Observation of VBS processes with the ATLAS detector

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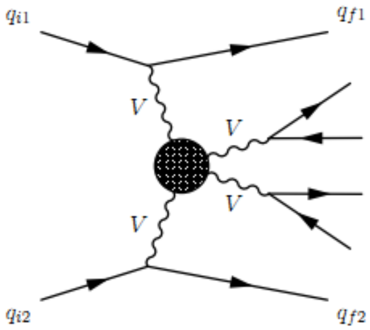
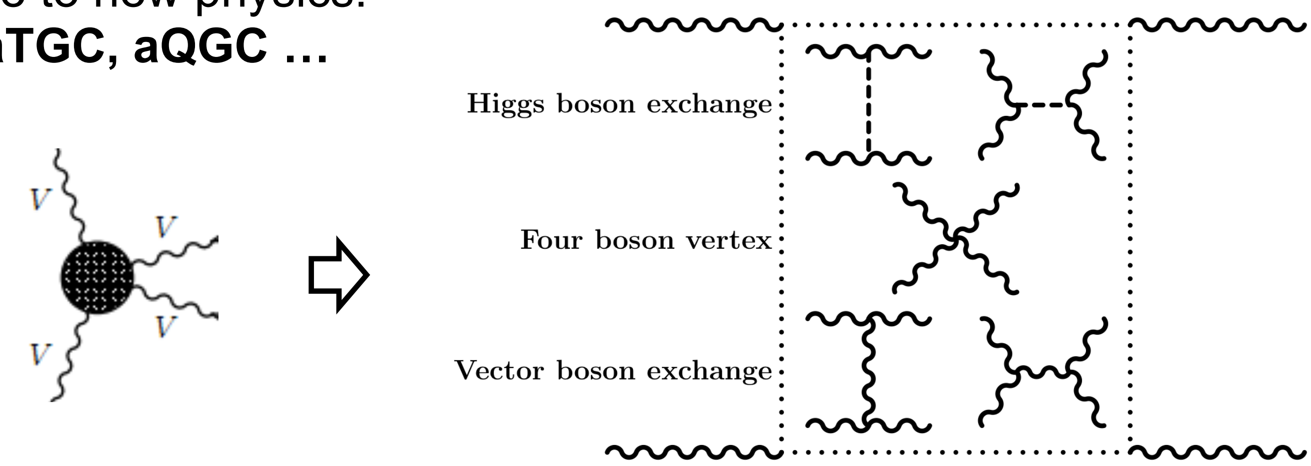
Introduction

- **Vector boson scattering (VBS)** measurements offers an important way to probe **electroweak symmetry breaking**.



- A good probe of the SM in the EW sector. Measure VBS via the corresponding EW productions.

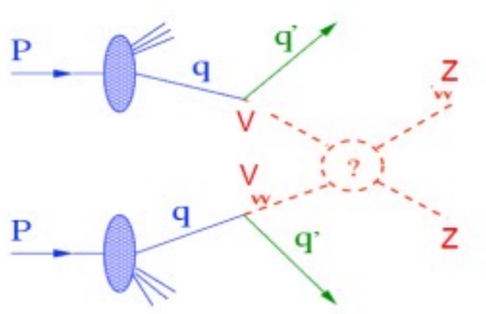
- Sensitive to new physics: **probe aTGC, aQGC …**

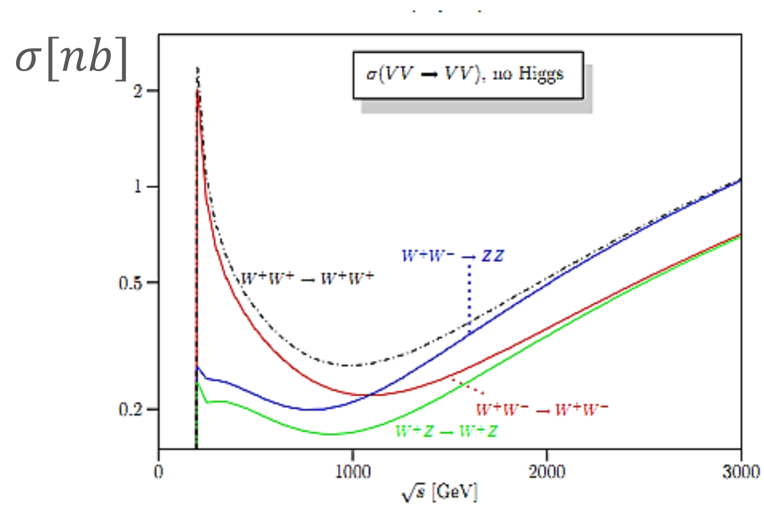


Main interest of VV scattering

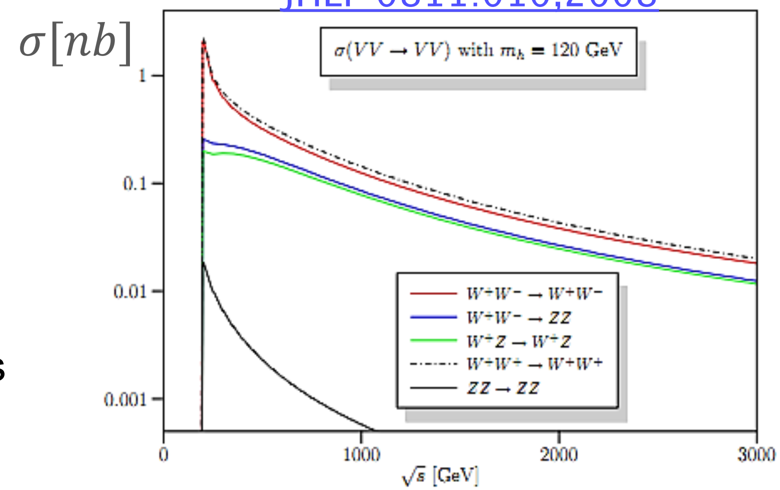
- Without Higgs, $W_L^+ W_L^- \to Z_L Z_L$ would break unitarity.

$$\mathcal{M}(W_L^+ W_L^- \to Z_L Z_L) \sim \frac{s}{m_W^2}$$





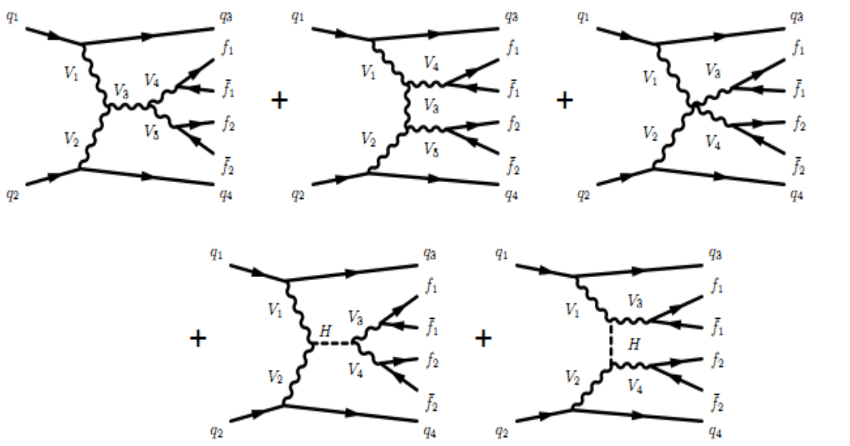
[JHEP 0811:010,2008]



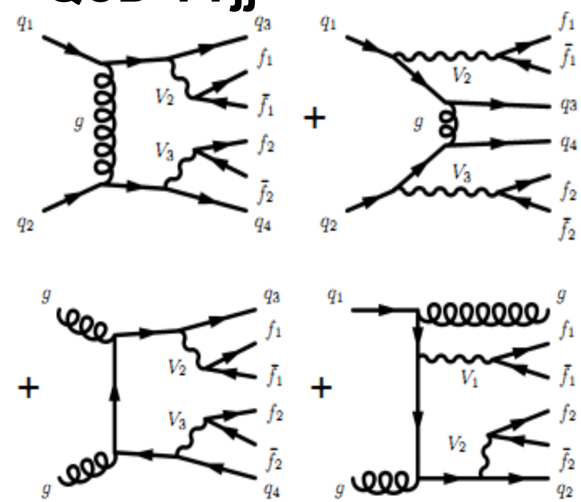
- The presence of the Higgs boson prevents the VBS amplitudes from violating unitarity at the TeV scale.
- To understand the nature of EWSB:
  - precise measurements of hVV couplings
  - Measurement of VV→VV cross-sections

VBS signature

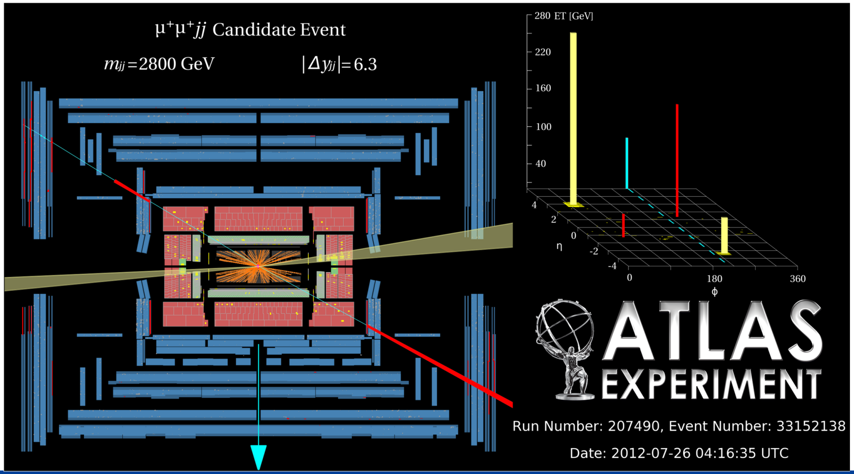
EW-VVjj



QCD-VVjj



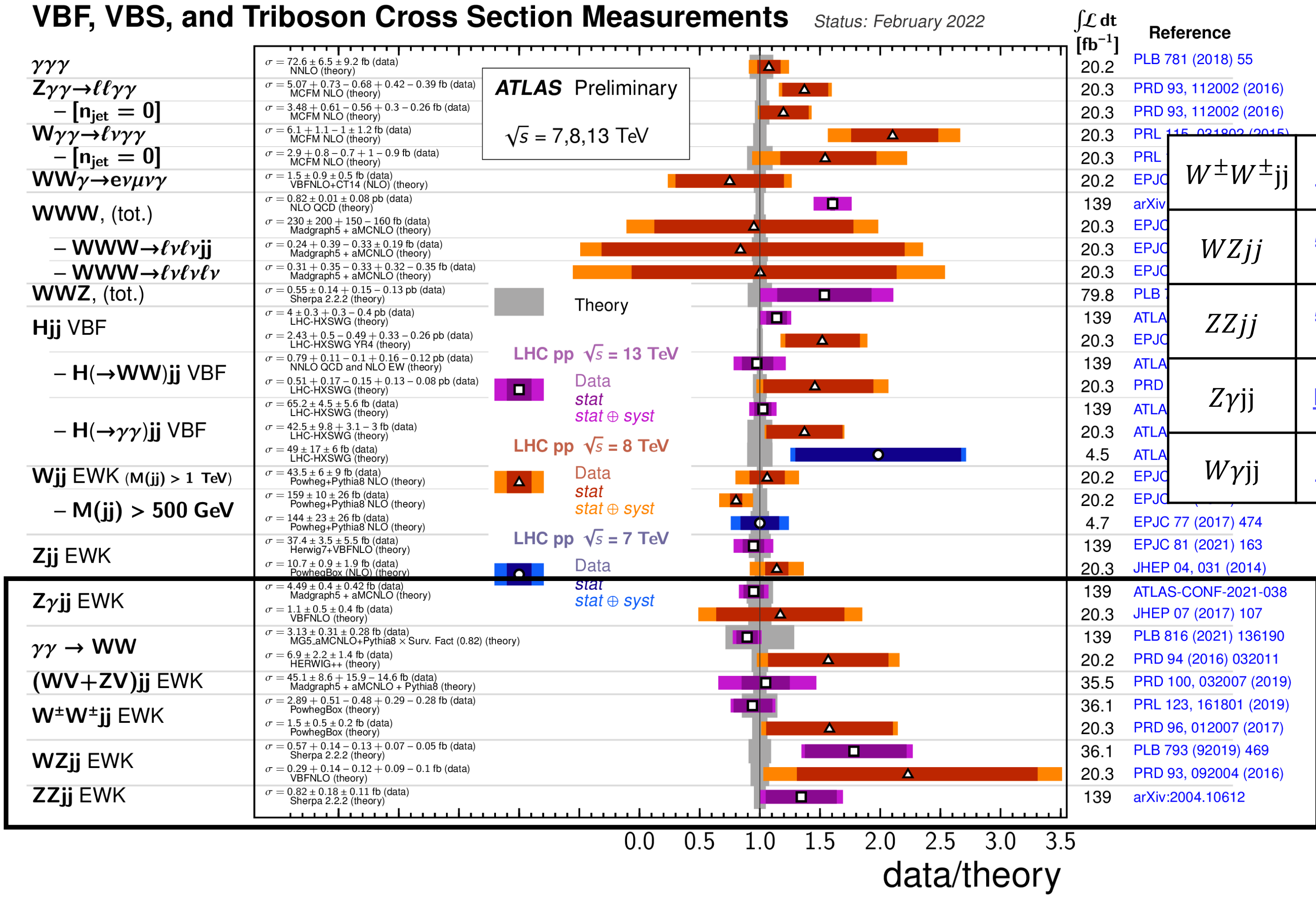
ssWWjj, 8TeV Phys. Rev. Lett. 113, 141803



- **VVjj category:**
  - EW-VVjj (including VBS)
  - QCD-VVjj

- **VBS topology:**
  - Two hard forward jets with large m_{jj} and large $\Delta\eta_{jj}$
  - Sensitive variables: $\Delta\eta_{jj}$, m_{jj}, central jet veto, centrality $max\left(\left|\frac{y_i - 0.5(y_{j1}+y_{j2})}{y_{j1}-y_{j2}}\right|\right)$

VBS measurements



CMS

$W^{\pm}W^{\pm}jj$	PRL 120 (2018) 081801
$WZjj$	*Phys. Lett. B 809 (2020) 135710*
$ZZjj$	*Phys. Lett. B 812 (2020) 135992*
$Z\gamma jj$	PRD 104 (2021) 072001
$W\gamma jj$	PLB 811 (2020) 135988

VBS observations

- VBS observations at the LHC:

13TeV	$W^{\pm}W^{\pm}$jj	$WZjj$	$ZZjj$	$Z\gamma$jj	$W\gamma$jj	$\gamma\gamma \to WW$
ATLAS	6.5σ	5.3σ	5.5σ	10σ	-	8.4σ
CMS	5.5σ	6.8σ	4.0σ	9.4σ	5.3σ	-

- For VBS processes, many channels have been measured and observed at LHC.

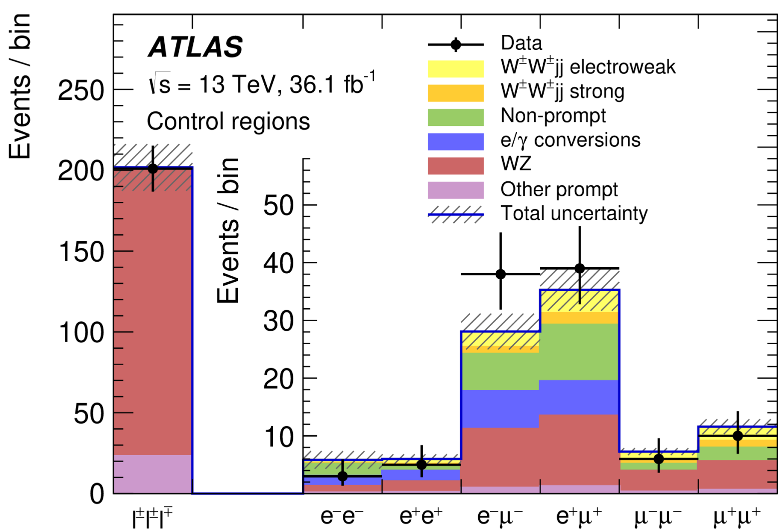
- More details of recent observations will show in the next pages.

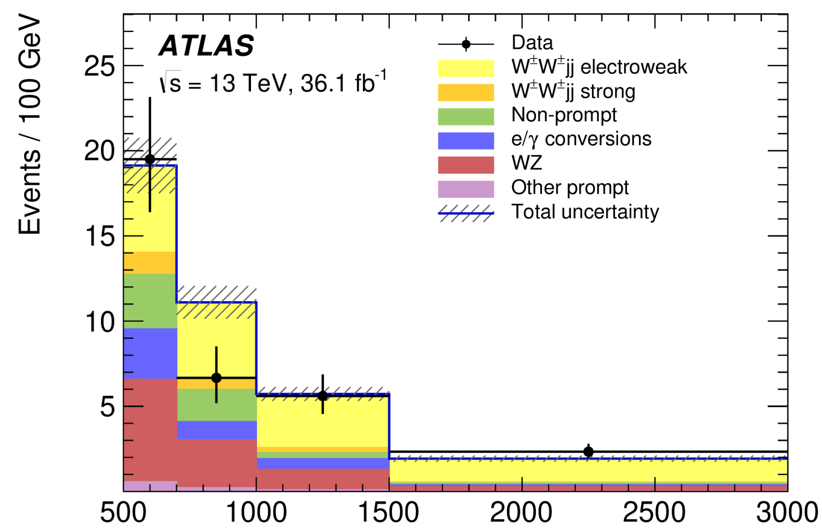
Same-sign WWjj

[Phys. Rev. Lett. 123 (2019) 161801](https://doi.org/10.1103/PhysRevLett.123.161801)

- 13TeV, 36.1fb^{-1}
- Dilepton channel
- Significance: 6.5σ(4.4σ)
- Cross-sections:
  - Measured: $\sigma^{fid} = 2.89^{+0.51}_{-0.48}(stat.)^{+0.24}_{-0.22}(exp.syst.)^{+0.14}_{-0.16}(mod\ syst.)^{+0.08}_{-0.06}(lumi) fb$
  - Predicted: $2.01^{+0.33}_{-0.23} fb$ (Sherpa) $3.08^{+0.45}_{-0.46} fb$ (Powheg+Pythia8)

	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





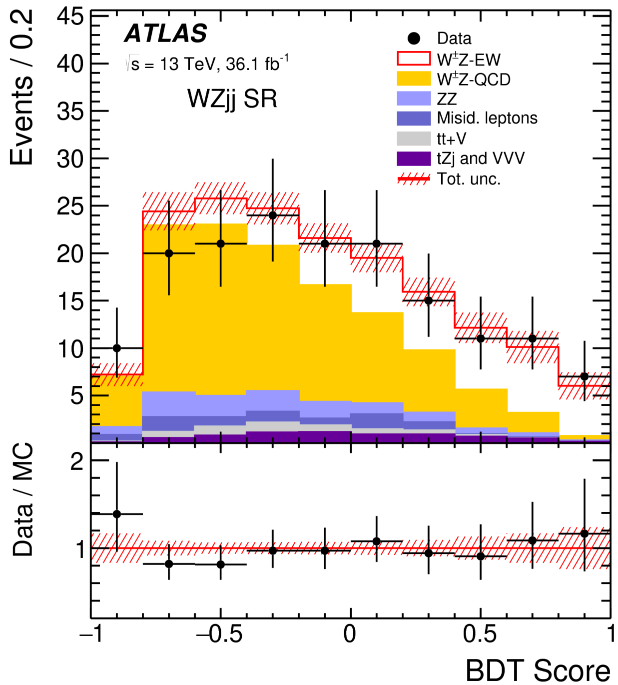
https://atlas.cern/updates/briefing/weak-lightsabers

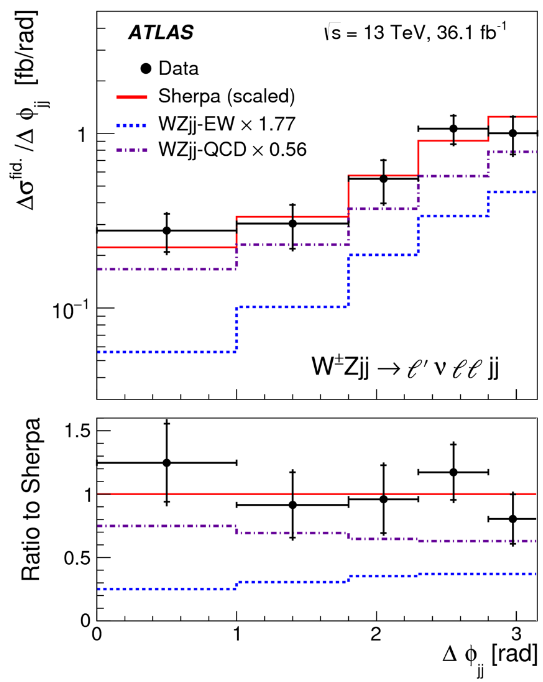
WZjj

Phys. Lett. B 793 (2019) 469

- 13TeV, 36.1fb^{-1}
- WZ decay leptonically
- Significance: 5.3σ(3.2σ)
- Best fit results:

$$\mu_{EW} = 1.77^{+0.49}_{-0.43}$$





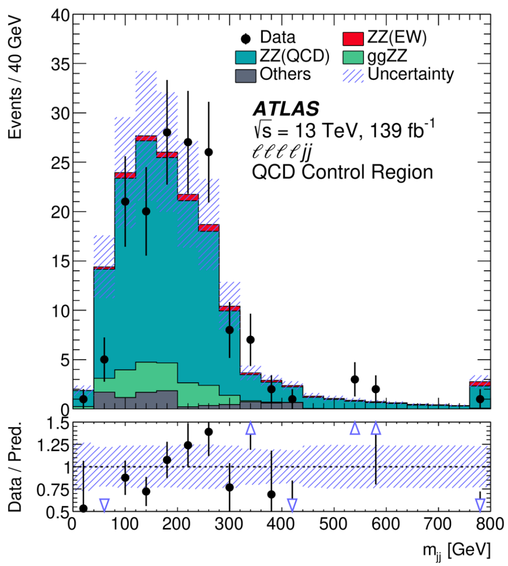
https://atlas.cern/updates/briefing/weak-lightsabers

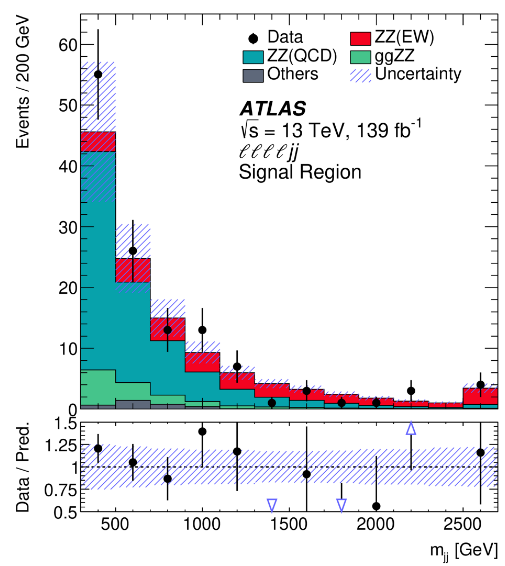
1st differential measurement

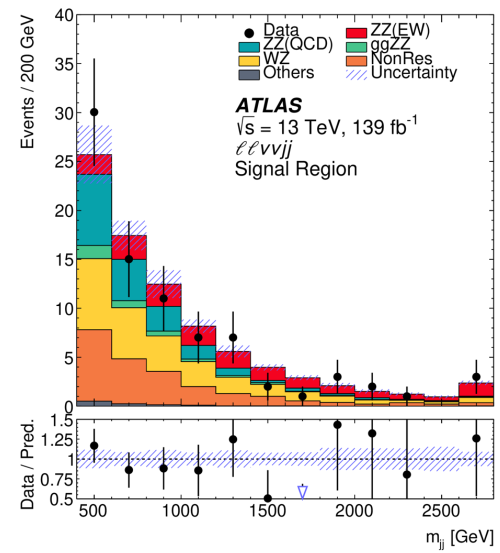
ZZjj

arXiv:2004.10612

- Full Run2 datasets (139 fb^{-1})
- Measure the inclusive ZZjj cross-section (EW + QCD)
- Evidence on EW-ZZjj production
  - Combine $llllјј$ and $llννjj$, fit the multivariate analysis (MVA) output to extract the significance of EW component and signal strength
- Two channels: $lllljj$, $llννjj$
- Backgrounds:
  - $lllljj$: QCD background, fake lepton background, WWZ…
  - $llννjj$: Non-Resonant background, WZ background, Z+jets background, ZZ → $llll$,VVV, ttV, ttVV



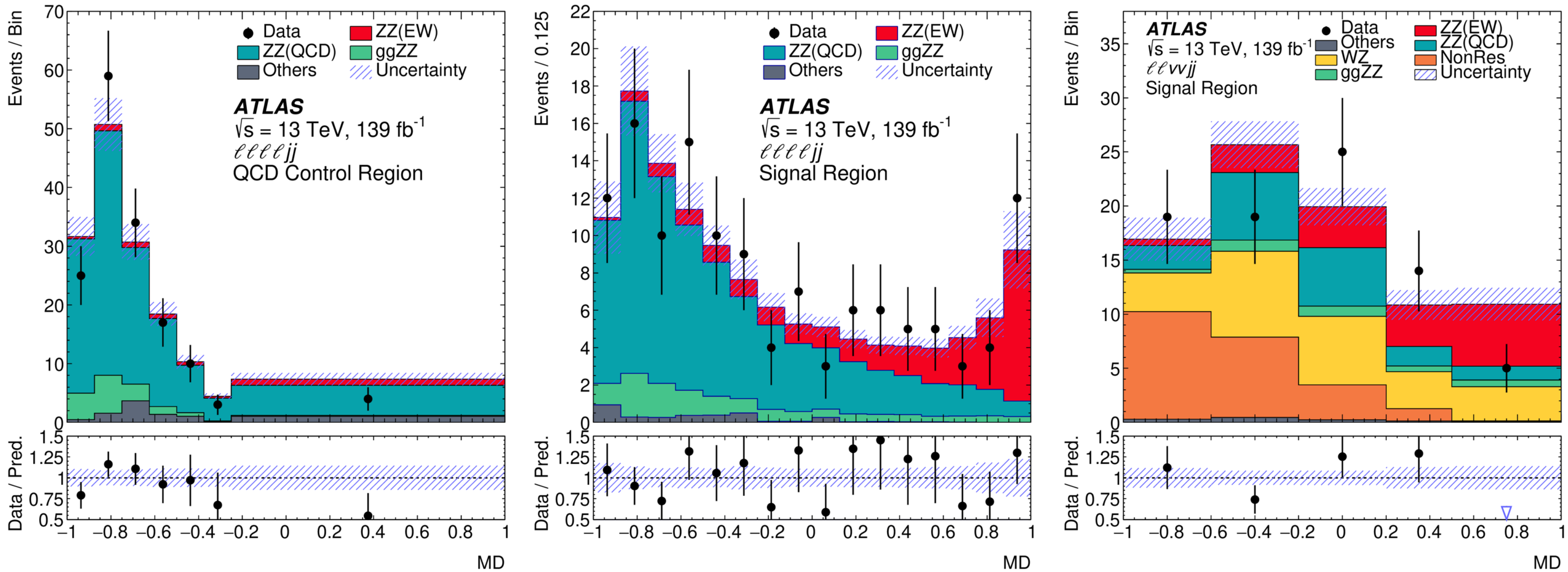




arXiv:2004.10612

ZZjj

- To extract EW process, a profile likelihood fit is performed on Gradient Boosted Decision Tree (BDTG) response.
- Observed and expected distributions:



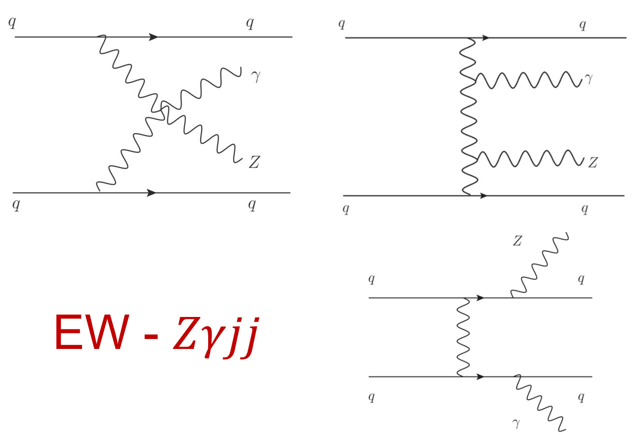
- Significance: 5.5σ(4.3σ) $\sigma_{EW-ZZjj} = \mu_{EW} \times \sigma_{SM} = 0.82 \pm 0.21 fb$
- Submitted to Nature Physics.

https://atlas.cern/updates/briefing/milestone-electroweak-symmetry-breaking

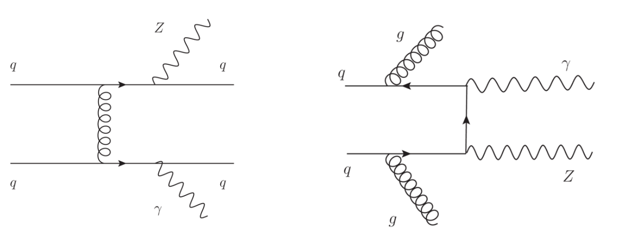
ATLAS-CONF-2021-038

Zγjj

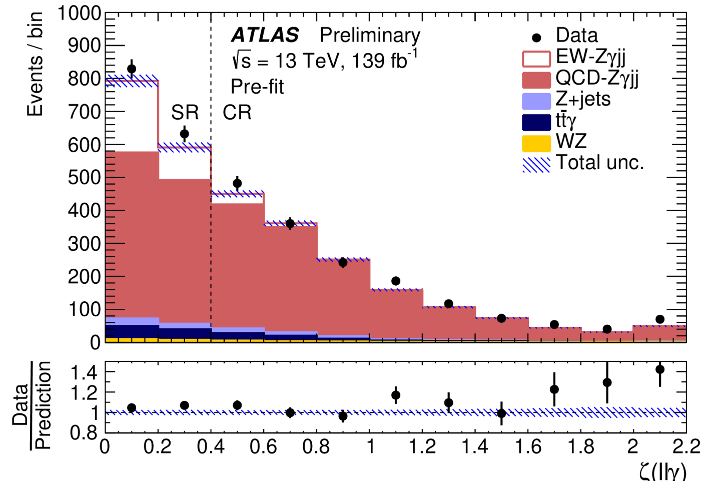
- Full Run2 datasets (139 fb^{-1})
- Channel: $Z(\rightarrow ee/\mu\mu)\gamma jj$



EW - $Z\gamma jj$



QCD - $Z\gamma jj$



Lepton	$p_{\mathrm{T}}^{\ell} > 20, 30(\mathrm{leading})$ GeV, $\lvert\eta_\ell\rvert < 2.47$ $N_\ell \geq 2$
Photon	$E_{\mathrm{T}}^{\gamma} > 25$ GeV, $\lvert\eta_\gamma\rvert < 2.37$ $E_{\mathrm{T}}^{cone20} < 0.07 E_{\mathrm{T}}^{\gamma}$ $\Delta R(\ell, \gamma) > 0.4$
Jet	$p_{\mathrm{T}}^{jet} > 50$ GeV, $\lvert y_{jet}\rvert < 4.4$ $\lvert\Delta y\rvert > 1.0$ $m_{jj} > 150$ GeV remove jets if $\Delta R(\gamma, j) < 0.4$ or if $\Delta R(\ell, j) < 0.3$
Event	$m_{\ell\ell} > 40$ GeV $m_{\ell\ell} + m_{\ell\ell\gamma} > 182$ GeV $\zeta(\ell\ell\gamma) < 0.4$ $N_{jets}^{gap} = 0$

Fiducial phase space

ATLAS-CONF-2021-038

Zγjj

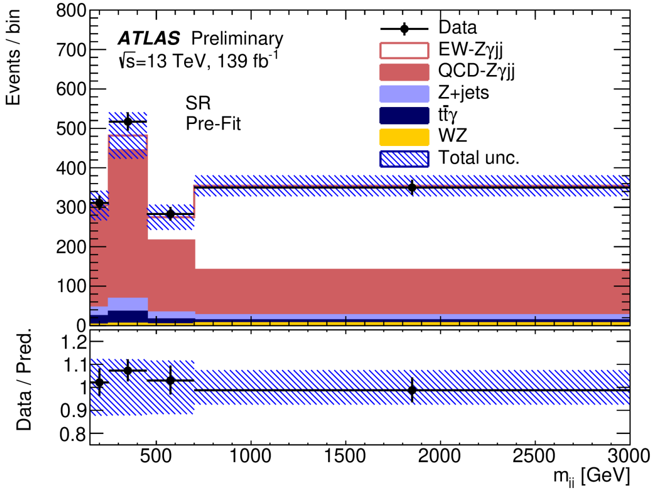
- EW component is extracted with a maximum likelihood on m_{jj} distribution.
- Simultaneously fit in SR and CR.
- Significance: $10\sigma (11\sigma)$
- Cross-sections:

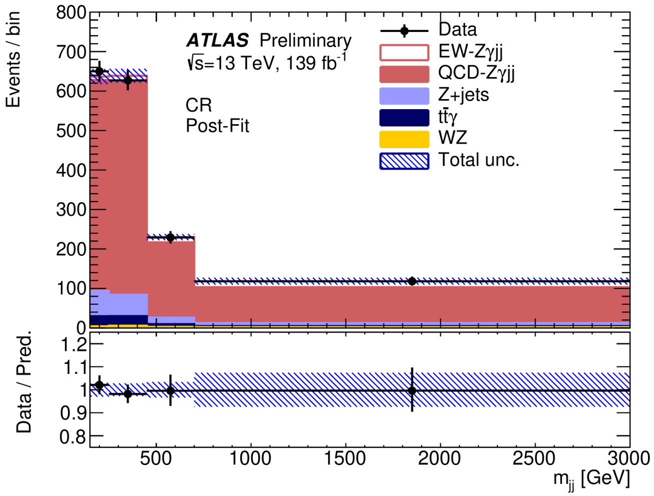
$$\sigma_{EW} = 4.49 \pm 0.40(stat.) \pm 0.42(syst.) fb$$

$$\sigma_{EW}^{pred} = 4.73 \pm 0.01(stat.) \pm 0.15(PDF)^{+0.23}_{-0.22}(scale) fb$$

$$\sigma_{EW+QCD} = 20.6 \pm 0.6(stat.)^{+1.2}_{-1.0}(syst.) fb$$

$$\sigma_{EW}^{pred} = 20.4 \pm 0.1(stat.) \pm 0.2(PDF)^{+2.6}_{-2.0}(scale) fb$$

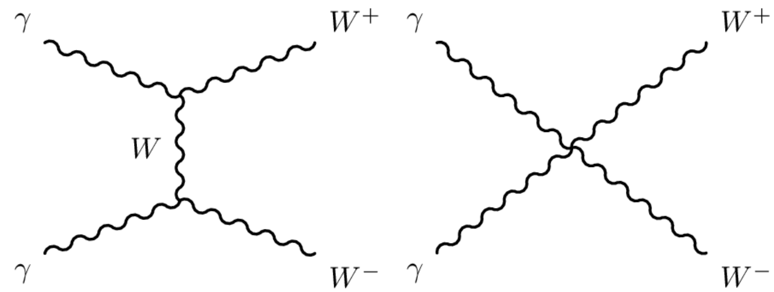




Phys. Lett. B 816 (2021) 136190

$\gamma\gamma \rightarrow WW$

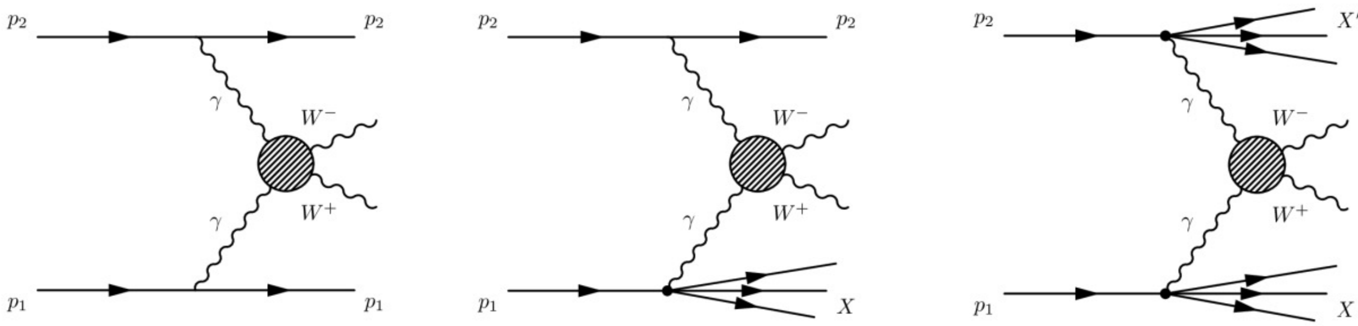
- Full Run2 datasets (139 fb^{-1})
- Photon-induced production of W-boson pairs, $WW \rightarrow e^{\pm}\nu\mu^{\pm}\nu$
- $\gamma\gamma \rightarrow WW$:
  - Trilinear and quartic gauge boson interactions.
  - At LO, only involves diagrams with self-couplings of the EW gauge bosons.



⇨ Directly test the gauge structure of the EW.

Sensitive to aTGC, aQGC.

- Signal process: $pp(\gamma\gamma) \rightarrow p^{*}W^{+}W^{-}p^{*}$



elastic single-dissociative double-dissociative

Phys. Lett. B 816 (2021) 136190

$\gamma\gamma \rightarrow WW$

- Signal characteristics:

  $n_{trk} = 0$

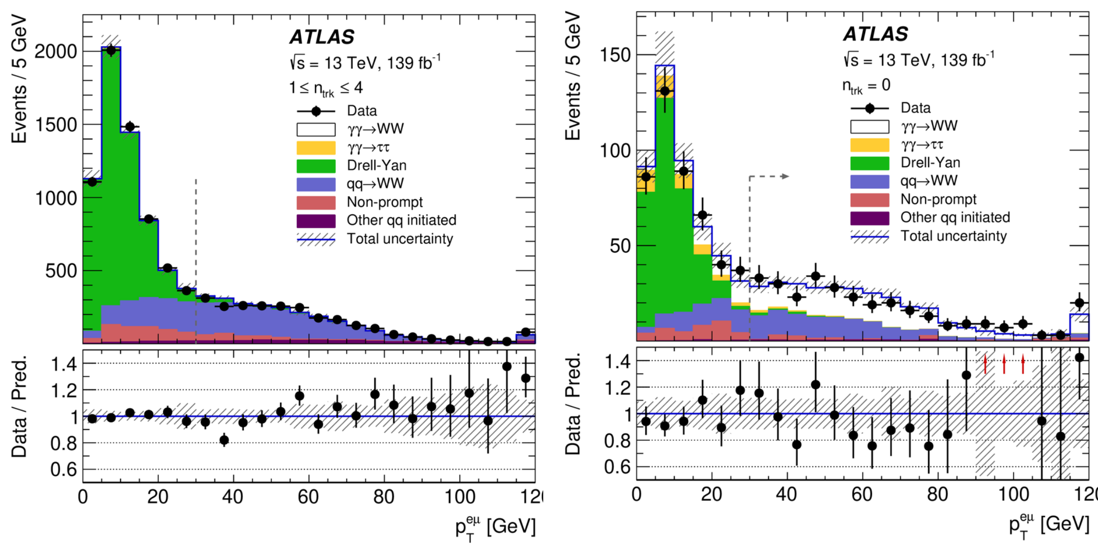
  Quark- and gluon-induced WW or top-quark production

  $e\mu$

  $\gamma\gamma \rightarrow ll$

  $p_T^{e\mu} > 30GeV$

  $\gamma\gamma \rightarrow \tau\tau$



- Significance: $8.4\sigma(6.7\sigma)$
- Cross-sections:
  - measured: $3.13 \pm 0.31(stat.) \pm 0.28(syst.)fb$
  - predicted: $3.5 \pm 1.0fb$

Summary

- VBS observations in ATLAS:

  ssWWjj, WZjj, ZZjj, Zγjj, $\gamma\gamma \rightarrow WW$

- CMS VBS measurements can be found in

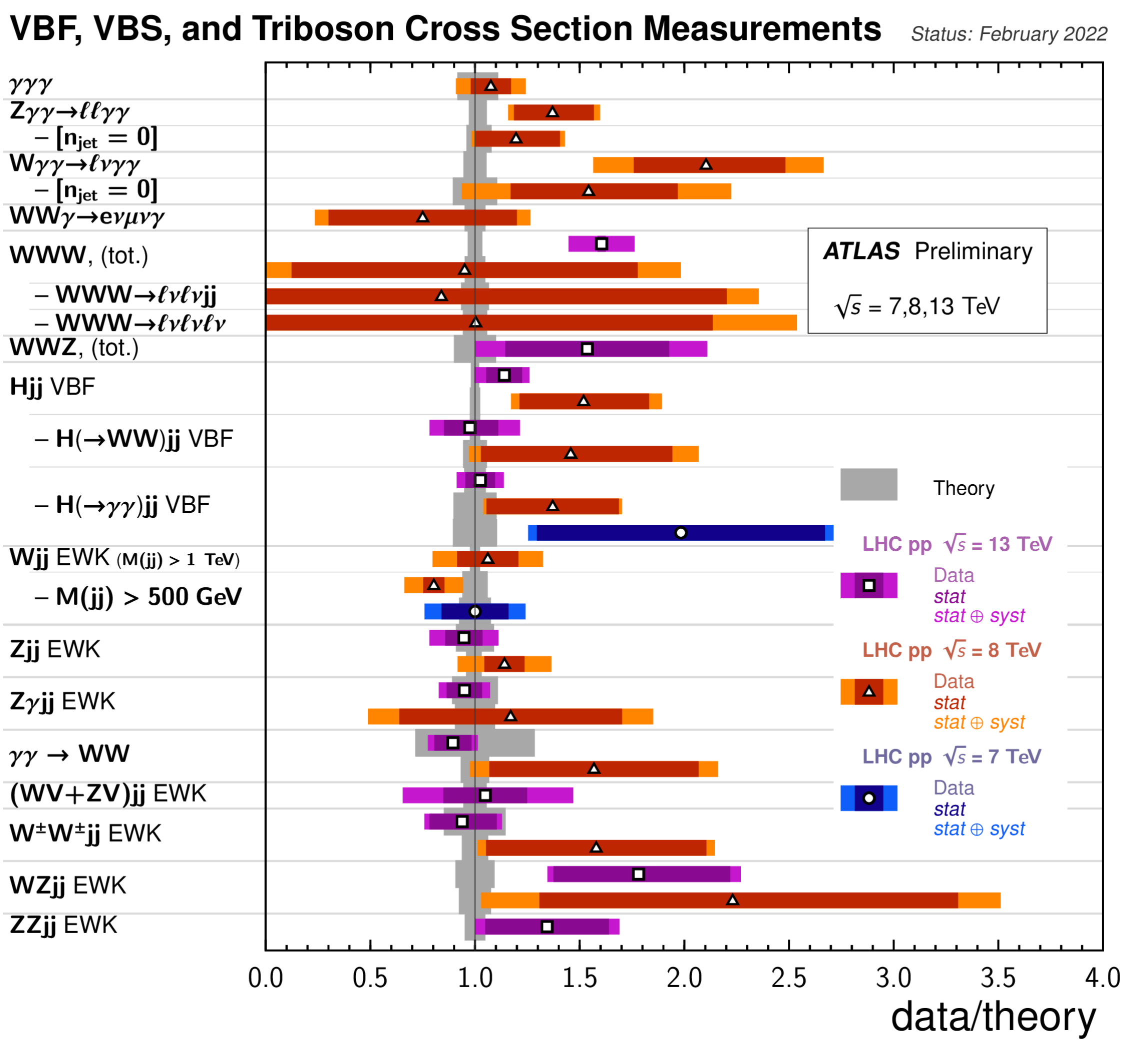
  W-Boson Scattering and Interactions at the LHC-CMS experiment- Qiang li(北京大学)

- Next step:

  More differential measurements, longitudinal polarization extraction, BSM constraints …

Backup

VBS measurements



CMS

$W^{\pm}W^{\pm}jj$	$5.5(5.7)\sigma$ PRL 120 (2018) 081801
$WZjj$	$6.8(5.3)\sigma$ *Phys. Lett. B 809 (2020) 135710*
$ZZjj$	$4.0(3.5)\sigma$ *Phys. Lett. B 812 (2020) 135992*
$Z\gamma jj$	$9.4(8.5)\sigma$ PRD 104 (2021) 072001
$W\gamma jj$	$5.3(4.8)\sigma$ PLB 811 (2020) 135988

ATLAS

$10(11)\sigma$ ATLAS-CONF-2021-038

$8.4(6.7)\sigma$ Phys. Lett. B 816 (2021) 136190

$2.7(2.5)\sigma$ Phys. Rev. D 100 (2019) 032007

$6.5(4.4)\sigma$ Phys. Rev. Lett. 123 (2019) 161801

$5.3(3.2)\sigma$ Phys. Lett. B 793 (2019) 469

$5.5(4.3)\sigma$ arXiv:2004.10612

EW-VVjj production at 13TeV

$VVjj$	final states	$\sigma(VVjj\text{-EW})$ / fb	$\sigma(VVjj\text{-QCD})$ / fb
$W^{\pm}W^{\pm}$	$\ell\nu\ell\nu jj$	4.28 ± 0.01	1.69 ± 0.02
$W^{+}W^{-}$	$\ell\nu\ell\nu jj$	15.57 ± 0.08	35.24 ± 0.13
ZZ	$\ell\ell\nu\nu jj$	0.39 ± 0.01	0.55 ± 0.01
ZV	$\ell\ell jjjj$	0.98 ± 0.07	3.13 ± 0.22
$Z\gamma$	$\ell\ell\gamma jj$	9.24 ± 0.02	71.28 ± 0.33
WZ	$\ell\nu\ell\ell jj$	2.36 ± 0.01	7.19 ± 0.01
ZZ	$\ell\ell\ell\ell jj$	0.12 ± 0.01	0.21 ± 0.01

Philipp Anger's thesis

Production cross-section for EW and QCD VVjj production:

-All results are obtained from SHERPA

-Pre-VBS cuts applied

ssWWjj

Source	Impact [%]
Experimental	
Electrons	0.6
Muons	1.3
Jets and $E_{\mathrm{T}}^{\mathrm{miss}}$	3.2
b-tagging	2.1
Pileup	1.6
Background, statistical	3.2
Background, misid. leptons	3.3
Background, charge misrec.	0.3
Background, other	1.8
Theory modeling	
$W^{\pm}W^{\pm}jj$ electroweak-strong interference	1.0
$W^{\pm}W^{\pm}jj$ electroweak, EW corrections	1.4
$W^{\pm}W^{\pm}jj$ electroweak, shower, scale, PDF & α_s	2.8
$W^{\pm}W^{\pm}jj$ strong	2.9
WZ	3.3
Luminosity	2.4

WZjj

Source	Uncertainty [%]
$WZjj$–EW theory modelling	4.8
$WZjj$–QCD theory modelling	5.2
$WZjj$–EW and $WZjj$–QCD interference	1.9
Jets	6.6
Pile-up	2.2
Electrons	1.4
Muons	0.4
b-tagging	0.1
MC statistics	1.9
Misid. lepton background	0.9
Other backgrounds	0.8
Luminosity	2.1
Total Systematics	10.7

ZZjj

arXiv:2004.10612

- **Event yields:**

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

- The definition of fiducial regions are very similar with detector-level selections by using particle-level physics objects.
- Fiducial cross-sections for the inclusive production of the EW and QCD processes are measured separately in individual channels.

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

***llllj j* C factor**	0.699 ± 0.031
***llvvjj* C factor**	0.216 ± 0.012

- **Cross-sections:**

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

ZZjj

- **Theoretical uncertainties:**

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

  - Interference effect between the EW and QCD processes is 6.8%(2.3%) in $lllljj(llvvjj)$ 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.

Zγjj

Source	Size [%]
Electron/photon calibration	$\pm$ 0.3
Photon	$\pm$ 0.3
Backgrounds	$\pm$ 1.0
Electron	$\pm$ 1.1
Flavour tagging	$\pm$ 1.1
Muon	$\pm$ 1.1
MC stat.	$\pm$ 1.4
Pileup	$\pm$ 2.6
Jets	$\pm$ 4.7
$QCD\text{-}Z\gamma jj$ modelling	$^{+4.8}_{-4.3}$
$EW\text{-}Z\gamma jj$ modelling	$^{+5.7}_{-4.6}$
Data stat.	$\pm$ 8.8
Total	$^{+13.4}_{-12.6}$

$\gamma\gamma \rightarrow WW$

Source of uncertainty	Impact [% of the fitted cross section]
Experimental	
Track reconstruction	1.1
Electron energy scale and resolution, and efficiency	0.4
Muon momentum scale and resolution, and efficiency	0.5
Misidentified leptons, systematic	1.5
Misidentified leptons, statistical	5.9
Other background, statistical	3.2
Modelling	
Pile-up modelling	1.1
Underlying-event modelling	1.4
Signal modelling	2.1
WW modelling	4.0
Other background modelling	1.7
Luminosity	1.7
Total	8.9