Observation of Electroweak Production of Two Jets and a Z-boson Pair with the ATLAS Detector at the LHC

Jing Li

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Shanghai Jiao Tong University

Motivation

- Vector boson scattering, unitarity violation at TeV scale
- VBS $\rightarrow$ measurable key process linked with electroweak symmetry breaking – whether the discovered higgs boson is fully responsible for EWSB
- relative small electroweak event rates

Motivation???


VBS PROCESS IS VERY IMPORTANT
WHO CARES???
BUT WE ARE BEHIND OF CMS…
WE HAVE TO DO SOMETHING!!!

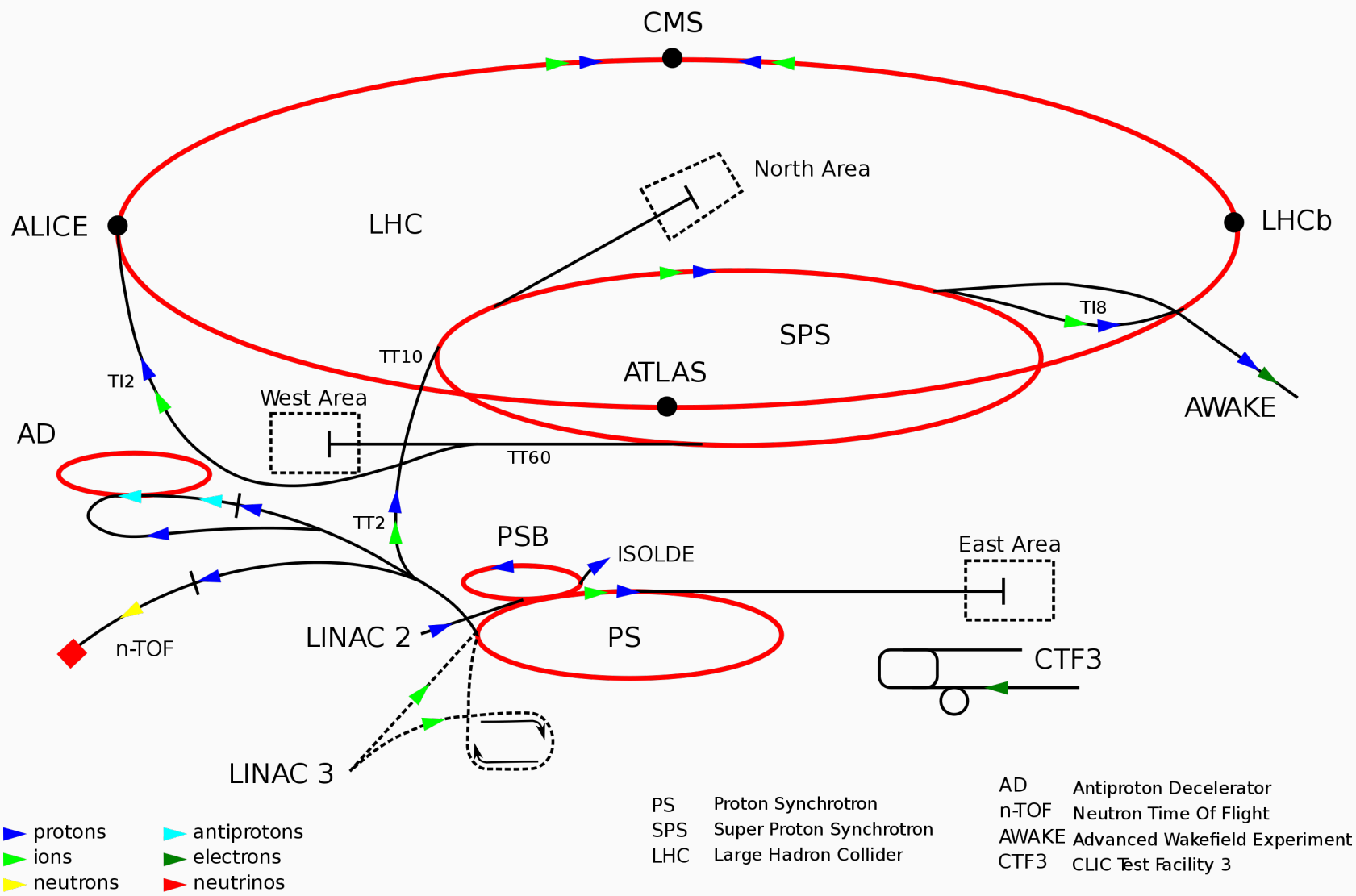
Overview of VBS Measurements in LHC @ 13 TeV

- status of December 2019

Channel	Observed (Expected) Significance		Challenges
	ATLAS	CMS	
ssWW	6.5(4.9) σ	5.5(5.7) σ	◇ first observation of VBS in this channel ◇ very good EW/QCD ratio ◇ mostly experimental backgrounds
WZ	5.3(3.2) σ	1.9(2.7) σ	◇ similar cross-section as ssWW ◇ but larger QCD background
ZZ	5.5(4.3) σ	2.7(1.6) σ	◇ very clean $\ell\ell\ell\ell jj$ channel ◇ low background but small cross section

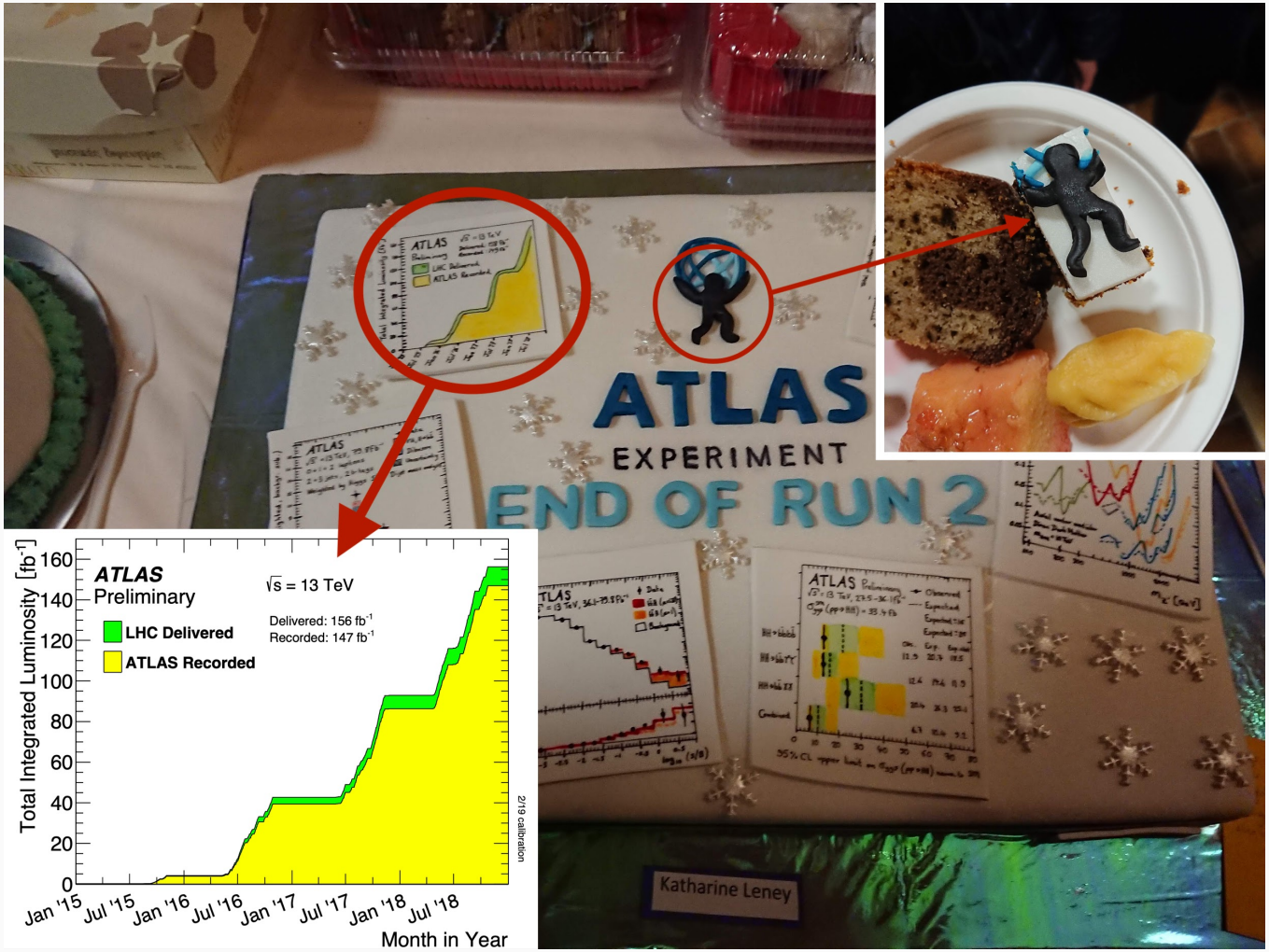
- CMS study in 2017: 35.9 fb^{-1} pp data @ 13 TeV, only consider $ZZ \to \ell\ell\ell\ell jj$
- LHC Run2 data @ 13 TeV allows to explore VBS with precision

LHC


CMS
North Area
ALICE
LHC
LHCb
SPS
TI8
ATLAS
TT10
TI2
West Area
AWAKE
AD
TT60
TT2
PSB
ISOLDE
East Area
n-TOF
LINAC 2
PS
CTF3
LINAC 3
protons
ions
neutrons
antiprotons
electrons
neutrinos
PS Proton Synchrotron
SPS Super Proton Synchrotron
LHC Large Hadron Collider
AD Antiproton Decelerator
n-TOF Neutron Time Of Flight
AWAKE Advanced Wakefield Experiment
CTF3 CLIC Test Facility 3

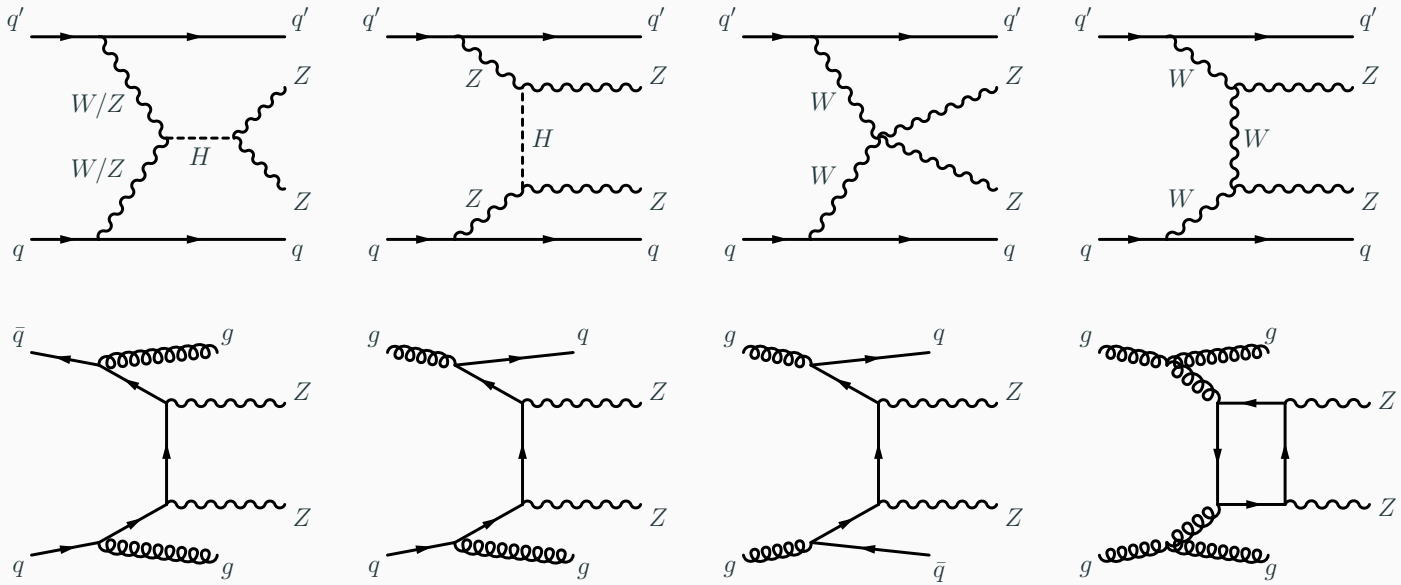
ATLAS Run2

- full Run2 dataset: 139 fb^{-1} pp data @ 13 TeV

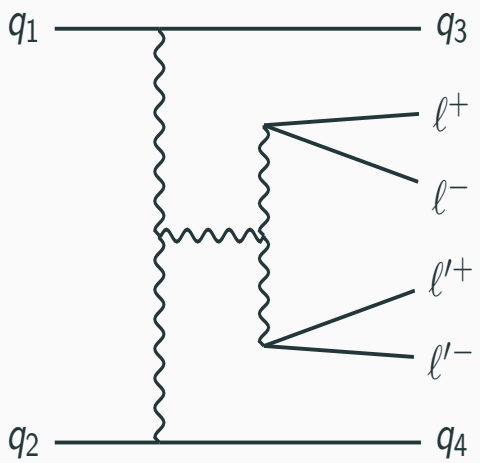


Analysis Overview

- use ATLAS full Run2 dataset, 139 fb^{-1}
- include both VBS $ZZjj \to \ell\ell\ell\ell jj$ and $ZZjj \to \ell\ell\nu\nu jj$ channels
- $\ell\ell\ell\ell jj$: clean, low background
- $\ell\ell\nu\nu jj$: larger branch ratio, complex backgrounds
- Gradient Boosted Decision Tree (BDTG) is used as the final discriminator to separate the signal and backgrounds
- typical diagrams for the production of ZZjj, including the relevant EW VBS diagrams (first row) and QCD diagrams (second row):



$[\ell\ell\ell\ell jj]$ Event Selections



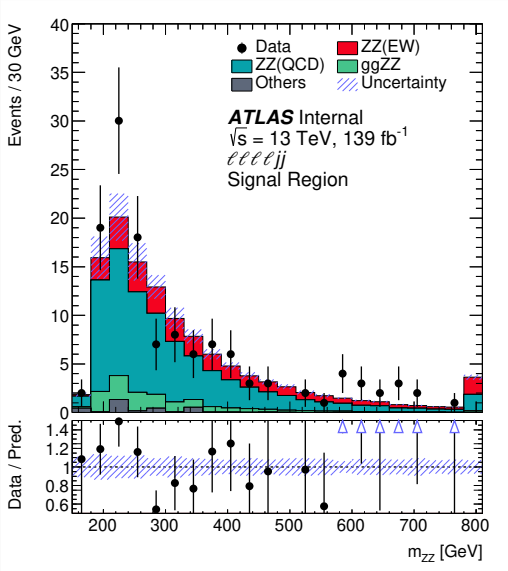
- leptons:
  - 2 opposite sign same flavor (OSSF) lepton pairs with the smallest

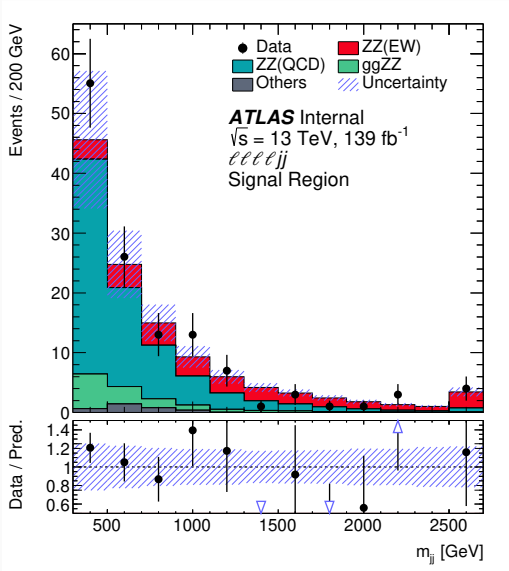
$$|m_{\ell^+\ell^-} - m_Z| + |m_{\ell'^+\ell'^-} - m_Z|$$

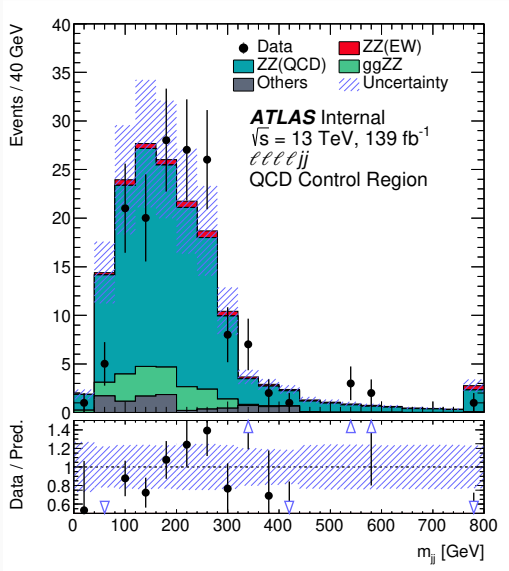
  - $66 < m_{\ell^+\ell^-} < 116$ GeV, $\Delta R(\ell\ell) > 0.2$
- jets:
  - 2 most energetic jets with $Y_{j_1} \times Y_{j_2} < 0$
  - $m_{jj} > 300$ GeV, $\Delta Y(jj) > 2$

[$\ell\ell\ell\ell jj$] QCD ZZjj Background

- reverse m_{jj} and $\Delta Y(jj)$ selections
- $m_{jj} < 300$ GeV or $\Delta Y(jj) < 2$







$[\ell\ell\ell\ell jj]$ Fake Background

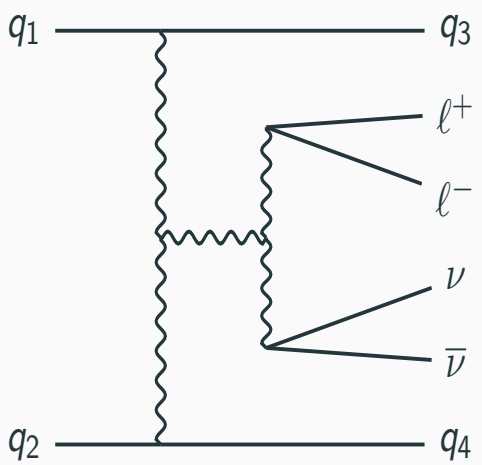
- fake factor method is used for jet-enriched samples: $t\bar{t}$, $Z + jets$...
- good lepton: objects passing standard lepton selections
- poor lepton: objects not fully passing standard lepton selections
- fake factor:

$$\text{fake factor } f = \frac{N_{\text{good lepton}}}{N_{\text{poor lepton}}}$$

- fake contribution in the signal region:

$$N_{\text{fake}} = (N_{gggp} - N_{gggp}^{ZZ}) \times f - (N_{ggpp} - N_{ggpp}^{ZZ}) \times f^2$$

$[\ell\ell\nu\nu jj]$ Event Selections



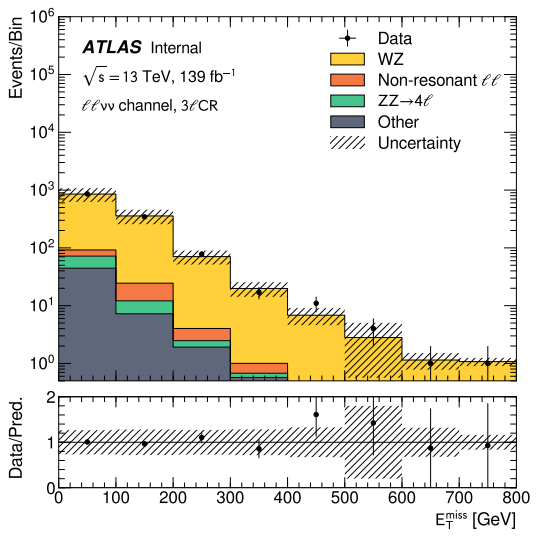
- leptons:
  - 1 OSSF lepton pairs, $80 < m_{\ell^+\ell^-} < 100$ GeV
  - veto b-jet
- jets:
  - 2 most energetic jets with $Y_{j_1} \times Y_{j_2} < 0$
  - $m_{jj} > 400$ GeV, $\Delta Y(jj) > 2$
- E_T^{miss}:
  - E_T^{miss}-significance> 12 for SR
  - $E_T^{miss} > 130$ GeV for fiducial volumne (FV)

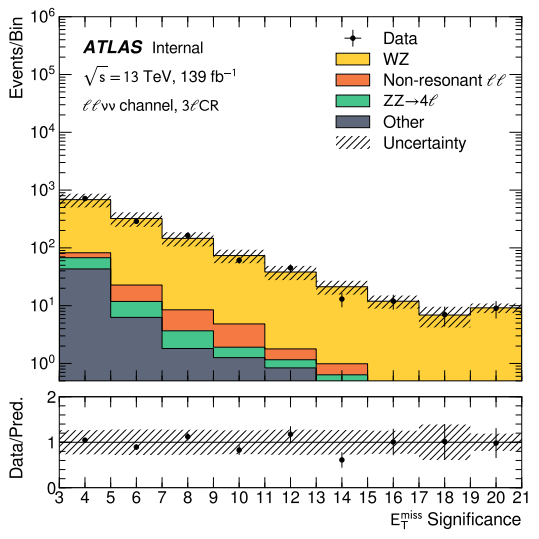
$[\ell\ell\nu\nu jj]$ *WZ* Background

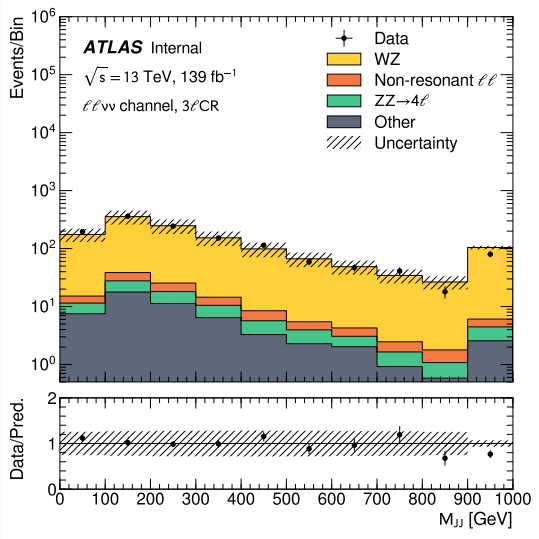
- $WZ \to \ell\nu\ell\ell$ events, where one lepton is not reconstructed
- 3ℓ CR selections:
  - a lepton pair near Z mass
  - a good 3rd lepton
  - other requirements to supress other backgrounds
    E_T^{miss}-significance$>$ 3...
  - at least 2 energetic jets (veto b-jet)
- estimate the WZ contribution in SR:

$$N_{WZ,data}^{2\ell SR} = N_{WZ,MC}^{2\ell SR} \times \boxed{\frac{N_{WZ,data}^{3\ell CR}}{N_{WZ,MC}^{3\ell CR}}}$$

[$\ell\ell\nu\nu jj$] *WZ* Background (cont')







- high purity 92%, and good DATA/MC agreement
- scale factor $= 0.81 \pm 0.03$

$[\ell\ell\nu\nu jj]$ non-resonant $\ell\ell$ Background

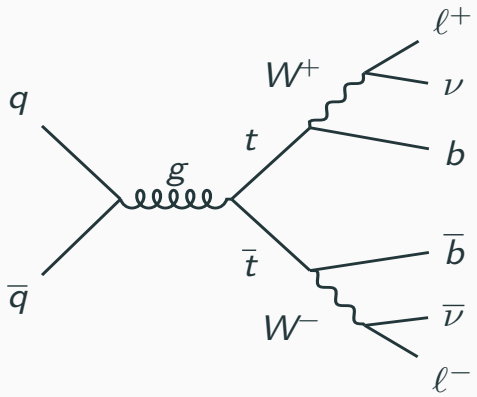
- $e\mu$CR: to study $t\bar{t}$, WW, Wt, $Z \to \tau\tau$
- $\epsilon-$factor represents the reconstruction efficiency difference between electrons and muons (selecting ee and $\mu\mu$ events after the Z mass cut):

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

- Apply the $\epsilon-$factor on the $e\mu$ data events(changing SR lepton pair to a $e\mu$ pair):

$$N^{est.}_{SRee} = \frac{1}{2} \times \epsilon \times N^{data,sub}_{e\mu}$$

$$N^{est.}_{SR\mu\mu} = \frac{1}{2} \times \frac{1}{\epsilon} \times N^{data,sub}_{e\mu}$$



$[\ell\ell\nu\nu jj]$ non-resonant $\ell\ell$ Background

- MC closure check: use only non-resonant $\ell\ell$ MC samples to check if the method is duable

channel	estimated from $e\mu$CR	selected from SR
ee	13.99 ± 0.55	13.80 ± 0.83
$\mu\mu$	15.75 ± 0.61	14.95 ± 0.86

$[\ell\ell\nu\nu jj]$ $Z + jets$ Background

- highly suppressed by the E_T^{miss}-significance cut
- use a exponential function to fit Data $-$ $\mathrm{MC}_{\text{non } Z+jets}$ E_T^{miss}-significance distribution
- extrapolate from the control region ($3 < E_T^{miss}$-significance < 4.7) to the validation region ($5 < E_T^{miss}$-significance < 10) and the signal region (E_T^{miss}-significance > 10)
- final estimation in the signal region $0.28 + 1.5 - 0.28$

Inclusive Cross Section Measurement

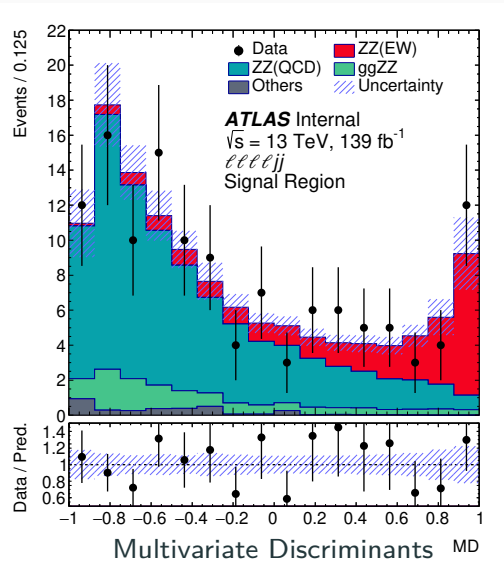
- Observed data and expected signal and background yields in 139 fb^{-1} of data in the $\ell\ell\ell\ell jj$ and $\ell\ell\nu\nu jj$ signal regions:

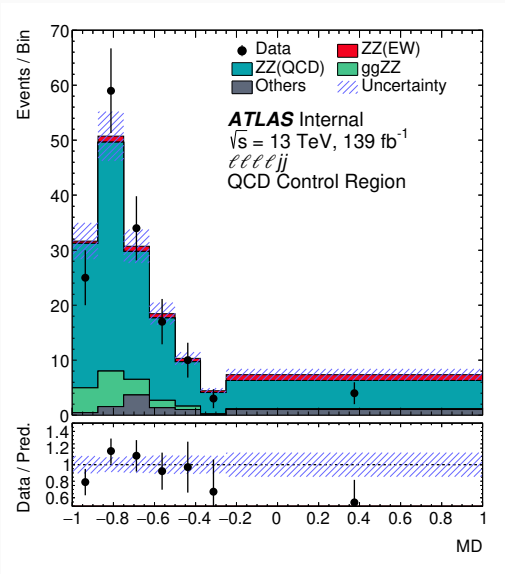
Process	$\ell\ell\ell\ell jj$	$\ell\ell\nu\nu jj$
EW *ZZjj*	20.6 ± 2.5	12.30 ± 0.65
QCD *ZZjj*	77 ± 25	17.2 ± 3.5
QCD *ggZZjj*	13.1 ± 4.4	3.5 ± 1.1
Non-resonant-$\ell\ell$	-	21.4 ± 4.8
WZ	-	22.8 ± 1.1
Others	3.2 ± 2.1	1.15 ± 0.89
Total	114 ± 26	78.4 ± 6.2
Data	127	82

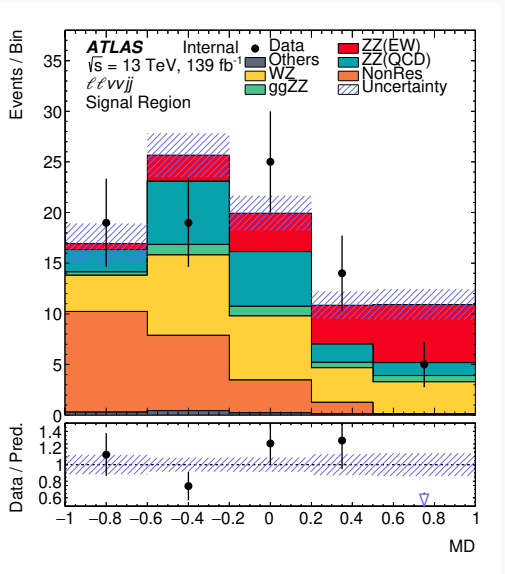
- Cross section in the fiducial volume

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

Observation of EWK ZZjj

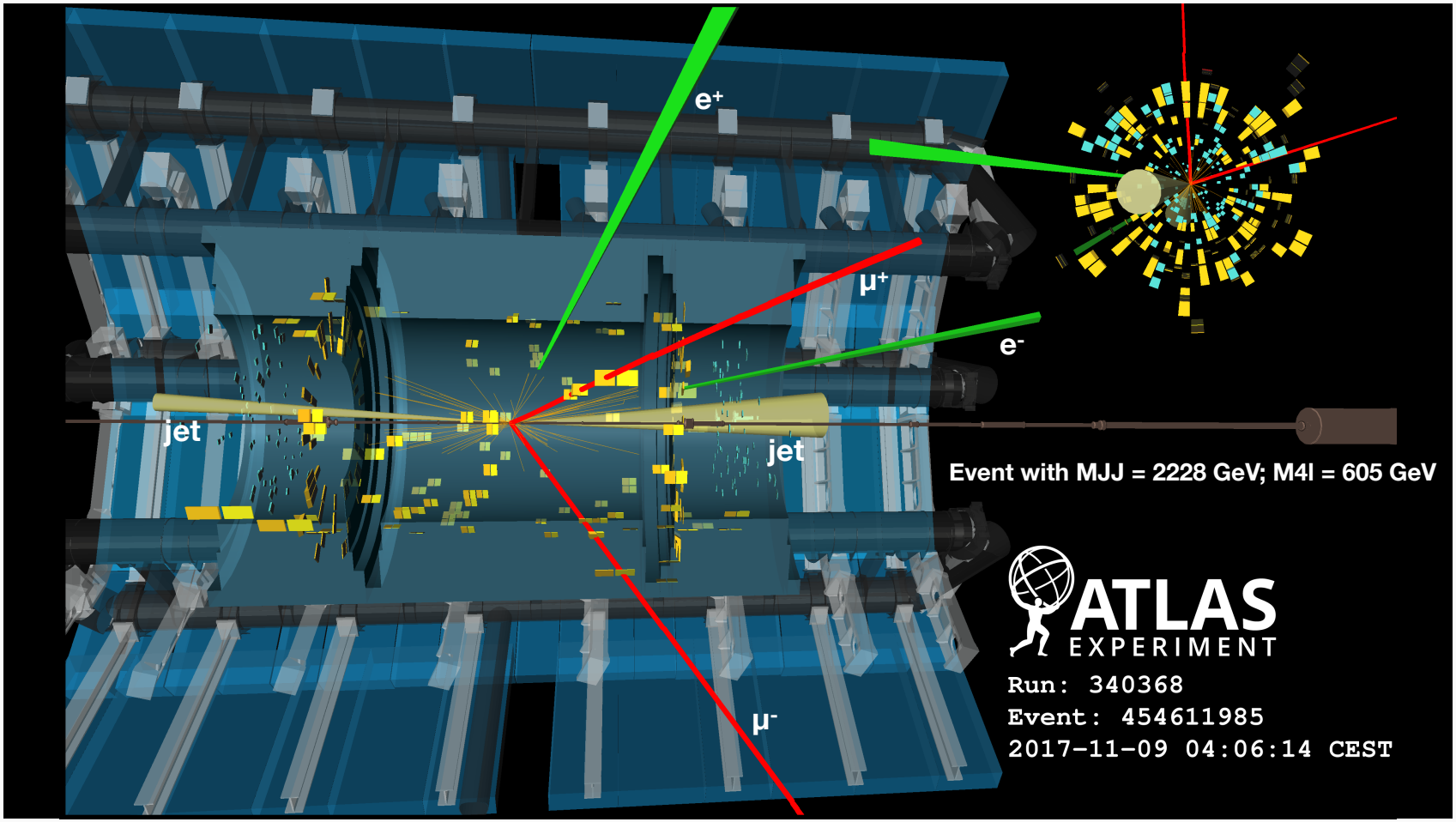






	μ_{EW}	$\mu_{\mathrm{QCD}}^{\ell\ell\ell\ell jj}$	Significance Obs. (Exp.)
$\ell\ell\ell\ell jj$	1.5 ± 0.4	0.95 ± 0.22	5.48 (3.89) σ
$\ell\ell\nu\nu jj$	0.7 ± 0.7	fixed	1.15 (1.80) σ
Combined	1.35 ± 0.34	0.96 ± 0.22	5.52 (4.29) σ

Event Display



Summary

- the first observation of EW ZZjj production is an important milestone for studies of EW VVjj production, which corresponds to a statistical significance of 5.5 σ
- cross-sections for inclusive production of ZZ plus two jets, as well as the observed signal strength of the EW production, are reported
- the differential cross section will be measured in the next round of analysis

Thank You!

Event Selection

	$\ell\ell\ell\ell jj$	$\ell\ell\nu\nu jj$
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 $\Delta R(\ell, \ell') > 0.2$ $66 < m_{\ell^+\ell^-} < 116$ GeV	$p_T > 30$ (20) GeV for the leading (sub-leading) lepton One OSSF lepton pair and no third leptons $80 < m_{\ell^+\ell^-} < 100$ GeV No b-tagged jets E_T^{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 $\Delta y(jj) > 2$

E_T^{miss}-significance

$$\mathcal{S} = 2 \ln \frac{\mathcal{L}(\vec{\epsilon} = \sum \vec{\epsilon_i})}{\mathcal{L}(\vec{\epsilon} = 0)}$$

- $\mathcal{L}(\vec{\epsilon} = \sum \vec{\epsilon_i})$: the likelihood of the hypothesis under test that the true value ($\vec{\epsilon}$) of the missing transverse energy is equal to observed value ($\sum \vec{\epsilon_i}$)
- $\mathcal{L}(\vec{\epsilon} = 0)$: the likelihood of the null hypothesis

Systematic Uncertainty Ranking