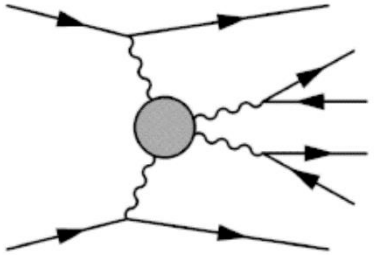
Observation of electroweak production of two jets and a Z-boson pair with the ATLAS detector at the LHC

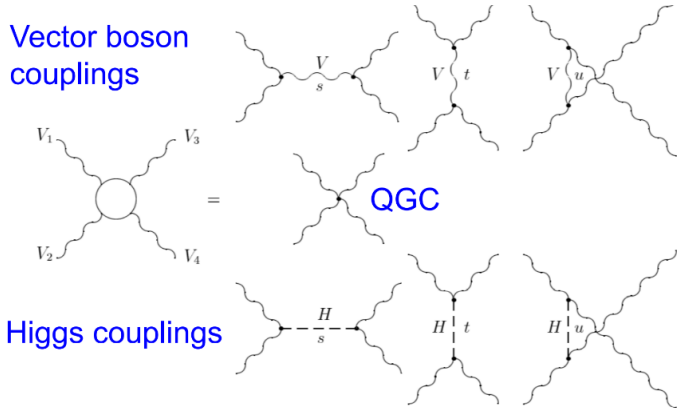
Shuzhou Zhang
University of Michigan
On behalf of the ATLAS Collaboration
SM@LHC 2021
arXiv:2004.10612

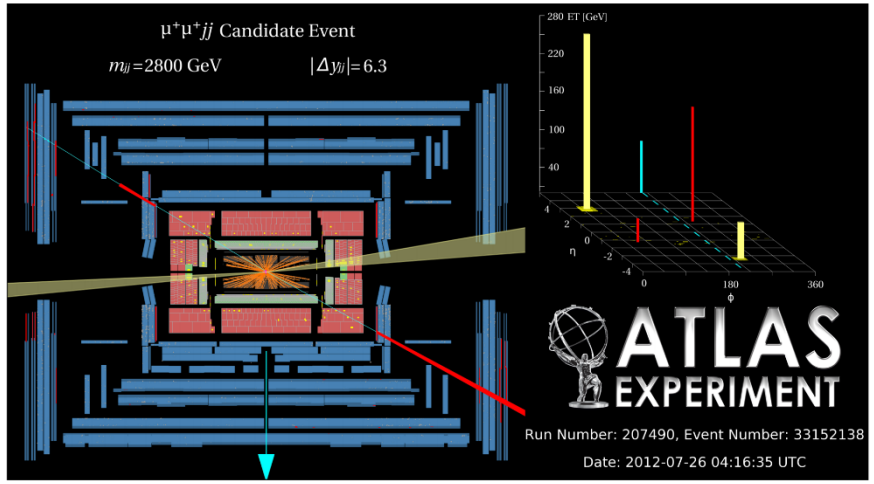
The VBS Processes at the LHC

- Vector Boson Scattering (VBS) is a key process to probe the mechanism of electroweak symmetry breaking, and has close connection with the SM Higgs boson, which cancel the VBS cross-section divergence at TeV energy scale
- **VBS processes are sensitive to new physics beyond SM:**
  - Constraint on anomalous QGCs (aQGCs).
  - Probe new physics through deviations from SM.
- **Experimental signatures of VBS:**
  - Two intermediate vector bosons radiated from two incoming quarks.
  - Final state with two vector bosons plus two outgoing jets.
  - In general, two "tag" jets in forward region with large rapidity separation and large invariant mass.
  - EW VBS has relatively smaller cross-sections,

  suffer from irreducible QCD VV + 2jets events





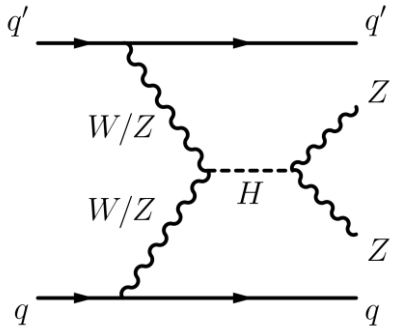


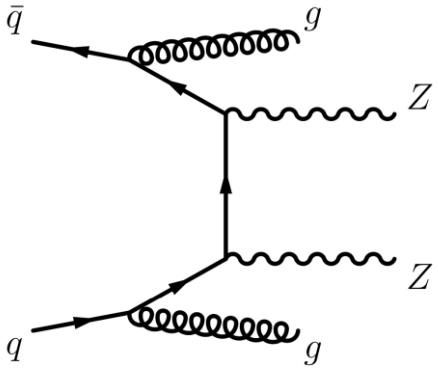
Candidate VBS event from same sign WW
Phys. Rev. Lett. 113, 141803

Overview of EW ZZjj Analysis

arXiv:2004.10612

- Full Run-II data, 139 fb^{-1}.
- Two ZZ decay channels: ZZ→ $4l$ and ZZ→ $llvv$.
- Our analysis is a measurement EW ZZjj production, not just VBS ZZ (VBS diagrams interfere with other EW diagrams).
- **4 lepton channel:**
  - Very clean experimental signature, small background contribution (~3%) from reducible backgrounds.
  - Large irreducible background from QCD ZZjj process.
    - EW/QCD is ~20% level overall, MVA is needed.
    - Large uncertainty from theoretical modeling of QCD ZZjj.
- ***llvv* channel:**
  - Background components are more complicated than 4l channel.
  - Backgrounds mainly come from WZ, WW+ttbar and irreducible QCD ZZjj processes.
  - Z+jets background is largely suppressed with tight cut on the MET-significance (MET significance is used to distinguish missing transverse energy arising from undetectable particles to object mis-reconstruction, finite detector resolution, or detector noise).



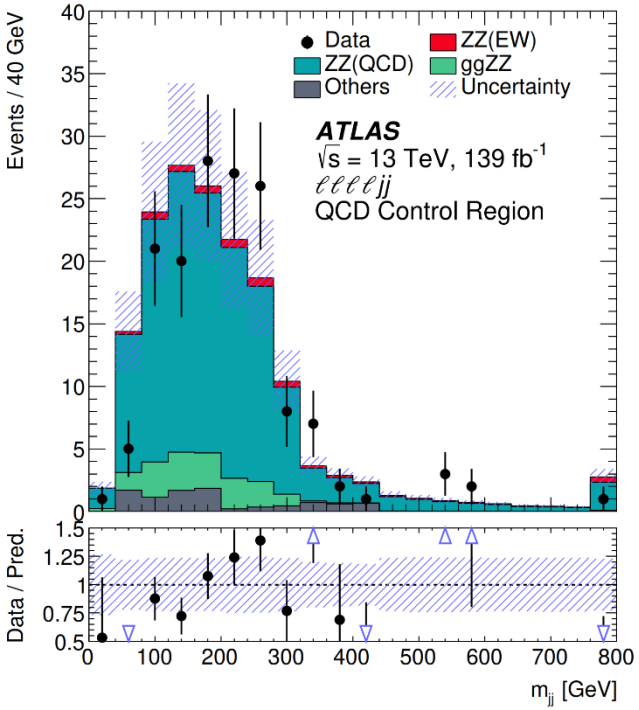


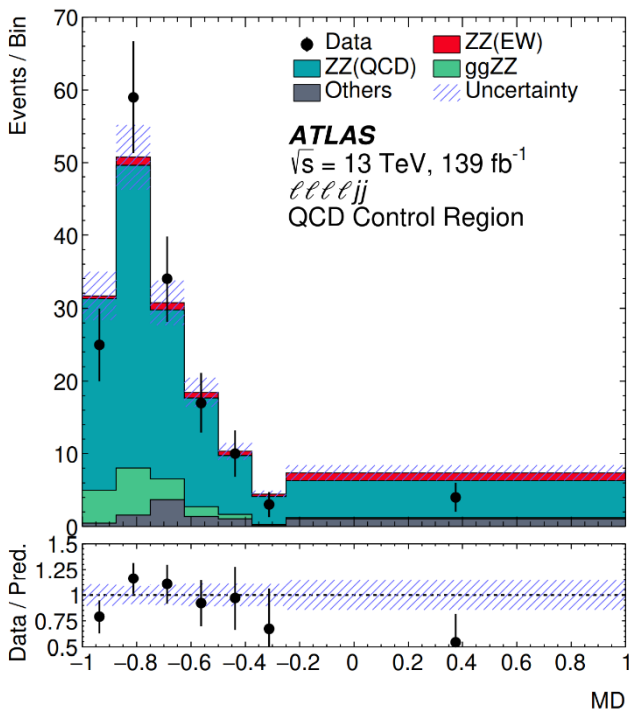
Object and Event Selections

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

Background Estimation

- **In 4 lepton channel**, a QCD CR, defined by reverting the m_{jj} or dY_{jj} cut, is used to constraint the QCD ZZjj background.
- Other minor backgrounds (fakes) in 4 lepton channel (fake background) is estimated using a fake-factor method.
  - Two dedicated CRs were used to derive fake factor from Z+jets and $t\bar{t}$.
  - Bad lepton is defined by reverting the lepton quality, isolation or impact parameters.
  - Final fake background estimation: 2.3 ± 1.6.
- **In llvv channel:**
  - WZ background is constrained by a dedicated 3l, WZ CR.
  - WW, top, $Z\tau\tau$ backgrounds are estimated with events in dedicated $e\mu$ data CR.
  - Z+jets background is estimated by extrapolation (with Exponential function) from data events in low MET-significance region to high MET-significance region



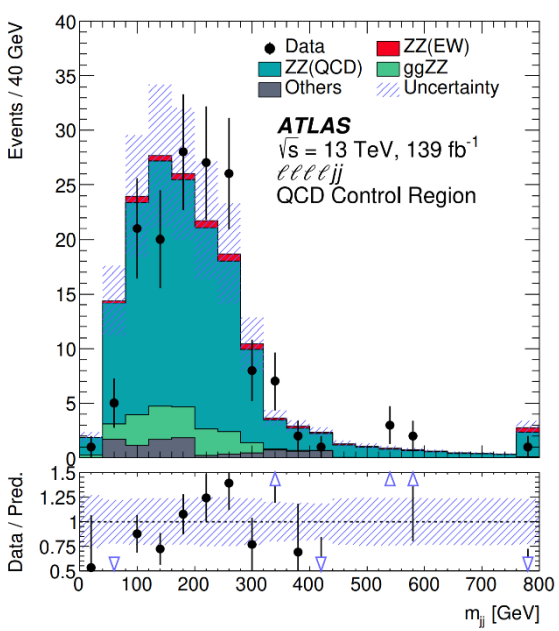


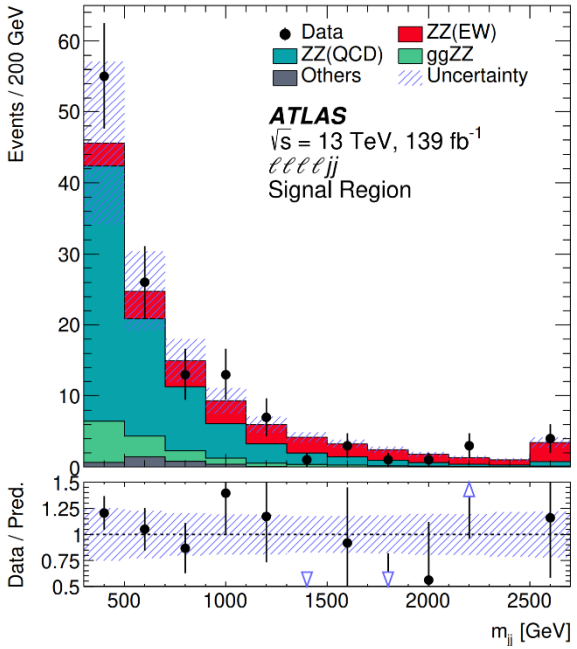
Data compared with predictions

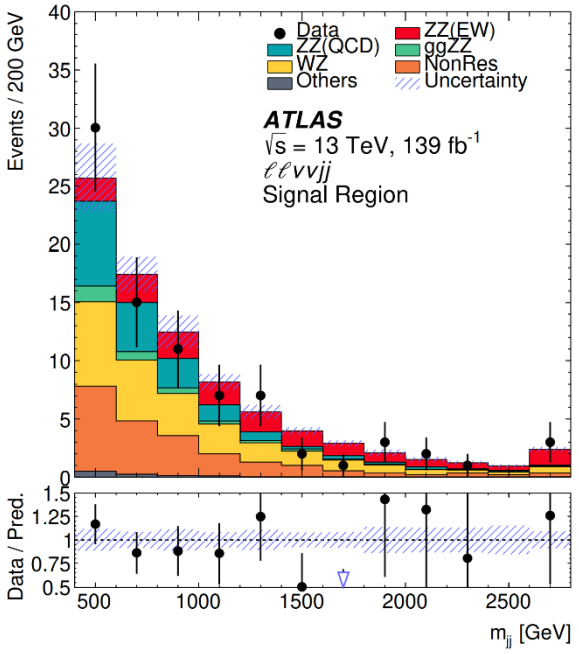
Process	$\ell\ell\ell\ell jj$	$\ell\ell\nu\nu jj$
EW $ZZjj$	20.6 ± 2.5	12.3 ± 0.7
QCD $ZZjj$	77 ± 25	17.2 ± 3.5
QCD $ggZZjj$	13.1 ± 4.4	3.5 ± 1.1
Non-resonant-$\ell\ell$	–	21.4 ± 4.8
WZ	–	22.8 ± 1.1
Others	3.2 ± 2.1	1.2 ± 0.9
Total	114 ± 26	78.4 ± 6.2
Data	127	82

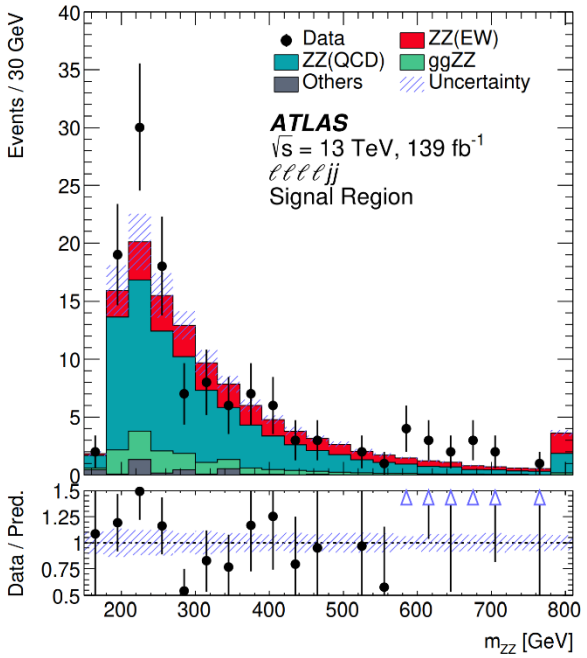
Kinematic distributions: data compared to predictions

- Predictions have been scaled with μ_{EW} and μ_{QCD} from combined fit using BDTG output.
  - μ_{EW} is POI, μ_{QCD} (4l channel) is used as a free parameter in the fit to constrain QCD normalization.









Inclusive ZZjj production Cross-section Measurements

- Inclusive ZZjj production cross sections are measured for the inclusive processes, in individual 4l and llvv channels in fiducial region.
- 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 previous CMS publication.
  - llvv 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).

Results

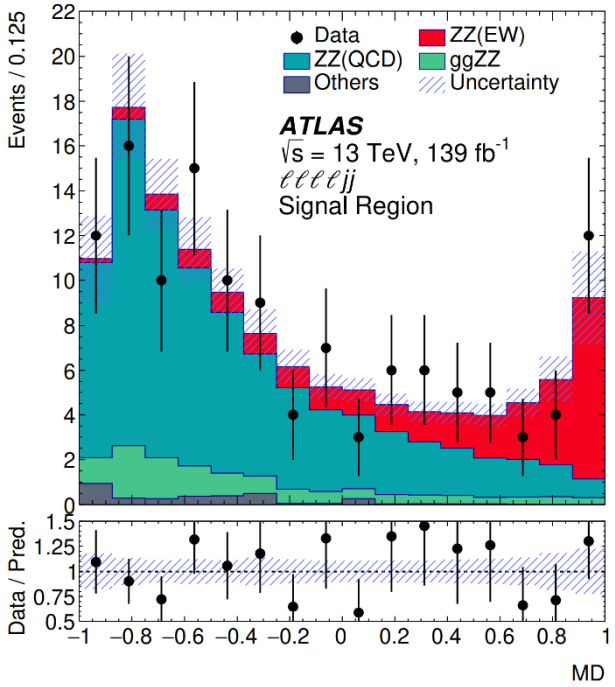
	Measured fiducial σ [fb]	Predicted fiducial σ [fb]
$\ell\ell\ell\ell jj$	$1.27 \pm 0.12(\text{stat}) \pm 0.02(\text{theo}) \pm 0.07(\text{exp}) \pm 0.01(\text{bkg}) \pm 0.03(\text{lumi})$	$1.14 \pm 0.04(\text{stat}) \pm 0.20(\text{theo})$
$\ell\ell\nu\nu jj$	$1.22 \pm 0.30(\text{stat}) \pm 0.04(\text{theo})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

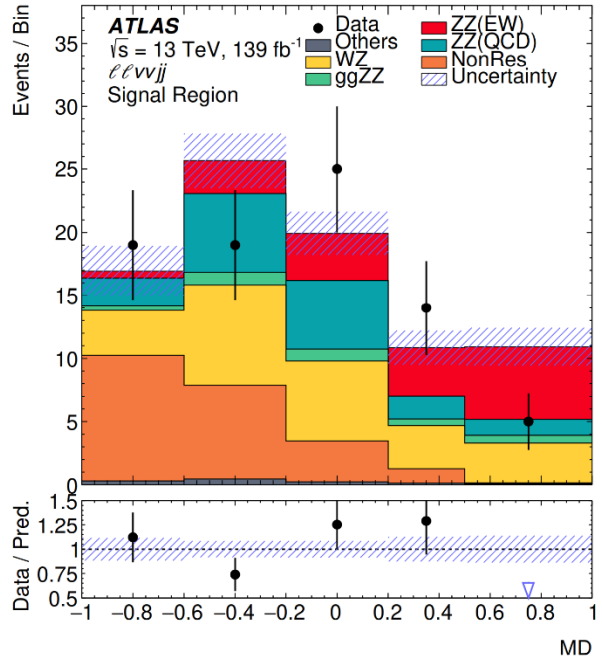
- Uncertainties: statistic dominant.

MVA Analysis to extract EW ZZjj signal

- Gradient boost decision tree (BDTG) is used in both channels
- 4l channel trained in SR using EW vs QCD events.
- llvv channel trained in SR using EW vs all backgrounds

BDT training output score spectra





BDT training input variables

Rank	*llll*	*llνν*
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

Statistic fitting and Results

- BDT score is used as final discriminator for fitting.
- 3 regions are used in fitting: 4l SR, 4l QCD CR, llvv SR.
- μ_{EW} is POI, μ_{QCD} (4l channel) is used as a free parameter in the fit to constrain QCD normalization.
- Experimental systematic uncertainties (electrons, muons, jets, lumi, pile-up) are fully correlated.
- Theoretical systematics are uncorrelated due to different fiducial definitions.

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

	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) σ
$\ell\ell\nu\nu jj$	0.7 ± 0.7	–	1.2 (1.8) σ
Combined	1.35 ± 0.34	0.96 ± 0.22	5.5 (4.3) σ

Summary

- The first observation of the EW ZZjj production with ZZjj channel with the ATLAS experiment at the LHC. The observed signal significance: 5.5σ, compared with predicted 4.3σ.

- The observation of EW ZZjj process completes the observations of weak boson scattering with same-sign WWjj, WZjj and ZZjj processes at the LHC

Thank you!