Recent observation and measurements of vector-boson fusion and scattering with ATLAS

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on behalf of the ATLAS Collaboration

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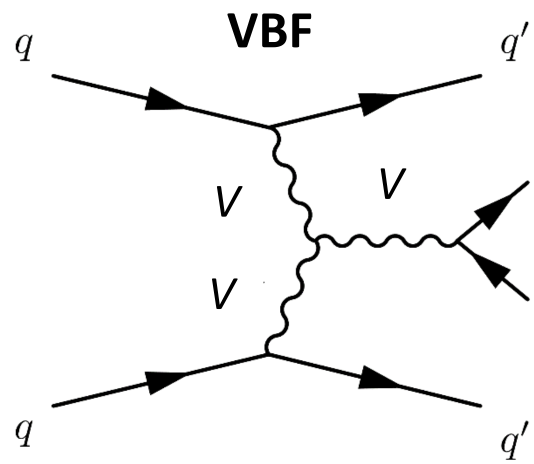
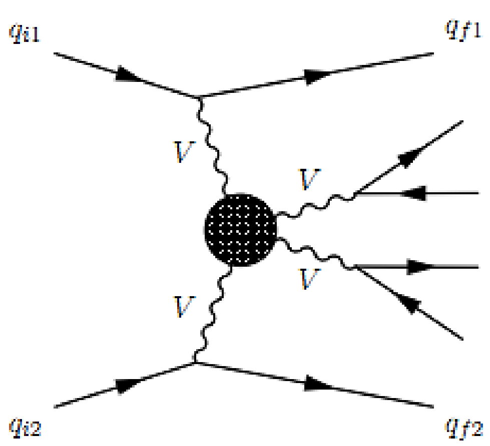
Introduction





Measure VBF/VBS via the corresponding EW productions.

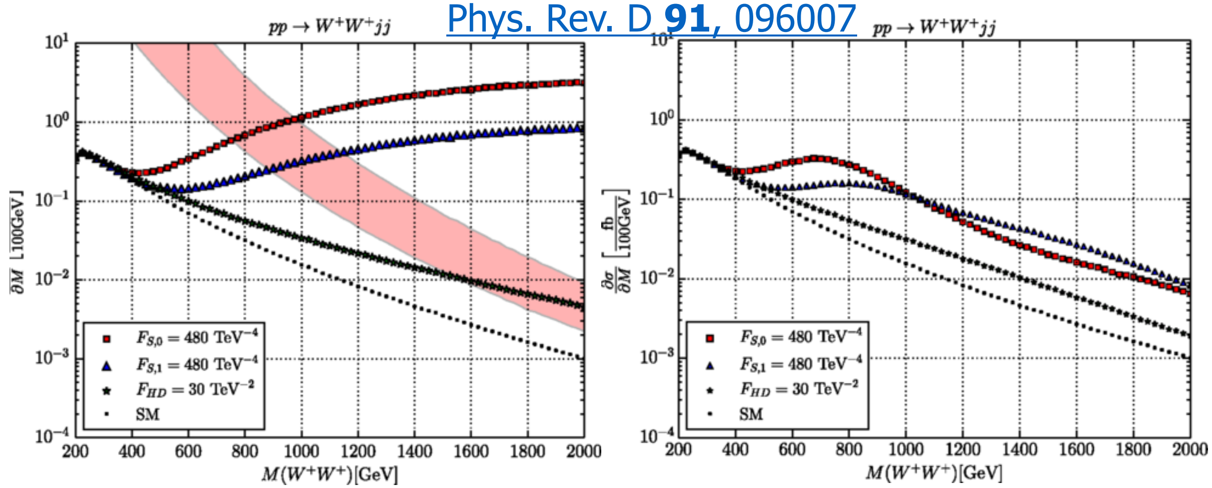
- **VBF/VBS→benchmark SM measurements**

  -- important test of electroweak sector and EW Symmetry Breaking.

- **Sensitive to anomalous triple and quartic couplings → aTGC and aQGC**

- **Involving Higgs interactions→Understanding the nature of EWSB**

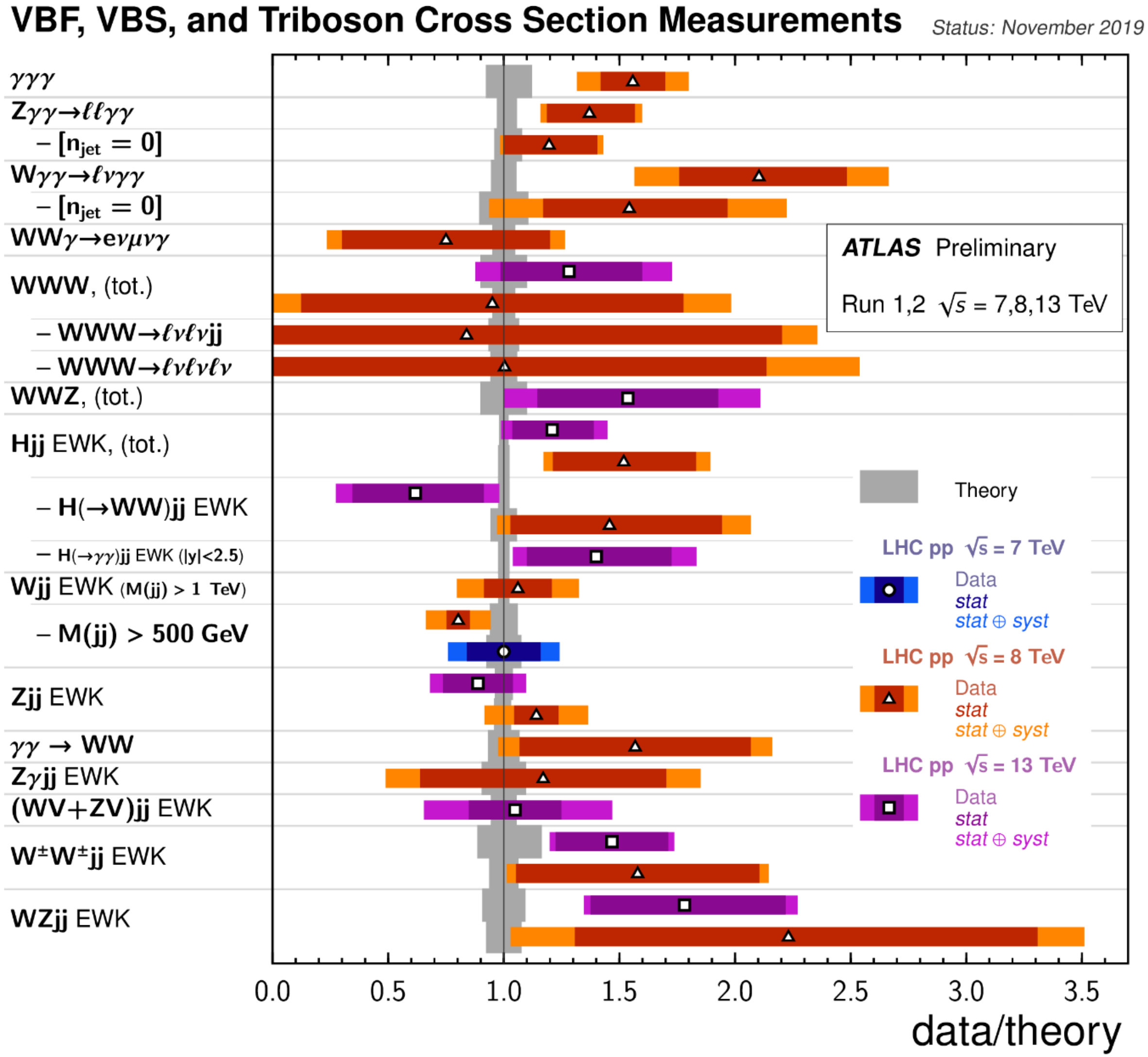
[Phys. Rev. D **91**, 096007](#)



w/o Higgs

w/ Higgs

VBF/VBS measurements in ATLAS



- $\sqrt{s} = 13\text{TeV}$

ZZjj 5.5(4.3)σ [arXiv:2004.10612]

$Z\gamma jj$ 4.1(4.1)σ [Phys. Lett. B 803 (2020) 135341]

VBF+VBS

ZZjj($lllljj$,$ll\nu\nu jj$)

-- Full Run2 datasets (139fb^{-1}).
-- Measure the ZZjj cross-section (EW + QCD).
-- Evidence of electroweak production of the ZZjj process.
-- Backgrounds:
  - $lllljj$: QCD background, fake lepton background, WWZ…
  - $ll\nu\nu jj$: Non-Resonant background, WZ background, Z+jets background, ZZ $\rightarrow$ $llll$,VVV, ttV, ttVV

arXiv:2004.10612

Selections for ZZjj

	$\ell\ell\ell\ell jj$	$\ell\ell\nu\nu jj$
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 ★ (grey) $\Delta R(\ell, \ell') > 0.2$ $66 < m_{\ell^+\ell^-} < 116$ GeV	$p_T > 30$ (20) GeV for the leading (sub-leading) lepton One OSSF lepton pair and no third leptons ★ (green) $80 < m_{\ell^+\ell^-} < 100$ GeV ★ (orange) ★ (green) No b-tagged jets ★ (orange) E_T^{miss} significance > 12 ★ (purple)
Dijet selection	Two most energetic jets with $y_{j_1} \times y_{j_2} < 0$ ★ (red) $m_{jj} > 300$ GeV and $\Delta y(jj) > 2$ ★ (blue) ★ (red)	$m_{jj} > 400$ GeV and $\Delta y(jj) > 2$ ★ (red)

- ★ (grey) To reject events from low mass resonances
- ★ (blue) Relatively loose m_{jj} cut to keep more events for further discrimination with an MVA
- ★ (orange) Reduce top background
- ★ (green) Suppress W background
- ★ (purple) Suppress Z+jets background
- ★ (red) Back-to-back topology, enhance S/B ratio

Background estimation

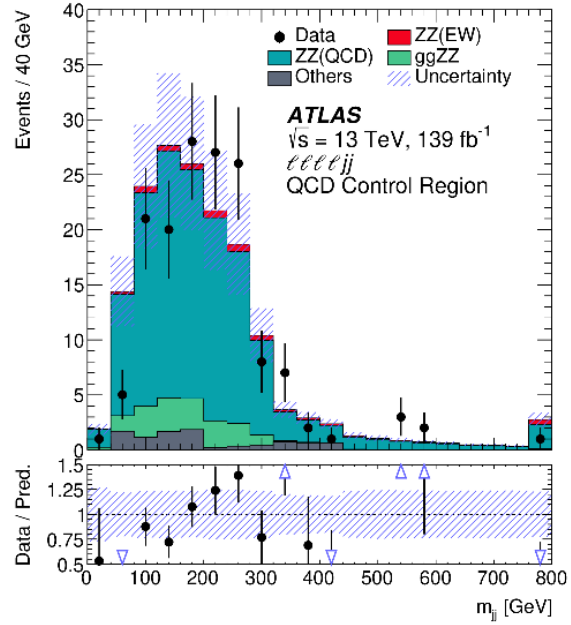
- ***llllj j*** **background**

  -- QCD background: $qq \rightarrow ZZjj$ and $gg \rightarrow ZZjj$

  - QCD CR: $|\Delta Y_{jj}| < 2$ or $m_{jj} < 300$ GeV

  - Simultaneous fit SR & QCD CR.

  -- Others background: Fake lepton background (data-driven techniques), WWZ…(MC).

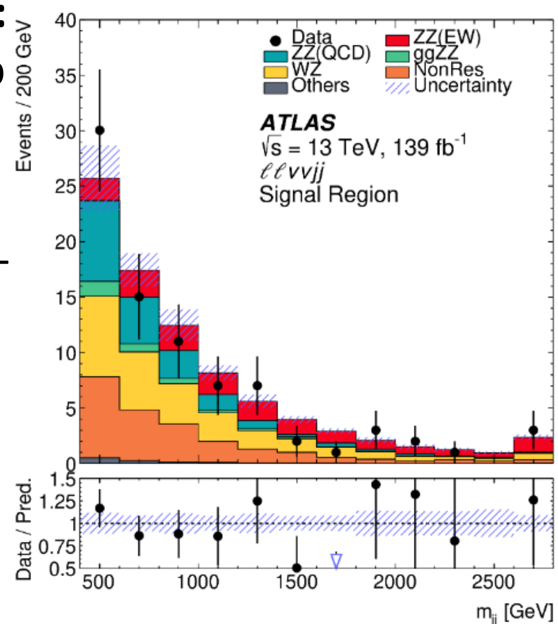


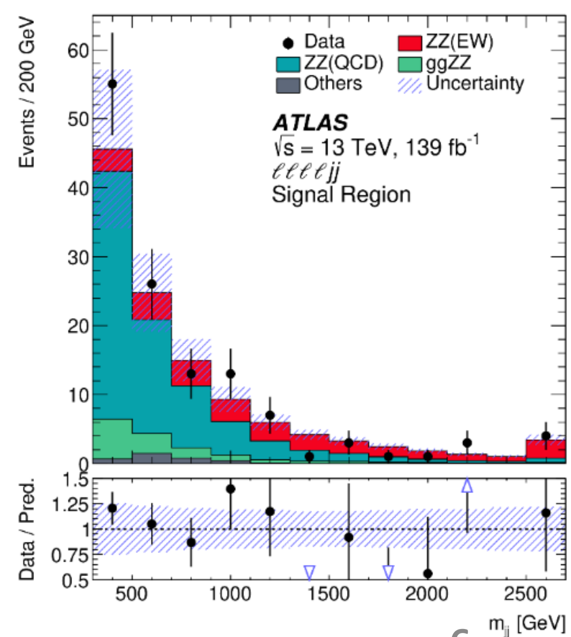
- ***llννjj*** **background**

  -- Non-Resonant background: $t\bar{t}$, WW, Wt, Z→ $\tau\tau$, single top ($e\mu$ CR, data-driven techniques).

  -- WZ background: 3lCR, data-driven techniques.

  -- Others background: Z+jets background (sideband method), ZZ → $llll$,VVV, ttV, ttVV backgrounds (MC).





Cross-section

- Fiducial phase space close to detector-level selections.

-- $llljj$ channel: extrapolate $m_{l^+l^-}$ to [60, 120]GeV.
-- $ll\nu\nu jj$ channel: extrapolate electron eta cut to 2.5 . Use truth E_T^{miss}>130GeV to instead of E_T^{miss} significance>12.

- Fiducial cross-sections for the inclusive production of the EW and QCD processes are measured separately in individual channels.

$$C = \frac{N_{detector-level}}{N_{FV-truth}} \qquad \sigma = \frac{N_{data} - N_{background}}{\mathcal{L} \times C}$$

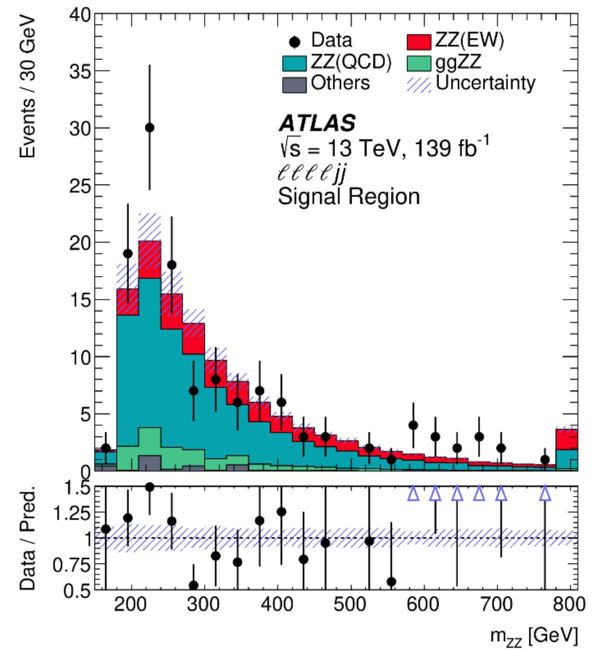
***lllljj* C factor**	0.699 ± 0.031
***llvvjj* C factor**	0.216 ± 0.012

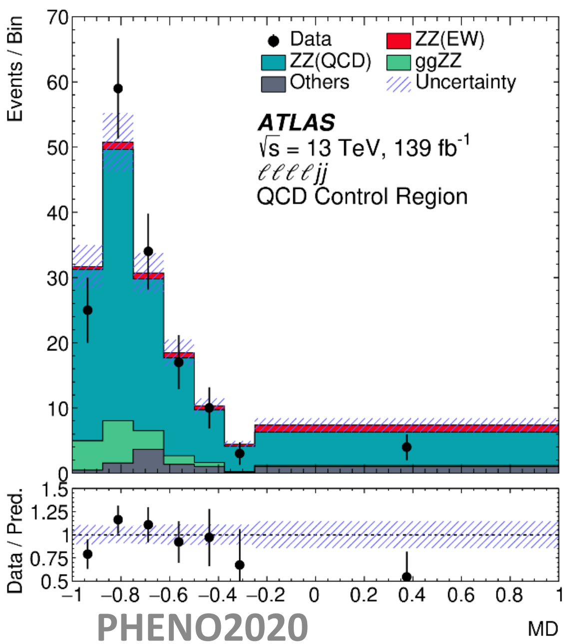
	Measured fiducial σ [fb]	Predicted fiducial σ [fb]
$\ell\ell\ell\ell jj$	$1.27 \pm 0.12(\text{stat}) \pm 0.02(\text{theo}) \pm 0.07(\text{exp}) \pm 0.01(\text{bkg}) \pm 0.03(\text{lumi})$	$1.14 \pm 0.04(\text{stat}) \pm 0.20(\text{theo})$
$\ell\ell\nu\nu jj$	$1.22 \pm 0.30(\text{stat}) \pm 0.04(\text{theo})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

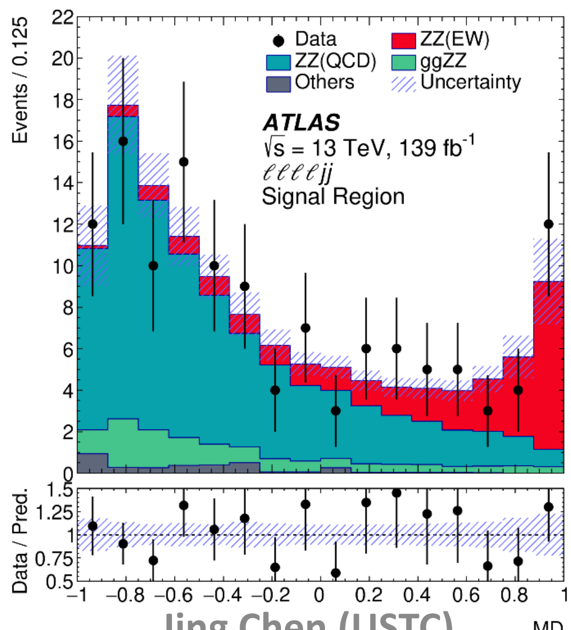
[arXiv:2004.10612](https://arxiv.org/abs/2004.10612)

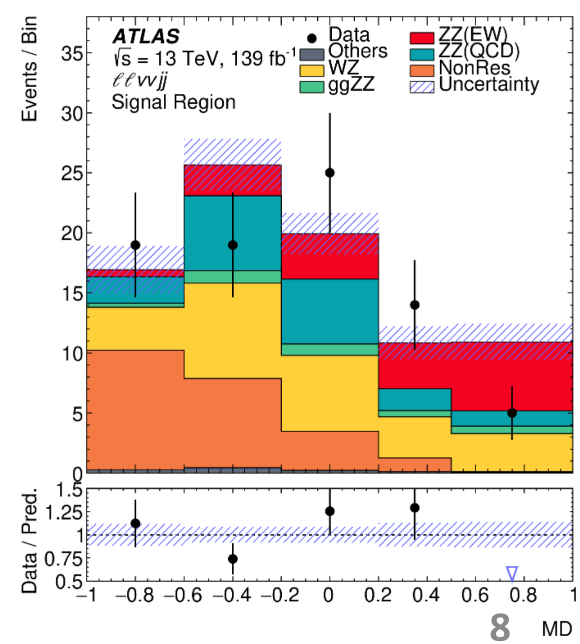
Search for EW ZZjj

- Gradient Boosted Decision Tree **(BDTG)** method is used. The BDTG is trained by a set of variables. These variables are sensitive to the VBS topology.
- To extract EW process, a profile likelihood fit is performed on BDTG response.
- Multivariate discriminant plots are post-fit results.
- Data distributions are consistent with predicted ones.









Search for EW ZZjj

- Normalizations and shapes uncertainties of background processes are considered.

$\boldsymbol{\mu_{EW}}$ **:** the measured fiducial cross-section over the SM prediction for EW ZZjj production.

	μ_{EW}	$\mu_{\mathrm{QCD}}^{\ell\ell\ell\ell jj}$	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	$5.5\ (4.3)\ \sigma$

- The EW ZZjj cross-section (combing the two channels) in the fiducial volume is **0.82 $\pm$ 0.21 fb**, calculated as $\mu_{EW} \times \sigma_{SM}$ ($\sigma_{SM} = 0.61 \pm 0.03$fb).
- **Interference** between EW and QCD processes was modelled with MadGraph calculated at LO and is treated as systematic on the predicted EW process. The effect is far smaller than the statistical uncertainty from data.

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Zγjj($ll\gamma$)

- 2015+2016 datasets (36.1fb^{-1}).
- Measure the Zγjj cross-section (EW).
- Evidence of electroweak production of the Zγjj process.
- Backgrounds: Z+jets background, $Z\gamma$ QCD background, $t\bar{t}\gamma$ background, other backgrounds (WZ,Wt).

Selections for $Z\gamma jj$

	$\ell^+\ell^-\gamma jj$ preselection
Lepton	$p_T^\ell > 20$ GeV $\lvert\eta_\ell\rvert < 2.47(2.5)$ for $e(\mu)$ remove e if $\Delta R(e,\mu) < 0.1$ $N_\ell = 2$
Boson	$m_{\ell^+\ell^-} > 40$ GeV $m_{\ell^+\ell^-} + m_{\ell^+\ell^-\gamma} > 182$ GeV ★
Photon	$E_T^\gamma > 15$ GeV $\lvert\eta_\gamma\rvert < 2.37$ (excl. $1.37 < \lvert\eta_\gamma\rvert < 1.52$) remove γ if $\Delta R(\ell,\gamma) < 0.4$ $N_\gamma \geq 1$
b-jet	$p_T^{\text{jet}} > 25$ GeV , $\lvert\eta_{\text{jet}}\rvert < 2.5$
Jet	$p_T^{\text{jet}} > 50$ GeV , $\lvert\eta_{\text{jet}}\rvert < 4.5$ $N_{\text{Jets}} \geq 2$ ★ remove jets if $\Delta R(\ell,\text{jet}) < 0.4$ OR $\Delta R(\gamma,\text{jet}) < 0.4$ $\lvert\Delta\eta_{jj}\rvert > 1.0$ $m_{jj} > 150$ GeV ★
b-CR	$\ell^+\ell^-\gamma jj$ preselection $\zeta(\ell\ell\gamma) < 5$ Nb–jet>0
Signal Region	$\ell^+\ell^-\gamma jj$ preselection $\zeta(\ell\ell\gamma) < 5$ Nb–jet=0

★ Twice the Z boson mass(ensure $m_{l^+l^-\gamma} > m_Z$). Suppress Z boson decays into $ll\gamma$.

★ To select electroweak processes.

★ To minimise triboson background, i.e. $Z\gamma + W/Z(\rightarrow jj)$.

$$\zeta(\ell\ell\gamma) = \left|\frac{y_{\ell\ell\gamma} - (y_{j_1} + y_{j_2})/2}{(y_{j_1} - y_{j_2})}\right|$$

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Background estimation

- **Z+jets background**

  -- A two-dimensional sideband method (ABCD method) is used.

$$\frac{N_D^{ZJet}}{N_B^{ZJet}} = R_{MC}\frac{N_C^{ZJet}}{N_A^{ZJet}}$$

  R_{MC}: correction factor (determined using SHERPA Z+jets MC sample).

- **$Z\gamma$ QCD background**

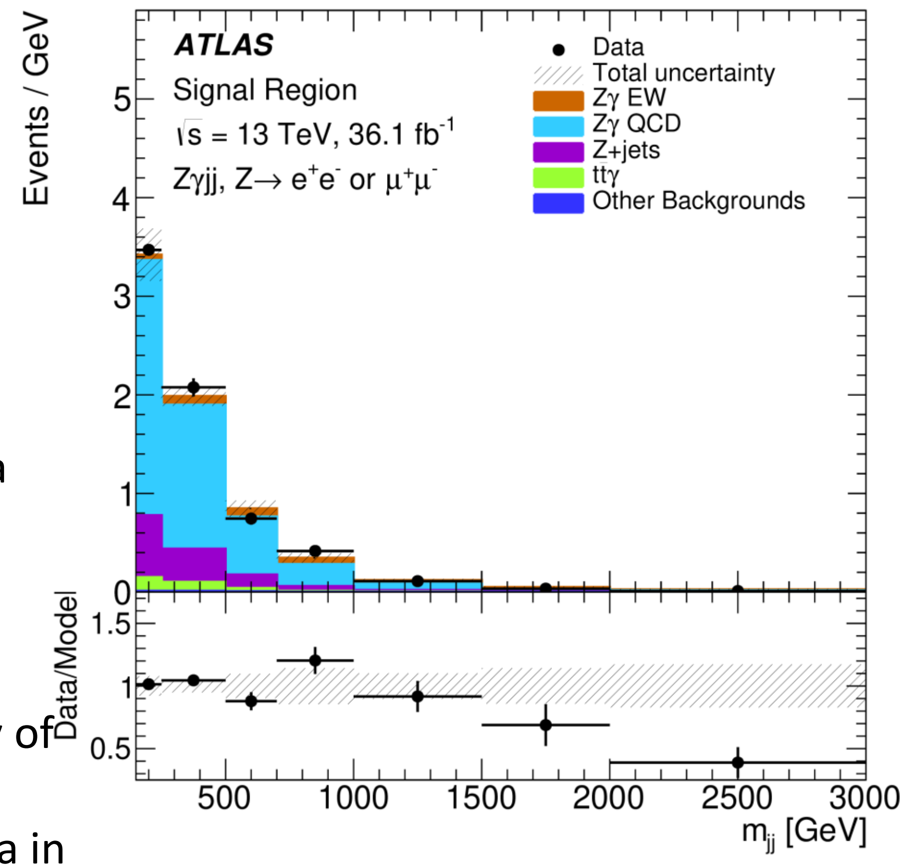
  -- Constrain $Z\gamma$ background by the data in the template fit.

- **$t\bar{t}\gamma$ background**

  -- b-Control Region (b-CR): check the modelling and mitigate the uncertainty of the modelling.

  -- Constrain $t\bar{t}\gamma$ background by the data in the template fit.

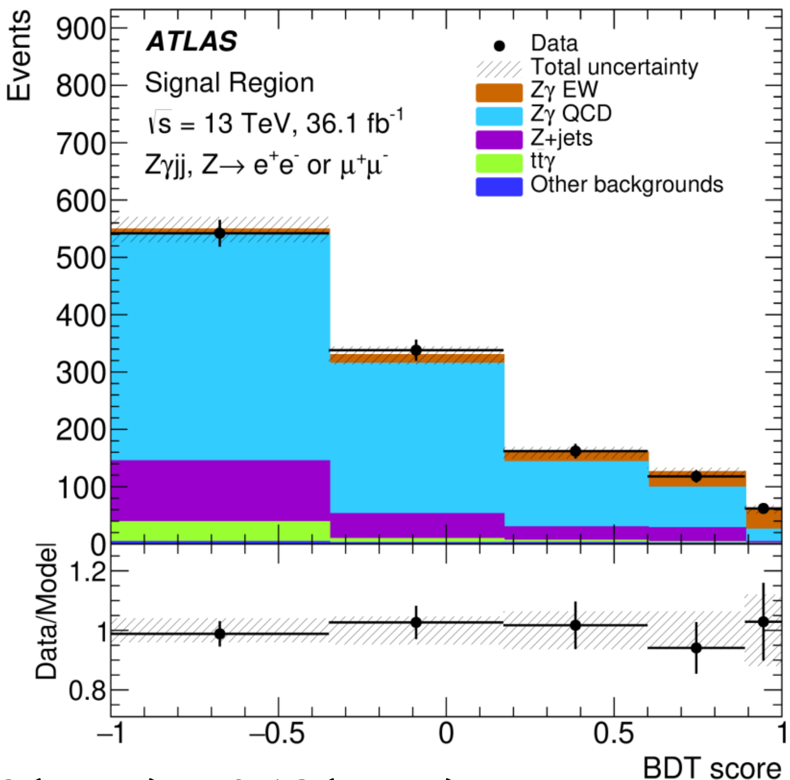
- **Other backgrounds (WZ,Wt):** MC



Signal extraction

- Boosted Decision Tree **(BDT)** method is used to separate the EW signal.
- A maximum-likelihood fit is performed to BDT distribution to measure the EW cross section and to determine the significance.

  -- $ee\gamma jj$ and $\mu\mu\gamma jj$ final states are combined.
  -- An extended likelihood function is built based on BDT score in SR and b-CR.



- the signal strength:

$$\mu_{Z\gamma jj-EW} = \frac{N^{data}_{Z\gamma jj-EW}}{N^{MC}_{Z\gamma jj\_EW}} = 1.00 \pm 0.19(stat.) \pm 0.13(syst.)$$

- Significance: **4.1σ** (both observed and expected).

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Cross-section

- Fiducial phase space close to detector-level selections.

  -- Extrapolate electron eta cut to 2.5 . Use $\mathrm{N}_l \geq 2$ to replace $\mathrm{N}_l = 2$, no $N_{b-jet} = 0$ requirements.
- The fiducial cross-sections (EW+interference) is derived using the signal strength parameter:

$$\sigma_{Z\gamma jj-EW}^{fid.,data} = \sigma_{Z\gamma jj-EW}^{fid.,MC} \times \mu_{Z\gamma jj-EW}$$

$\sigma^{\text{fid.}}_{Z\gamma jj-\text{EW}}$	$=$	$7.8 \pm 1.5\,(\text{stat.}) \pm 1.0\,(\text{syst.})\,^{+1.0}_{-0.8}\,(\text{mod.})$ fb
$\sigma^{\text{fid., MadGraph}}_{Z\gamma jj-\text{EW}}$	$=$	$7.75 \pm 0.03\,(\text{stat.}) \pm 0.20\,(\text{PDF} + \alpha_{\text{S}}) \pm 0.40\,(\text{scale})$ fb
$\sigma^{\text{fid., Sherpa}}_{Z\gamma jj-\text{EW}}$	$=$	$8.94 \pm 0.08\,(\text{stat.}) \pm 0.20\,(\text{PDF} + \alpha_{\text{S}}) \pm 0.50\,(\text{scale})$ fb

- The fiducial cross-sections (EW+QCD):

$\sigma^{\text{fid.}}_{Z\gamma jj}$	$=$	$71 \pm 2\,(\text{stat.})\,^{+9}_{-7}\,(\text{syst.})\,^{+21}_{-17}\,(\text{mod.})$ fb
$\sigma^{\text{fid., MadGraph+Sherpa}}_{Z\gamma jj}$	$=$	$88.4 \pm 2.4\,(\text{stat.}) \pm 2.3\,(\text{PDF} + \alpha_{\text{S}})^{+29.4}_{-19.1}\,(\text{scale})$ fb.

Summary

- First observation of EW ZZjj production with full Run2 datasets (139fb^{-1}).

  -- Inclusive cross sections for $llll jj$ and $ll\nu\nu jj$ channels **are measured** in dedicated fiducial volume and found to be **consistent** with the SM predictions.
  -- Observed(expected) significance of EW production is **5.5σ(4.3σ)**.
  -- The observation of EW ZZjj production is a new milestone reached in the study of EW VVjj production.

- Evidence for EW Zγjj with 36.1fb^{-1} at 13TeV is presented.

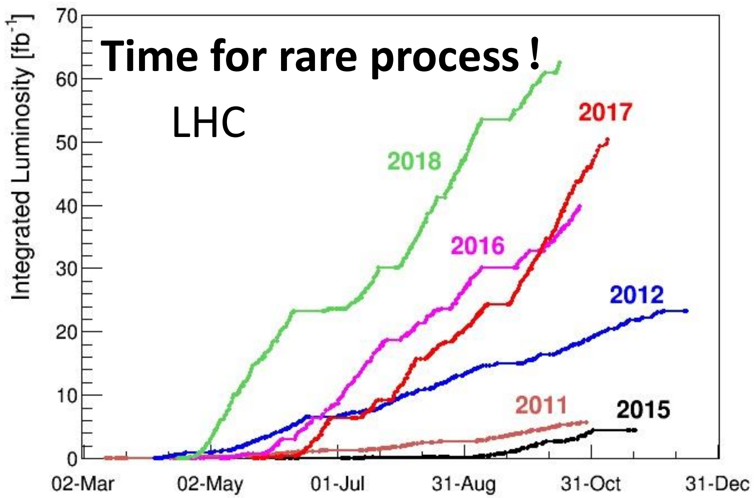
  -- The EW cross section of Zγjj process is measured which is in good agreement with the SM prediction .
  -- The background-only hypothesis is excluded with observed and expected significances of **4.1σ**.

- The precision measurements can help us probe the SM and understand the nature of EWSB.

- More results will come with 13 TeV data!

backup

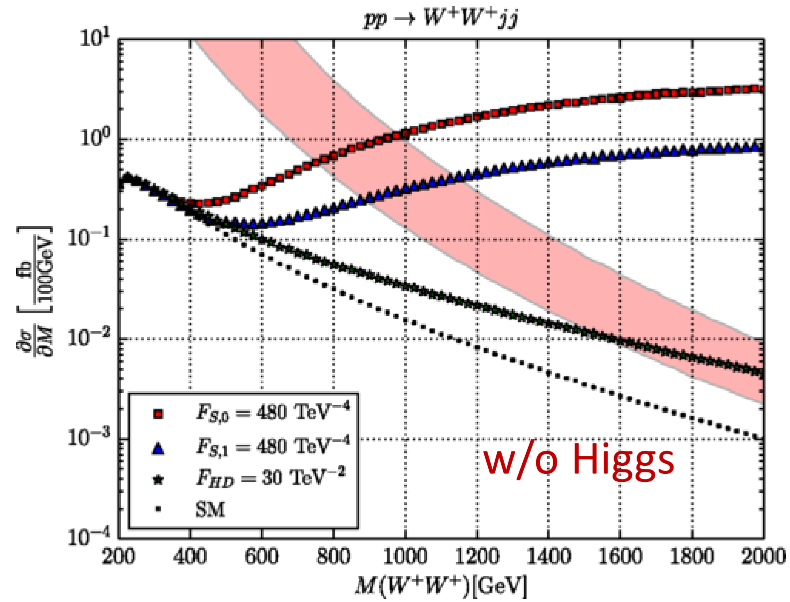
Probe EWSB

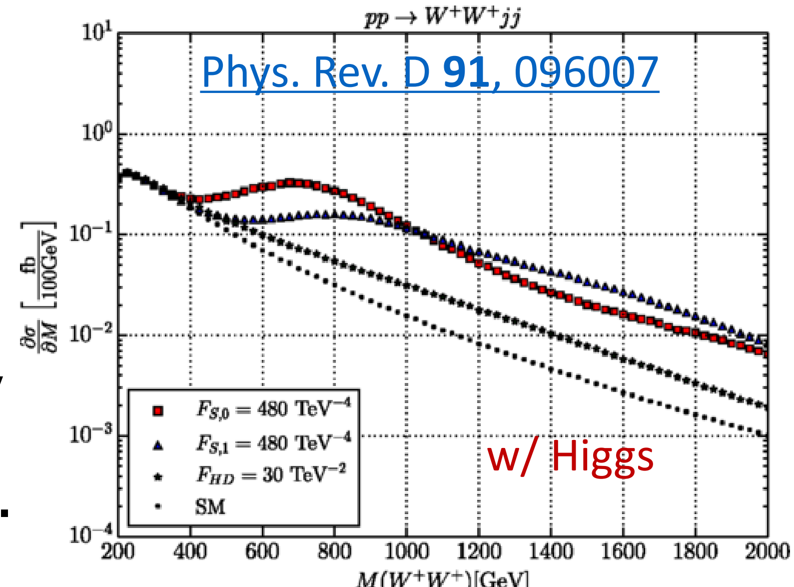


https://www.lhc-closer.es/taking_a_closer_look_at_lhc/0.luminosity

- The presence of the Higgs boson prevents the VBS amplitudes from violating unitarity at the TeV scale!

- **Vector boson scattering is a key process to probe the nature of electroweak symmetry breaking.**





VBS VVjj measurements

13TeV	Observed (expected) significance		Challenges
	ATLAS	CMS	
ssWW	$6.5(4.4)\sigma$ Phys. Rev. Lett. 123 (2019) 161801	$5.5(5.7)\sigma$ PRL 120 (2018) 081801	First observation of VBS: large ratio of EW to strong production cross-sections.
WZ	$5.3(3.2)\sigma$ Phys. Lett. B 793 (2019) 469	$2.2(2.5)\sigma$ PLB 795 (2019) 281	Similar cross-section as ssWW, but larger QCD background.
ZZ	$llllj j + ll\nu\nu jj$ $5.5(4.3)\sigma$ ATLAS-CONF-2019-033	$lllljj$ $2.7(1.6)\sigma$ *Phys. Lett. B 774 (2017) 682*	$lllljj$ channel: small cross-section, low background, fully reconstructed final state. $ll\nu\nu jj$ channel: relatively large cross-section, complex background components, large uncertainties from jet/E_T^{miss} reconstruction.
$Z\gamma$	$4.1(3.8)\sigma$ Phys. Lett. B 803 (2020) 135341	$3.9(5.2)\sigma$ CMS-SMP-18-007	Photon provide more statistics.

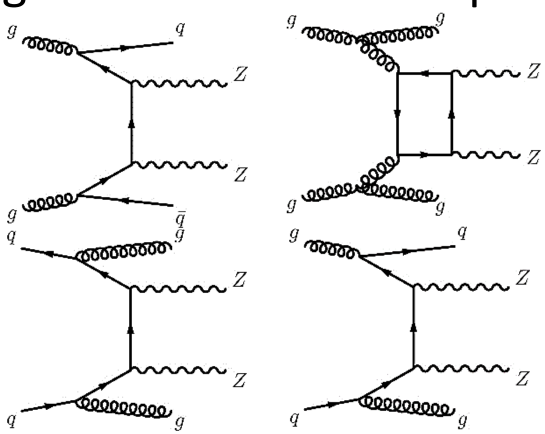
arXiv:2004.10612
Phys. Lett. B 803 (2020) 135341

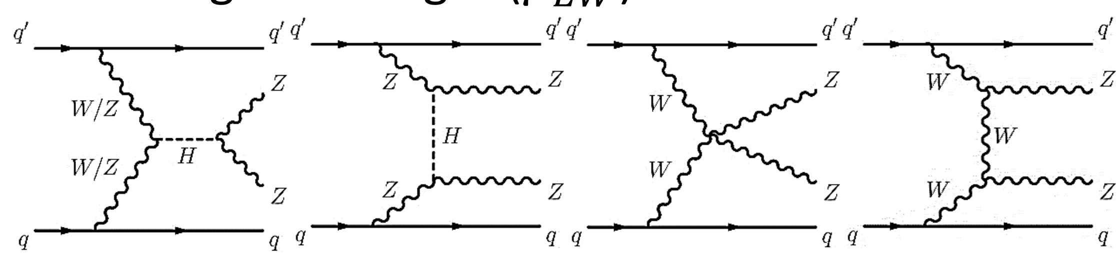
Analysis overview

- **ZZjj:**
  - Measure the ZZjj cross-section (EW + QCD).
  - Evidence of electroweak production of the ZZjj process:
    Combine $lllljj$ and $ll\nu\nu jj$, fit the MVA output to extract the significance of EW component and signal strength (μ_{EW}).
  - Full Run2 datasets (139fb^{-1}).
- **Zγjj:**
  - Measure the Zγjj cross-section (EW).
  - Evidence of electroweak production of the Zγjj process:
    A maximum-likelihood fit is performed to measure the EW cross section and to determine the significance of the signal.
  - 2015+2016 datasets (36.1fb^{-1}).

Analysis overview

- **Physics goals**
  - Measure the ZZjj cross-section (EW + QCD):
    Measure the inclusive cross-section for $llllj j$ and $ll\nu\nu jj$ separately in their corresponding fiducial volume.
  - Evidence on EW VBS ZZjj
    Combine $lllljj$ and $ll\nu\nu jj$, fit the MVA output to extract the significance of EW component and signal strength (μ_{EW}).





- **Data and MC samples**
  - Full Run2 datasets (139fb^{-1})
  - MC samples

EW ZZjj - LO	MadGraph
QCD qqZZjj - NLO(LO)	Sherpa222
QCD ggZZjj	$lllljj$:Sherpa222; $ll\nu\nu jj$:gg2vv
Triboson and other diboson	Sherpa222, Powheg
Z+jets	Sherpa221
Top	Powheg, MadGraph, Sherpa221

MC samples

Item	Process	Generator	PDF
EWK	ZZ+2jets	MadGraph5_aMC@NLO 2.6.1	NNPDF2.3LO
QCD	qqZZ	Sherpa 2.2.2	NNPDF3.0NNLO
	ggZZ($lllljj$)	Sherpa 2.2.2	NNPDF3.0NNLO
	ggZZ($ll\nu\nu$)	gg2VV	CT10NNLO
Diboson	$WW \to l\nu qq$	Powheg-Box v2	CT10
	$WZ \to llqq$	Powheg-Box v2	CT10
	$WZ \to lll\nu$	Sherpa 2.2.2	NNPDF3.0NNLO
Triboson	VVV	Sherpa 2.2.2	NNPDF3.0NNLO
Top	top-quark pair	Powheg-Box v2	CT10
	single top-quark	Powheg-Box v1	CT10f4
	$t\bar{t}$	Powheg-Box v2	NNPDF3.0
	$t\bar{t}V$	MadGraph5_aMC@NLO 2.2.2	NNPDF2.3
ZJets	Z+jets	Sherpa 2.2.1	NNPDF3.0NNLO

Background estimation

- $\boldsymbol{lllljj}$ **QCD background ($\boldsymbol{qq \to ZZjj}$ and $\boldsymbol{gg \to ZZjj}$):**

  -- QCD CR: $|\Delta Y_{jj}| < 2$ or $m_{jj} < 300$ GeV

  -- Simultaneous fit SR & QCD CR.

  -- Theoretical uncertainty mainly from generator modelling uncertainty (**Sherpa vs. MG**).

  -- Jet pile-up uncertainty: high-mu vs. low-mu comparison as additional systematic.

  -- The modelling of QCD ZZjj has been cross checked in another high centrality CR.

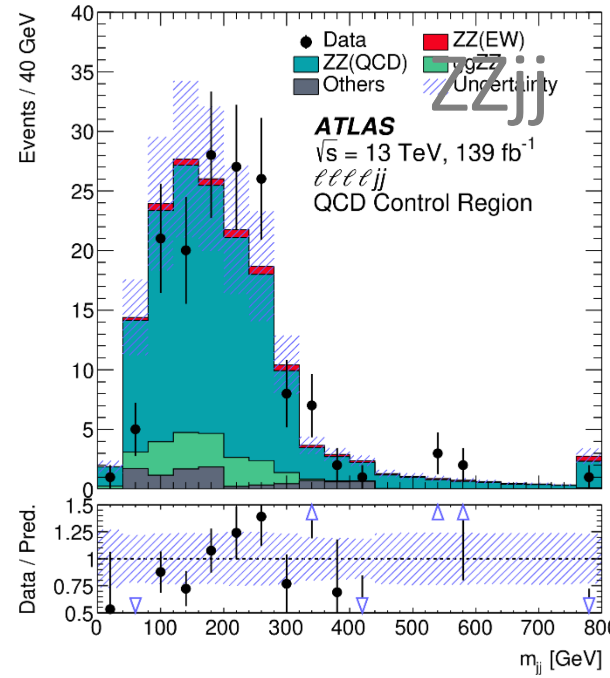
- $\boldsymbol{lllljj}$ **Others background:**

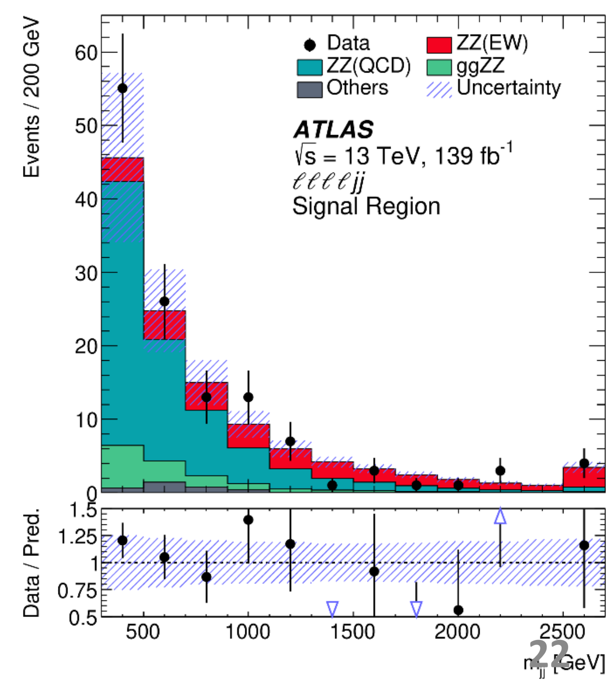
  -- Fake lepton background

  - Fake factor method is used.
  - Systematics: varying “poor” lepton definition, MC contamination, use one bin fake factor instead of p_T/η dependent ones, fake factor difference from data and MC

  -- WWZ…: MC

ZZjj





Background estimation

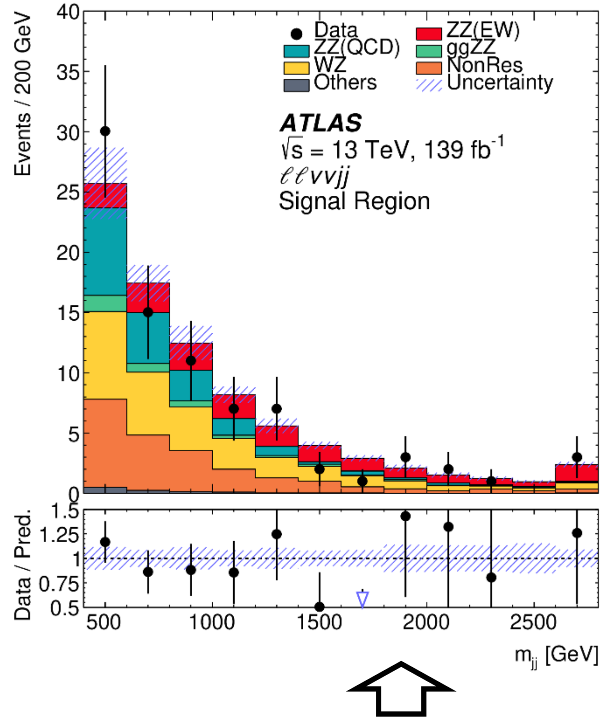
- **ll$\nu\nu$ Non-Resonant ($t\bar{t}$, WW, Wt, Z→ $\tau\tau$, single top) background:**

-- Non-Resonant background: eμ CR
  - Exploit ratio of decays ee:$\mu\mu$:eμ = 1:1:2
  - In kinematic region $Q(p_T, \eta)$:

$$\epsilon^Q = \sqrt{\frac{N_{ee}^Q}{N_{\mu\mu}^Q}}$$

$$N_{SR\ ee}^{Q,e\mu} = \frac{1}{2} \times \epsilon^Q \times N_{e\mu\ CR}^{sub,bkg}$$

$$N_{SR\ \mu\mu}^{Q,e\mu} = \frac{1}{2} \times \frac{1}{\epsilon^Q} \times N_{e\mu\ CR}^{sub,bkg}$$



Main backgrounds: **Non-Resonant** and **WZ.**

-- Systematics:
  - ϵ factor's dependency on different binning method.
  - ϵ factor's uncertainty due to data stat. uncertainty.
  - Shape difference between MC and data driven based methods.

Background estimation

ZZjj

- **ll$\nu\nu$ WZ background:**

-- WZ background: 3l CR (eee, eeμ, μμe, μμμ)

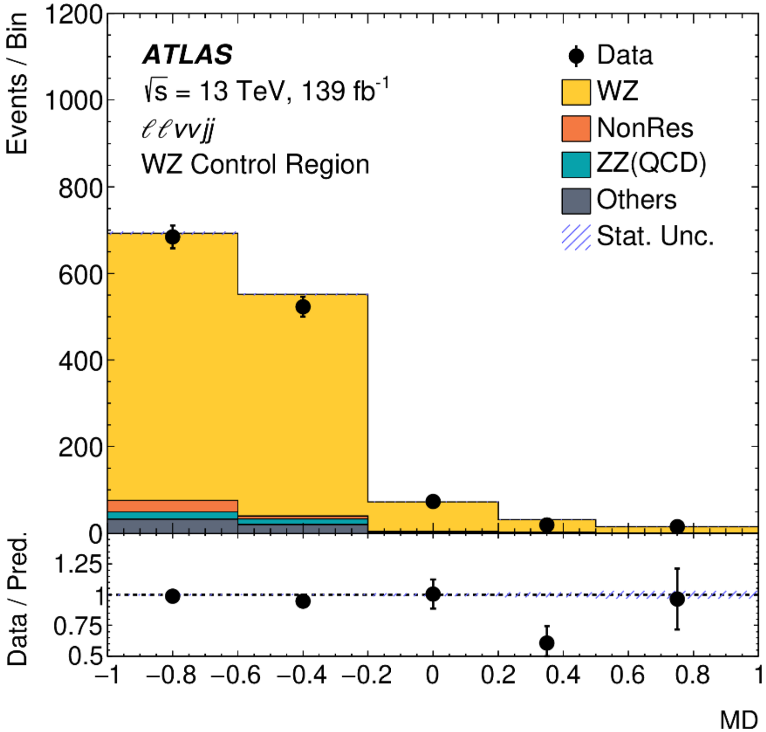
$$N_{WZ}^{est} = N_{MC}^{2l\,SR} \times sf_{WZ} = N_{MC}^{2l\,SR} \times \frac{N_{data-nonWZMC}^{3l\,CR}}{N_{MC}^{3l\,CR}} = N_{data-nonWZMC}^{3l\,CR} \times \frac{N_{MC}^{2l\,SR}}{N_{MC}^{3l\,CR}}$$

-- Scale factor: 0.85

-- Systematics:

- Statistical uncertainty on sf_{WZ} due to CR data.
- Experiment and theory uncertainties on the WZ transfer factor and signal region WZ shape.
- EW WZ cross section: Use the SM cross section for EW WZ. Treat the prediction v.s. measurement ($\mu_{EWKWZ} = 1.77$) difference as the cross-section uncertainty for EW WZ.

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



Background estimation

- **ll$\nu\nu$ Others background:**

-- Z+jets background:

- Use SR MC to estimate Z+jets shape.
- Choose low E_T^{miss} significance region as CR.
- Fit CR data – nonZjMC. Extrapolate fit result to SR to derive SR Z+jets event yield.
- Systematics: variations in the fitting functions, differences between estimated and simulated yields and distributions.

-- ZZ → $\mathbf{llll}$,VVV, ttV, ttVV backgrounds: MC

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

- **Event yields:**

-- uncertainties: stat.+syst.

-- Minor backgrounds are summed together as 'Others'.

Background estimation

ZZjj

- $\boldsymbol{lllljj}$ **background: Fake lepton backgroun**

-- Fake-factor measured in jet-enriched samples

- Z+jets CR: same-flavor opposite-charge lepton pair under Z mass and two additional jets.
- $t\bar{t}$ CR: two jets (at least one bjet) and two high p_T isolated leptons forming an $e\mu$ pair with $E_T^{miss} > 50\text{GeV}, m_T^W < 60GeV$.
- $f = N_{good}/N_{poor}$ (flavor and pT/eta dependent).
- Poor electrons are defined by reverting isolation or eleID cuts.
- Poor muons are defined by reverting isolation or d0 significance cut (but still pass |d0significance|<10).

-- $lllljj$ fake CR : SR with 1 or 2 leptons passing poor lepton definition.

-- Fake contribution in signal region:

- $N_{fake} = \left(N_{gggp} - N_{gggp}^{ZZ}\right) \times f - \left(N_{ggpp} - N_{ggpp}^{ZZ}\right) \times f \times f$
- ZZ contribution is subtracted.
- The second term is due to double counting of N_{gggp} and N_{ggpp}.

-- Systematics: varying "poor" lepton definition, MC contamination, use one bin fake factor instead of p_T/η dependent ones, fake factor difference from data and MC

3l CR & eμ CR

The $e\mu$CR selections are listed as:

- two different-flavour opposite-charge leptons
- veto events with any additional lepton with Loose ID and $P_T > 7$GeV
- $80 < M_{\ell\ell} < 100$GeV
- $P_T^{\ell_1} > 30$GeV, $P_T^{\ell_2} > 20$GeV,$|\eta_\ell| < 2.5$
- $n_{jets} \geq 2$, $P_T^{j_1} > 60$GeV, $P_T^{j_2} > 40$GeV, $|\eta_j| < 4.5$
- $M_{jj} > 400$GeV, $\Delta Y_{JJ} > 2$, $Y_{j1} \times Y_{j2} < 0$
- B-jet veto
- MET Significance > 12

The definition of 3lCR is:

- $80 < M_{\ell\ell} < 100$GeV
- $P_T^{\ell_1} > 30$GeV, $P_T^{\ell_2} > 20$GeV,$|\eta_\ell| < 2.5$, medium
- $p_{\mathrm{T}}^{\ell 3rd} > 20$GeV, $|(\eta^{\ell 3rd})| < 2.5$, medium
- Transverse mass $m_T^W > 40$GeV
- B-jet veto: 85% working point
- $n_{jets} \geq 2$
- $P_T^{J_1} > 60$GeV, $P_T^{J_2} > 40$GeV
- MET Significance > 3

Z+jets

$$m_{\mathrm{T}}^{W} = \sqrt{2 P_T^{\ell 3} E_{\mathrm{T}}^{\mathrm{miss}} \left[1 - \cos\left(\Delta\phi\left(P_T^{\ell 3}, E_{\mathrm{T}}^{\mathrm{miss}}\right)\right)\right]}$$

To keep more statistics, no m_{jj} or $|\Delta Y_{jj}|$ cuts and loose MET significance.

Uncertainties

- **Theoretical uncertainties:**

  -- PDF, QCD scale, α_s, parton showering (PS).

  - PDF: the envelope of the NNPDF internal errors and the differences between the nominal and alternative PDFs.

  - QCD scales: 7-point scale variations of the renormalization (μ_r) and the factorization scale (μ_f) ({0.5,0.5}, {1,0.5}, {0.5,1}, {1,1}, {2,1}, {1,2}, {2,2}). The largest deviation is chosen as the uncertainty.

  - PS: comparing the nominal Pythia8 parton showering with the alternative Herwig7 algorithm.

  - α_s: varying the α_s value within $\pm$0.001.

  -- Interference effect between the EW and QCD processes is 7%(2%) in $llll jj$($ll\nu\nu jj$) channel. Treat as an extra uncertainty in the EW signal predictions.

  -- Generator modelling uncertainty: estimated by comparing Sherpa with MadGraph5 _aMC@NLO 2.6.1 predictions at particle level.

- **Experimental uncertainties:**

  -- luminosity: 1.7%.

  -- The momentum scale and resolution of leptons and jets, lepton reconstruction and selection efficiencies, trigger selection efficiency, the calculation of the E_T^{miss} soft-term, the pile-up correction, and the b-jet identification efficiency: 5-10%.

  -- Jet pile-up uncertainty.

Systematic Uncertainties

- The uncertainties in the predicted yields:

Source	Uncertainty
Total experimental uncertainty	10%($lllljj$), 5%($ll\nu\nu jj$)
Luminosity	1.7%
non-ZZjj backgrounds	15%
Total theoretical uncertainty in EW ZZjj	10%
Total theoretical uncertainty in QCD ZZjj	30%
Interference	10% to 2% in different MD region
Modelling of the QCD ZZjj process	-30% to +20%

Search for EW ZZjj

- **MVA**
  - Gradient Boosted Decision Tree **(BDTG)** method is used.
  - In $llll jj$ channel, training is performed based on EW and QCD samples.
  - In $ll\nu\nu jj$ channel, the training signal is EW, all other backgrounds are used except Z+jets.
- **Fit procedure**
  - To extract EW process, a profile likelihood fit is performed on BDTG response.
  - Simultaneous fit in SR and QCD $llll jj$ CR. The measured fiducial cross-section over the SM prediction for EW ZZjj production **($\boldsymbol{\mu_{EW}}$)** is taken as the **parameter of interest**. μ_{QCD}^{lllljj} represents the normalization factor of QCD ZZjj production.
  - Systematics enter the likelihood as nuisance parameters with Gaussian constrains.
  - For **signal process**, only **shapes uncertainties** are considered.
  - An additional 1.7 k-factor is applied to gg sample.Phys. Rev. D 92 (9 2015) 094028
  - Experiment systematics are treated as correlated.
  - Theoretical uncertainties for the ZZjj production are uncorrelated between the two channels (different fiducial volume).
  - QCD scale uncertainty in $llll jj$ SR, CR and generator modelling uncertainty are uncorrelated (large phase-space difference).

Uncertainties

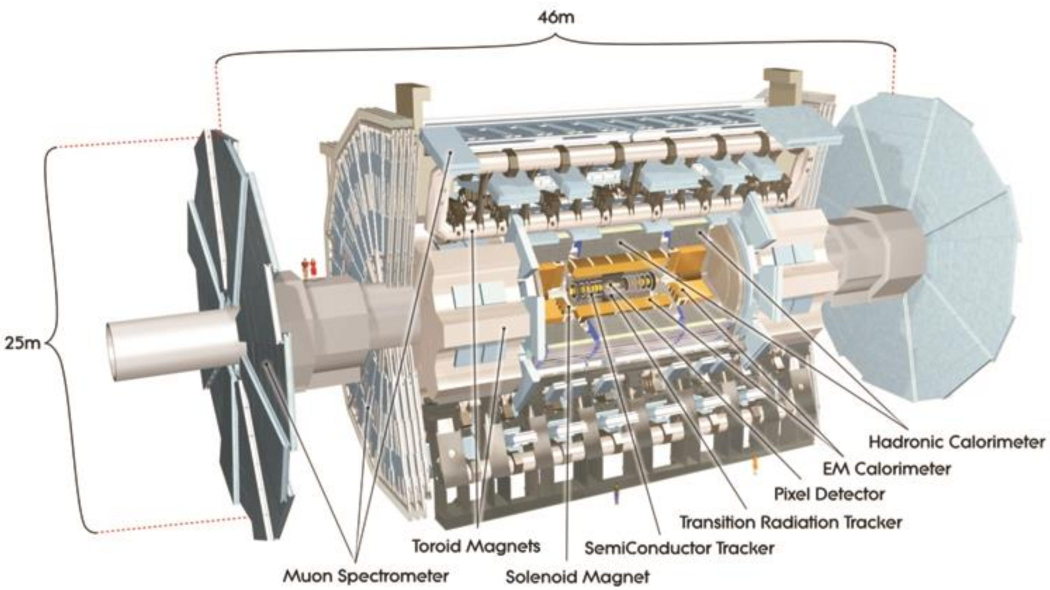
Source	Uncertainty [%]
Statistical	$^{+19}_{-18}$
$Z\gamma jj$–EW theory modelling	$^{+10}_{-6}$
$Z\gamma jj$–QCD theory modelling	± 6
$t\bar{t} + \gamma$ theory modelling	± 2
$Z\gamma jj$–EW and $Z\gamma jj$–QCD interference	$^{+3}_{-2}$
Jets	± 8
Pile-up	± 5
Electrons	± 1
Muons	$^{+3}_{-2}$
Photons	± 1
Electrons/photons energy scale	± 1
b-tagging	± 2
MC statistical uncertainties	± 8
Other backgrounds normalisation (including Z+jets)	$^{+9}_{-8}$
Luminosity	± 2
Total uncertainty	± 26

Signal extraction

- Boosted Decision Tree **(BDT)** method is used to separate EW signal. The BDT is trained by $Z\gamma$ EW events from all background processes, excluding Z +jets.

- $t\bar{t}\gamma$ and $Z\gamma$ QCD backgrounds are constrained by the data. The normalisations of these backgrounds are introduced in the likelihood fit as unconstrained nuisance parameters. These parameters are relative normalisation factors, defined with respect to the SM predictions. Background normalisations and shapes can vary within the uncertainties, constrained by Gaussian distributions.

The ATLAS detector



Calorimeters (CALO)
-Pb/LAr accordion structure
-e/γ trigger identification and measurement : $\sigma/E \sim 10\%/\sqrt{E}$
-HAD: trigger and measurement of jets and E_T^{miss}
-Forward calorimeters(FCAL): covers up to |η|< 4.9

Inner detector (ID)
-|η|< 2.5
-Si pixels, Si strips, TRT
-Precise tracking and vertexing(in 2014, add Insertable B-layer)
-e/π separation

Muon Spectrometer (MS)
-Triggering|η|< 2.4
-Precision Tracking |η|< 2.7
-Magnetic filed produced by toroids
-Muon momentum resolution < 10% up to 1 TeV

Performance of the ATLAS detector