

# Electroweak Physics at ATLAS and CMS

## (Multi-boson production)



**YuChul YANG (Kyungpook National University)**  
**On behalf of CMS and ATLAS collaborations**

**La Thuile 2022 - Les Rencontres de Physique de la Vallée d'Aoste,**  
**2022 March 06-12**

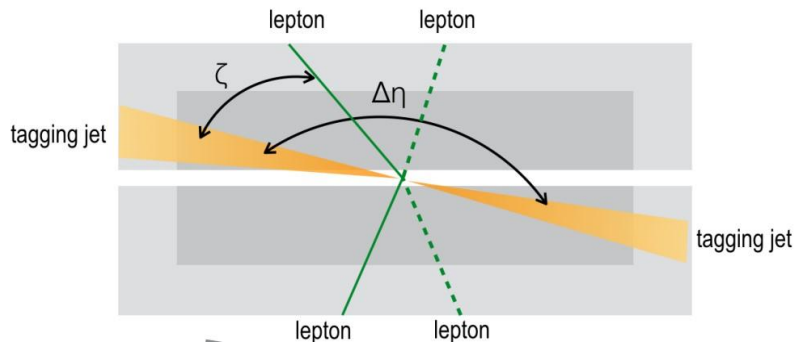
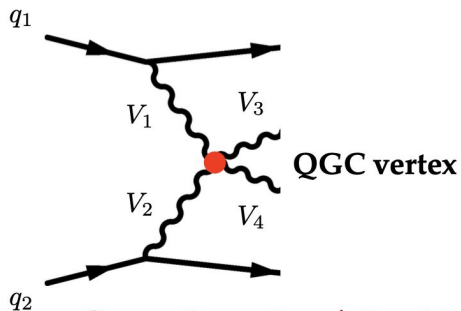
# Introduction

- **Measurement of MultiBoson productions**

- Probing the non-Abelian gauge structure of the EW interactions
- Precision tests of the Standard Model
- Search for the Beyond SM using Effective Field Theory framework

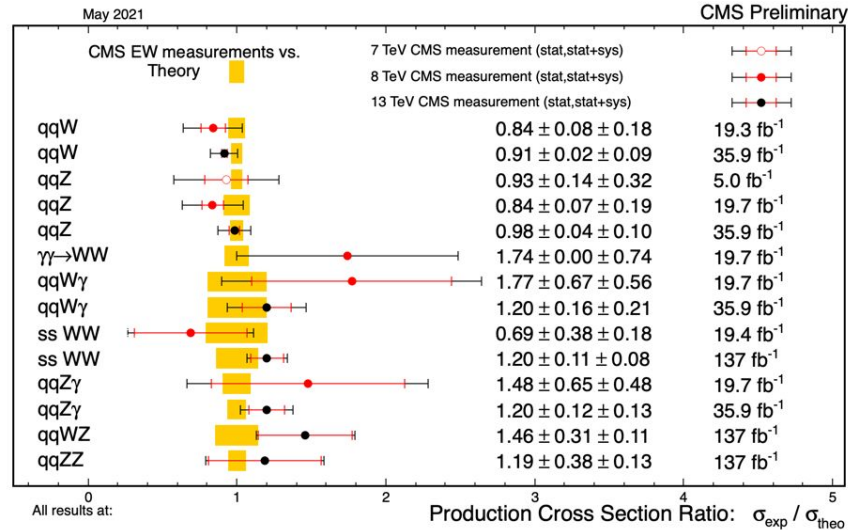
- **Vector boson scattering (VBS) at the LHC**

- is scattering between two vector bosons radiated from incoming partons
- Key process to investigate electroweak symmetry breaking
- Two energetic jets with large di-jet mass( $m_{jj}$ ) and rapidity separation( $\Delta\eta_{jj}$ )
- Centrality of the diboson system with respect to the two forward jets

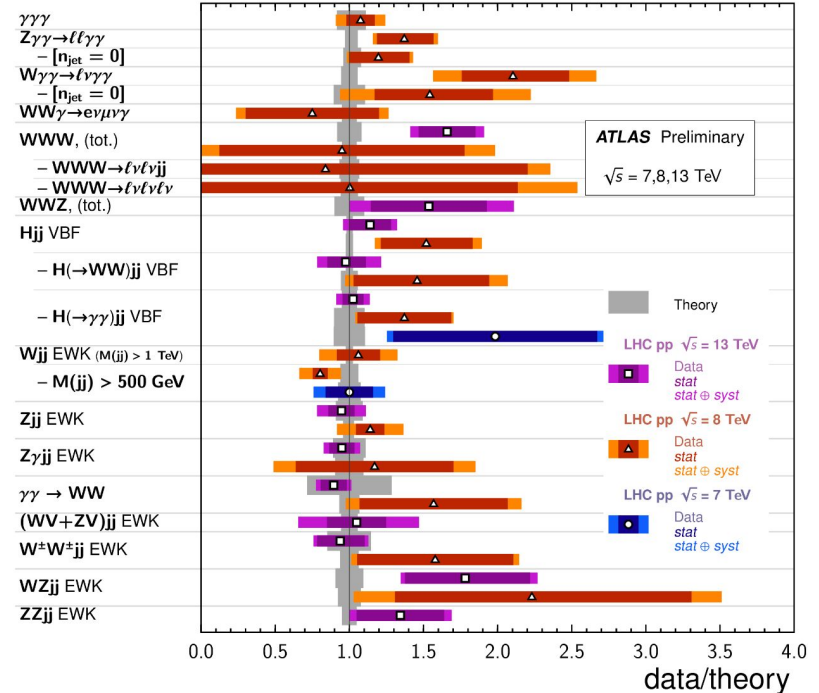


# VBS Diboson and Tri-boson production at CMS and ATLAS

- Multi-boson production cross section ratio of data and theory



## VBF, VBS, and Triboson Cross Section Measurements Status: July 2021



# Today's talks....

[CMS] VBS  $W(\rightarrow lv)\gamma + 2\text{jets}$

[CMS] VBS  $Z(\rightarrow ll)\gamma + 2\text{jets}$

[ATLAS] VBS  $Z(\rightarrow ll)\gamma + 2\text{jets}$

[ATLAS] VBS  $Z(\rightarrow \nu\nu)\gamma + 2\text{jets}$

[ATLAS] VBS  $\gamma\gamma \rightarrow WW$

[CMS] VBS  $W^+W^- + 2\text{jets}$

[CMS] VBS  $W(l\nu)V(qq) + 2\text{Jets}$

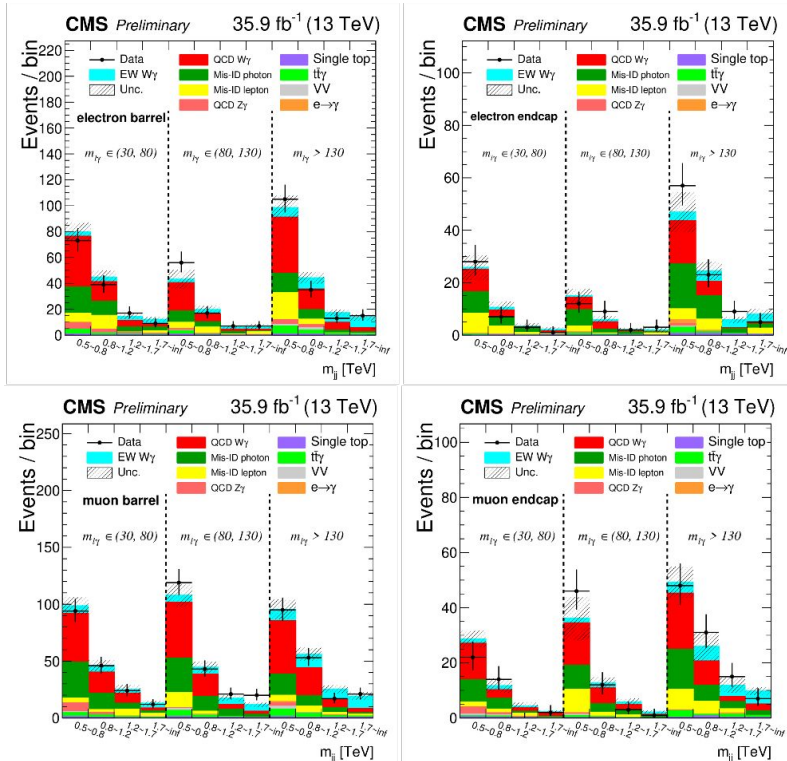
[ATLAS]  $WW + \geq 1\text{jet}$

[ATLAS]  $WWW$  production

# [CMS] VBS $W\gamma$ + 2jets

- 1 lepton + photon + 2jets final states
- $m_{jj}$  and  $m_{l\gamma}$  are used to extract EW signal in 4 categories

(2(e or  $\mu$ ) x 2(barrel or endcap photon))



## • Main backgrounds:

- QCD  $W\gamma$  : estimated from MC, constrained by simultaneous fit to data
- Non-prompt photon: estimated using photon shower shape using data driven method
- Non-prompt lepton : data-driven method used

## • Signal Region:

- $m_{jj} > 500$  GeV,  $|\Delta\eta_{jj}| > 2.5$

## • Results (36fb<sup>-1</sup>@13TeV):

- Observed(expected) significance :  $5.3\sigma$  ( $4.8\sigma$ ) combining with Run I data (20fb<sup>-1</sup>@8TeV)
- EW cross section :  $20.4 \pm 4.5$  fb
- EW+QCD cross section :  $108 \pm 16$  fb

# [CMS] VBS $Z\gamma$ + 2jets

- 2 leptons( $ee, \mu\mu$ ,  $70 < m_{ll} < 110$  GeV) + photon + 2jets using full Run2 data
- $m_{jj} > 500$  GeV,  $|\Delta\eta_{jj}| > 2.5$  for EWK fiducial volume

## Main backgrounds:

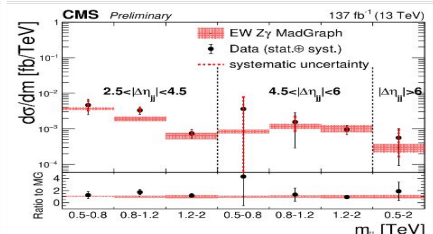
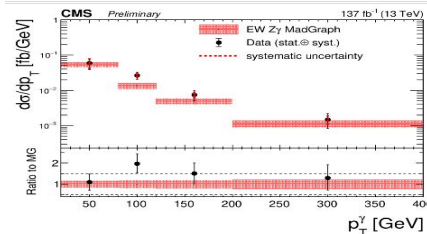
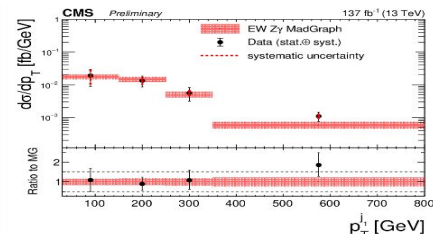
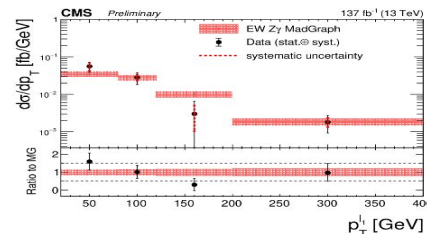
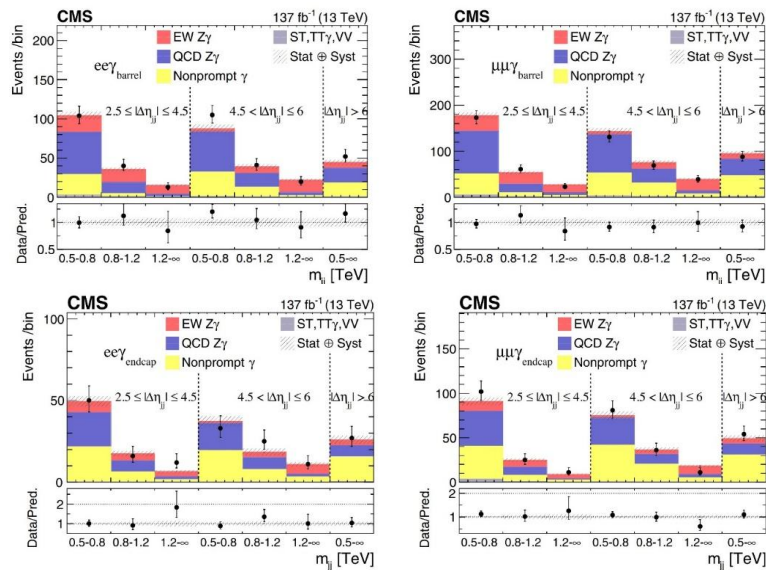
- QCD  $Z\gamma$  : estimated from MC, constrained by simultaneous fit to data
- Non-prompt photon: estimated using photon shower shape using data driven method

## Results:

- Observed/expected significance :  $> 5\sigma$
- EW cross section :  $5.21 \pm 0.76$  fb
- EW+QCD cross section :  $14.7 \pm 1.53$  fb

## Differential cross section

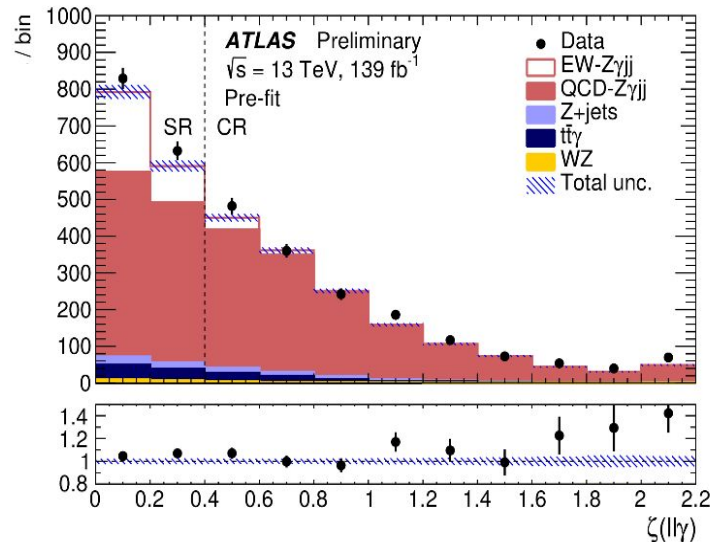
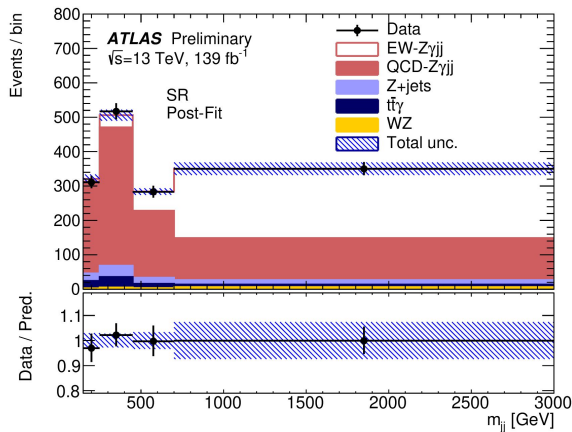
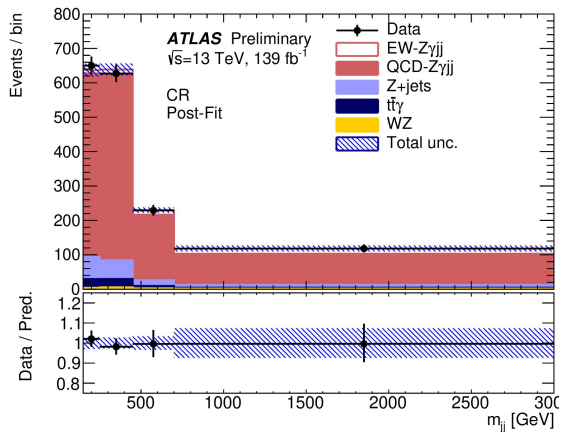
✓ Good agreements between data and prediction



# [ATLAS] VBS $Z\gamma$ + 2jets

- 2leptons + photon + 2jets
- Major Bkgs. : QCD  $Z\gamma$  + jets and fake-photon
- SR and CR separation using Centrality (SR < 0.4 < CR)
- simultaneous fit in SR and CR on  $m_{jj}$

$$\zeta(\ell\ell\gamma) = \left| \frac{y_{\ell\ell\gamma} - (y_{j_1} + y_{j_2})/2}{y_{j_1} - y_{j_2}} \right|$$



## • Cross sections( 10 $\sigma$ significance)

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

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

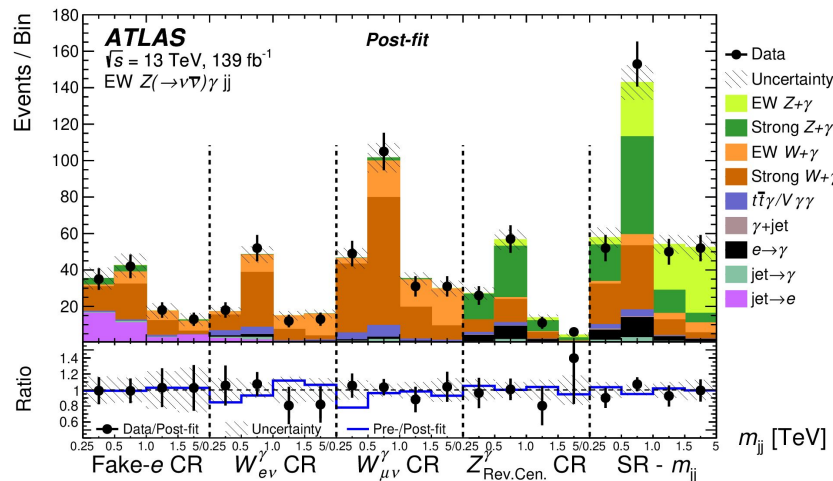
$$\sigma_{EW}^{pred} = 4.73 \pm 0.01 \text{ (stat.)} \pm 0.15 \text{ (PDF)}_{-0.22}^{+0.23} \text{ (scale) fb.}$$

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



# [ATLAS] VBS $Z(\rightarrow \nu\nu)\gamma + 2\text{jets}$

- Z boson decaying to neutrinos (MET > 150 GeV)
- Major Bkgs. : QCD  $Z\gamma + \text{jets}$ ,  $W\gamma + \text{jets}$  (lost lepton) and fake-photon



- Maximum-likelihood fit used to extract strength
- in SR and CRs

| $\mu_{Z\gamma_{EW}}$ | $\beta_{Z\gamma_{strong}}$ | $\beta_{W\gamma}$ |
|----------------------|----------------------------|-------------------|
| $1.03 \pm 0.25$      | $1.02 \pm 0.41$            | $1.01 \pm 0.20$   |

- EW  $Z(\rightarrow \nu\nu)\gamma jj$  process observed with a significance  $5.2\sigma$  (expected  $5.1\sigma$ )
- Measured fiducial cross section :  $1.31 \pm 0.29 \text{ fb}$
- Upper limits are set on branching ratio of Higgs to invisible particles and ( $H \rightarrow \nu\nu_{\text{dark}}$ )

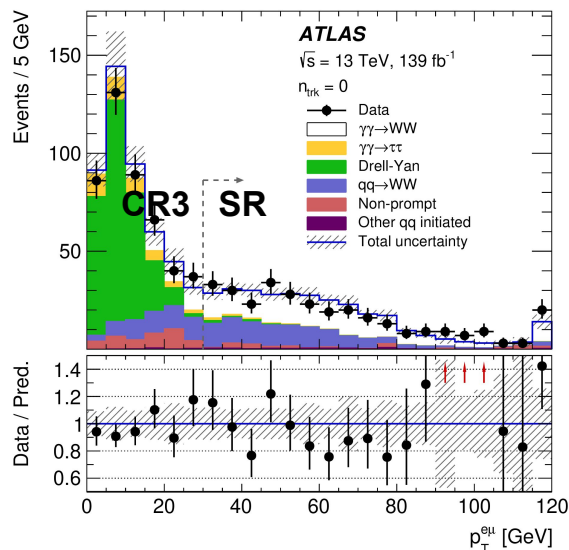
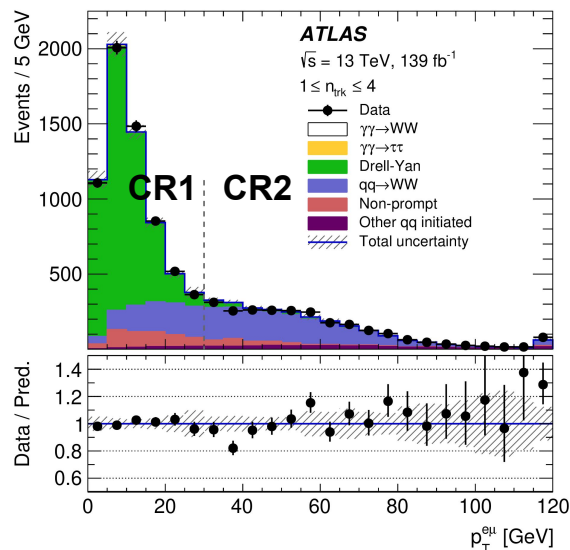
## • Fiducial Volume

| Observable   | Requirements  |
|--|---------------|
| $N_{\text{jet}}$ with $p_T > 25 \text{ GeV}$               | $\geq 2$      |
| $ \eta(j_{1,2}) $  | $< 4.5$       |
| $p_T(j_1) [\text{GeV}]$                                    | $> 60$        |
| $p_T(j_2) [\text{GeV}]$                                    | $> 50$        |
| $\Delta R(j, \ell)$  | $> 0.4$       |
| $ \Delta\eta_{jj} $  | $> 3.0$       |
| $C_3$  | $< 0.7$       |
| $m_{jj} [\text{TeV}]$                                      | $> 0.5$       |
| $\text{truth-}E_T^{\text{miss}} [\text{GeV}]$              | $> 150$       |
| $\Delta\phi(\text{truth-}\vec{E}_T^{\text{miss}}, j_i)$    | $> 1.0$       |
| $p_T(\gamma) [\text{GeV}]$                                 | $> 15, < 110$ |
| $ \eta(\gamma) $   | $< 2.37$      |
| $E_T^{\text{cone20}}/E_T^\gamma$                           | $< 0.07$      |
| $\Delta R(\gamma, \text{jet-or-}\ell)$                     | $> 0.4$       |
| $C_\gamma$   | $> 0.4$       |
| $\Delta\phi(\text{truth-}\vec{E}_T^{\text{miss}}, \gamma)$ | $> 1.8$       |
| $N_\ell$ with $p_T > 4 \text{ GeV}$ and $ \eta  < 2.47$    | 0             |

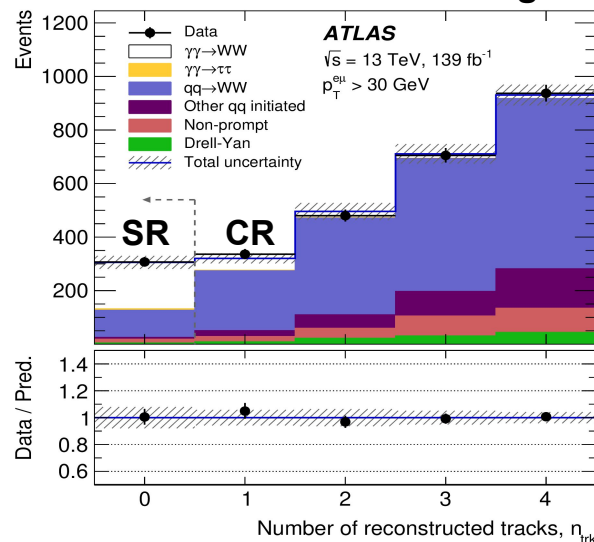


# [ATLAS] VBS $\gamma\gamma \rightarrow WW$

- Signal process can be proceed via only EWK boson couplings at LO
  - ideal probe for anomalous couplings
- $e^\pm \mu^\mp$  channel : opposite-sign and different flavour dilepton
- Major Bkgs. : inclusive WW and non-prompt lepton from W + jets
- Simultaneous profile likelihood fit performed in signal and 3 control regions( $n_{\text{trk}}$ ,  $p_T(e\mu)$ )



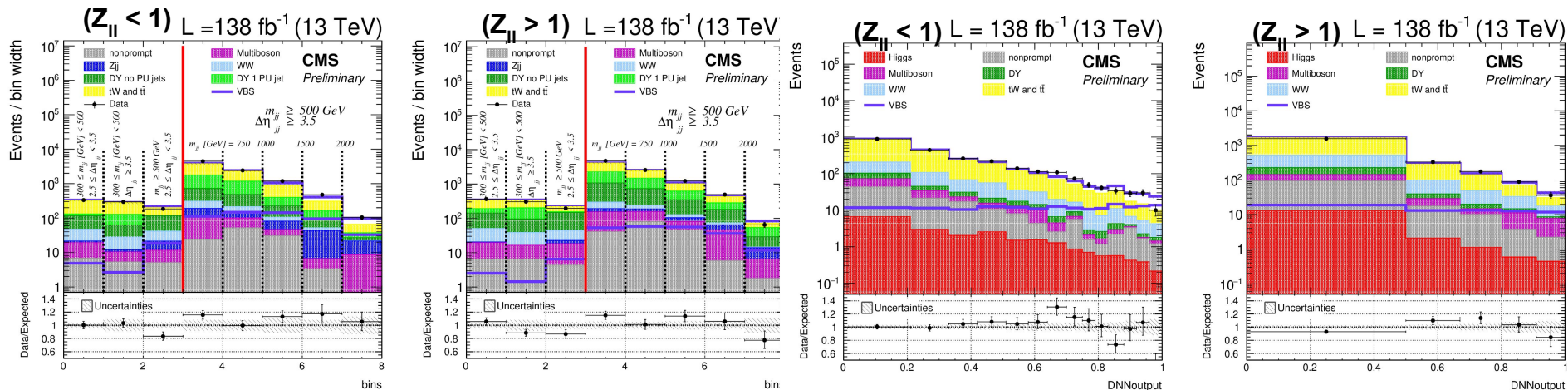
## • No additional track for signal



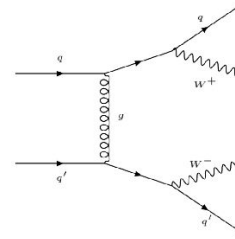
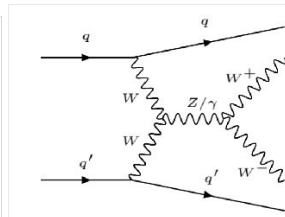
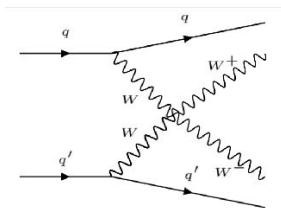
- First observation of  $\gamma\gamma \rightarrow WW$  with a significance of  $8.4\sigma$
- Measured cross section :  $\sigma_{\text{mead}} = 3.13 \pm 0.31(\text{stat.}) \pm 0.28(\text{syst.}) \text{ fb}$

# [CMS] VBS $W^+W^- + 2\text{jets}$

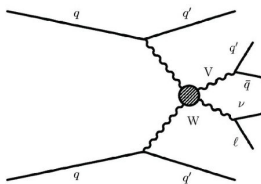
- Measurement of EWK production of a pair of opposite-sign W bosons
- Major backgrounds : top, QCD-induced WW, and DY+jets (control regions)
- Discriminating variables : used  $m_{jj}$  bins(ee,  $\mu\mu$ ) and DNN(e $\mu$ )



- First observation VBS  $W^+W^-$  pair in fully leptonic channel
- Observed Significance :  $5.6\sigma$  ( $5.2\sigma$  exp)
- Measured cross section :  $10.2 \pm 2.0 \text{ fb}$

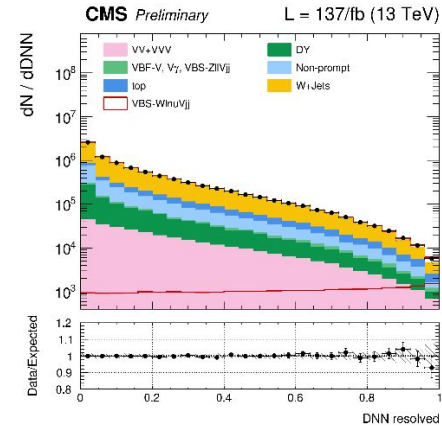
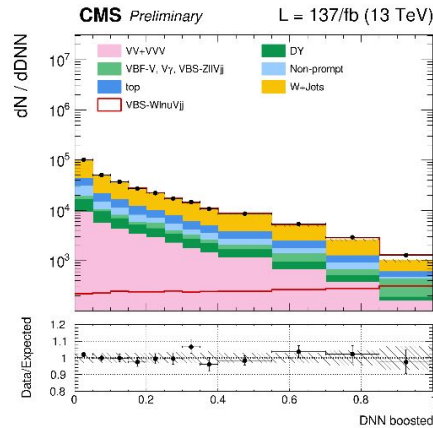
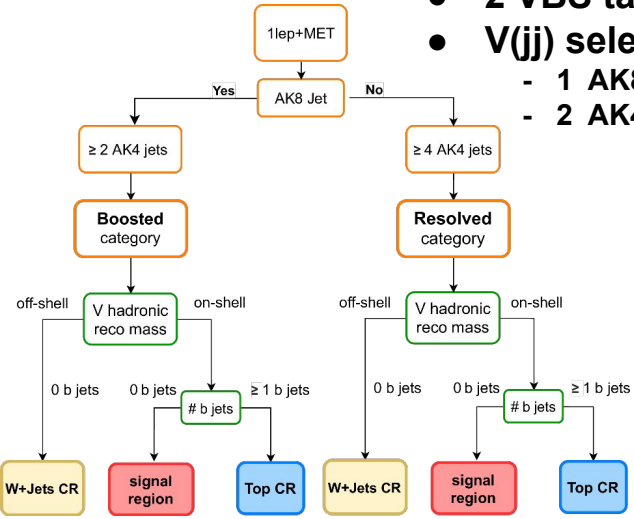


# [CMS] VBS W(lv)V(jj) + 2Jets



- W is leptonic decay, V is hadronic decay
- Larger XS than fully leptonic, but larger bkg from W+jets and ttbar
- DNN for signal extraction

- Analysis workflow
- 1 lepton + MET
- 2 VBS tagged jets
- V(jj) selections
  - 1 AK8 jet  $p_T > 200\text{ GeV}$
  - 2 AK4 jet  $p_T > 30\text{ GeV}$



✓ Good agreement (data vs. pred.)

- First evidence( $4.4\sigma(\text{obs})$ ,  $5.1\sigma(\text{exp})$ ) for VBS WV in semi-leptonic
- Signal strength:

$$\mu_{EW} = \sigma^{\text{obs}} / \sigma^{\text{SM}} = 0.85^{+0.24}_{-0.20} = 0.85^{+0.21}_{-0.17}(\text{syst})^{+0.12}_{-0.12}(\text{stat}),$$

$$\mu_{EW+QCD} = \sigma^{\text{obs}} / \sigma^{\text{SM}} = 0.98^{+0.20}_{-0.17} = 0.98^{+0.19}_{-0.16}(\text{syst})^{+0.07}_{-0.07}(\text{stat}),$$

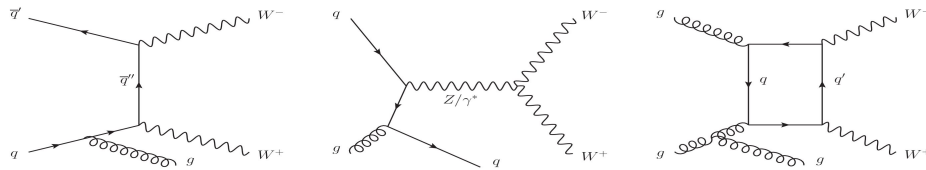
# [ATLAS] $WW + \geq 1\text{jet}$

## • Measurement of fiducial and differential cross sections

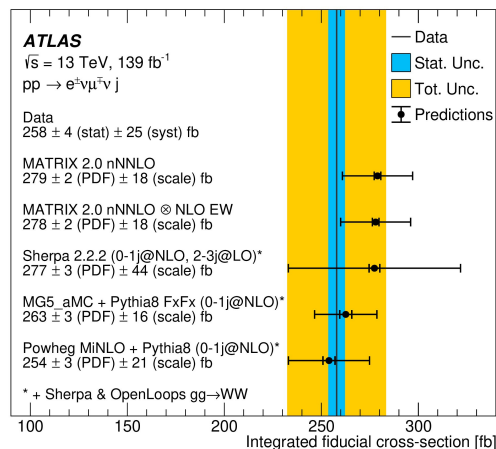
- stringent test of theoretical predictions
- hard jet requirement : improving sensitivity for aTGC with enhance interference(SM+aTGC)  
([Ref: A. Azatov et al., JHEP 10 \(2017\) 027](#))

## • Event Selections

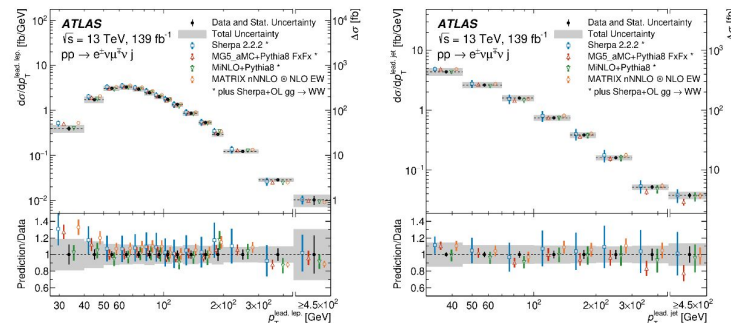
- $e\mu$  pair,  $m_{e\mu} > 85$  GeV
- b-jet(>20GeV) veto
- $\geq 1\text{jet}(35 \text{ GeV})$



## • Fiducial cross section



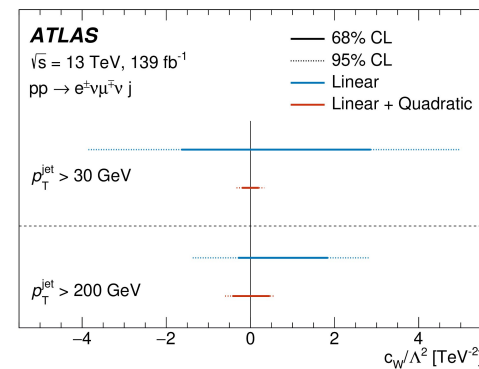
## • Differential cross sections (12 variables)



✓ Excellent agreement with predictions

## • EFT(dim-6) interpretation

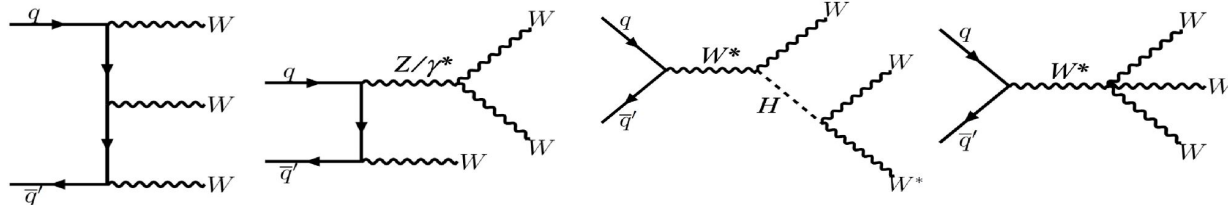
- using  $m_{e\mu}$  dist.
- set the limit on  $c_W$



# [ATLAS] WWW observation (1)

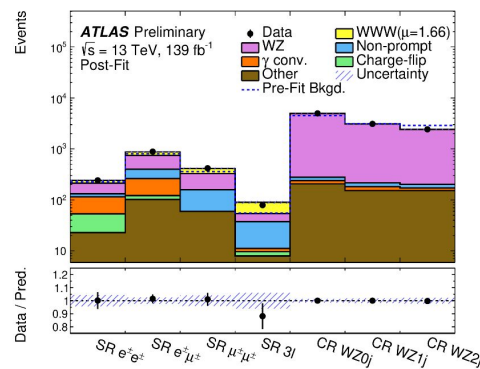
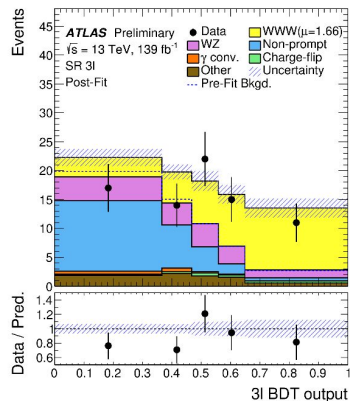
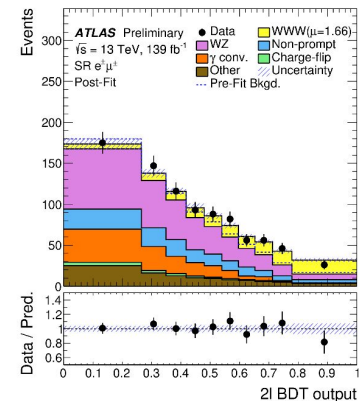
ATLAS-CONF-2021-039  
arXiv:2201.13045

- WWW production
- $l^\pm \nu l^\pm \nu jj$  (2l; same charge) and  $l^\pm \nu l^\pm \nu l^\mp \nu$  (3l) channels
- Major backgrounds : WZ + jets
- BDT train is performed
- Simultaneous maximum-likelihood fit of BDT score in signal(2l, 3l) and control regions



- BDT variables (ordered by importance)

| 2l                               | 3l   |
|----------------------------------|--|
| $ m_{jj} - m_W $                 | $E_T^{\text{miss}}$ significance $\times 10 / E_T^{\text{miss}}$ |
| $p_T$ (forward jet)              | $p_T(\ell_2)$  |
| $E_T^{\text{miss}}$ significance | $N(\text{jets})$   |
| $p_T(j_2)$                       | same flavor $m_{\ell\ell}$                                       |
| minimum $m(\ell, j)$             | $m_T(\ell\ell, E_T^{\text{miss}})$                               |
| $m(\ell_2, j_1)$                 | $m(\ell_2, \ell_3)$  |
| $N(\text{jets})$                 | $\Delta\phi(\ell\ell, E_T^{\text{miss}})$                        |
| $p_T(\ell_2)$                    | minimum $\Delta R(\ell, \ell)$                                   |
| $m_{\ell\ell}$                   | $p_T(\ell_3)$  |
| $ \eta(\ell_1) $                 | $m_T(\ell_2, E_T^{\text{miss}})$                                 |
| $N(\text{leptons in jets})$      | $E_T^{\text{miss}}$ significance                                 |
| $m(\ell_1, j_1)$                 |  |





# [ATLAS] WWW observation (2)

## ● Number of Events

|                      | $e^{\pm}e^{\pm}$ | $e^{\pm}\mu^{\pm}$ | $\mu^{\pm}\mu^{\pm}$ | $3\ell$        |
|----------------------|------------------|--------------------|----------------------|----------------|
| WWW signal           | $28.4 \pm 4.3$   | $124 \pm 19$       | $82 \pm 12$          | $34.8 \pm 5.2$ |
| WZ                   | $81.1 \pm 5.7$   | $346 \pm 22$       | $170 \pm 10$         | $16.4 \pm 1.5$ |
| Charge-flip          | $31.1 \pm 7.3$   | $19 \pm 5$         | -                    | $1.7 \pm 0.4$  |
| $\gamma$ conversions | $60.8 \pm 8.5$   | $139 \pm 15$       | -                    | $1.5 \pm 0.1$  |
| Non-prompt           | $17.0 \pm 4.0$   | $145 \pm 23$       | $104 \pm 21$         | $26.6 \pm 2.9$ |
| Other                | $22.3 \pm 2.4$   | $100 \pm 10$       | $58 \pm 6$           | $8.0 \pm 0.9$  |
| Total predicted      | $241 \pm 11$     | $873 \pm 22$       | $415 \pm 17$         | $89.0 \pm 5.4$ |
| Data                 | 242              | 885                | 418                  | 79             |

## ● Observed(expected) significances

| Fit                  | $\mu(WWW)$      | Significance observed (expected) |
|----------------------|-----------------|----------------------------------|
| $e^{\pm}e^{\pm}$     | $1.54 \pm 0.76$ | $2.2 (1.4) \sigma$               |
| $e^{\pm}\mu^{\pm}$   | $1.44 \pm 0.39$ | $4.1 (3.0) \sigma$               |
| $\mu^{\pm}\mu^{\pm}$ | $2.23 \pm 0.46$ | $5.6 (2.7) \sigma$               |
| $2\ell$              | $1.75 \pm 0.30$ | $6.6 (4.0) \sigma$               |
| $3\ell$              | $1.32 \pm 0.37$ | $4.8 (3.8) \sigma$               |
| Combined             | $1.61 \pm 0.25$ | $8.0 (5.4) \sigma$               |

## ● The first observation of WWW at LHC

| Uncertainty source                   | $\Delta\sigma/\sigma$ [%] |
|--------------------------------------|---------------------------|
| Data-driven background               | 6.0                       |
| Prompt-lepton-background modeling    | 3.0                       |
| Jets and $E_T^{\text{miss}}$         | 2.6                       |
| MC statistics                        | 2.5                       |
| Lepton                               | 2.2                       |
| Luminosity                           | 1.9                       |
| Signal modeling                      | 1.5                       |
| Pile-up modeling                     | 1.0                       |
| <b>Total systematic uncertainty</b>  | <b>9.9</b>                |
| Data statistics                      | 11.6                      |
| WZ normalizations                    | 3.1                       |
| <b>Total statistical uncertainty</b> | <b>12.0</b>               |

## ● Cross sections:

- $\sigma(\text{obs}) = 820 \pm 100(\text{stat}) \pm 80(\text{syst}) \text{ fb}$
- $\sigma(\text{prd}) = 511 \pm 18 \text{ fb}(\text{NLO QCD and LO EW})$

# Summary

- CMS and ATLAS have performed comprehensive studies of the multiboson production
  - Observed significance of VBS diboson productions using 13 TeV data

|       | $W^\pm W^\pm$ | WZ  | ZZ  | $W\gamma$ | $Z\gamma$ | $Z(\nu\nu)\gamma$ | $\gamma\gamma \rightarrow WW$ | WV  | $W^\pm W^\mp$ |
|-------|---------------|-----|-----|-----------|-----------|-------------------|-------------------------------|-----|---------------|
| ATLAS | 6.5           | 5.3 | 5.5 |           | 10        | 5.2               | 8.4                           |     |               |
| CMS   | > 5           | 6.8 | 4.0 | 5.3       | 9.4       |                   |                               | 4.4 | 5.6           |

- Precision measurement of  $WW + \geq 1$  jet performed using Run2 full dataset
- First observation of  $WWW$  production at LHC performed by ATLAS
- The results is in agreement with the SM predictions and serve as input EFT interpretations (set the limits on anomalous gauge couplings parameters)
  - ATLAS : [global EFT fit of dim6 operators in ATL-PHYS-PUB-2021-022](#)
  - CMS : [Limits on aTGC and aQGC](#)
- Run3 and HL-LHC are coming,  
it is expected that it will give us more interesting results with more data