Measurements of Vector Boson Scattering in ATLAS and CMS

Junjie Zhu

University of Michigan

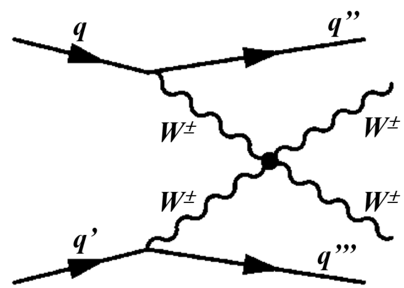
July 25, 2019

Physics Workshop at the LPC: Multibosons at the energy frontier

Introduction

- I gave a Fermilab W&C seminar talk about the first evidence of same-sign WW VBS production about five years ago
- It was the first evidence for a VBS process at the LHC

First Evidence of Same-sign WW Vector Boson Scattering Process at ATLAS



Junjie Zhu

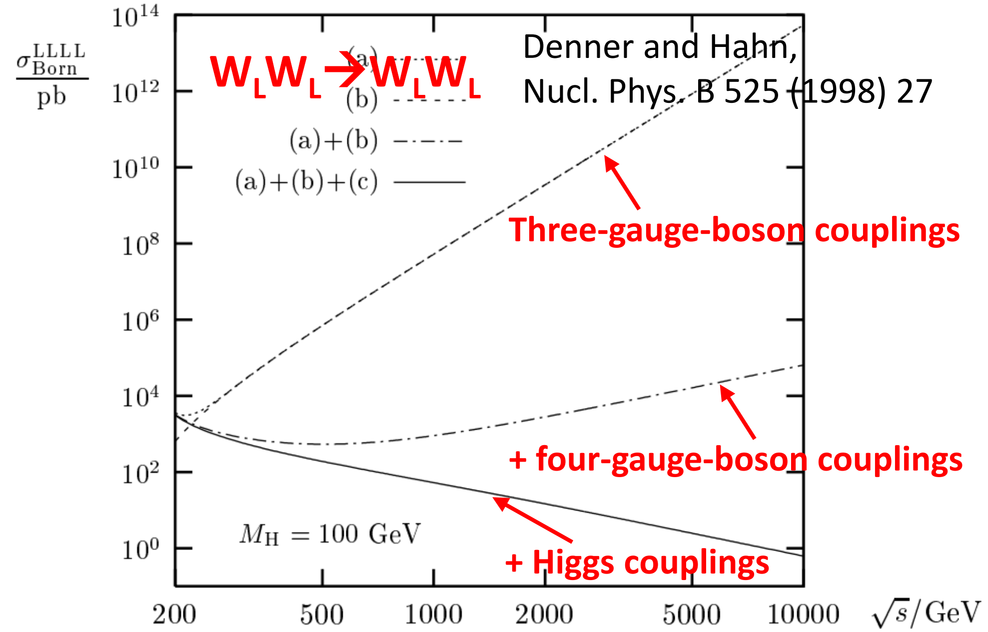
University of Michigan

Fermilab Wine Cheese Seminar

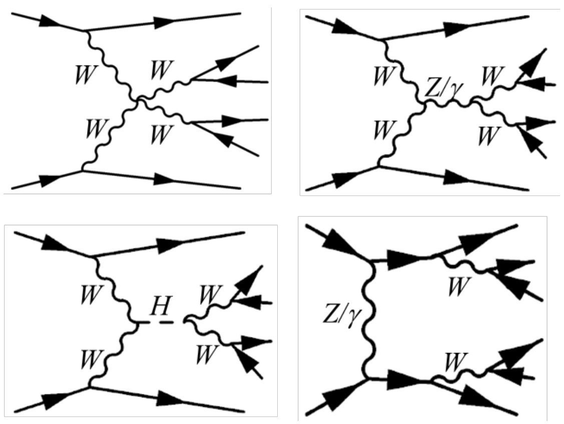
May 23, 2014

Introduction

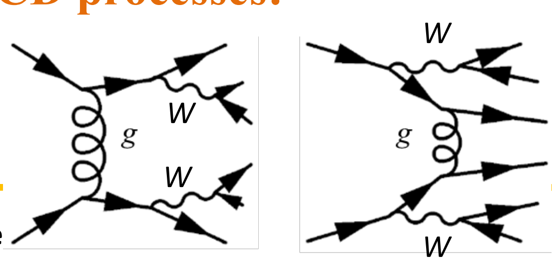
- VBS processes are least-studied SM processes and could be used to study the dynamics of EWSB
  - Interaction with the Higgs boson unitarizes the scattering amplitude
  - Complementary to Higgs boson property studies

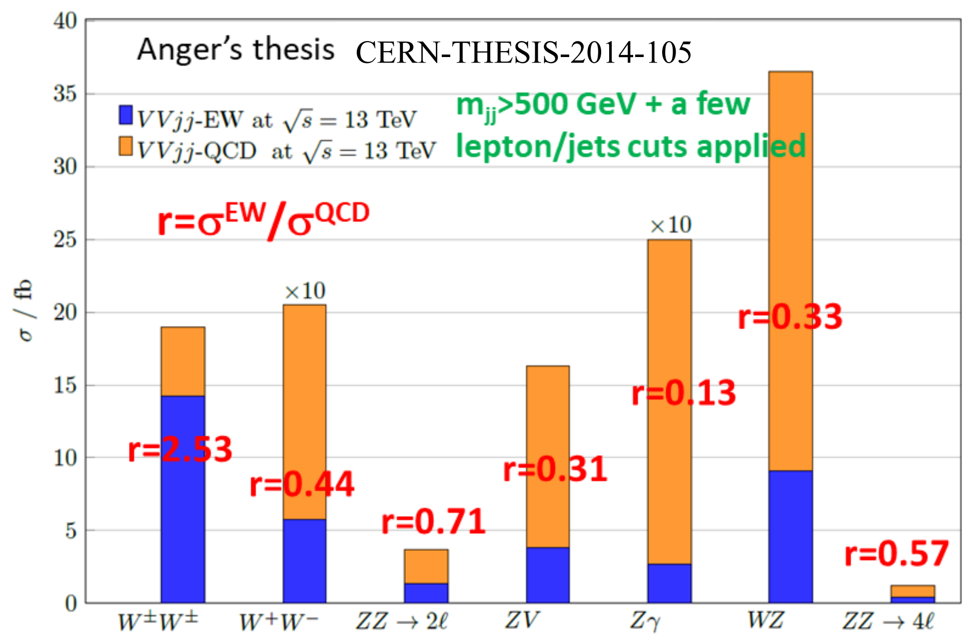


- **EW VBS processes:**



- **QCD processes:**





Introduction

- Lots of progress made in the past five years for EW VBS processes

EW VBS process	ATLAS	CMS
$W^{\pm}W^{\pm}$	8 TeV (20.3 fb^{-1}): 3.6(2.8)σ arXiv:1405.6241, Evidence	8 TeV (19.4 fb^{-1}): 2.0(3.1)σ arXiv:1410.6315
	13 TeV (36.1 fb^{-1}): 6.5(4.4)σ arXiv:1906.03203, Observation	13 TeV (35.9 fb^{-1}): 5.5(5.7)σ arXiv:1709.05822, Observation
WZ	8 TeV (20.3 fb^{-1}): upper limit set on σ (WZ VBS), arXiv:1603.02151	8 TeV (19.4 fb^{-1}): extracted σ(WZjj), arXiv:1410.6315
	13 TeV (36.1 fb^{-1}): 5.3(3.2) σ arXiv:1812.09740, Observation	13 TeV (35.9 fb^{-1}): 2.2(2.5)σ arXiv:1901.04060
ZZ	13 TeV (139 fb^{-1}): 5.5(4.3)σ ATLAS-CONF-2019-033 (7/2019), Observation	13 TeV (35.9 fb^{-1}): 2.7(1.6)σ arXiv:1708.02812
WV semileptonic	8 TeV (20.2 fb^{-1}): limits setup on aQGCs, arXiv:1609.05122	X
	13 TeV (35.5 fb^{-1}): 2.7(2.5)σ arXiv:1905.07714	13 TeV (35.9 fb^{-1}), limits setup on aQGCs, arXiv:1905.07445

Introduction

- Lots of progress made in the past five years for EW VBS processes

EW VBS process	ATLAS	CMS
Zγ	8 TeV (20.2 fb^{-1}): 2.0 (1.8)σ arXiv:1705.01966	8 TeV (19.7 fb^{-1}): 3.0(2.1)σ arXiv:1702.03025, Evidence
	X	13 TeV (35.9 fb^{-1}): 3.9(5.2)σ CMS-PAS-SMP-18-007 (7/2019)
Wγ	X	8 TeV (19.7 fb^{-1}): 2.7(1.5)σ arXiv:1612.09256

- I will describe results that are less than one year old (which means 13 TeV results for all VBS processes listed on slides 4 and 5 except Wγ)

$W^{\pm}W^{\pm}$ VBS

- Select events with two same-sign leptons and two jets with large m_{jj} and $\Delta\eta_{jj}$
  - EW production dominant over QCD production
  - Distinct same-sign (SS) dilepton final state
- Event selection:

	ATLAS (arXiv:1906.03203)	CMS (arXiv:1709.05822)
– 2 SS leptons (e, μ)	p_T>27 GeV	p_T>25, 20 GeV
	$\|\eta\|<2.5$ (<1.37 for ee)	$\|\eta\|<2.5$ (e), 2.4 (μ)
	-	$\max(\|[\eta_\ell-(\eta_{j1}+\eta_{j2})/2]/\Delta\eta_{jj}\|)<0.75$
	$\|m_{ee}-m_Z\|>15$ GeV → reject charge-flipped Z→ee events	
– 2 jets:	p_T>65, 35 GeV	p_T>30 GeV
	$\|\eta\|<4.5$	$\|\eta\|<5$
	$\|\Delta y_{jj}\|>2.0$	$\|\Delta\eta_{jj}\|>2.5$
	m_{jj} > 500 GeV	
– Missing E_T:	> 30 GeV	> 40 GeV

  - Veto events with 3rd lepton → reject WZ+jets events
  - Veto events with b-jets → reject top events
- Events failing some SR selection cuts are used as CRs to check background modelling

$W^{\pm}W^{\pm}$ VBS

Backgrounds:

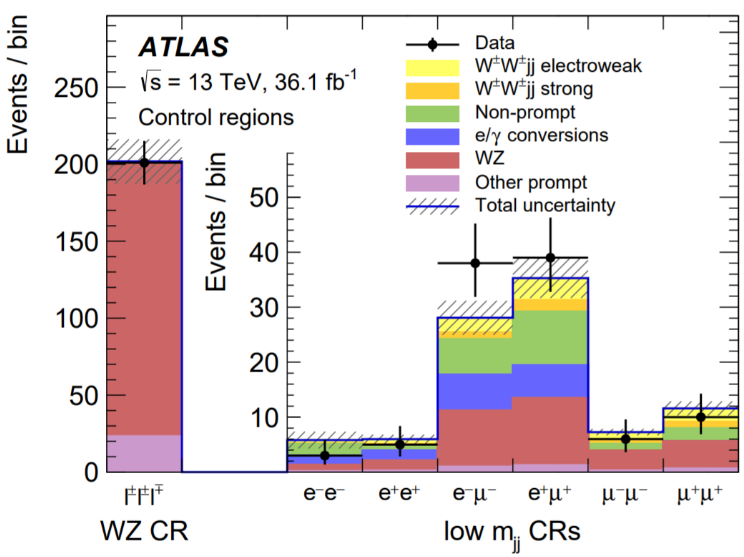
- Nonprompt background estimated from data using the fake factor method
- Electron charge flip rate measured from data
- WZ estimation from MC with the normalization determined from the WZ CR

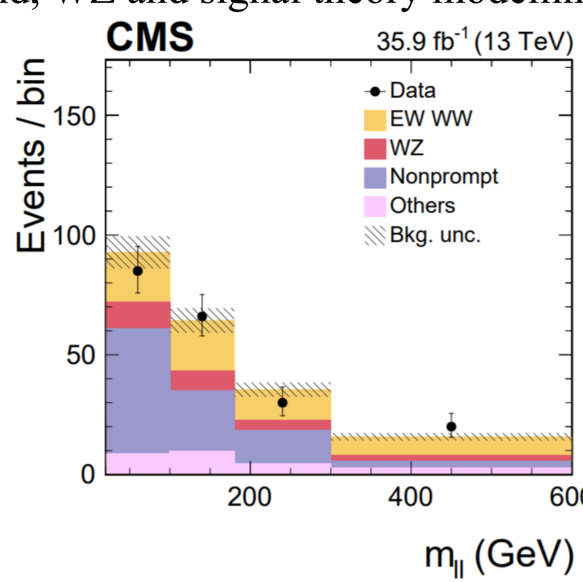
Signal extraction:

- ATLAS used the m_{jj} distribution in 6 SRs (based on lepton charge and flavor) and two CRs (six low m_{jj} CRs and one WZ CR)
- CMS used 2D (m_{jj}, $m_{\ell\ell}$) and WZ CR

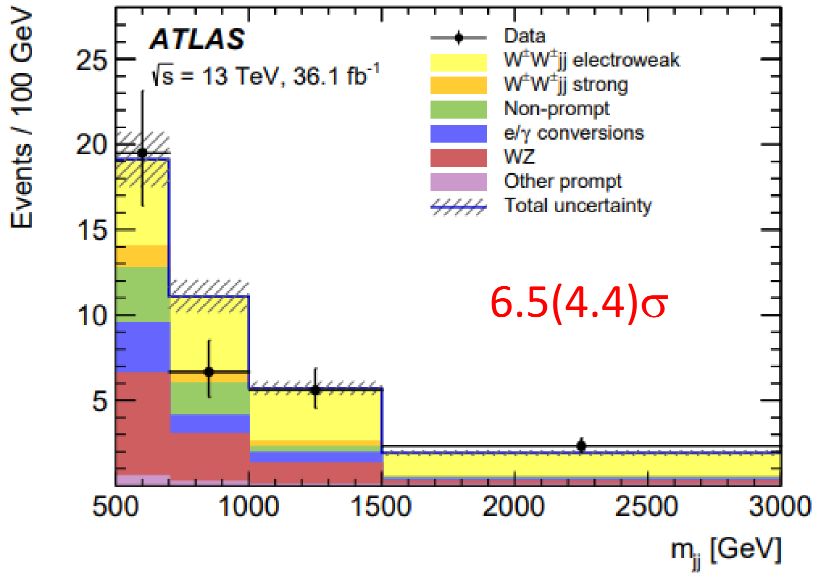
Systematic uncertainties:

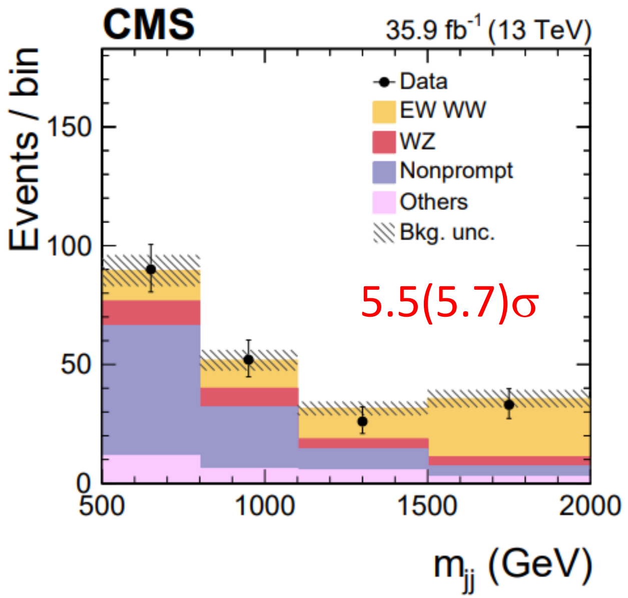
- Dominated by jet energy scale, fake background, WZ and signal theory modelling





W±W± VBS





60 signal and 69 background expected

67 signal and 138 background expected

Fiducial region definitions:

Requirement	CMS	ATLAS
Exclude τ leptonic decays	Yes	Yes
$p_T^\ell >$ [GeV]	20	27
$\lvert\eta^\ell\rvert <$	2.5	2.5
$p_T^j >$ [GeV]	30/30	65/35
$\lvert\eta^j\rvert <$	4.7	4.5
$m_{jj} >$ [GeV]	500	500
$\lvert\Delta\eta_{jj}\rvert >$	2.5	2.0
E_T^{miss} [GeV]	N/A	30
$m_{\ell\ell} >$ [GeV]	N/A	20

ATLAS:

$$\sigma^{\text{fid}} = 2.89^{+0.51}_{-0.48}(\text{stat})^{+0.29}_{-0.28}(\text{syst})\ \text{fb}$$

$$\sigma^{\text{th.}} = 2.01^{+0.33}_{-0.23}\ \text{fb}$$ (Sherpa)

$$\sigma^{\text{th.}} = 3.08^{+0.45}_{-0.46}\ \text{fb}$$ (Powheg+Pythia)

CMS:

$$\sigma^{\text{fid}} = 3.83 \pm 0.66(\text{stat}) \pm 0.35(\text{syst})\ \text{fb}$$

$$\sigma^{\text{th.}} = 4.25 \pm 0.27\ \text{fb}$$ (MadGraph_aMC@NLO)

WZ VBS

- Select events with three charged leptons and two jets
  - Clean channel and most kinematics can be reconstructed
- Event selection:

	ATLAS (arXiv:1812.09740)	CMS (arXiv:1901.04060)
– 3 leptons (e, μ)	p_T>27, 15, 15 GeV	p_T>25, 15, 20 (for W) GeV
	$\|\eta\|<2.47$ (e), 2.5(μ)	$\|\eta\|<2.5$ (e), 2.4 (μ)
	$\|m_{ll}-m_Z\|<10$ GeV	$\|m_{ll}-m_Z\|<15$ GeV
– 2 jets:	p_T>40 GeV	p_T>50 GeV
	$\|\eta\|<4.5$	$\|\eta\|<4.7$
	$\eta_{j1}\times\eta_{j2}<0$	$\|\Delta\eta_{jj}\|>2.5$
	-	$\|\eta_{3\ell}-(\eta_{j1}+\eta_{j2})/2\|<2.5$
	m_{jj} > 500 GeV	
– Missing E_T:	> 30 GeV	

  - Veto events with 4th lepton → reject ZZ+jets events
  - Veto events with b-jets → reject top events
  - ATLAS trained a BDT with 15 variables to distinguish EW WZ signal from QCD WZ
- Events failing some SR selection cuts are used as CRs to check background modelling

WZ VBS

Backgrounds:

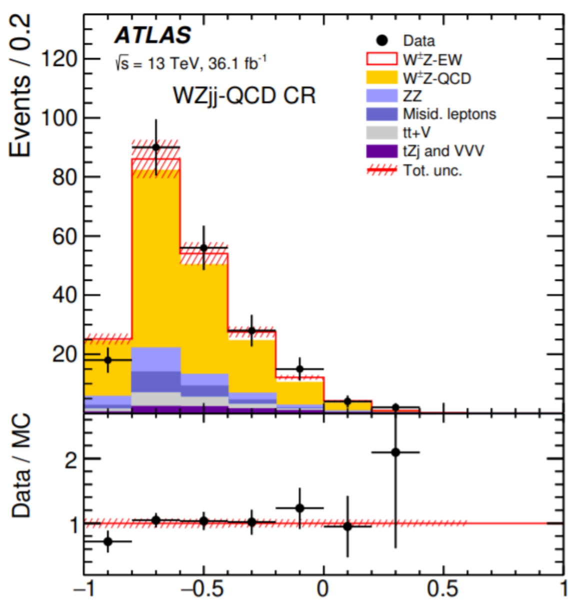
- QCD WZ contribution is estimated using MC simulation with normalization determined in a dedicated WZ CR
- ZZ and ttV backgrounds are determined in CRs

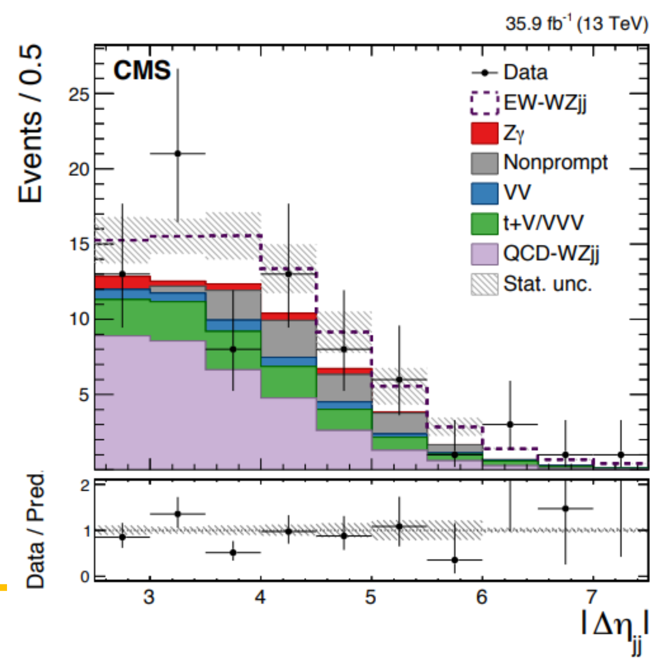
Signal extraction:

- ATLAS fitted the BDT distribution in the SR and the m_{jj} distributions in WZjj-QCD, ZZjj-QCD and b-jet CRs
- CMS used 2D (m_{jj}, $\Delta\eta_{jj}$) and QCD WZ sideband CR

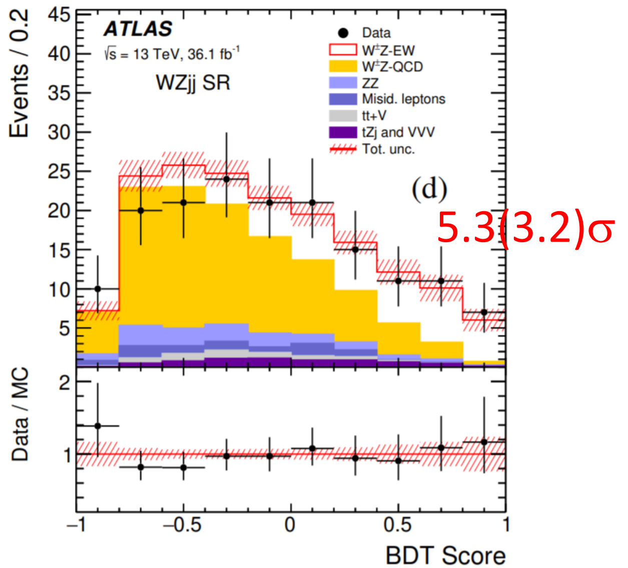
Systematic uncertainties:

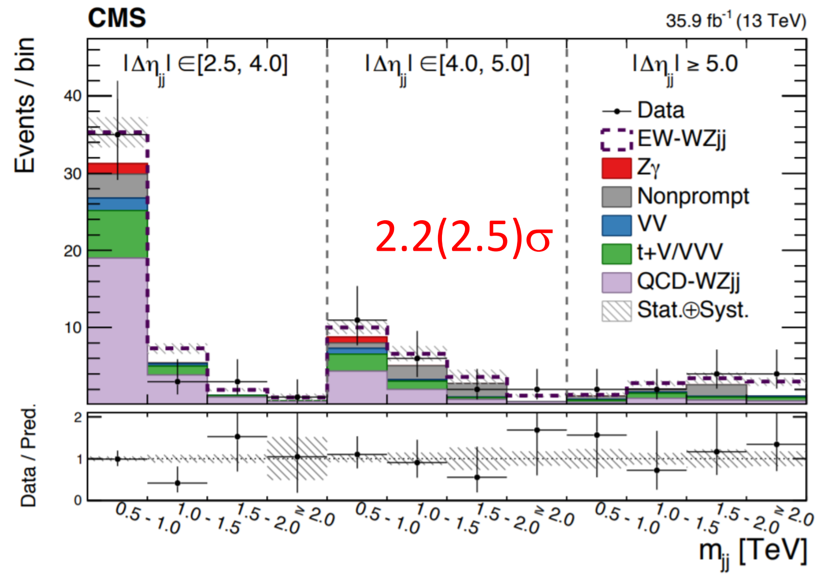
- Dominated by jet energy scale, EW and QCD WZ theoretical modelling





WZ VBS





44 signal and 123 background expected

15 signal and 62 background expected

Fiducial region definitions:

CMS

	Tight fiducial
$p_T^{\ell_1}$ [GeV]	>25
$p_T^{\ell_2}$ [GeV]	>15
p_T^{ℓ} [GeV]	>20
$\|\eta^{\mu}\|$	<2.5
$\|\eta^{e}\|$	<2.5
$\|m_{\ell\ell'} - m_Z\|$ [GeV]	<15
$m_{3\ell}$ [GeV]	>100
$m_{\ell\ell}$ [GeV]	>4
p_T^{miss} [GeV]	—
$\|\eta^{j}\|$	<4.7
p_T^{j} [GeV]	>50
$\|\Delta R(j,\ell)\|$	>0.4
n_j	≥2
p_T^{b} [GeV]	—
$\|\eta^{b}\|$	—
n_b	—
m_{jj}	>500
$\|\Delta\eta_{jj}\|$	>2.5
$\|\eta^{3\ell} - (\eta^{j_1} + \eta^{j_2})/2\|$	<2.5

ATLAS:

Z lepton p_T>15 GeV

W lepton p_T>20 GeV

Lepton $|\eta|$<2.5

$|m_{\ell\ell}-m_Z|$<10 GeV

m_T^W>30 GeV

Jet p_T>40 GeV and $|\eta|$<4.5

m_{jj}>500 GeV

$\eta_{j1}\times\eta_{j2}<0$

ATLAS: $\sigma^{\text{fid}} = 1.68 \pm 0.16(\text{stat}) \pm 0.18(\text{syst})$ fb

$$\sigma^{\text{th.}} = 2.15 \pm 0.01(\text{stat})^{+0.65}_{-0.44}(\text{syst}) \text{ fb}$$

(Sherpa)

CMS: $\sigma^{\text{fid}} = 3.18^{+0.57}_{-0.52}(\text{stat})^{+0.45}_{-0.36}(\text{syst})$ fb

$$\sigma^{\text{th.}} = 3.27^{+0.39}_{-0.32}(\text{scale}) \pm 0.15(\text{PDF}) \text{ fb}$$

(MadGraph_aMC@NLO)

ZZ VBS

- Select events with four charged leptons and two jets
  - Cleanest channel, low cross section, and all kinematics can be reconstructed for the channel with four leptons
- ATLAS also analyzed Z(→ll)Z(→νν) events, in general tighter cuts are applied
- Event selection:

	ATLAS (ATLAS-CONF-2019-033)	CMS (arXiv:1708.02812)
– 4 leptons (e, μ)	p_T>20, 20, 10, 7 GeV	p_T>20, 12(10), 7(5), 7(5) GeV
	|η|<2.5 (e), 2.7(μ)	|η|<2.5 (e), 2.4 (μ)
	$66<m_{\ell\ell}<116$ GeV for 4l events	$40<m_{Z1}<120$ GeV, $m_{Z2}<120$ GeV
– 2 leptons (e, μ)	p_T>30, 20 GeV	
	$80<m_{\ell\ell}<100$ GeV for 2l2ν events	
– 2 jets:	p_T>30 (40) GeV for 4l events	p_T>30 GeV
	p_T>60, 40 GeV for 2l2ν events	
	|η|<4.5	|η|<4.7
	m_{jj}>300 GeV for 4l events	m_{jj}>100 GeV
	m_{jj}>400 GeV for 2l2ν events	
	$\|\Delta y_{jj}\|>2$	
	$y_{j1}\times y_{j2}<0$	
– Missing E_T:	significance>12 for 2l2ν events	

  - Veto events with b-jets → reject top events
  - Both ATLAS and CMS trained BDTs to distinguish EW ZZ signal from QCD ZZ
- Events failing some SR selection cuts are used as CRs to check background modelling

ZZ VBS

Backgrounds:

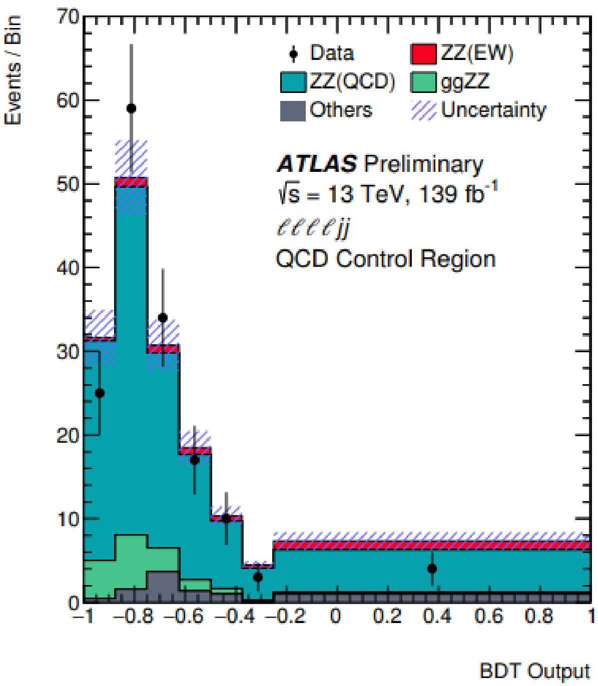
- QCD ZZ contribution is estimated using MC simulations with normalization determined from data with either the m_{jj} or Δy_{jj} requirement reverted

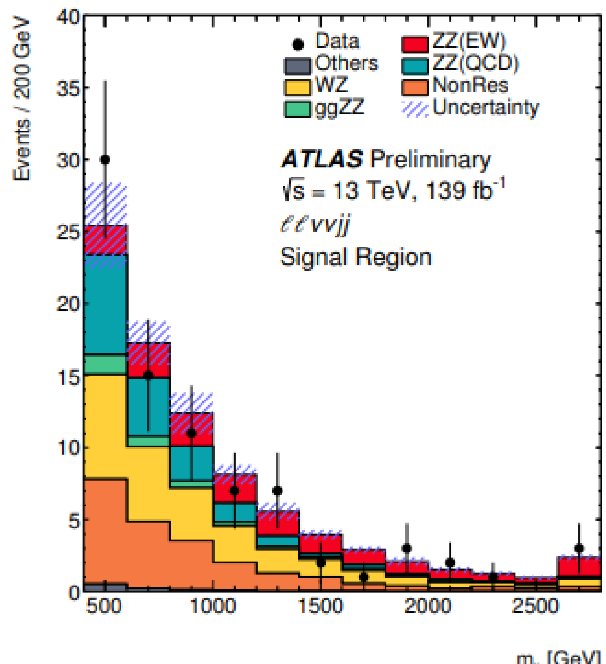
Signal extraction:

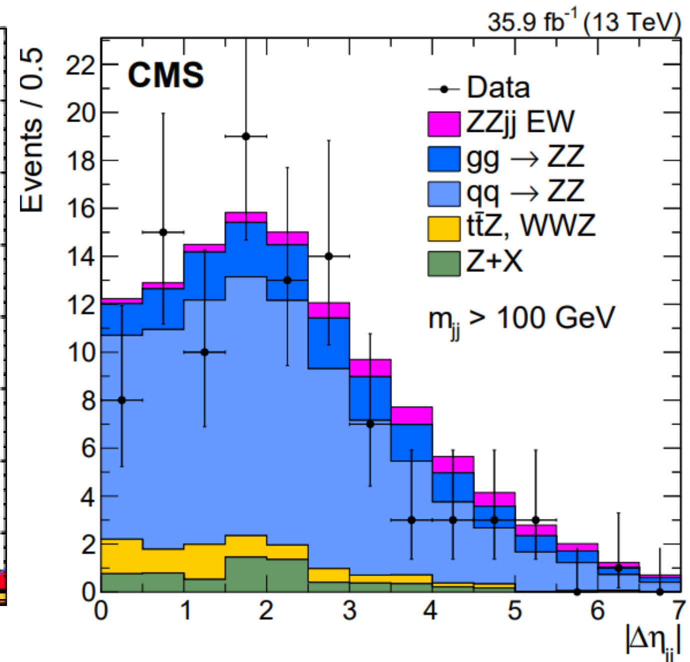
- Fit to the BDT distribution in the SR and CRs

Systematic uncertainties:

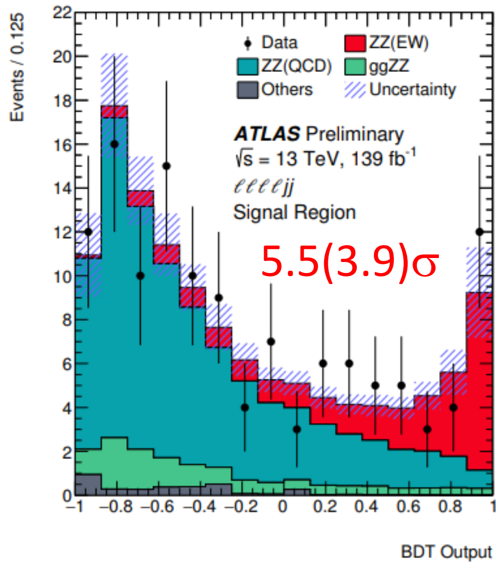
- Dominated by jet energy scale, EW and QCD ZZ theoretical modelling

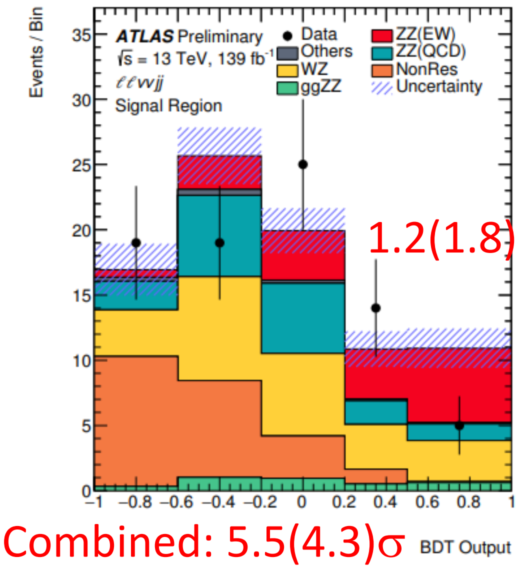


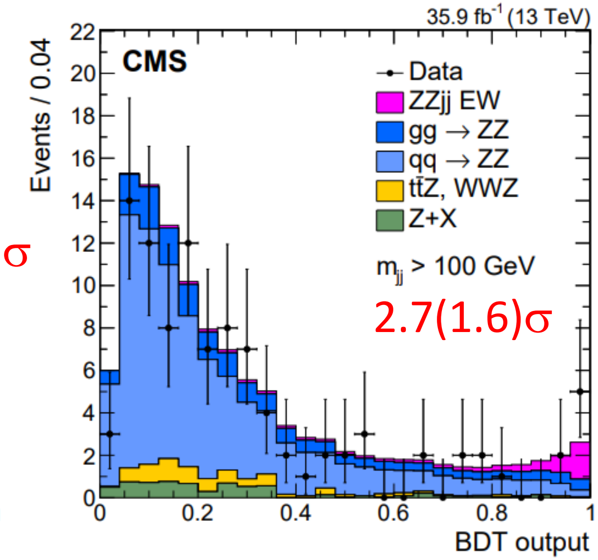




ZZ VBS







Combined: 5.5(4.3)σ

21 signal and 93 background expected for 4l
12 signal and 66 background expected for 2l2ν

6 signal and 111 background expected

Fiducial regions are defined to be close to the selections applied on data:

- CMS used p_T>5 GeV and $|\eta|$<2.5 for all leptons
- ATLAS relaxed the dilepton mass requirement for the 4l channel, and used $|\eta|$<2.5 for all leptons and dropped the missing E_T significance cut (but required missing E_T>130 GeV) in the 2l2ν channel

ATLAS (4l):

$$\sigma^{\text{fid}} = 1.27 \pm 0.12(\text{stat}) \pm 0.79(\text{syst})\ \text{fb}$$

$$\sigma^{\text{th.}} = 1.14 \pm 0.04(\text{stat}) \pm 0.20(\text{syst})\ \text{fb}$$

ATLAS (2l2ν):

$$\sigma^{\text{fid}} = 1.22 \pm 0.30(\text{stat}) \pm 0.18(\text{syst})\ \text{fb}$$

$$\sigma^{\text{th.}} = 1.07 \pm 0.01(\text{stat}) \pm 0.12(\text{syst})\ \text{fb}$$

CMS:

$$\sigma^{\text{fid}} = 0.40^{+0.21}_{-0.16}(\text{stat})^{+0.13}_{-0.09}(\text{syst})\ \text{fb}$$

$$\sigma^{\text{th.}} = 0.29^{+0.02}_{-0.03}\ \text{fb}$$

(MadGraph5_aMC@NLO)

V(→ll/lν/νν)V(→jj/J) VBS

- Select events with 0/1/2 leptons and two jets (or one large-radius jet)
  - Large backgrounds and also large cross sections
  - Not sensitive to EW processes yet, set limits on production cross sections and aQGCs
- ATLAS:

Selection	0-lepton	1-lepton	2-lepton
Trigger	E_T^{miss} triggers	Single-electron triggers Single-muon or E_T^{miss} triggers	Single-lepton triggers
Leptons	0 'loose' leptons with $p_T > 7$ GeV	1 'tight' lepton with $p_T > 27$ GeV 0 'loose' leptons with $p_T > 7$ GeV	2 'loose' leptons with $p_T > 20$ GeV ≥ 1 lepton with $p_T > 28$ GeV
E_T^{miss}	> 200 GeV	> 80 GeV	–
$m_{\ell\ell}$	–	–	$83 < m_{ee} < 99$ GeV $-0.0117 \times p_T^{\mu\mu} + 85.63 < m_{\mu\mu} < 0.0185 \times p_T^{\mu\mu} + 94$ GeV
Small-R jets	$p_T > 20$ GeV if $\lvert\eta\rvert < 2.5$, and $p_T > 30$ GeV if $2.5 < \lvert\eta\rvert < 4.5$		
Large-R jets	$p_T > 200$ GeV, $\lvert\eta\rvert < 2$		
$V_{had} \to J$ $V_{had} \to jj$	V boson tagging, $\min(\lvert m_J - m_W\rvert, \lvert m_J - m_Z\rvert)$ $64 < m_{jj} < 106$ GeV, jj pair with $\min(\lvert m_{jj} - m_W\rvert, \lvert m_{jj} - m_Z\rvert)$, leading jet with $p_T > 40$ GeV		
Tagging-jets	$j \notin V_{had}$, not b-tagged, $\Delta R(J, j) > 1.4$ $\eta_{tag,j_1} \cdot \eta_{tag,j_2} < 0$, $m_{jj}^{tag} > 400$ GeV, $p_T > 30$ GeV		
Num. of b-jets	–	0	–
Multijet removal	$p_T^{miss} > 50$ GeV $\Delta\phi(\vec{E}_T^{miss}, \vec{p}_T^{miss}) < \pi/2$ $\min[\Delta\phi(\vec{E}_T^{miss}, \text{small-}R\text{ jet})] > \pi/6$ $\Delta\phi(\vec{E}_T^{miss}, V_{had}) > \pi/9$	–	–

BDTs are trained to further separate signal from backgrounds

- CMS (Analyzed 1/2 lepton events):
  - Lepton p_T>50 GeV, missing E_T>80 (50) GeV for the 1-lepton analysis
  - Lepton p_T>20 GeV for the 2-lepton analysis
  - One V-jet with p_T>200 GeV, $|\eta|$<2.4, τ_2/τ_1<0.55, 65<m_V<105 GeV or two jets with p_T>30 GeV and $|\eta|$<5
  - Require the Zeppenfeld variable < 0.3 and the boson centrality < 0.3

V(→ll/lν/νν)V(→jj/J) VBS

Backgrounds:

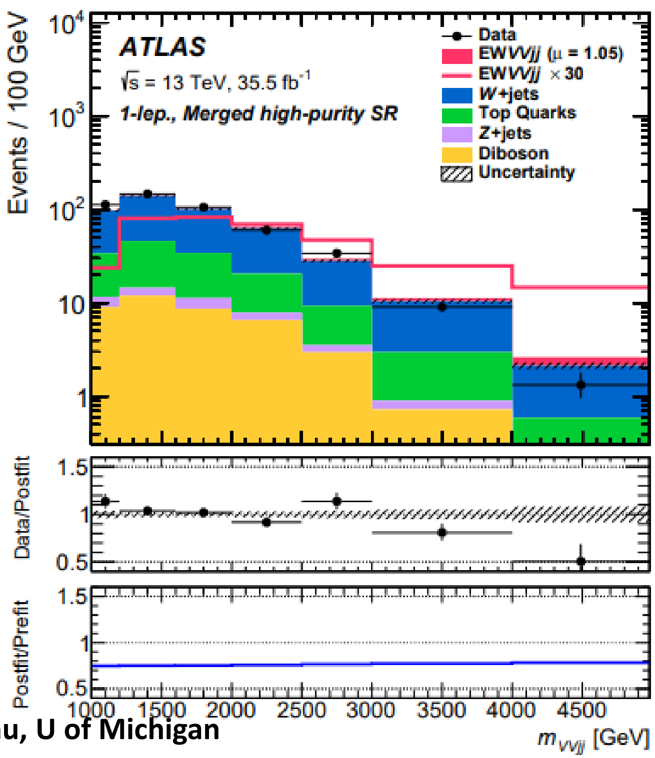
- W+jets and Z+jets are the dominant backgrounds
  - MC simulated shapes used with normalization determined from fit to data in W(Z)+jets enriched control region (m_V sideband regions)

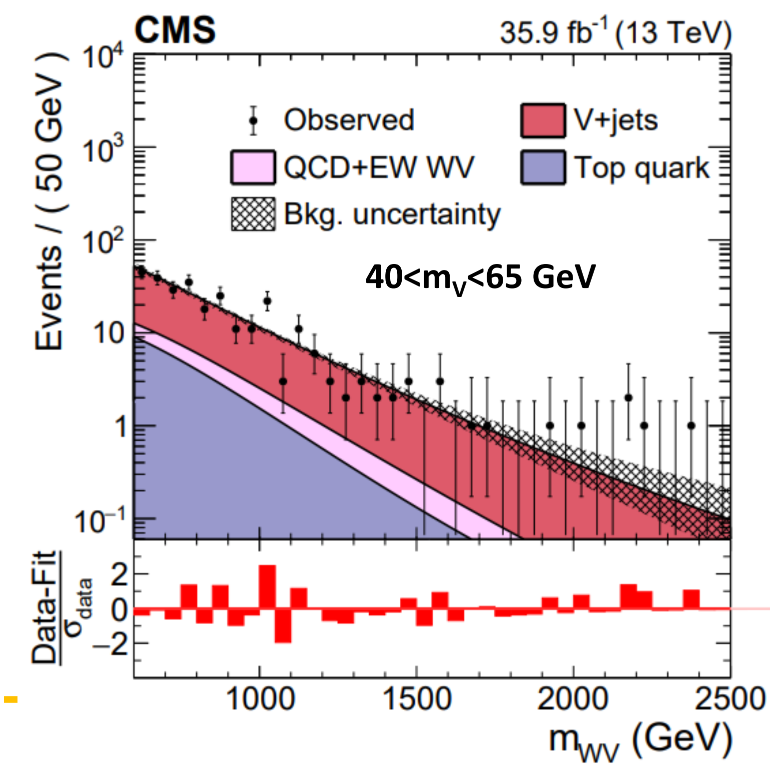
Signal extraction:

- Fit to the BDT distribution in SRs (ATLAS)

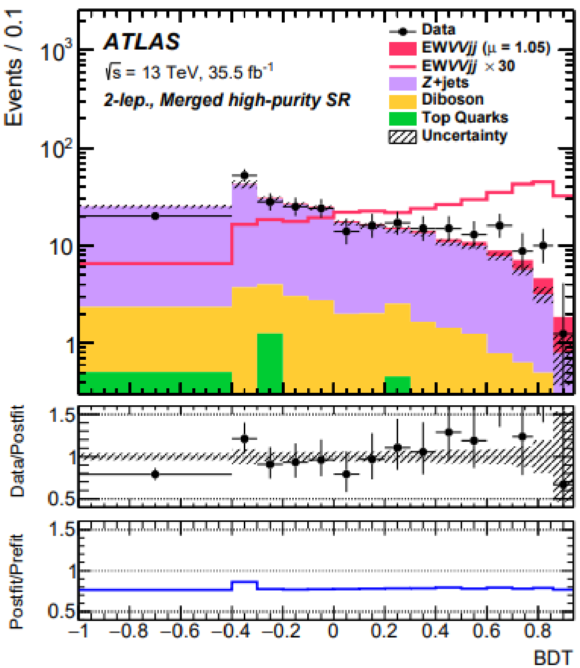
Systematic uncertainties:

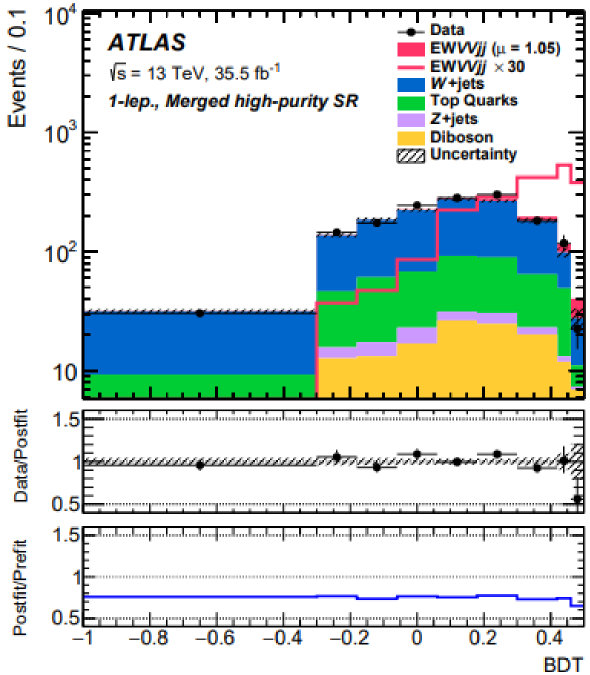
- Dominated by W(Z)+jets theoretical modelling and jet-related systematics

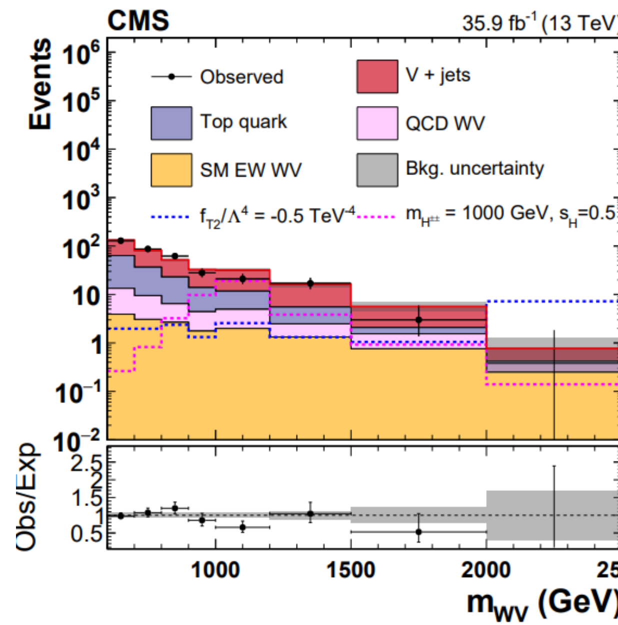




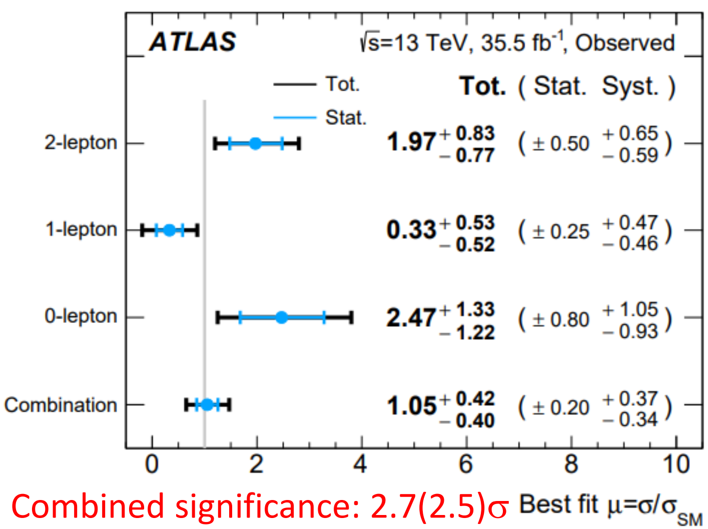
V(→ll/lν/νν)V(→jj/J) VBS







Fiducial cross sections from ATLAS:



Combined significance: 2.7(2.5)σ

aQGC limits from CMS:

	Observed (WV) (TeV^{-4})	Expected (WV) (TeV^{-4})	Observed (ZV) (TeV^{-4})	Expected (ZV) (TeV^{-4})	Observed (TeV^{-4})	Expected (TeV^{-4})
f_{S0}/Λ^4	[−2.7, 2.7]	[−4.2, 4.2]	[−40, 40]	[−31, 31]	[−2.7, 2.7]	[−4.2, 4.2]
f_{S1}/Λ^4	[−3.3, 3.4]	[−5.2, 5.2]	[−32, 32]	[−24, 24]	[−3.4, 3.4]	[−5.2, 5.2]
f_{M0}/Λ^4	[−0.69, 0.69]	[−1.0, 1.0]	[−7.5, 7.5]	[−5.3, 5.3]	[−0.69, 0.70]	[−1.0, 1.0]
f_{M1}/Λ^4	[−2.0, 2.0]	[−3.0, 3.0]	[−22, 23]	[−16, 16]	[−2, 0, 2.1]	[−3.0, 3.0]
f_{M6}/Λ^4	[−1.4, 1.4]	[−2.0, 2.0]	[−15, 15]	[−11, 11]	[−1.3, 1.3]	[−1.4, 1.4]
f_{M7}/Λ^4	[−3.4, 3.4]	[−5.1, 5.1]	[−35, 36]	[−25, 26]	[−3.4, 3.4]	[−5.1, 5.1]
f_{T0}/Λ^4	[−0.12, 0.11]	[−0.17, 0.16]	[−1.4, 1.4]	[−1.0, 1.0]	[−0.12, 0.11]	[−0.17, 0.16]
f_{T1}/Λ^4	[−0.12, 0.13]	[−0.18, 0.18]	[−1.5, 1.5]	[−1.0, 1.0]	[−0.12, 0.13]	[−0.18, 0.18]
f_{T2}/Λ^4	[−0.28, 0.28]	[−0.41, 0.41]	[−3.4, 3.4]	[−2.4, 2.4]	[−0.28, 0.28]	[−0.41, 0.41]

$Z\gamma$ VBS

- Select events with $Z\rightarrow ee(\mu\mu)$, one photon and two jets
- CMS:
  - Two leptons with p_T>25 (20) GeV for e(μ) and $|\eta|<2.5(2.4)$ for e(μ)
  - $70< m_{\ell\ell} <110$ GeV
  - Photon p_T>20 GeV and $|\eta|<2.5$
  - Veto events with 3rd lepton
  - At least two jets with p_T>30 GeV and $|\eta|<4.7$
  - $m_{Z\gamma}$>100 GeV and $\Delta R_{l\gamma}$>0.7
  - m_{jj}>500 GeV and $|\Delta\eta_{jj}|$>2.4
  - Zeppenfeld variable $|\eta_{Z\gamma}-(\eta_{j1}+\eta_{j2})/2|< 2.4$
  - $|\phi_{Z\gamma}-\phi_{jj}|>1.9$
- Events with $150<m_{jj}<400$ GeV and $m_{Z\gamma}$>100 GeV are used as a QCD $Z\gamma$ CR

Zγ VBS

Backgrounds:

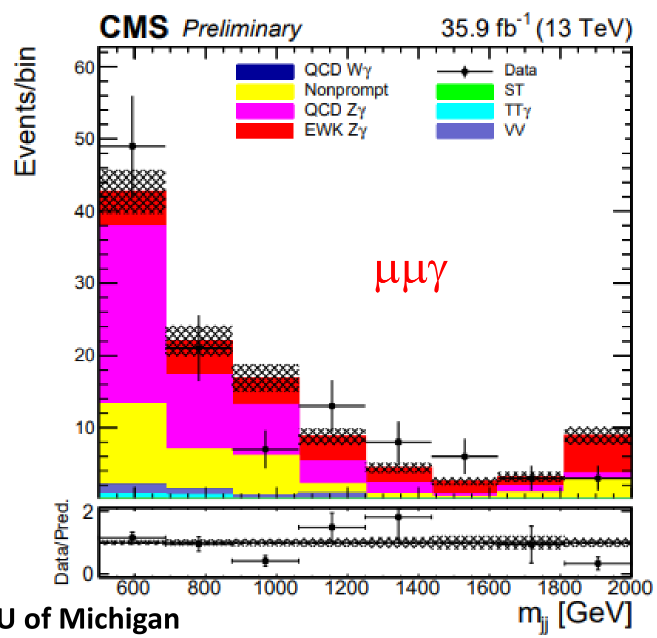
- QCD Zγ+jets is the dominant background
  - MC simulation used and a simultaneous fit in the SR and CR is used to constrain its uncertainty
  - Z+jets background estimated from data with a mutually exclusive photon selection applied and then extrapolated to the SR photon selection

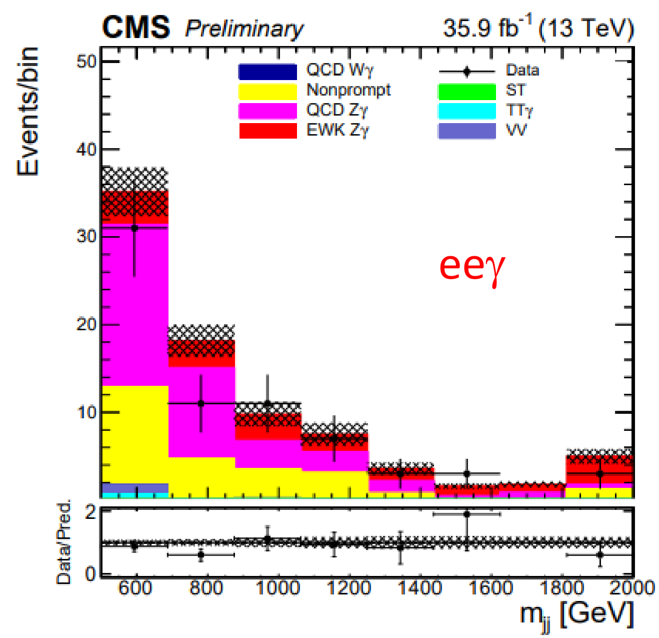
Signal extraction:

- Fit to the 2D (m_{jj}, $\Delta\eta_{jj}$) distribution and QCD Zγ CR

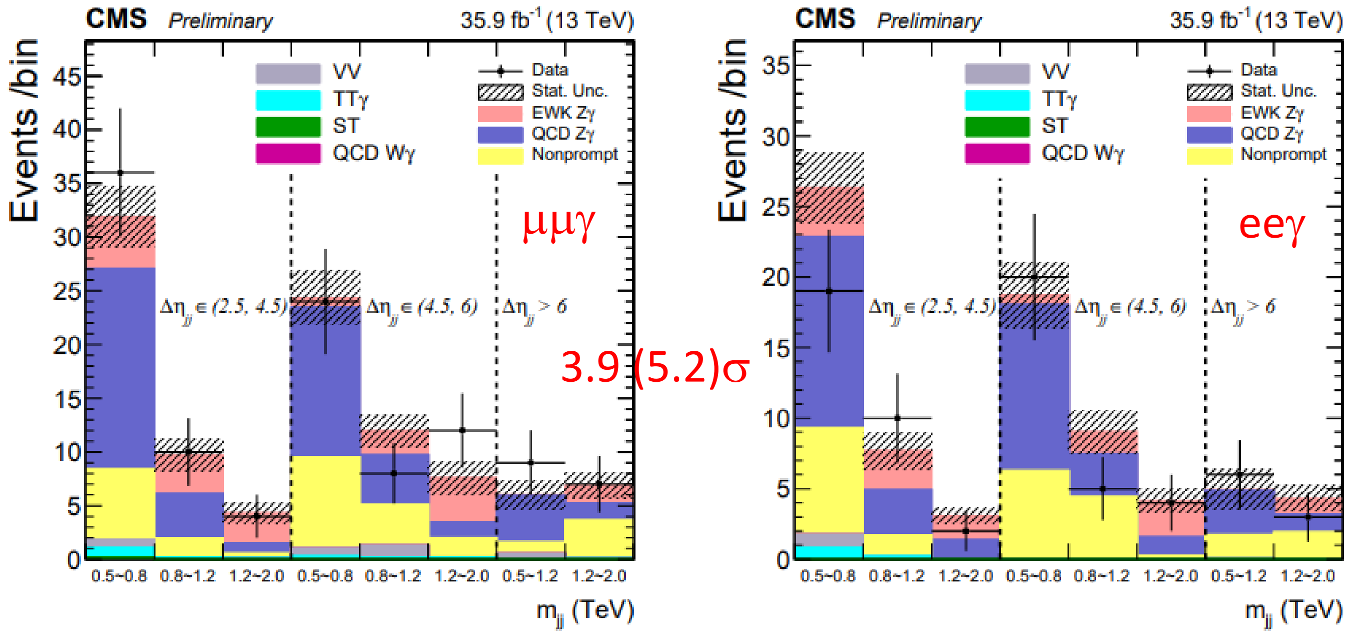
Systematic uncertainties:

- Dominated by QCD Zγ+jets theoretical modelling and jet-related systematics





Zγ VBS



36 signal and 81 background expected

25 signal and 66 background expected

- Combined with 8 TeV measurement and obtained a sensitivity of 4.7 (5.5) σ

Fiducial region:

Common selection	$p_T^{l1,l2} > 25$ (20) GeV, $\|\eta^{l1,l2}\| < 2.5$ (2.4), electron (muon), $p_T^{\gamma} > 20$ GeV, $\|\eta^{\gamma}\| < 1.4442$ or $1.566 < \|\eta^{\gamma}\| < 2.5$, $p_T^{j1,j2} > 30$ GeV, $\|\eta^{j1,j2}\| < 4.7$, $70 < m_{ll} < 110$ GeV, $\Delta R_{jj}, \Delta R_{j\gamma}, \Delta R_{jl} > 0.5, \Delta R_{l\gamma} > 0.7$,
Fiducial region	$500\text{ GeV} < m_{jj}, \Delta\eta_{jj} > 2.5$, Common selection

$$\sigma^{\text{fid}} = 3.20 \pm 1.00(\text{stat}) \pm 0.57(\text{syst})\ \text{fb}$$

$$\sigma^{\text{th.}} = 4.97 \pm 0.25(\text{scale}) \pm 0.14(\text{PDF})\ \text{fb}$$

(MadGraph5_aMC)

Conclusions

- VBS are important processes to understand the dynamics of EWSB
- Lots of progress made in the past five years for EW VBS processes
  - Observations of EW $W^{\pm}W^{\pm}$, WZ and ZZ VBS processes
  - Evidence for EW $Z\gamma$ process (expected significance > 5σ)
  - Many aQGC, new physics searches, and differential cross section measurements performed with these final states but not covered here
- Ongoing studies at ATLAS and CMS:
  - Analyzing the whole Run 2 dataset to get more precise measurements and extracting polarization fractions
  - Developing new techniques to improve the forward jet tagging (for example, gluon vs quark jet separation, reducing forward jet energy scale uncertainties)
- Need to have precise theoretical predictions for both signal and background processes (especially most analyses use shape fits or multivariate analysis) and also separation of polarization states

Five years after the first evidence of a VBS process …