Observation of VBS VVjj processes with the ATLAS detector

Jing Chen

2021.11.25

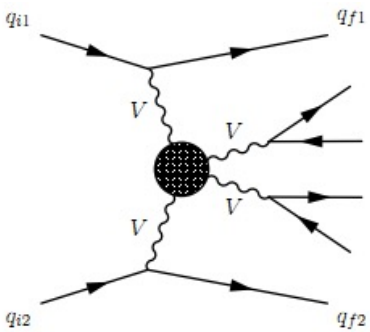
李政道研究所
Tsung-Dao Lee Institute

ATLAS EXPERIMENT

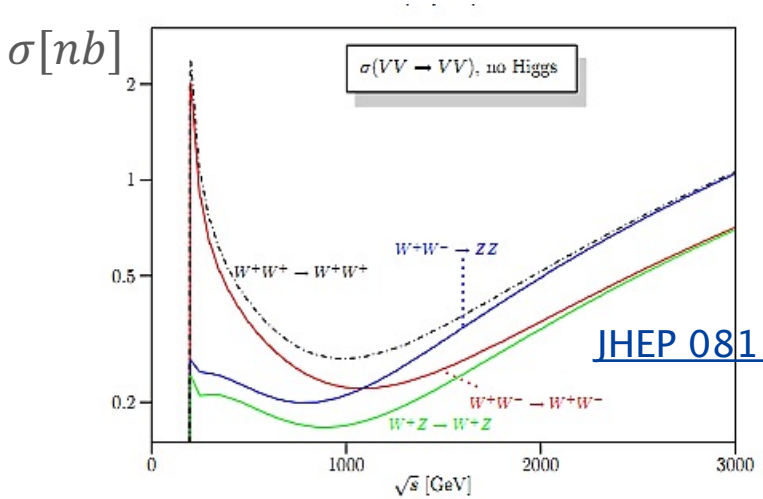
上海交通大學
SHANGHAI JIAO TONG UNIVERSITY

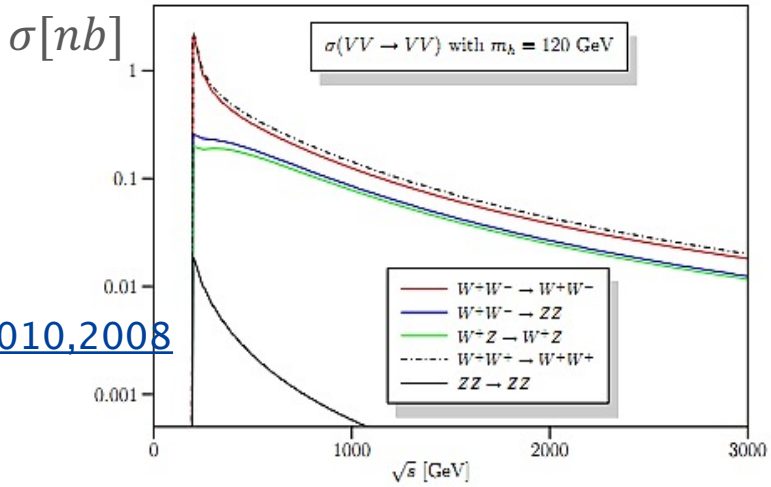
Introduction

- **Vector boson scattering (VBS)** measurements offers an important way to probe **electroweak symmetry breaking**.
- The presence of the Higgs boson prevents the VBS amplitudes from violating **unitarity** at the TeV scale.



- Sensitive to anomalous quartic coupling: **probe aQGC, test SM, search for new physics**
- Measure VBS via the corresponding EW productions.

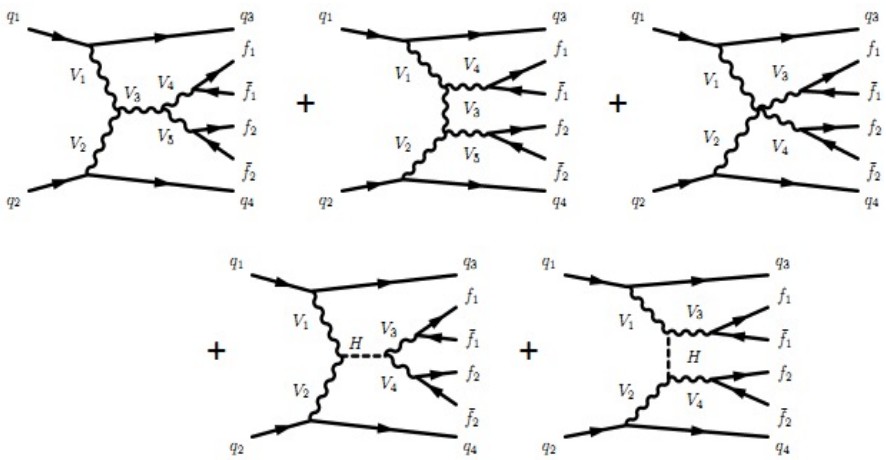




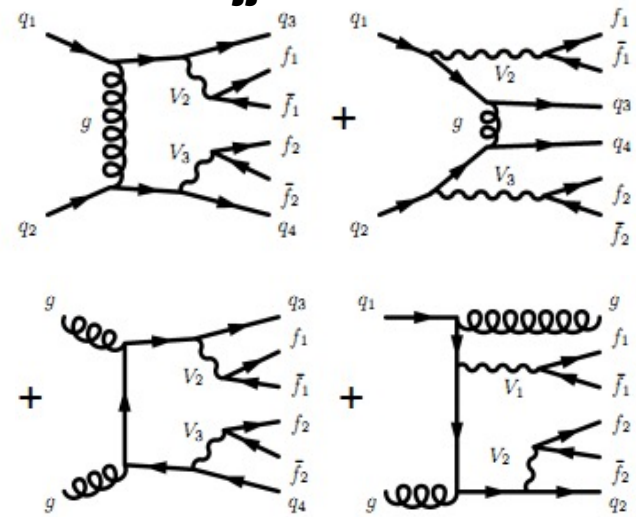
JHEP 0811:010,2008

VVjj productions

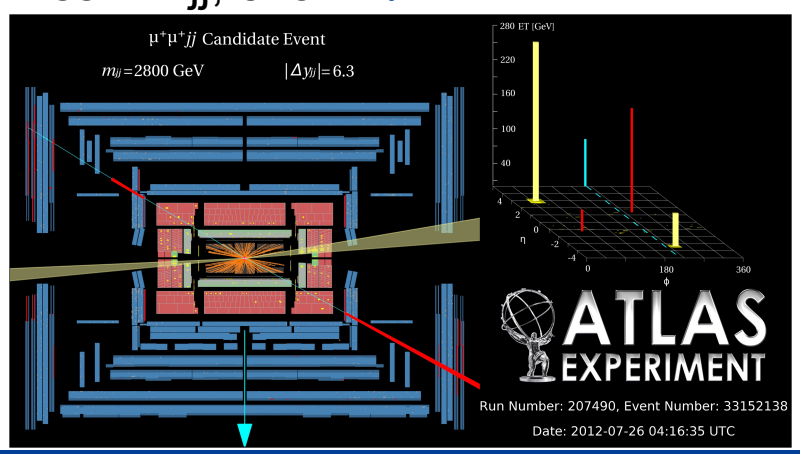
EW-VVjj



QCD-VVjj

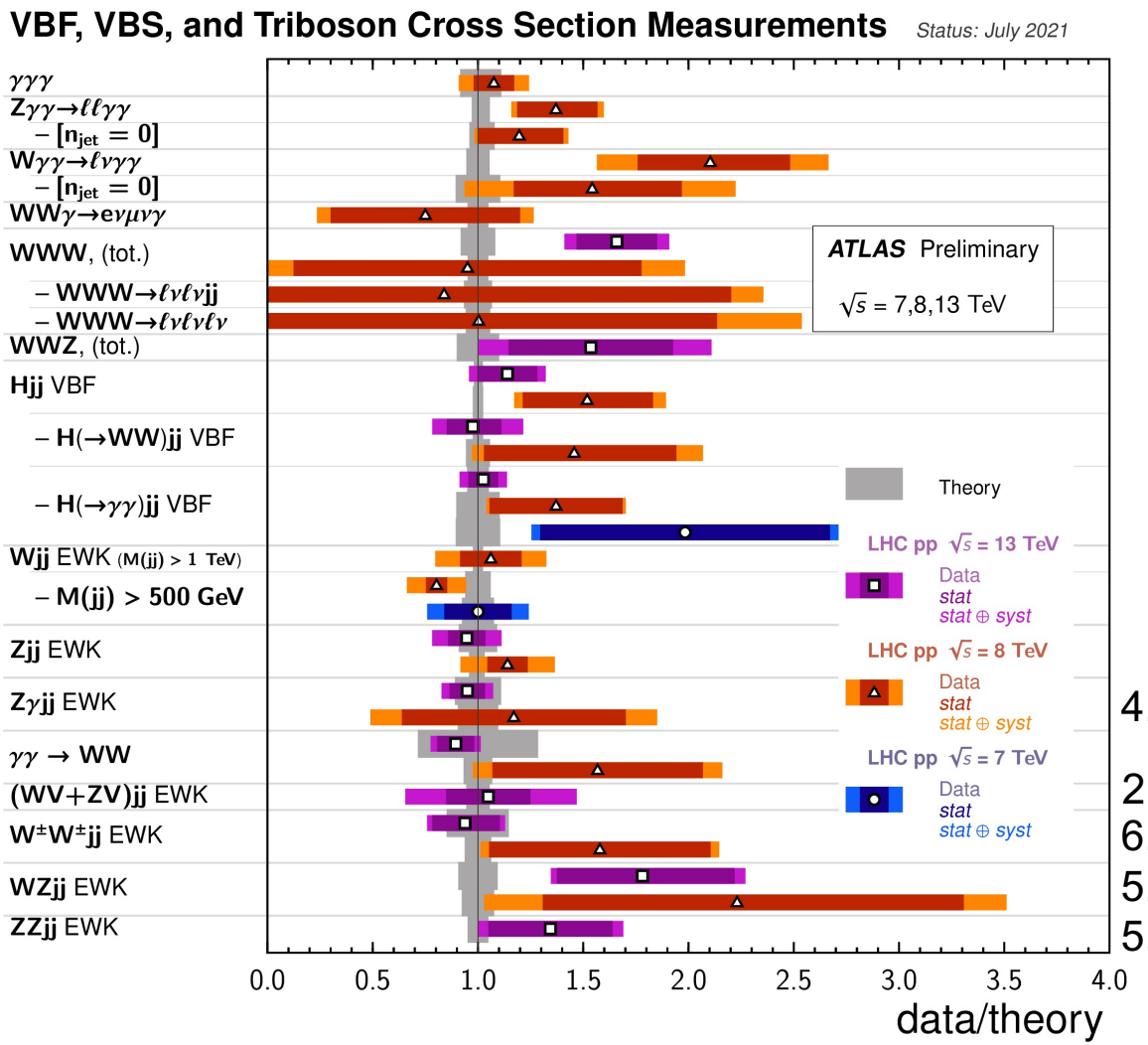


ssWWjj, 8TeV Phys. Rev. Lett. 113, 141803



- **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} — search for VBS

VBS measurements



CMS

$W^{\pm}W^{\pm}$jj	5.5(5.7)σ PRL 120 (2018) 081801
$WZjj$	6.8(5.3)σ Phys. Lett. B 809 (2020) 135710
$ZZjj$	4.0(3.5)σ Phys. Lett. B 812 (2020) 135992
$Z\gamma$jj	3.9(5.2)σ JHEP 06 (2020) 076

ATLAS

4.1(3.8)σ Phys. Lett. B 803 (2020) 135341

2.7(2.5)σ Phys. Rev. D 100 (2019) 032007

6.5(4.4)σ Phys. Rev. Lett. 123 (2019) 161801

5.3(3.2)σ Phys. Lett. B 793 (2019) 469

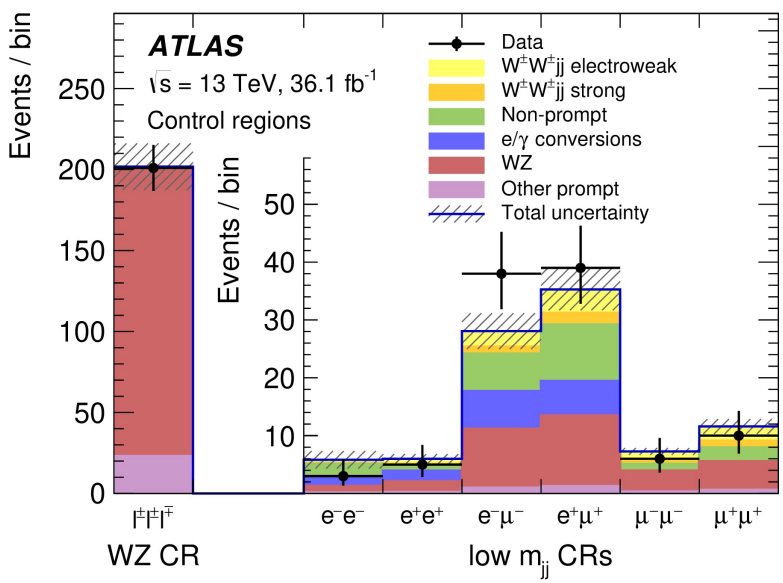
5.5(4.3)σ arXiv:2004.10612

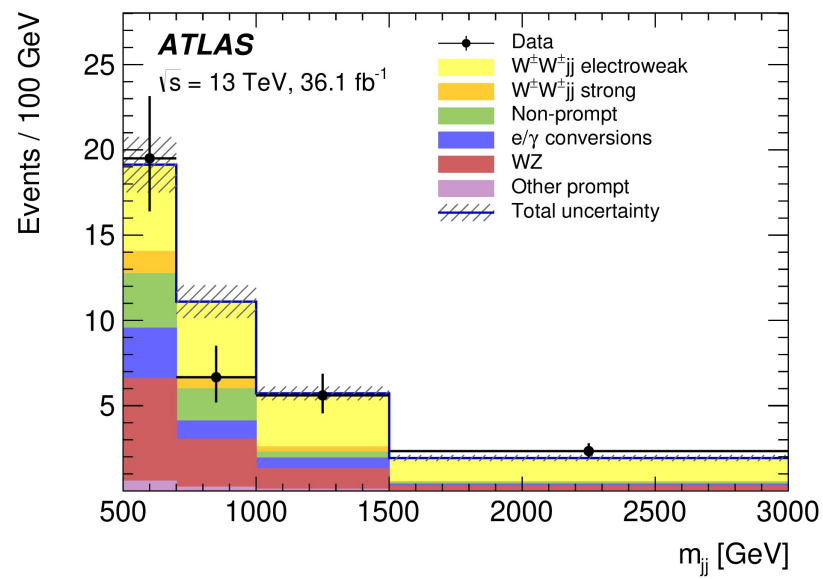
Same-sign WWjj

Phys. Rev. Lett. 123 (2019) 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

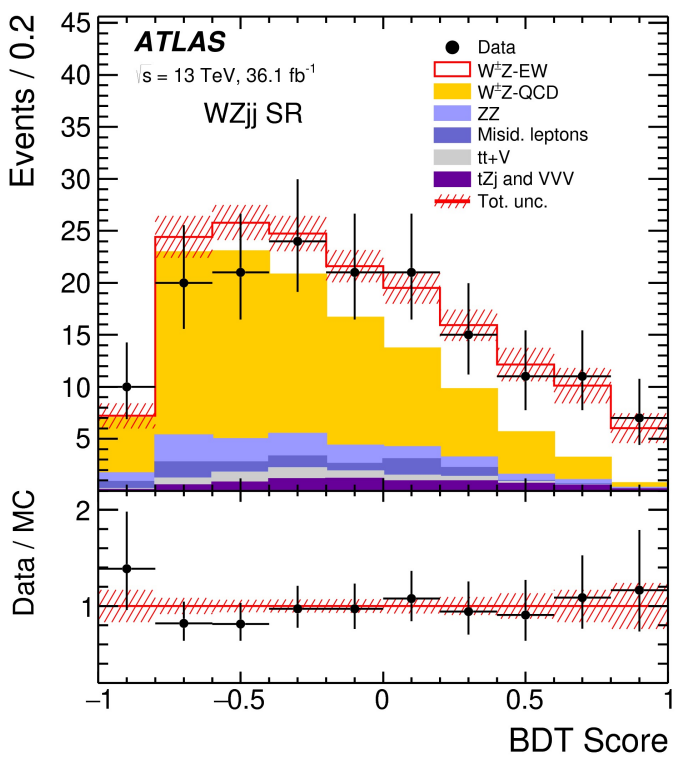




WZjj

Phys. Lett. B 793 (2019) 469

- 13TeV, 36.1fb^{-1}
- WZ decay leptonically



	SR	$WZjj$−QCD CR	b-CR	ZZ-CR
Data	161	213	141	52
Total predicted	200 ± 41	290 ± 61	160 ± 14	45.2 ± 7.5
$WZjj$−EW (signal)	24.9 ± 1.4	8.45 ± 0.37	1.36 ± 0.10	0.21± 0.12
$WZjj$−QCD	144 ± 41	231 ± 60	24.4 ± 1.7	1.43± 0.22
Misid. leptons	9.8 ± 3.9	17.7 ± 7.1	30 ± 12	0.47± 0.21
$ZZjj$−QCD	8.1 ± 2.2	15.0 ± 3.9	1.96 ± 0.49	35 ± 11
tZj	6.5 ± 1.2	6.6 ± 1.1	36.2 ± 5.7	0.18± 0.04
$t\bar{t}+V$	4.21 ± 0.76	9.11 ± 1.40	65.4 ±10.3	2.8 ± 0.61
$ZZjj$−EW	1.80 ± 0.45	0.53 ± 0.14	0.12 ± 0.09	4.1 ± 1.4
VVV	0.59 ± 0.15	0.93 ± 0.23	0.13 ± 0.03	1.05± 0.30

- Significance: 5.3σ(3.2σ)
- Cross-section

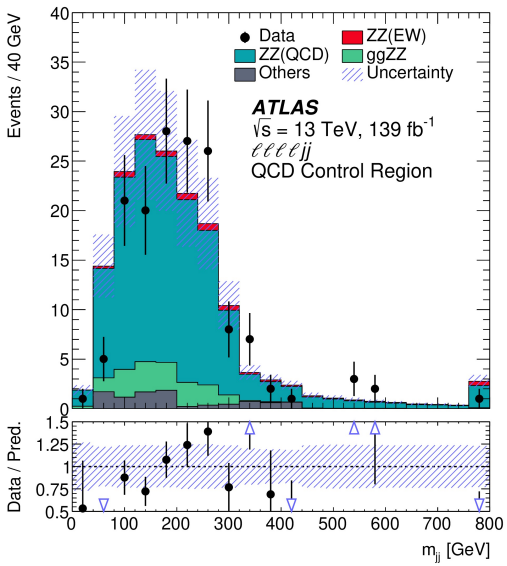
$$\sigma^{fid} = 0.57^{+0.14}_{-0.13}(stat.)^{+0.05}_{-0.04}(exp.syst.)^{+0.05}_{-0.04}(mod\ syst.)^{+0.01}_{-0.01}(lumi)fb$$

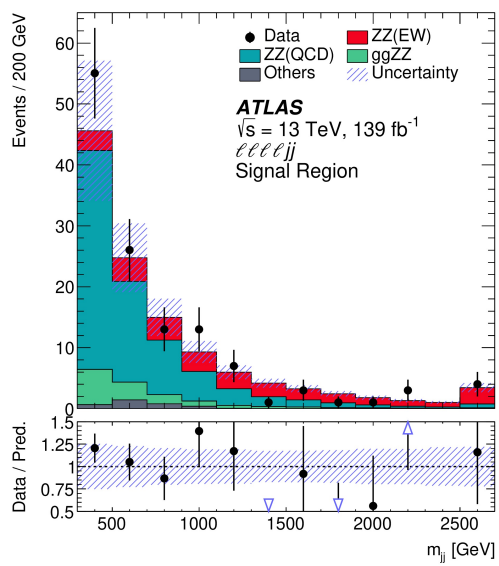
ZZjj

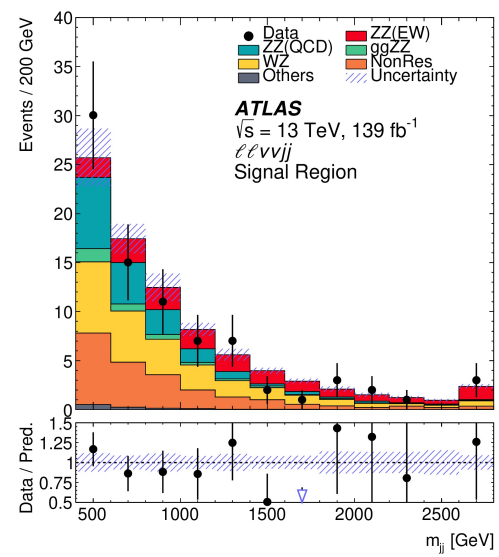
arXiv:2004.10612

- Full Run2 datasets ($139 fb^{-1}$)
- Measure the inclusive ZZjj cross-section (EW + QCD)
- Evidence on EW-ZZjj production
  - Combine $llllj j$ and $llvvjj$, fit the multivariate analysis (MVA) output to extract the significance of EW component and signal strength (μ_{EW}).

- Two channels: $llllj j$, $llvvjj$
- Backgrounds:
  - $llllj j$: QCD background, fake lepton background, WWZ…
  - $llvvjj$: Non-Resonant background, WZ background, Z+jets background, ZZ → $llll$,VVV, ttV, ttVV







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.

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

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

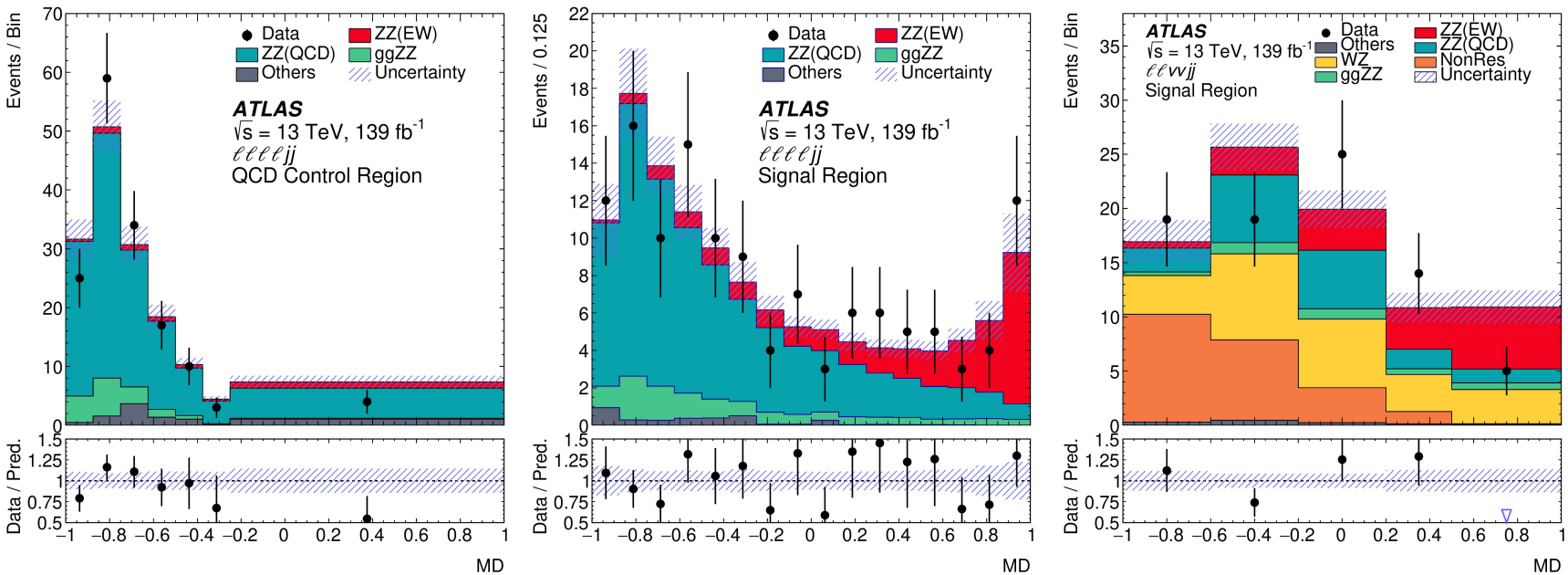
- **Cross-sections:**

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

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:**
  - Multivariate discriminants (MDs) are used to further separate the EW signal from the backgrounds.
  - Data distributions are consistent with predict ones.



- Significance: $5.5\sigma(4.3\sigma)$

$$\sigma_{EW-ZZjj} = \mu_{EW} \times \sigma_{SM} = 0.82 \pm 0.21 fb$$

Summary

- VBS ssWWjj, WZjj, ZZjj processes had been observed. More precise measurements will come with full Run2 datasets.
- The observation of EW-ZZjj production is a new milestone reached in the study of EW-VVjj production.
- Based on the precision measurement, we can move to the **longitudinal polarization measurement**, **aQGC** searches …
- VBS Zγjj measurements can be found in Despoina Sampsonidou's talk.

Backup

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

- **Theoretical uncertainties:**

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

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