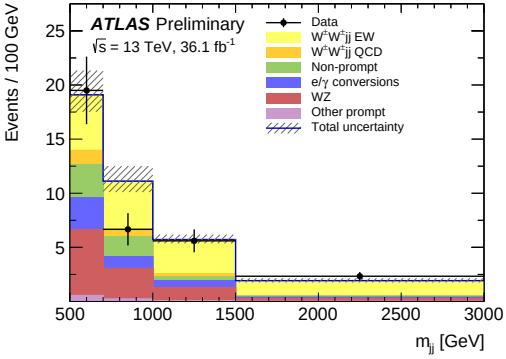
Multi-bin likelihood fit:

- 4-bin m_{jj} distribution in signal region ($m_{jj} > 500\,\text{GeV}$)
- 6 lepton flavour- and charge-split channels:
  $e^{\pm}e^{\pm}$, $e^{\pm}\mu^{\pm} + \mu^{\pm}e^{\pm}$, $\mu^{\pm}\mu^{\pm}$
- Background estimates constrained in two control regions:
  $\Rightarrow W^{\pm}Z$ CR: Require a third lepton with one OSSF pair
  $\Rightarrow$ Low m_{jj} CR: SR selection, $m_{jj} \in (200, 500)$ GeV
- $W^{\pm}Z$ normalisation reduced by $\sim 12\%$

Result:

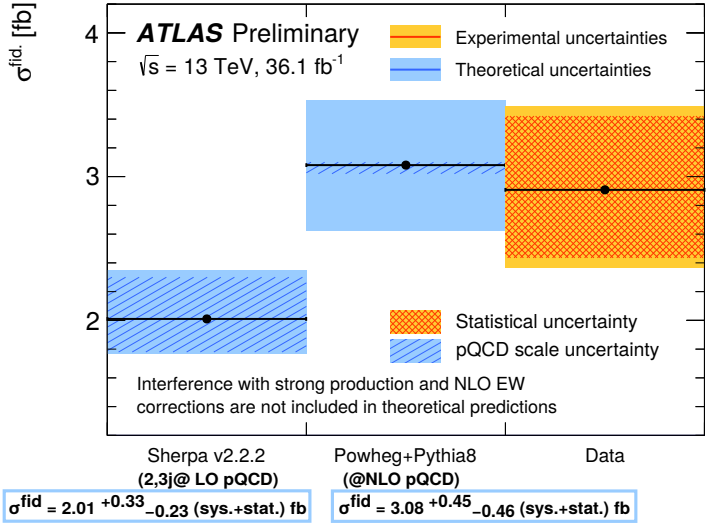
Observed (expected with Sherpa) significance is 6.9σ (4.9σ)

Di-jet invariant mass distribution in region $m_{jj} > 500\,\text{GeV}$ after fit



Measurement of electro-weak production in $W^{\pm}W^{\pm}jj$

Measurement of fiducial cross section



Measured fiducial cross section:

$$\sigma^{\text{fid}}_{\text{meas}} = 2.91^{+0.51}_{-0.47}(\text{stat.}) \pm 0.27(\text{sys.})\ \text{fb}$$

Signal predictions do not include:

- Interference between EWK and QCD-induced production (+6%)
  [VBSCan 1803.07943]
- NLO EWK corrections (−16%)
  [A. Denner, M. Pellen et al. (1708.00268)]
  (More details in Pietro Govoni's talk)

Measurement of electro-weak production in $W^{\pm}Zjj$

Major backgrounds and experimental selection

ATLAS publication with Run-2 data (2015+2016, $\sqrt{s} = 13\,\text{TeV}$, $36.1\,\text{fb}^{-1}$): ATLAS-CONF-2018-033

Fiducial selection:

Cut	3 leptons (e or μ)		$\geqslant 2$ jets
$W^{\pm}Zjj$ final state	Z-candidate (OSSF)	W-candidate	anti-k_T ($R = 0.4$)
$p_T >$	15 GeV	20 GeV	40 GeV
$\lvert\eta\rvert <$	2.5		4.5
	$\lvert m_{ll} - m_Z \rvert > 10\,\text{GeV}$	$m_T^W > 30\,\text{GeV}$	
VBS selection			$m_{jj} > 500\,\text{GeV}$, opposite hemispheres
	Veto on initial state b-quarks (excluding tZj processes from signal definition)		

Main background contributions:

1. Processes with 3 real prompt leptons:

   ⇒ Mainly QCD-induced $W^{\pm}Z$ +jets, ZZ+jets, top processes

2. Experimental backgrounds:

   ⇒ Processes with non-prompt ("fake") leptons from mis-identified jets, or leptons from hadron

⇒ Suppression via additional experimental cuts:

- Fourth lepton veto ($p_T^{l_4} > 5\,\text{GeV}$)
- Tight reconstruction and isolation requirements on lepton candidates
- B-jet veto
- VBS tagging jet selection

Measurement of electro-weak production in $W^{\pm}Zjj$

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Sensitivity estimate

Signal extraction using a BDT and a multi-bin likelihood fit:

- BDT discriminant based on 15 variables in the signal region
  - ⇒ Variables related to kinematic properties of the two tagging jets (7) or the vector bosons (5)
  - ⇒ Variables relating lepton and jet kinematics (3)
- Background estimates constrained in 3 control regions and fitted simultaneously with signal region
  - ⇒ $W^{\pm}Z$ QCD CR in m_{jj}
  - ⇒ b-tagged CR in $N_{\text{b-jet}}$
  - ⇒ ZZ CR in m_{jj}
- Post-fit normalisation for background estimates:

  $W^{\pm}Z$ QCD: $\mu_{WZ-QCD} = 0.60 \pm 0.25$

  $t\bar{t}V$: $\mu_{t\bar{t}V} = 1.18 \pm 0.19$

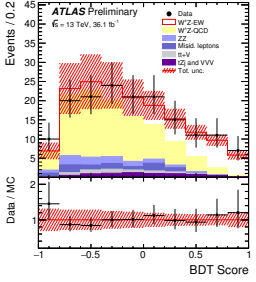
  ZZ: $\mu_{ZZ} = 1.34 \pm 0.29$

Event yields in all regions before the fit

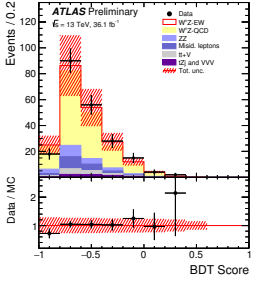
	SR	QCD-CR	b-CR	ZZ-CR
Data	161	213	141	52
Total MC	199.2 ± 1.4	289.4 ± 1.9	159.2 ± 1.8	44.7 ± 6.4
$WZjj$-EW (signal)	24.93 ± 0.18	8.46 ± 0.10	1.36 ± 0.05	0.21 ± 0.12
$WZjj$-QCD	144.17 ± 0.85	231.2 ± 1.1	24.44 ± 0.29	1.43 ± 0.69
Misid. leptons	9.2 ± 1.1	17.7 ± 1.5	29.7 ± 1.6	0.50 ± 0.32
ZZ-QCD	8.10 ± 0.19	14.98 ± 0.34	1.96 ± 0.08	35.0 ± 5.9
tZ	6.46 ± 0.18	6.56 ± 0.19	36.19 ± 0.45	0.18 ± 0.09
$t\bar{t} + V$	4.21 ± 0.18	9.11 ± 0.23	65.36 ± 0.64	2.8 ± 1.3
ZZ-EW	1.50 ± 0.10	0.44 ± 0.05	0.10 ± 0.08	3.4 ± 1.6
VVV	0.59 ± 0.03	0.93 ± 0.04	0.13 ± 0.01	1.0 ± 1.0

BDT score distribution after the fit

signal region



QCD control region



Measurement of electro-weak production in $W^{\pm}Zjj$

Sensitivity estimate

Signal extraction using a BDT and a multi-bin likelihood fit:

- BDT discriminant based on 15 variables in the signal region
  - ⇒ Variables related to kinematics of the tagging jets (7)
  - ⇒ Variables relating lepton and jet kinematics (3)
- Background estimates constrained in 3 control regions and fitted simultaneously with signal region:
  - ⇒ $W^{\pm}Z$ QCD CR in m_{jj}
  - ⇒ b-tagged CR in $N_{b\text{-jets}}$
  - ⇒ ZZ CR in m_{jj}
- Post-fit background scale factors:

$W^{\pm}Z$ QCD:	$\mu_{WZ-QCD} = 0.80 \pm 0.23$
$t\bar{t}V$:	$\mu_{t\bar{t}V} = 1.18 \pm 0.19$
ZZ:	$\mu_{ZZ} = 1.34 \pm 0.29$

Event yields in all regions before the fit

	SR	QCD-CR	b-CR	ZZ-CR
Data	161	213	141	52
Total MC	199.2 ± 1.4	289.4 ± 1.9	159.2 ± 1.8	44.7 ± 6.4
$WZjj$-EW (signal)	24.93 ± 0.18	8.46 ± 0.10	1.36 ± 0.05	0.21 ± 0.12

First observation of $W^{\pm}Zjj$ EWK production!
With observed (expected with Sherpa) significance is 5.6σ (3.3σ)

Measured fiducial cross section:

$$\sigma^{\text{fid}}_{\text{meas}} = 0.57^{+0.14}_{-0.13}(\text{stat})^{+0.05}_{-0.04}(\text{syst})^{+0.04}_{-0.03}(\text{theo})\,\text{fb}$$

Predicted fiducial cross section:

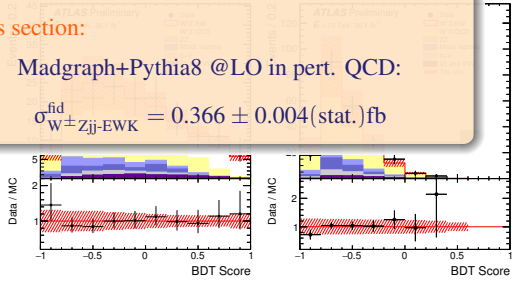
Sherpa 2.2.2 LO in pert. QCD:

$$\sigma^{\text{fid}}_{W^{\pm}\text{Zjj-EWK}} = 0.321^{+0.028}_{-0.024}(\text{sys.+stat.})\,\text{fb}$$

Madgraph+Pythia8 @LO in pert. QCD:

$$\sigma^{\text{fid}}_{W^{\pm}\text{Zjj-EWK}} = 0.366 \pm 0.004(\text{stat.})\,\text{fb}$$

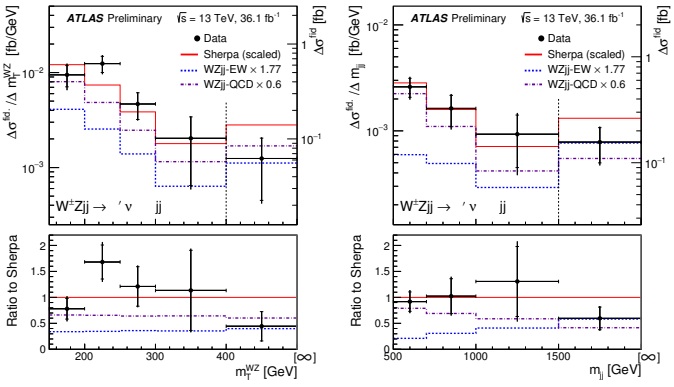
BDT score distribution after the fit



Measurement of electro-weak production in $W^{\pm}Zjj$

Differential cross section measurement

- In 8 different variables:
  - ⇒ Variables sensitive to aQGC effects:
    m_T^{WZ}, $\sum p_T^{\ell}$, $\Delta\Phi(W,Z)$
  - ⇒ Variables sensitive to pQCD modelling:
    N_{jet}, N_{jet}^{gap}, m_{jj}, $\Delta\Phi_{jj}$, Δy_{jj}
- Compared to post-fit scaled Sherpa predictions for separate and combined $W^{\pm}Zjj$ EWK + QCD in signal region



Summary

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ATLAS has published new result on VBS measurements
using 36.1 fb^{-1} of data collected in 2015+2016 at $\sqrt{s} = 13\,\text{TeV}$

- Run 2 of the LHC has revealed access to further exploration of final states in VBS
  - $\Rightarrow$ First observation of electro-weak $W^{\pm}Zjj$ production
  - $\Rightarrow$ Observation of electro-weak production of $W^{\pm}W^{\pm}jj$ final state
- Measurement of fiducial cross sections for these final states
- With more data being collected for the full Run 2
  - $\Rightarrow$ Higher order theoretical computations are becoming more important
  - $\Rightarrow$ Improving sensitivity for BSM

VBS final states continue to be a playground for exciting physics to be explored!

MORE MATERIAL

Phase space information

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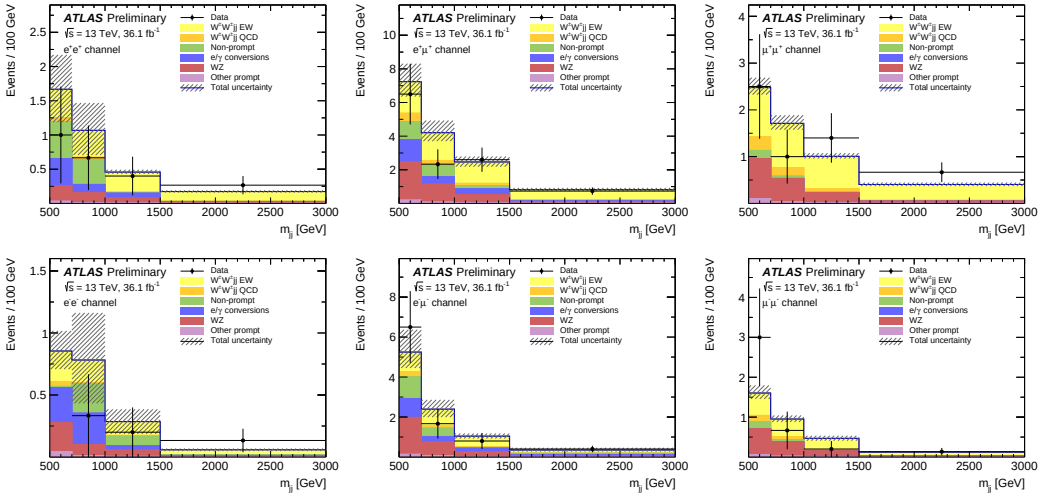
$W^{\pm}W^{\pm}jj$ EWK fiducial PS:

Cut	Value
Lepton pT, $\lvert\eta\rvert$	$> 27\,\text{GeV}, < 2.5$
Lepton dressing	for γ with $dR(l,\gamma) < 0.1$
Jet pT, $\lvert\eta\rvert$	$> 30\,\text{GeV}, < 4.5$
τ-veto	$N_{taus} == 0$
Exactly two leptons	$N_{leptons} == 2$
same charge leptons	$q_{l1} \times q_{l2} > 0$
N_{jets}	$\geqslant 2$
$dR(l,l)$	> 0.3
$dR(l,j)$	> 0.3
$p_{T,vv}$	$> 30\,\text{GeV}$
m_{ll}	$> 20\,\text{GeV}$
m_{jj}	$> 500\,\text{GeV}$
$dY(j,j)$	> 2.4

$W^{\pm}W^{\pm}jj$ fit results divided into channels



Measurement of electro-weak production in $W^{\pm}W^{\pm}jj$

Event yields in signal region

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Event yields in all channels in signal region before the fit:

	e^+e^+	e^-e^-	$e^+\mu^+$	$e^-\mu^-$	$\mu^+\mu^+$	$\mu^-\mu^-$	combined
WZ	1.7 ± 0.6	1.2 ± 0.4	13 ± 4	8.1 ± 2.5	5.0 ± 1.6	3.3 ± 1.1	32 ± 9
Non-prompt	4.1 ± 2.4	2.3 ± 1.8	9 ± 6	6 ± 4	0.57 ± 0.16	0.67 ± 0.26	23 ± 12
e/γ conversions	1.74 ± 0.31	1.8 ± 0.4	6.1 ± 2.4	3.7 ± 1.0	-	-	13.4 ± 3.5
Other prompt	0.17 ± 0.06	0.14 ± 0.05	0.90 ± 0.24	0.60 ± 0.25	0.36 ± 0.12	0.19 ± 0.07	2.4 ± 0.5
$W^{\pm}W^{\pm}$jj strong	0.38 ± 0.13	0.16 ± 0.06	3.0 ± 1.0	1.2 ± 0.4	1.8 ± 0.6	0.76 ± 0.26	7.3 ± 2.5
Expected background	8.1 ± 2.4	5.6 ± 1.9	32 ± 7	20 ± 5	7.7 ± 1.7	4.9 ± 1.1	78 ± 15
$W^{\pm}W^{\pm}$jj electroweak	3.80 ± 0.30	1.49 ± 0.13	16.5 ± 1.2	6.5 ± 0.5	9.1 ± 0.7	3.50 ± 0.29	40.9 ± 2.9
Data	10	4	44	28	25	11	122

Measurement of electro-weak production in $W^{\pm}Zjj$

Measurement of fiducial cross section

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Measured fiducial cross section:

$$\sigma^{\text{fid}}_{\text{meas}} = 0.57^{+0.14}_{-0.13}(\text{stat})^{+0.05}_{-0.04}(\text{syst})^{+0.04}_{-0.03}(\text{theo})\,\text{fb}$$

$\Rightarrow$ Including $W^{\pm}Zjj$ EWK and interference with $W^{\pm}Zjj$ QCD

$\Rightarrow$ $W^{\pm}Zjj$ QCD-induced production subtracted as background (from Sherpa)

Predicted fiducial cross section:

Sherpa 2.2.2 LO in pert. QCD:

$$\sigma^{\text{fid}}_{W^{\pm}\text{Zjj-EWK}} = 0.321 \pm 0.002(\text{stat.}) \pm 0.005(\text{PDF})^{+0.027}_{-0.023}(\text{scale})\,\text{fb}$$

Madgraph+Pythia8 @LO in pert. QCD:

$$\sigma^{\text{fid}}_{W^{\pm}\text{Zjj-EWK}} = 0.366 \pm 0.004(\text{stat.})\,\text{fb}$$

Uncertainties on the measured cross section

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

Signal predictions do not include:

- Interference between EWK and QCD-induced production (10%)
- NLO EWK corrections

VBS topology

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Two energetic forward jets with high dijet invariant mass and separation in rapidity

- Use jet information to enhance VBS signal:

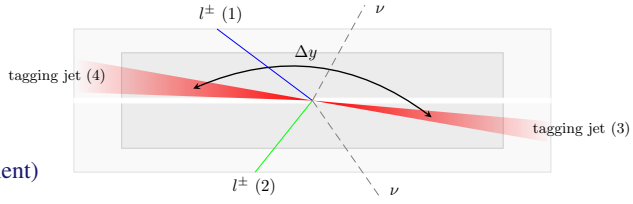
$\Rightarrow$ Large transverse momenta $p_T(j_1)$, $p_T(j_2)$

$\Rightarrow$ m_{jj} or ΔY_{jj}

$\Rightarrow$ central jet veto

Leptonically decaying $W^{\pm}$, Z:

- Central leptons (lepton centrality requirement)
- MET or m_T^W requirements



Purpose of the VBS cuts:

- Separate the $W^{\pm}W^{\pm}jj$ QCD background from the EWK signal
- Reduce the impact of the inference between the two process (which is typically not modelled)
- A high cut in m_{jj} reduces non-VBS EWK diagrams (such as tri-boson production)

VBS in the context of SM cross section measurements