Measurements of multi-boson production including vector-boson scattering at ATLAS

Junjie Zhu

University of Michigan

On behalf of the ATLAS Collaboration

LEPTON PHOTON 2021 MAN

30th International Symposium on Lepton Photon Interactions at High Energies

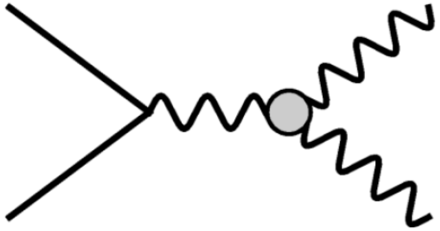
Introduction

Multi-bosons

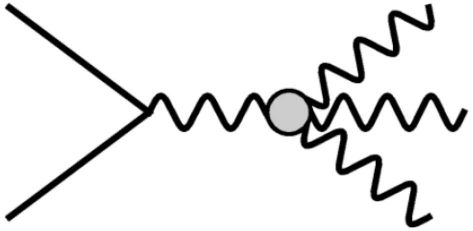
Two or more electroweak bosons V: W, Z, γ

Vector boson scattering

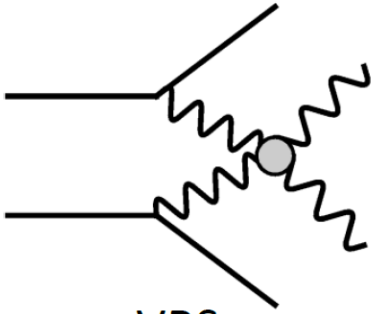
VV → VV



Dibosons



Tribosons



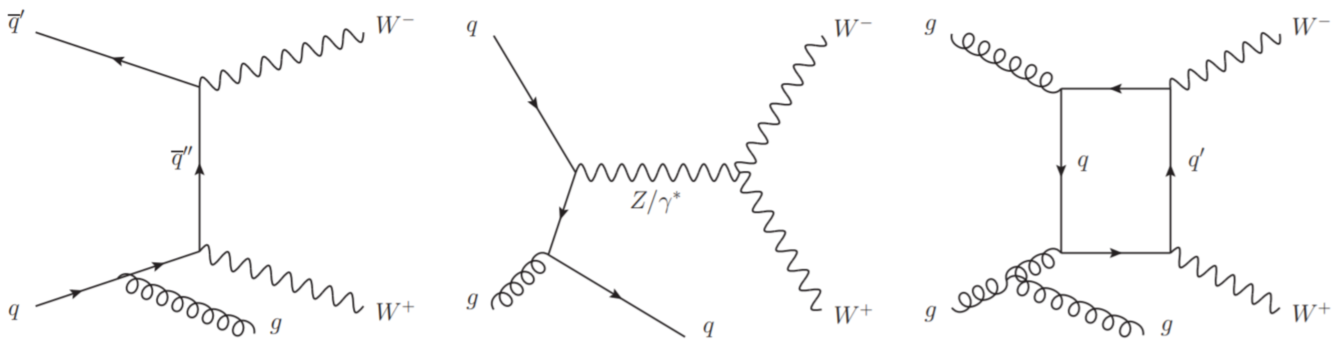
VBS

- Test SM predictions for gauge boson self-interactions
- Gain a better understanding of the dynamics of electroweak symmetry breaking
- Test higher-order QCD and electroweak corrections
- Look for deviations from SM predictions and search for new physics:
  - Typically parameterized using effective field theory (EFT)
  - Expect high sensitivity for operators generating anomalous triple (TGC) and quartic (QGC) gauge couplings

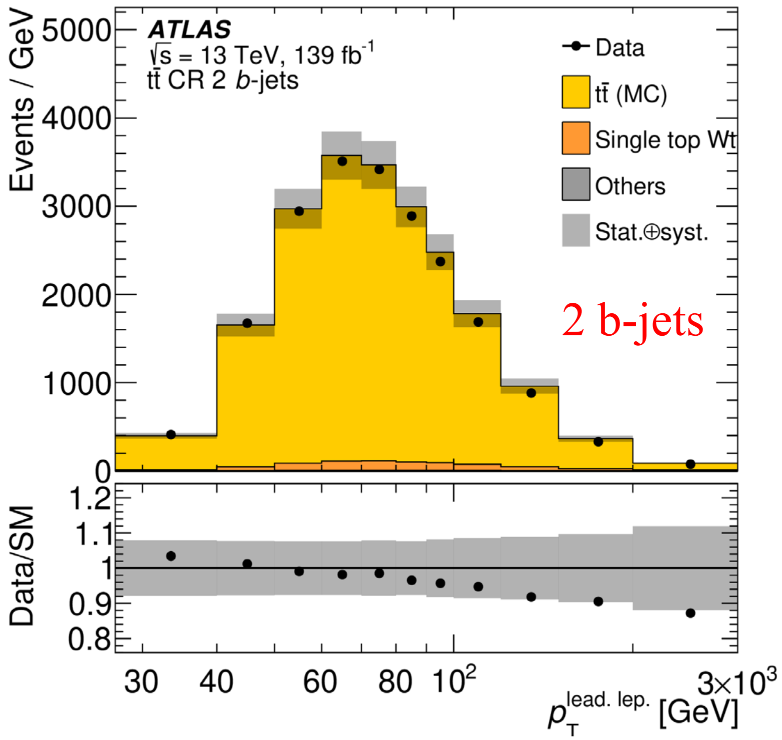
WW+≥1 jet

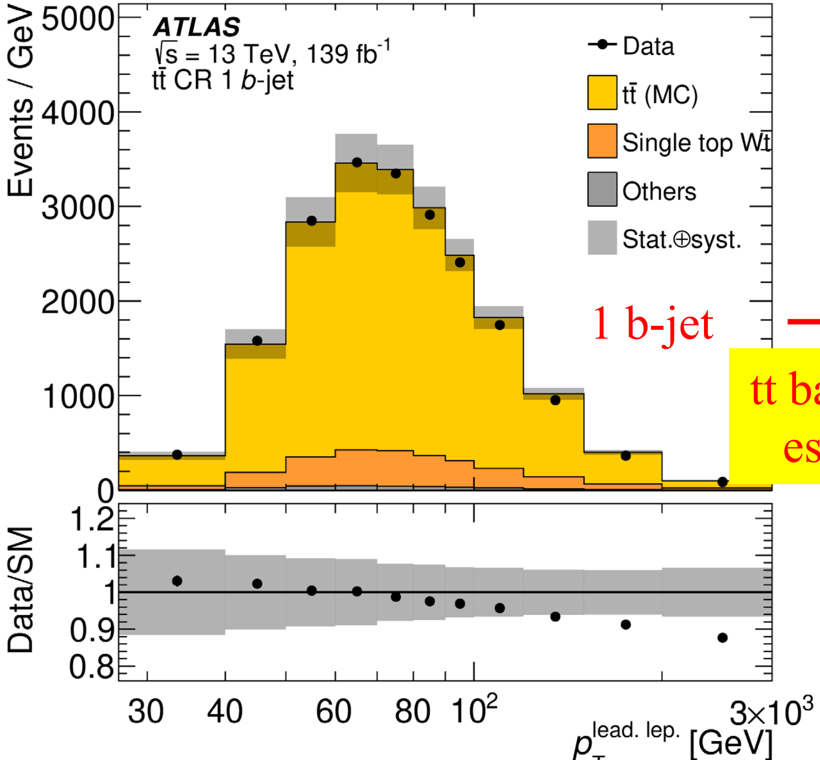
JHEP 06 (2021) 003

- b-veto and jet veto are often used for WW diboson studies
  - Jet veto introduces jet-energy scale uncertainties, uncertainty increases for more stringent veto cuts
  - Jet veto also theoretically challenging
- WW→$e^{\pm}\nu\mu^{\mp}\nu$ events with at least one jet (p_T>30 GeV), b-jet veto

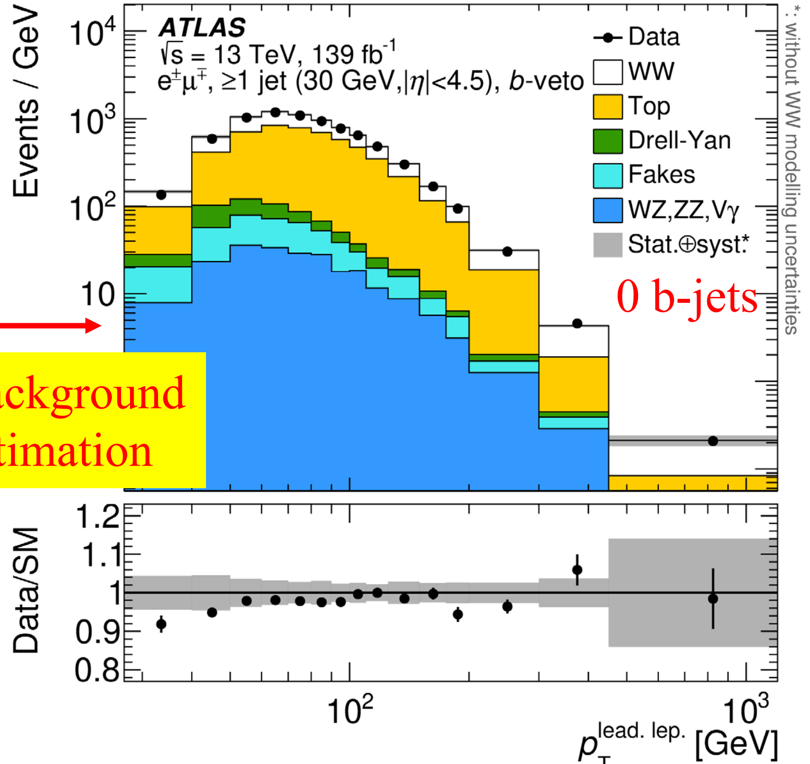


$N_{tt}/N_{WW} \sim 2$



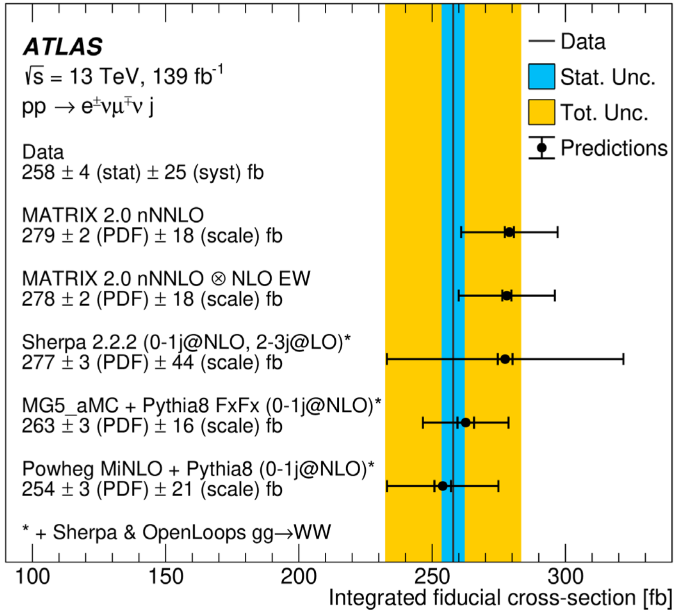


tt background estimation

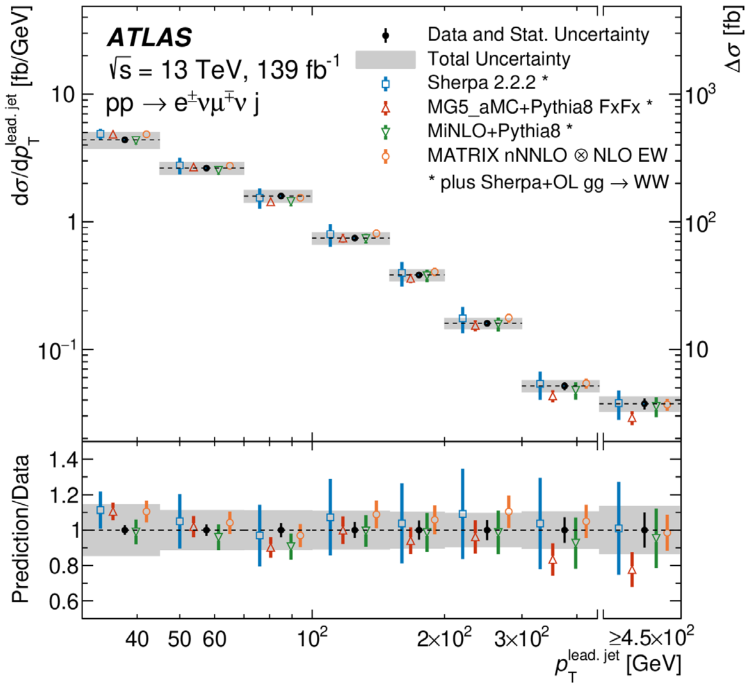


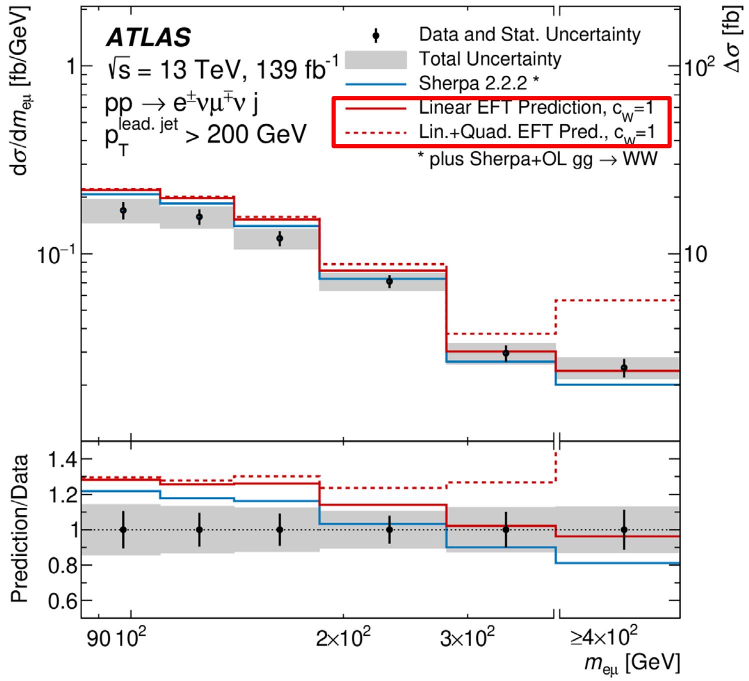
WW+≥1 jet

- ~10% uncertainty on the inclusive cross section measurement:
  - Jet calibration: 6.3%, Top modelling: 4.5%, Fake-lepton modelling: 4.3%
- Similar uncertainty on the predicted cross sections
- Differential cross sections (12 variables) measured for the inclusive fiducial region and two regions with p^{jet}_T>200 GeV and p^{ℓ}_T>200 GeV



Process	Generator	Parton shower	PDF	Matrix element $O(\alpha_S)$
$q\bar{q} \to WW$	MATRIX 2.0	–	NNPDF3.1	NNLO
$gg \to WW$	MATRIX 2.0	–	NNPDF3.1	NLO
$q\bar{q} \to WW$	Sherpa 2.2.2	Sherpa	NNPDF3.0	NLO (0–1 jet), LO (2–3 jets)
$q\bar{q} \to WW$	Powheg MiNLO	Pythia 8	NNPDF3.0	NLO (0–1 jet)
$q\bar{q} \to WW$	MadGraph 2.3.3	Pythia 8	NNPDF3.0	NLO (0–1 jet)
$gg \to WW$	Sherpa 2.2.2 + OpenLoops	Sherpa	NNPDF3.0	LO (0–1 jet)

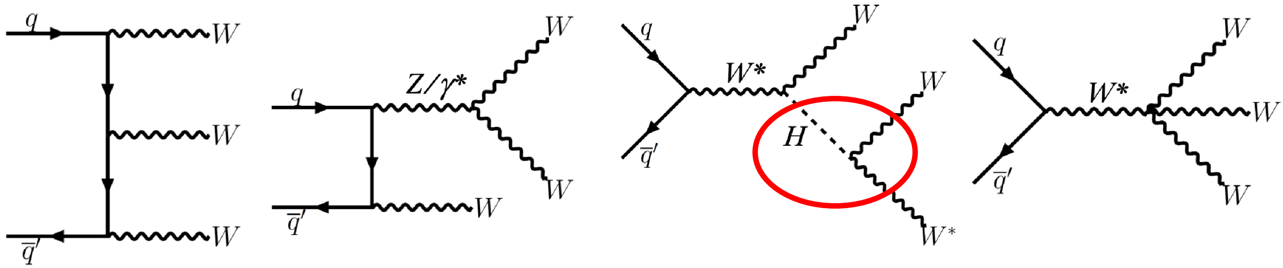




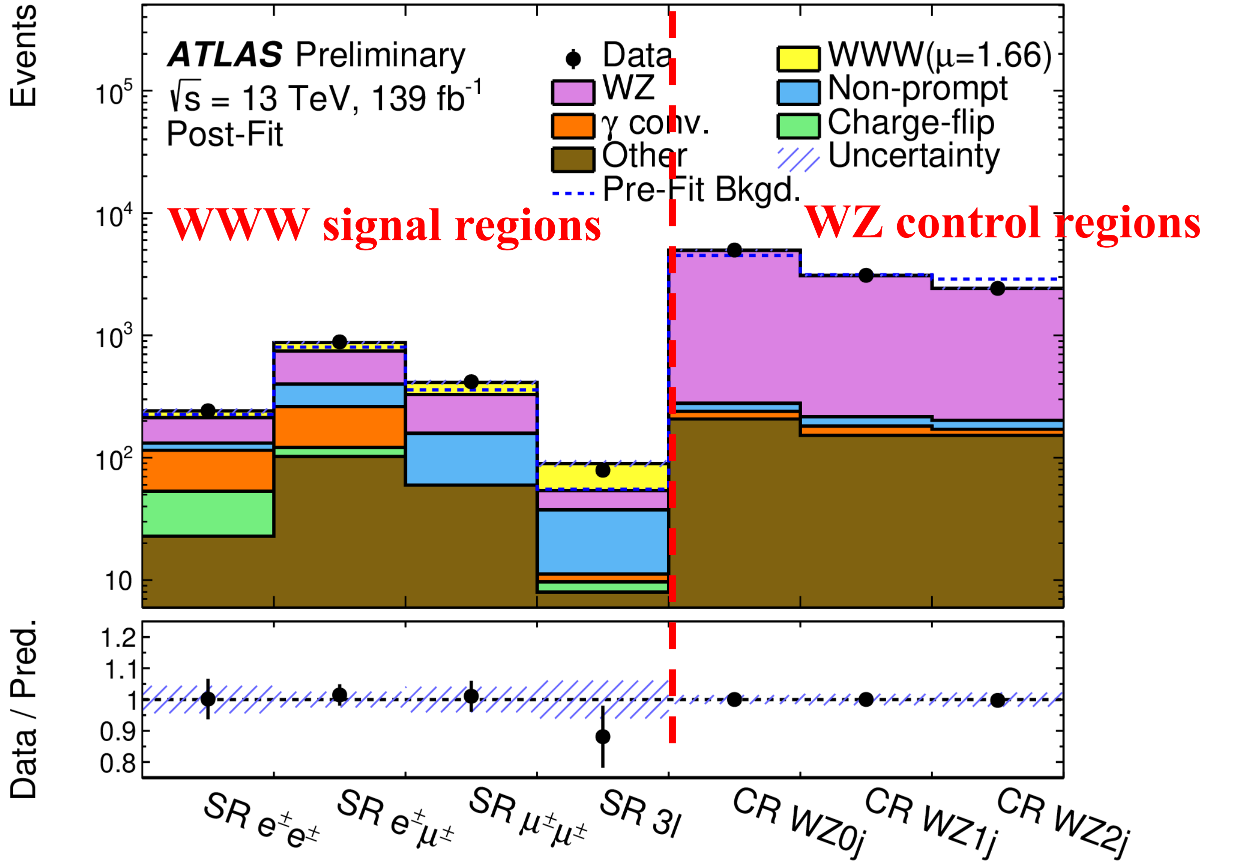
WWW observation

ATL-CONF-2021-039

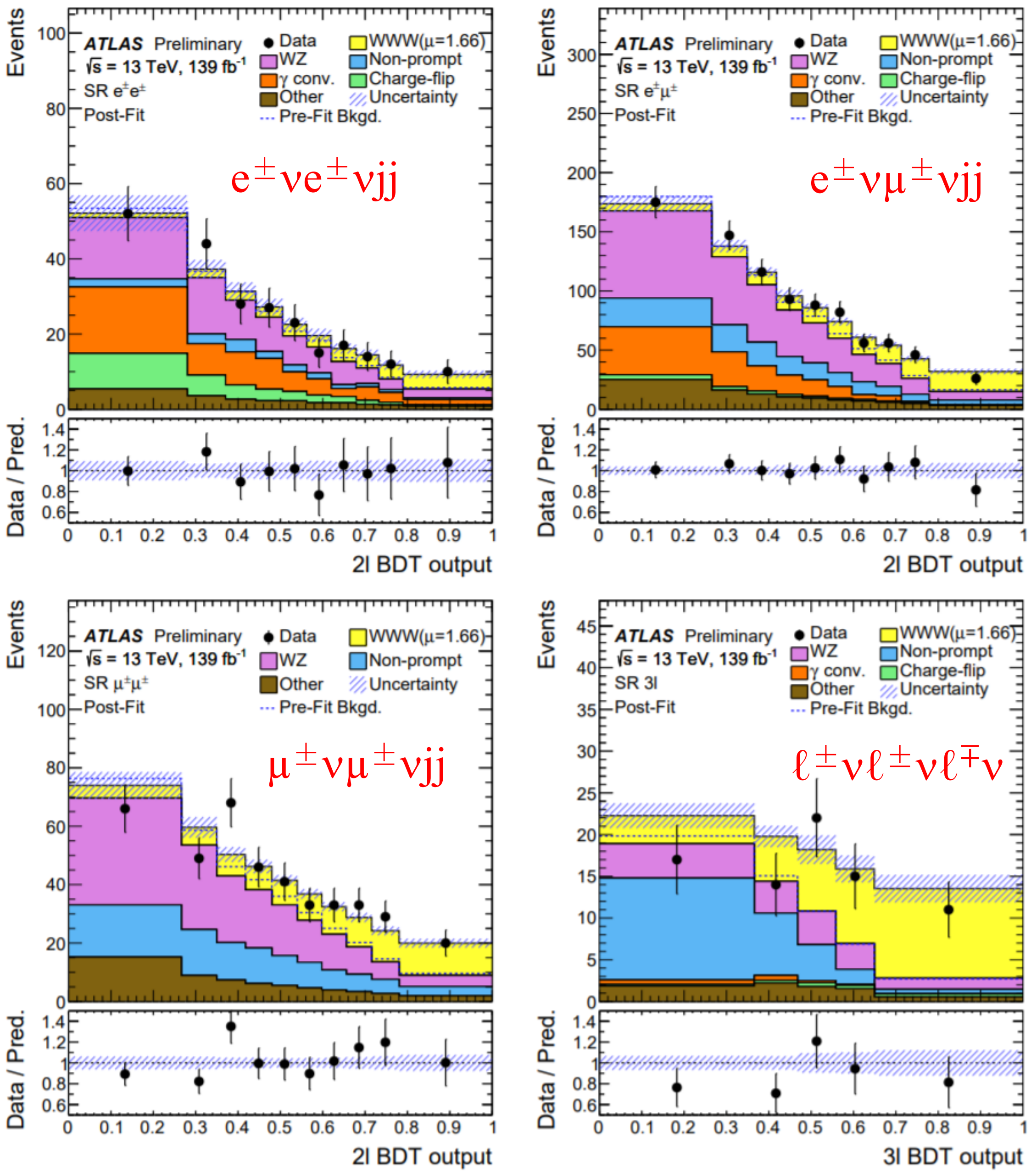
- Two decay channels considered:
  - 2ℓ channel: WWW→$\ell^\pm\nu\ell^\pm\nu jj$ (two same-sign leptons, m_{jj} close to the W pole mass)
  - 3ℓ channel: WWW→$\ell^\pm\nu\ell^\pm\nu\ell^\mp\nu$ (no same-flavor opposite-sign lepton pair: $e^\pm e^\pm \mu^\mp$, $\mu^\pm\mu^\pm e^\mp$)
- WZ+0 jets, 1 jet, and ≥2 jets events are used to constrain the normalizations of WZ+n jets processes
- Charge-flip, γ conversion, non-prompt backgrounds determined by data-driven techniques



	$e^\pm e^\pm$	$e^\pm\mu^\pm$	$\mu^\pm\mu^\pm$	3ℓ
WWW	29.3 ± 4.4	128 ± 19	84 ± 12	35.8 ± 5.2
WZ	80.6 ± 5.7	344 ± 22	171 ± 10	16.4 ± 1.4
Charge-flip	30.3 ± 7.2	18.8 ± 4.5	–	1.7 ± 0.4
γ conversions	62.1 ± 8.7	142 ± 15	–	1.5 ± 0.1
Non-prompt	16.6 ± 4.1	138 ± 24	98 ± 21	26.3 ± 2.9
Other	22.8 ± 3.7	102 ± 15	59.7 ± 9.0	8.0 ± 0.9
Total predicted	242 ± 11	872 ± 22	414 ± 17	89.7 ± 5.4
Data	242	885	418	79

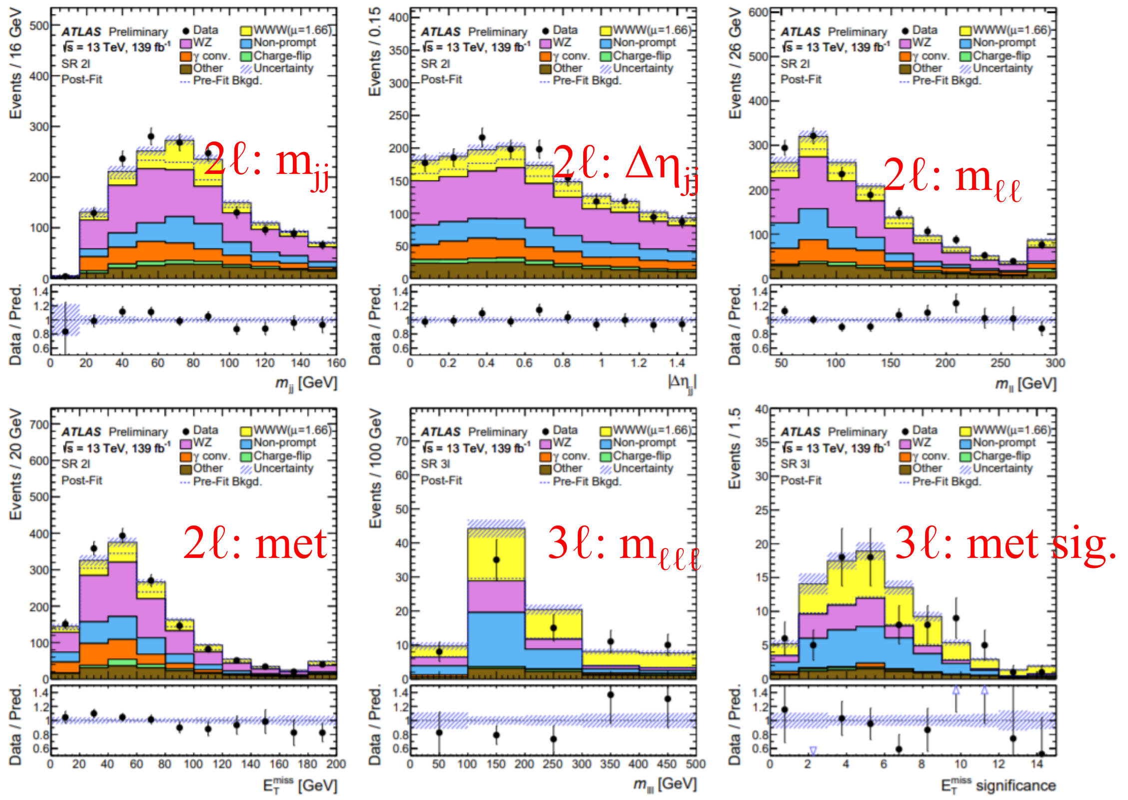


WWW observation



2ℓ	3ℓ
$\lvert m_{jj} - m_W \rvert$	$E_{\mathrm{T}}^{\mathrm{miss}}$ significance $\times 10/E_{\mathrm{T}}^{\mathrm{miss}}$
p_{T} (forward jet)	$p_T(\ell_2)$
$E_{\mathrm{T}}^{\mathrm{miss}}$ significance	N(jets)
$p_T(j_2)$	same flavor $m_{\ell\ell}$
minimum $m(\ell, j)$	$m_T(\ell\ell\ell, E_{\mathrm{T}}^{\mathrm{miss}})$
$m(\ell_2, j_1)$	$m(\ell_2, \ell_3)$
N(jets)	$\Delta\phi(\ell\ell\ell, E_{\mathrm{T}}^{\mathrm{miss}})$
p_{T} (ℓ_2)	minimum $\Delta R(\ell, \ell)$
$m_{\ell\ell}$	p_{T} (ℓ_3)
$\lvert\eta(\ell_1)\rvert$	$m_T(\ell_2, E_{\mathrm{T}}^{\mathrm{miss}})$
N(leptons in jets)	$E_{\mathrm{T}}^{\mathrm{miss}}$ significance
$m(\ell_1, j_1)$	

Variables used to train BDTs



WWW observation

- First observation of WWW production with a significance of 8.2σ
- Measured inclusive cross section: σ(pp→WWW) = 850 ± 100 (stat.) ± 80 (syst.) fb
- Systematic uncertainties dominated by non-prompt background and prompt background modelling

Fit	Observed (expected) significances [σ]	$\mu(WWW)$
$e^{\pm}e^{\pm}$	2.3 (1.4)	1.69 ± 0.79
$e^{\pm}\mu^{\pm}$	4.6 (3.1)	1.57 ± 0.40
$\mu^{\pm}\mu^{\pm}$	5.6 (2.8)	2.13 ± 0.47
2ℓ	6.9 (4.1)	1.80 ± 0.33
3ℓ	4.8 (3.7)	1.33 ± 0.39
Combined	**8.2 (5.4)**	$\mathbf{1.66 \pm 0.28}$

- Latest higher-order calculations:
  - Three on-shell W bosons: NLO in EW and QCD
    - $\sigma(W^+W^+W^-) = 136\ ^{+6}_{-5}$ (scale) ± 4 (PDF) fb
    - $\sigma(W^-W^-W^+) = 76\ ^{+4}_{-3}$ (scale) ± 2 (PDF) fb
  - $W^{\pm}H$: NNLO in QCD and NLO in EW:
    - $\sigma(W^{\pm}H \rightarrow W^{\pm}WW^*) = 293\ ^{+1}_{-2}$ (scale) $^{+6}_{-5}$ (PDF) ± 3 (α_s) fb
  - Total: 505 fb
- About 2.5σ tension between measured and predicted cross sections, various checks performed

Z(→ℓℓ)γ VBS process

ATLAS-CONF-2021-038

Lepton	$p_{\mathrm{T}}^{\ell} > 20, 30(\text{leading})$ GeV, $\lvert\eta_\ell\rvert < 2.47$ $N_\ell \geq 2$
Photon	$E_{\mathrm{T}}^{\gamma} > 25$ GeV, $\lvert\eta_\gamma\rvert < 2.37$ $E_{\mathrm{T}}^{cone20} < 0.07 E_{\mathrm{T}}^{\gamma}$ $\Delta R(\ell, \gamma) > 0.4$
Jet	$\boxed{p_{\mathrm{T}}^{jet} > 50 \text{ GeV}, \ \lvert y_{jet}\rvert < 4.4, \ \lvert\Delta y\rvert > 1.0, \ m_{jj} > 150 \text{ GeV}}$ remove jets if $\Delta R(\gamma, j) < 0.4$ or if $\Delta R(\ell, j) < 0.3$
Event	$m_{\ell\ell} > 40$ GeV $\boxed{m_{\ell\ell} + m_{\ell\ell\gamma} > 182 \text{ GeV}}$ $\boxed{\zeta(\ell\ell\gamma) < 0.4, \ N_{jets}^{gap} = 0}$

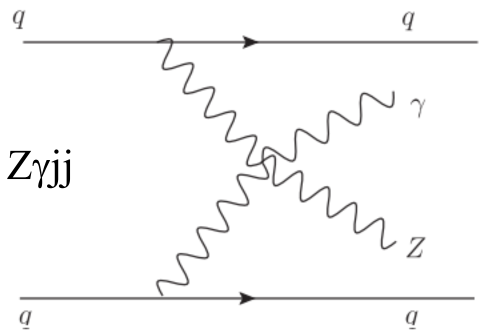
VBS-enriched

reduce the Z+jets photon ISR/FSR contribution

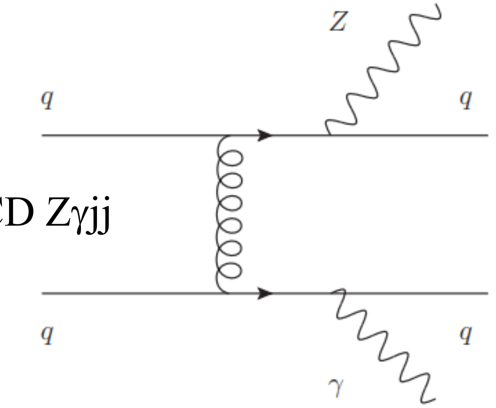
reduce the QCD Zγjj contribution

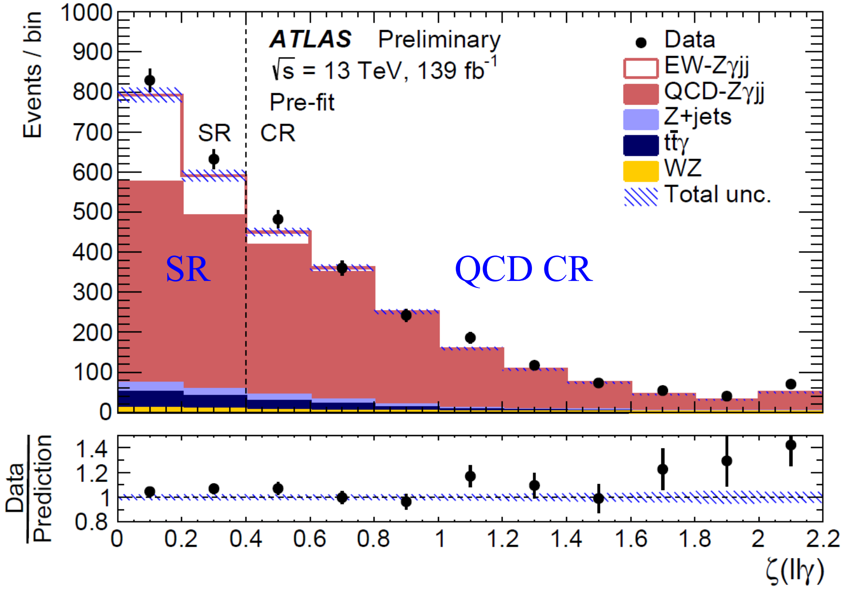
$$\zeta(\ell\ell\gamma) = \left| \frac{y_{\ell\ell\gamma} - (y_{j_1} + y_{j_2})/2}{y_{j_1} - y_{j_2}} \right|$$

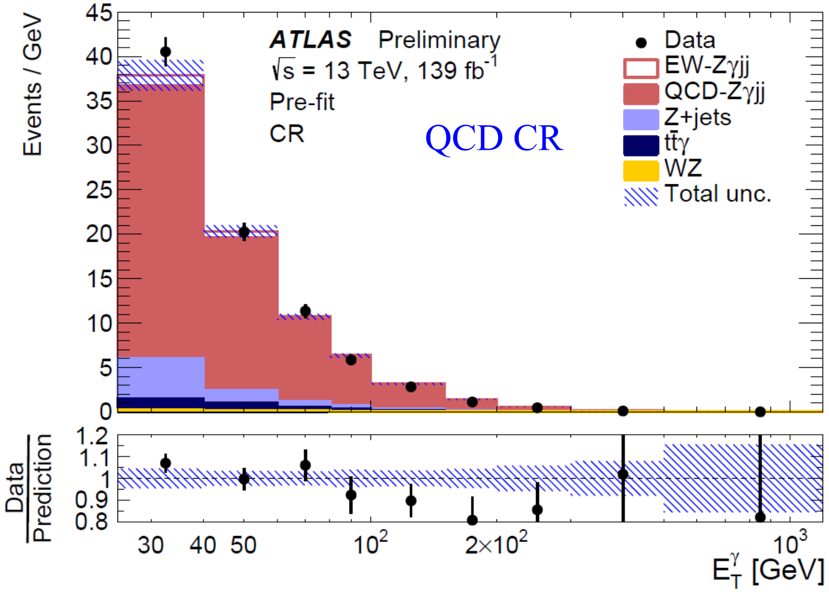
EW Zγjj

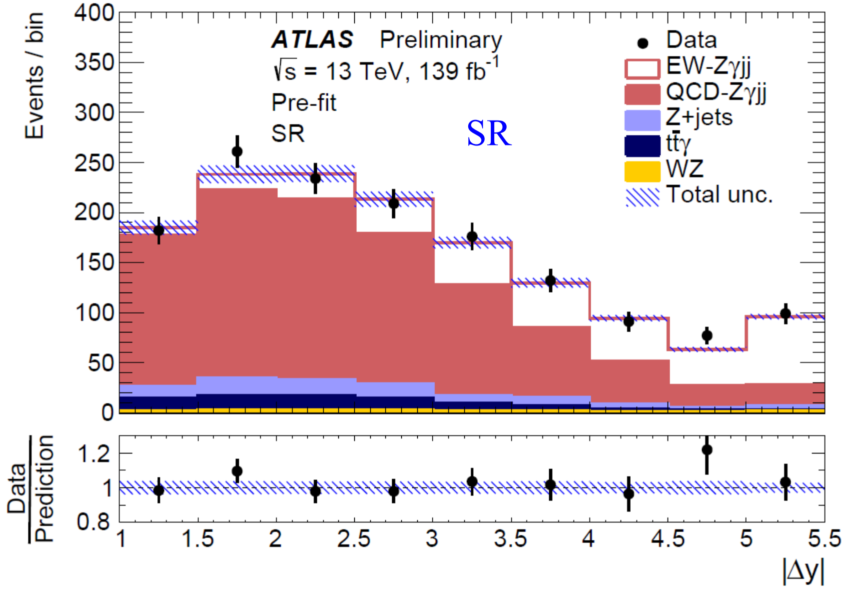


QCD Zγjj





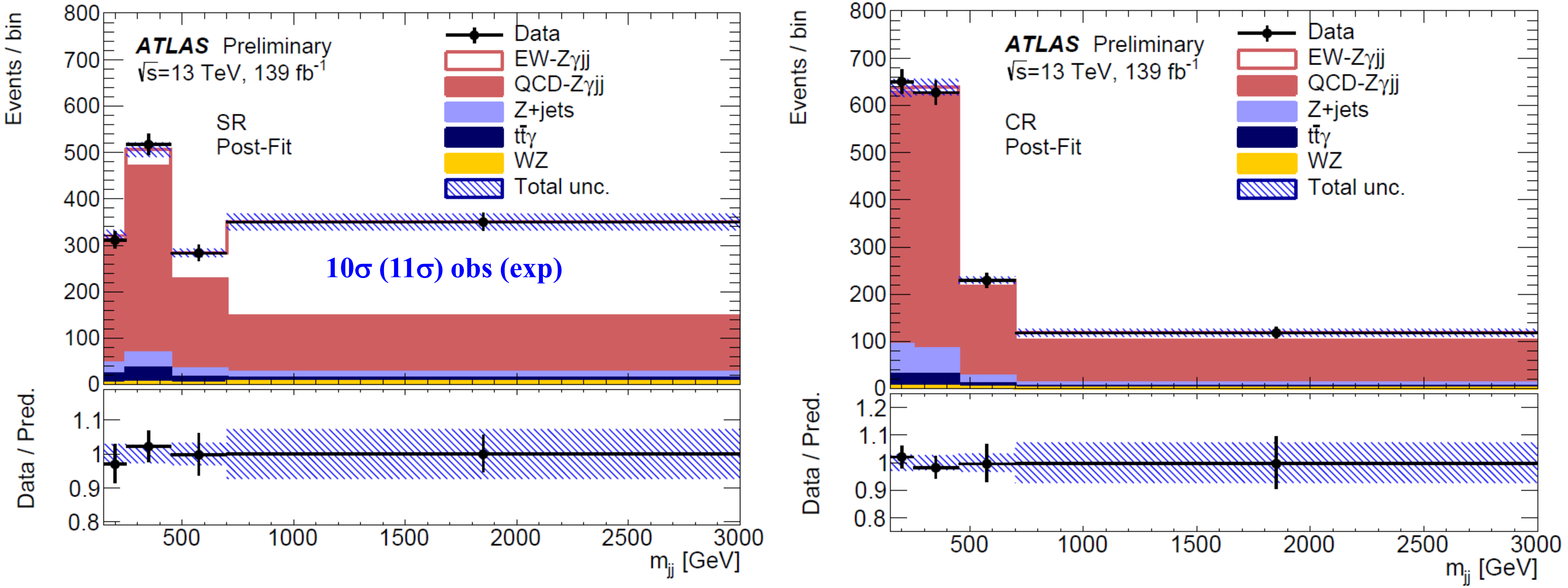




Z(→ℓℓ)γ VBS process

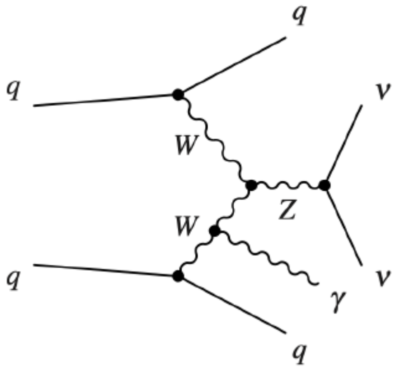
- m_{jj} distribution fitted simultaneously in SR and CR
- Measured cross sections:
  - $\sigma_{EW} = 4.49 \pm 0.40$ (stat.) ± 0.42 (syst.) fb
  - $\sigma_{EW+QCD} = 20.6 \pm 0.6$ (stat.) $^{+1.2}_{-1.0}$ (syst.) fb
  - Systematic uncertainties dominated by jet uncertainties, Zγjj EW (MadGraph) and QCD (Sherpa) modellings

Sample	SR	CR
$N_{EW-Z\gamma jj}$	300 ± 36	55 ± 7
$N_{QCD-Z\gamma jj}$	987 ± 55	1352 ± 60
$N_{t\bar{t}\gamma}$	72 ± 11	59 ± 9
N_{WZ}	17 ± 3	14 ± 3
N_{Z+jets}	85 ± 30	143 ± 43
Total	1461 ± 38	1624 ± 40
N_{obs}	1461	1624



$Z(\rightarrow\nu\nu)\gamma$ VBS process

arXiv:2109.00925

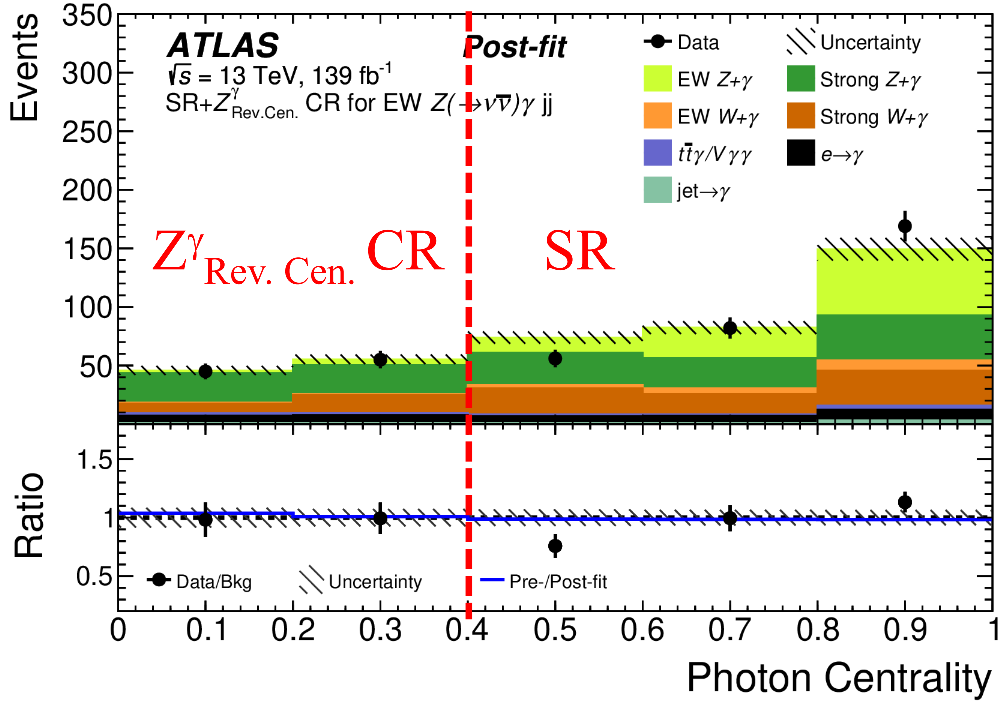


- The photon centrality:

$$C_\gamma = \exp\left[-\frac{4}{(\eta_1-\eta_2)^2}\left(\eta_\gamma - \frac{\eta_1+\eta_2}{2}\right)^2\right]$$

- $C_\gamma=1$ when photon in the middle between the two tagging jets, and $\rightarrow 0$ when farther forward in η than the jets
- A 3rd jet with $p_T>25$ GeV can be present, if $C_3<0.7$ (similar to C_γ but replacing η_γ with the 3rd jet η)

Variable	SR	$W^\gamma_{\mu\nu}$ CR	$W^\gamma_{e\nu}$ CR	$Z^\gamma_{\text{Rev.Cen.}}$ CR	Fake-e CR	Low-E_T^{miss} VR
$p_T(j_1)$ [GeV]	>60					
$p_T(j_2)$ [GeV]	>50					
$p_T(j_{>2})$ [GeV]	>25					
N_{jet}	2,3					
$N_{b\text{-jet}}$	<2					
$\Delta\phi_{jj}$	<2.5 [2.0]					
$\lvert\Delta\eta_{jj}\rvert$	>3.0					
$\eta(j_1)\times\eta(j_2)$	<0					
C_3	<0.7					
m_{jj} [TeV]	>0.25					0.25–1.0
E_T^{miss} [GeV]	>150	–	>80	>150	<80	110–150
$E_T^{\text{miss,lep-rm}}$ [GeV]	–	>150	>150	–	>150	110–150
$E_T^{\text{jets,no-jvt}}$ [GeV]	>130					>100
$\Delta\phi(j_i, \vec{E}_T^{\text{miss,lep-rm}})$	>1.0					
N_γ	1					
$p_T(\gamma)$ [GeV]	>15, <110 [>15, $<\max(110, 0.733\times m_T)$]					
C_γ	>0.4	>0.4	>0.4	<0.4	>0.4	>0.4
$\Delta\phi(\gamma, \vec{E}_T^{\text{miss,lep-rm}})$	>1.8 [–]					
N_ℓ	0	1 μ	1 e	0	1 e	0
$p_T(\ell)$ [GeV]	–	>30	>30	–	>30	–



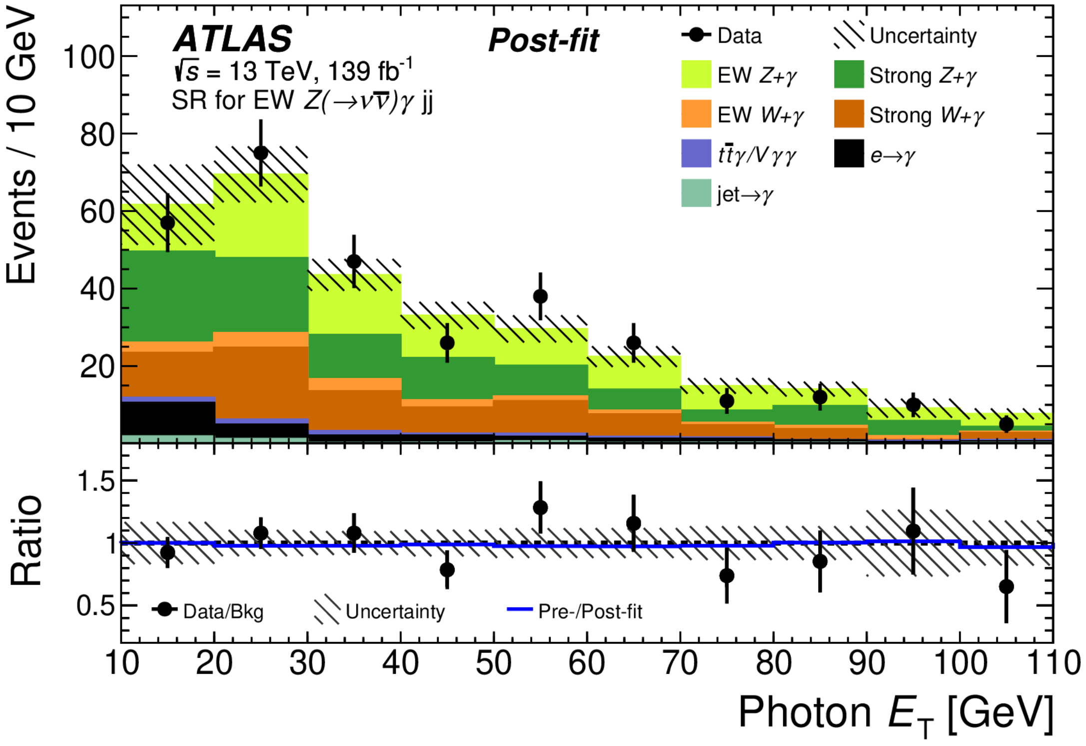
- Dominant backgrounds: $W\gamma jj$ and $Z\gamma jj$ QCD processes
- $W^\gamma_{\ell\nu}$ CRs: additional lepton to constrain $W\gamma jj$
- $Z^\gamma_{\text{Rev. Cen.}}$ CR: reverse centrality cut to constrain QCD $Z\gamma jj$
- Fake-e CR: similar to $W^\gamma_{e\nu}$ but reverse the E_T^{miss} cut

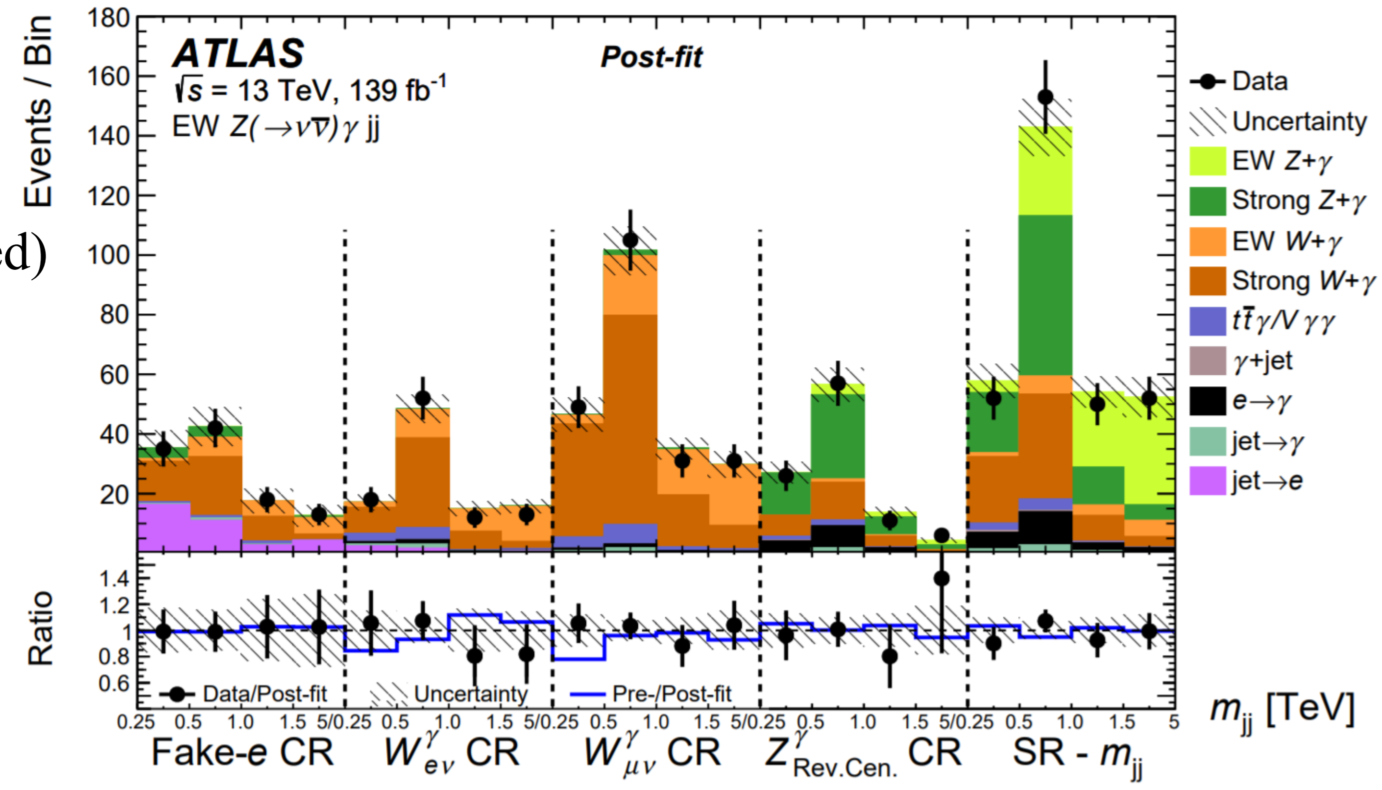
Z(→νν)γ VBS process

- Simultaneous fit to the m_{jj} distributions with 4 SR bins and 16 CR bins

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

- EW Z(→νν)γjj observed with 5.2σ (5.1σ expected)
- $\sigma^{fid} = 1.31 \pm 0.20$ (stat.) ± 0.20 (syst.) fb





Combined EFT interpretation

ATL-PHYS-PUB-2021-022

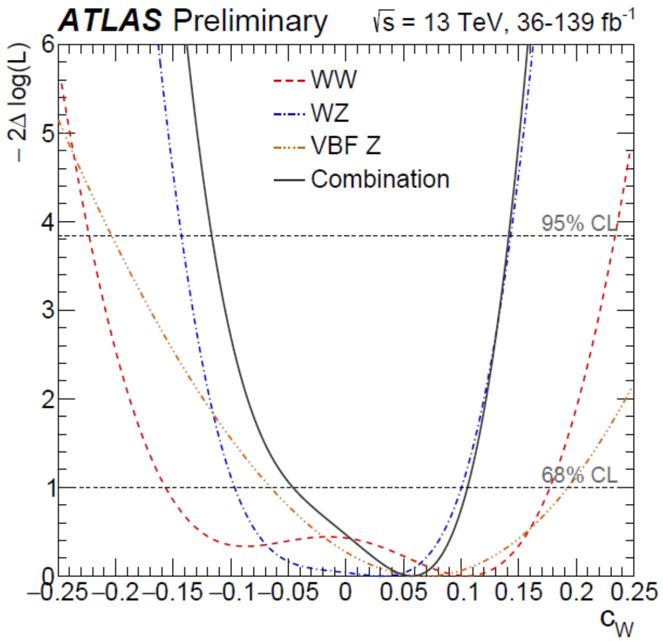
- First attempt of a combined EFT interpretation of four ATLAS electroweak analysis:
  - Diboson WW with 36 fb^{-1} (leading lepton p_T): Eur. Phys. J. C 79 (2019) 884
  - Diboson WZ with 36 fb^{-1} (m_T^{WZ}), Eur. Phys. J. C 79 (2019) 535
  - Inclusive four-lepton with 139 fb^{-1} (m_{Z2}), JHEP 07 (2021) 005
  - Zjj via vector boson fusion with 139 fb^{-1} ($\Delta\phi_{jj}$): Eur. Phys. J. C 81 (2021) 163
- 33 CP-even dimension-6 operators considered using the Warsaw basis
- The expansion of the cross section contains linear and quadratic/cross terms in Wilson coefficient $c_i^{(6)}$
- Quadratic/cross terms are of the same order as those of EFT dim-8 interfering with the SM
- EFT dim-8 not considered in the model → report limits based on linear and quadratic fits, difference gives an estimate of the size of the missing $1/\Lambda^4$ terms

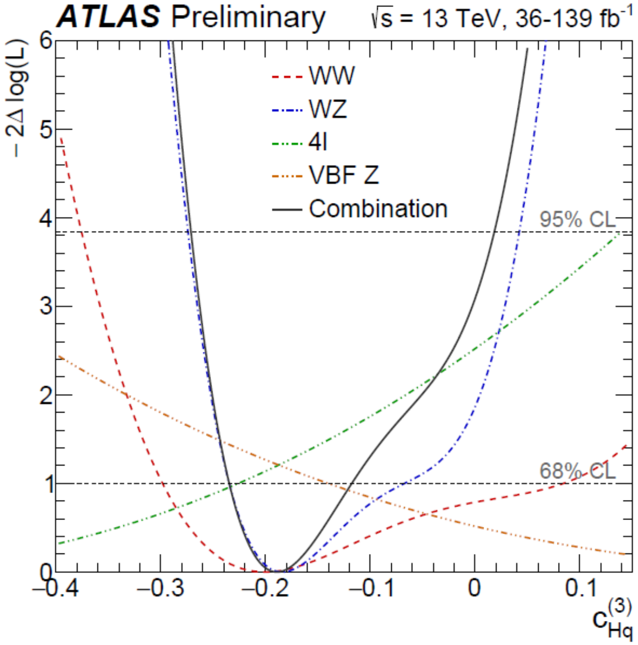
$$\boxed{\mathcal{L}_{\mathrm{SMEFT}} \approx \mathcal{L}_{\mathrm{SM}}^{(4)} + \sum_i \frac{c_i^{(6)}}{\Lambda^2} O_i^{(6)}}$$

$$\sigma \propto |\mathcal{M}_{\mathrm{SM}}|^2 + \sum_i \frac{c_i^{(6)}}{\Lambda^2} \underbrace{2\mathrm{Re}\left(\mathcal{M}_i^{(6)} \mathcal{M}_{\mathrm{SM}}^*\right)}_{\text{linear}} + \sum_i \frac{\left(c_i^{(6)}\right)^2}{\Lambda^4} \underbrace{\left|\mathcal{M}_i^{(6)}\right|^2}_{\text{quadratic}} + \sum_{i<j} \frac{c_i^{(6)} c_j^{(6)}}{\Lambda^4} \underbrace{2\mathrm{Re}\left(\mathcal{M}_i^{(6)} \mathcal{M}_j^{(6)*}\right)}_{\text{cross}}$$

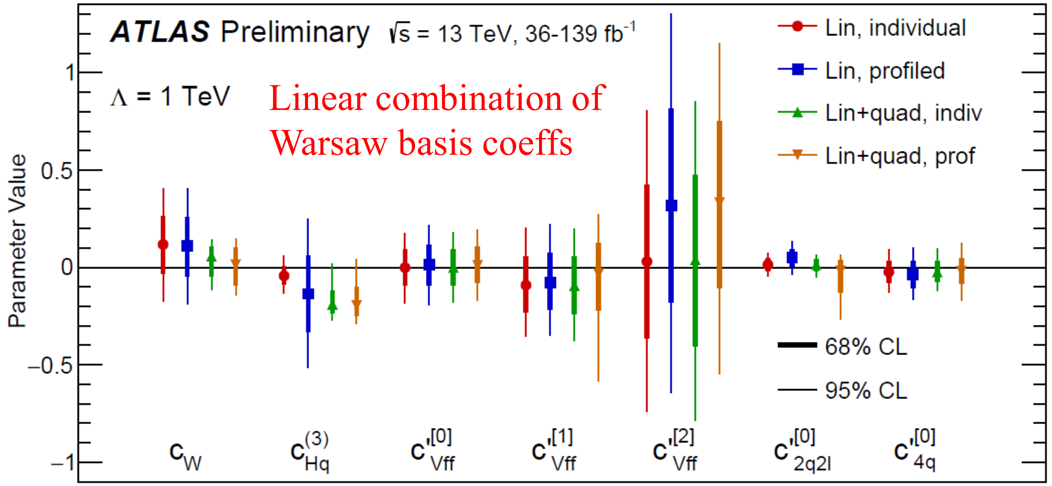
- Dedicated samples representing SM, linear and quadratic effects of dim-6 operators, as well as dim-6 cross terms, are generated with MadGraph5_aMC@NLO using the SMEFTsim model

Combined EFT interpretation





- Correlation of systematics between measurements taken into account
- Limits at 68% and 95% CLs for linear and linear+quadratic fits
- Fits of individual coefficients (with others set to 0) as well as combined profile fits
- No deviations from SM found



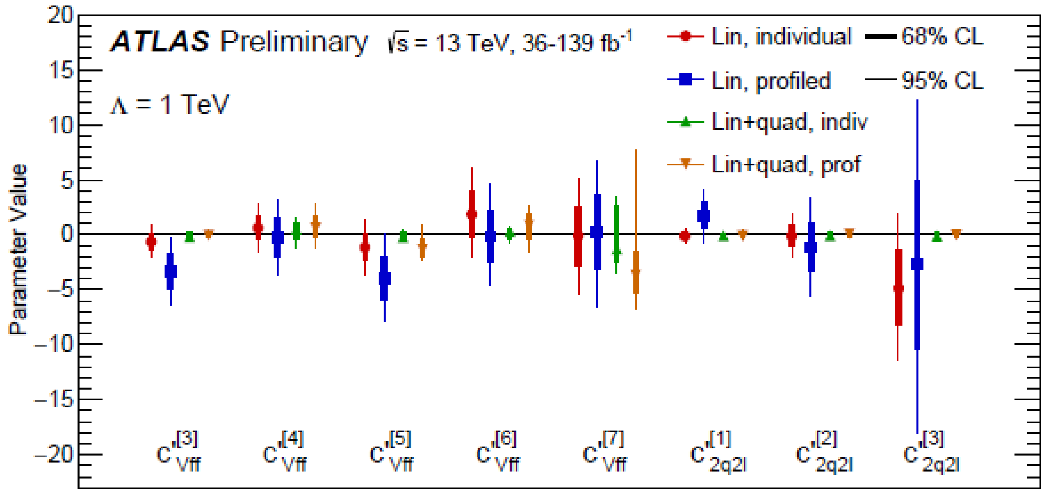
$c'^{[0]}_{Vff} \approx 0.81c_{HWB} + 0.38c_{HD} + 0.13c^{(1)}_{Hl} + 0.37c^{(3)}_{Hl} - 0.14c^{(1)}_{ll} + 0.12c^{(1)}_{Hq}$

$c'^{[1]}_{Vff} \approx 0.73c^{(1)}_{Hl} - 0.28c^{(3)}_{Hl} - 0.48c_{He} + 0.38c^{(1)}_{ll} + 0.13c^{(1)}_{Hq}$

$c'^{[2]}_{Vff} \approx 0.37c_{HWB} + 0.17c_{HD} - 0.31c^{(1)}_{Hl} - 0.53c^{(3)}_{Hl} + 0.25c_{He} + 0.59c^{(1)}_{ll} - 0.21c^{(1)}_{Hq}$

$c'^{[0]}_{2q2l} \approx -0.37c^{(1)}_{lq} + 0.89c^{(3)}_{lq} - 0.11c_{lu} - 0.21c_{eu} - 0.13c_{qe}$

$c'^{[0]}_{4q} \approx 0.11c^{(11)}_{qq} + 0.22c^{(18)}_{qq} + 0.95c^{(31)}_{qq} - 0.2c^{(38)}_{qq}$



$c'^{[3]}_{Vff} \approx -0.19c^{(1)}_{Hl} - 0.14c^{(3)}_{Hl} + 0.86c^{(1)}_{Hq} + 0.41c_{Hu} - 0.17c_{Hd}$

$c'^{[4]}_{Vff} \approx -0.35c_{HWB} + 0.49c_{HD} + 0.26c^{(1)}_{Hl} + 0.35c^{(3)}_{Hl} + 0.51c_{He} + 0.38c^{(1)}_{ll} + 0.18c^{(1)}_{Hq}$

$c'^{[5]}_{Vff} \approx 0.25c_{HD} + 0.33c^{(1)}_{Hl} - 0.22c^{(3)}_{Hl} + 0.18c_{He} - 0.35c^{(1)}_{ll} - 0.3c^{(1)}_{Hq} + 0.71c_{Hu} - 0.16c_{Hd}$

$c'^{[6]}_{Vff} \approx -0.22c^{(1)}_{Hl} + 0.52c^{(3)}_{Hl} - 0.39c_{He} + 0.44c^{(1)}_{ll} - 0.22c^{(1)}_{Hq} + 0.52c_{Hu}$

$c'^{[7]}_{Vff} \approx -0.28c_{HWB} + 0.71c_{HD} - 0.31c^{(1)}_{Hl} - 0.21c^{(3)}_{Hl} - 0.5c_{He} - 0.14c^{(1)}_{ll}$

$c'^{[1]}_{2q2l} \approx 0.56c^{(1)}_{lq} + 0.44c^{(3)}_{lq} + 0.61c_{eu} - 0.1c_{ed} + 0.34c_{qe}$

$c'^{[2]}_{2q2l} \approx 0.68c^{(1)}_{lq} + 0.15c^{(3)}_{lq} + 0.33c_{lu} - 0.51c_{eu} + 0.13c_{ed} - 0.37c_{qe}$

$c'^{[3]}_{2q2l} \approx -0.27c^{(1)}_{lq} + 0.79c_{lu} - 0.39c_{ld} + 0.26c_{eu} - 0.22c_{ed} - 0.16c_{qe}$

Conclusions

- Multiboson and VBS processes are interesting physics processes to test SM predictions and to search for new physics
  - Diboson: large statistics to perform precision measurements and study boson polarizations, experimental uncertainties often close to theoretical uncertainties
  - VBS: almost all SM VBS processes have been observed, move to differential cross section measurements and polarization measurements
  - Triboson: only a few triboson processes have been observed so far, continue to search for these rare physics processes
  - First attempt for a combined EFT interpretation of WW, WZ, four-lepton, and Zjj VBF data → important step towards an ATLAS global EFT interpretations. Data and some predictions available on HEPdata and Rivet, which allows to perform similar re-interpretations outside the ATLAS collaboration
- Looking forward to higher precision measurements and new observations with Run 3 data