Overview of recent Vector Boson Scattering results from ATLAS

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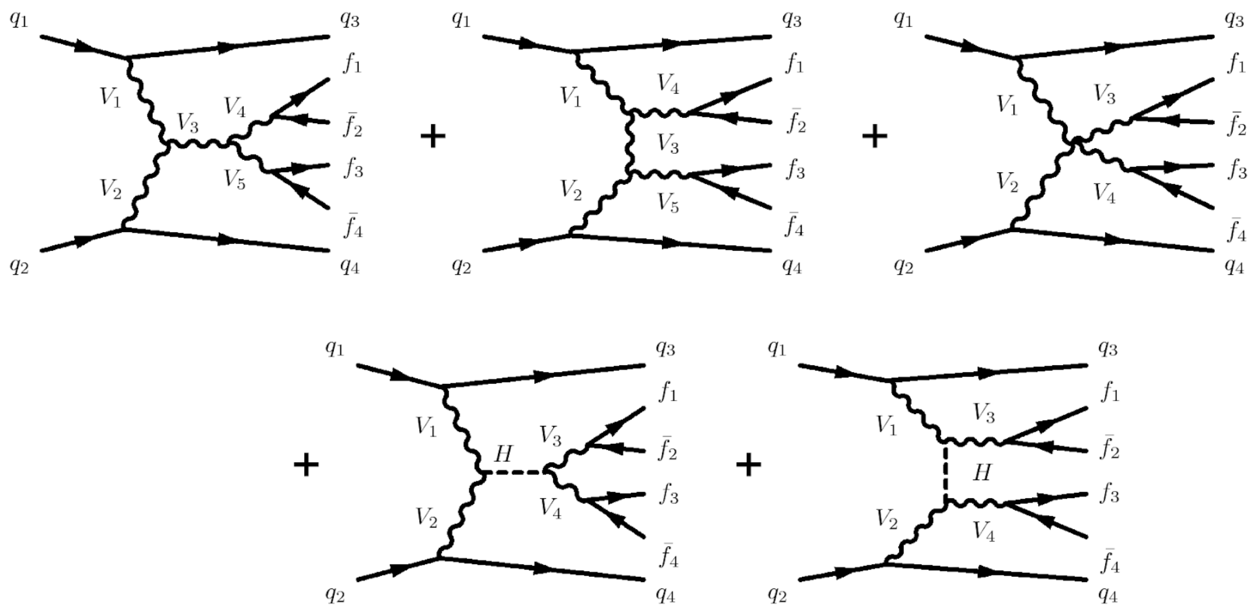
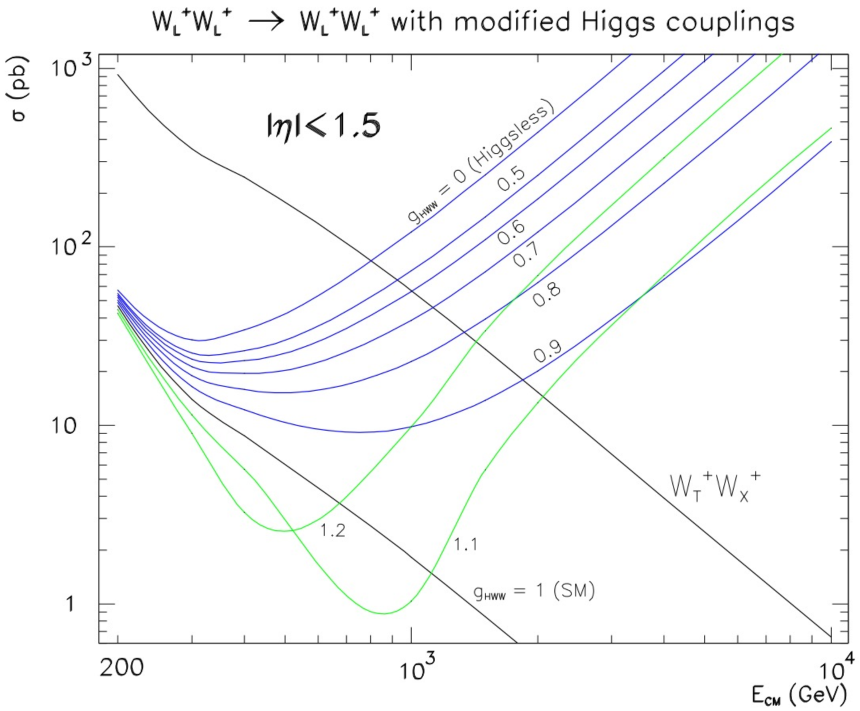
Introduction

- Vector boson scattering (VBS)
  - No-lose theorem for the LHC: Higgs or New Physics
  - Crucial to understand the Electroweak Symmetry Breaking
  - Sensitive to New Physics



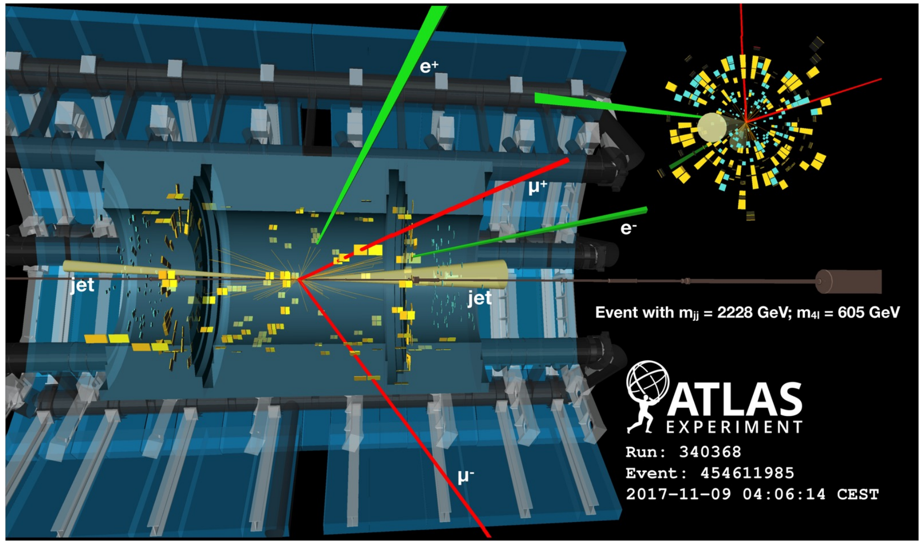


M. Szleper, arXiv:1412.8367

Experimental challenges

- Typical VBS topology
  - Two tagging jets
    - Large rapidity gap: $\Delta Y(jj)$
    - Invariant mass M_{jj} significantly harder than for non-VBS contributions
  - Centrality
    - Little hadronic activity is expected in the gap between the two jets, due to color singlet exchange

Allows to effectively distinguish between EW VVjj and QCD VVjj, and also VBS and non-VBS EW VVjj contributions

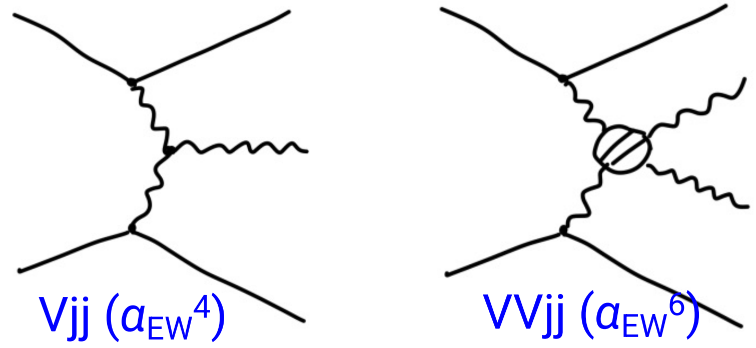


A candidate ZZ(4l)jj VBS event

- Measuring VBS is experimentally challenging
  - Overall low statistics, and complicated backgrounds
  - Forward jet tagging (e.g. subject to pileup effects)
  - Can not extract VBS due to gauge invariance ➔ only EW VVjj is measurable
  - Also non-negligible QCD VVjj contamination, and the interference effects

Theoretical challenges

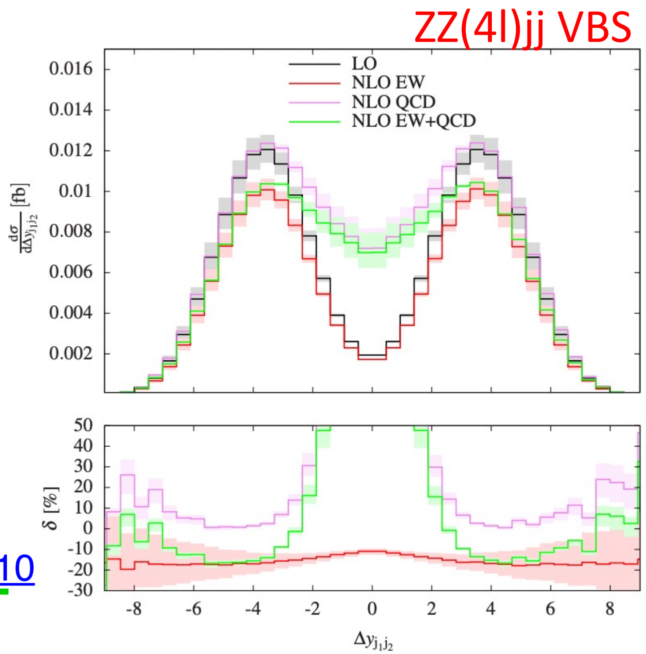
- Precise theory predictions challenging for both EW and QCD Vjj/VVjj productions
- For the EW production
  - Includes both VBS/VBF diagrams and non-VBS/VBF diagrams
  - Also diboson (VV) for EW Vjj, and triboson (VVV) for EW VVjj
  - High-order corrections:
    - Including QCD, EW and mixed corrections
    - NLO corrections available: with VBF approximation
  - Parton shower effects also matter



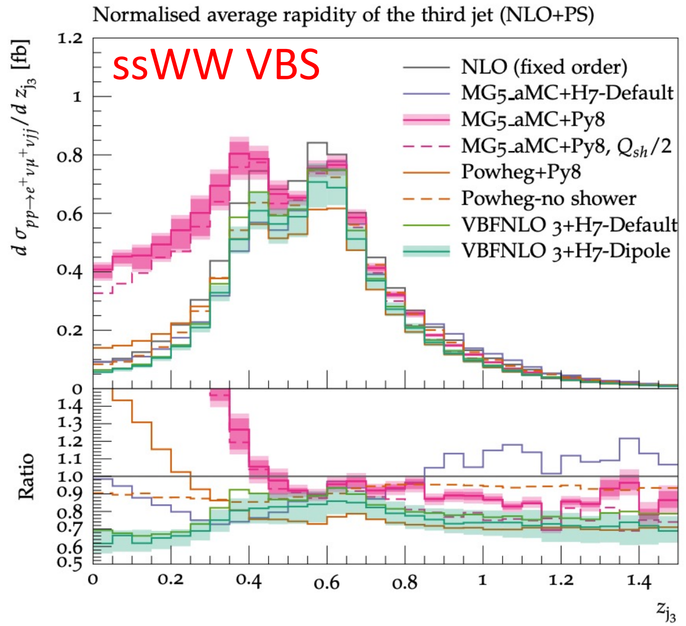
See also the theory talk by Barbara Jager

- For the QCD production
  - Needs NLO predictions for VV+2jets

See also the theory talk by Marek Schoenherr



A. Denner et al, JHEP 11 (2020) 110



M. Pellen et al EPJC 78, 671 (2018)

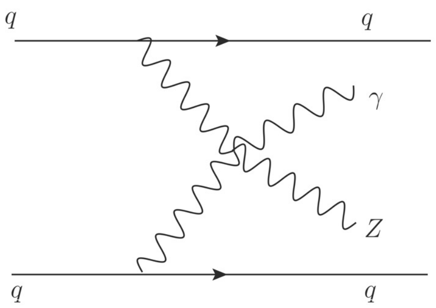
Overview of ATLAS results

	Channel	Final states	ATLAS results	Dataset
VBF	W	$l\nu$ jj	EPJC77(2017)474	(7, 8 TeV)
	Z	ll jj	EPJC81(2021)163 ($\gg$5 σ)	139 fb^{-1}
VBS	$W^{\pm}W^{\pm}$	$l^{\pm}l^{\pm}$ jj	PRL123(2019)161801 6.5 σ	36 fb^{-1}
	$W^{\pm}W^{\mp}$	$l^{\pm}l^{\mp}$ jj		
	WZ	$l\nu ll$ jj	PLB793(2019)469 5.3 σ	36 fb^{-1}
	WV	$l\nu$jj jj	PRD100(2019)032007 2.7 σ	36 fb^{-1}
	ZV	lljj jj		
	ZV	ννjj jj		
	ZZ	$llll$ jj	arXiv:2004.10612 5.5 σ (combined)	139 fb^{-1}
		$ll\nu\nu$ jj		
	$W\gamma$	$l\nu$ jj		
	$Z\gamma$	ll jj	ATLAS-CONF-2021-038 10 σ	139 fb^{-1}
		$\nu\nu$ jj	EPJC 82 (2022) 105 5.1 σ	139 fb^{-1}
	$\gamma\gamma \to W^{\pm}W^{\mp}$	$e\nu\mu\nu$ + X	PLB 816 (2021) 136190 8.4 σ	139 fb^{-1}

Observation of EW Z(→ll)γjj production

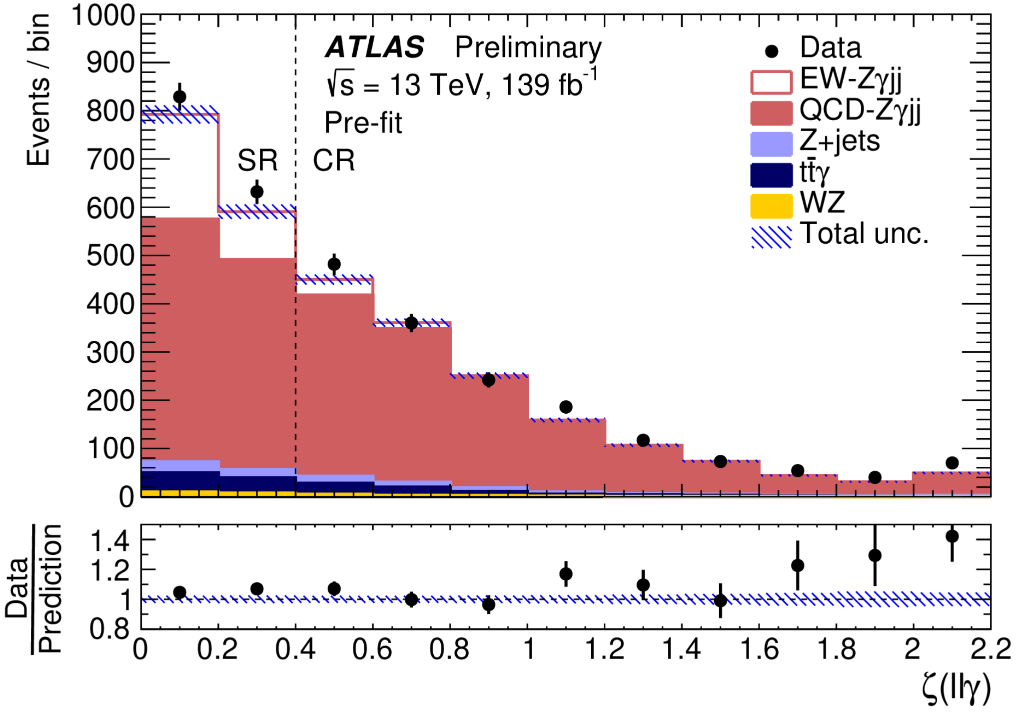
- Probes the neutral quartic gauge couplings
- Using 139 fb^{-1} data with Z→ee/μμ final states
- Dominant background is QCD Zγjj

ATLAS-CONF-2021-038



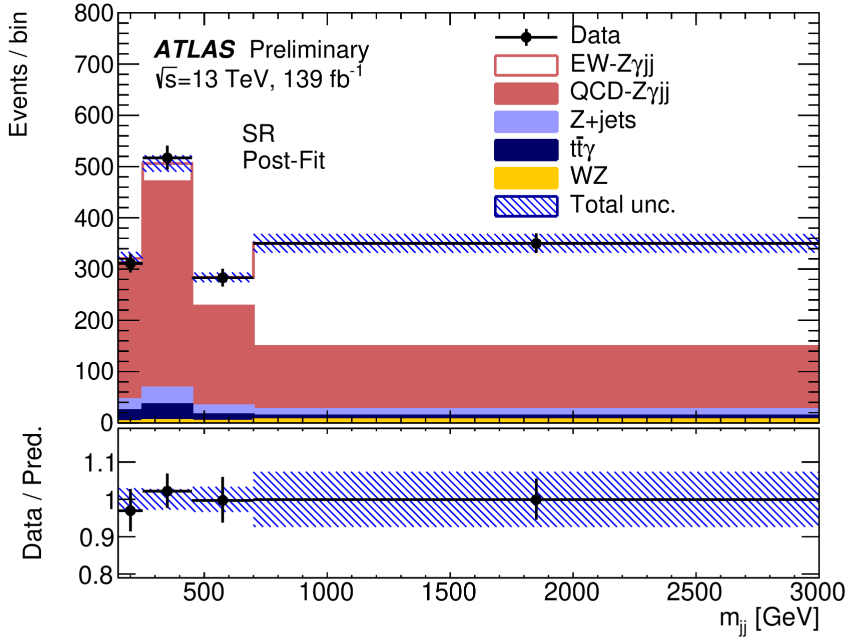
$$\zeta(\ell\ell\gamma) = \left| \frac{y_{\ell\ell\gamma} - (y_{j_1} + y_{j_2})/2}{y_{j_1} - y_{j_2}} \right|$$

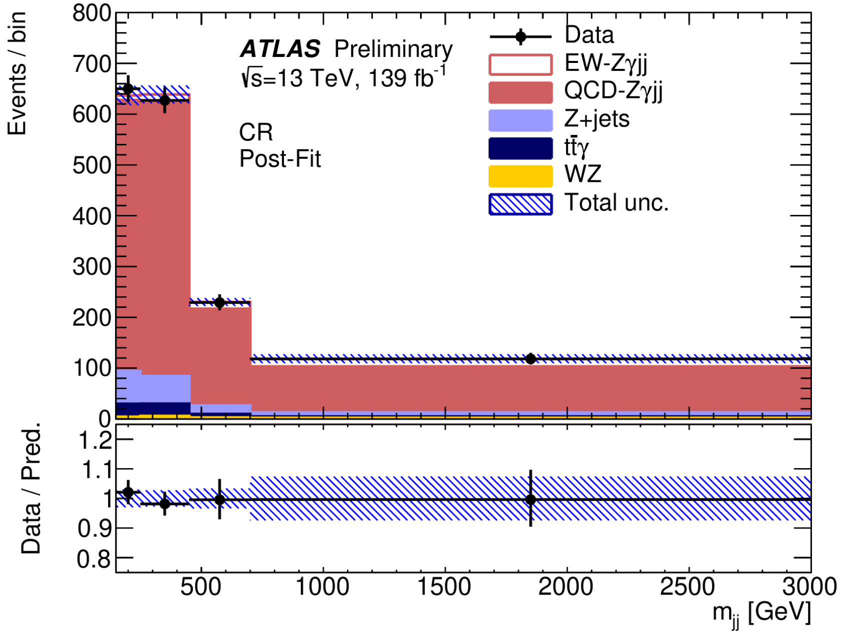
Lepton	$p_T^\ell > 20, 30(\text{leading})$ GeV, $\lvert\eta_\ell\rvert < 2.47$ $N_\ell \geq 2$
Photon	$E_T^\gamma > 25$ GeV, $\lvert\eta_\gamma\rvert < 2.37$ $E_T^{cone20} < 0.07 E_T^\gamma$ $\Delta R(\ell, \gamma) > 0.4$
Jet	$p_T^{jet} > 50$ GeV, $\lvert y_{jet}\rvert < 4.4$ $\lvert\Delta y\rvert >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



Observation of EW Z(→ll)γjj production

- Control regions (CRs) are used to constrain the normalization of the QCD Zγjj
  - Two normalization parameters are introduced separately in the SR and CR
- EW signal strength extracted using simultaneous fit to m_{jj} distributions in the SR and CR using template MC distributions

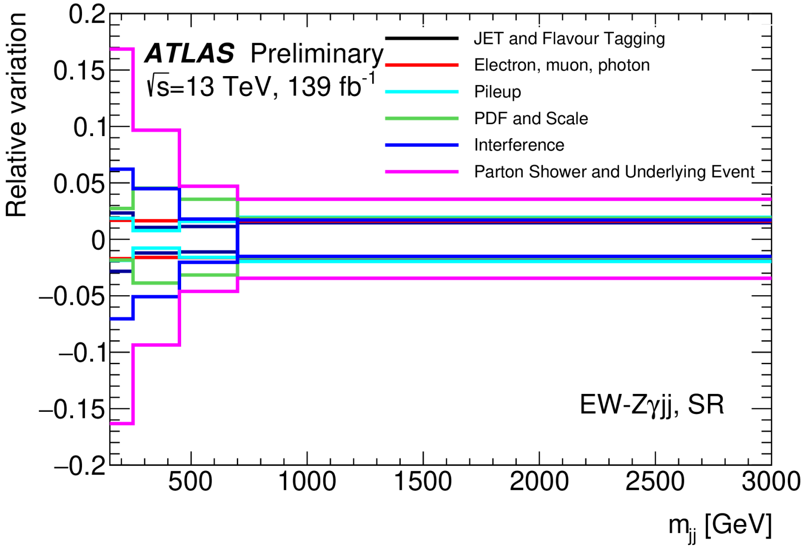


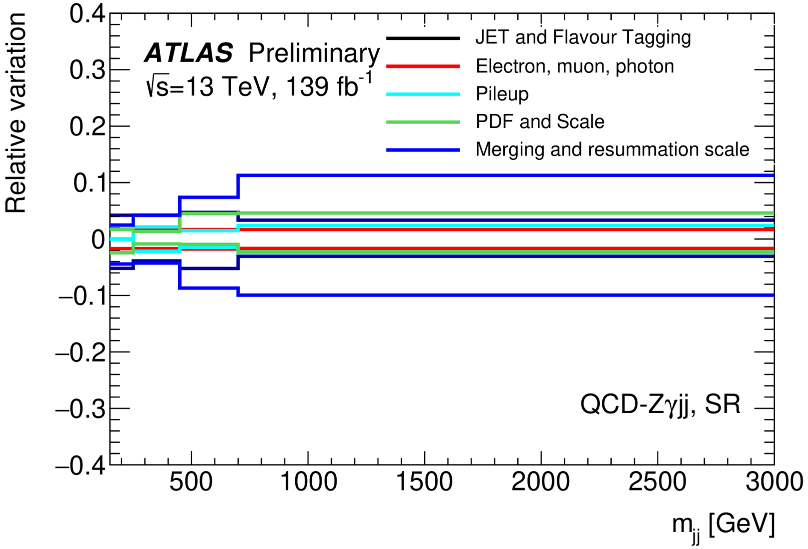


Observation of EW Z(→ll)γjj production

- EW Zγjj observed at 10σ
- Largest uncertainties from theoretical modelling of the two processes

	$\Delta\sigma_{EW}/\sigma_{EW}$ [%]	
EW mod.	QCD mod.	Total
$^{+6}_{-5}$	$^{+5}_{-4}$	±13





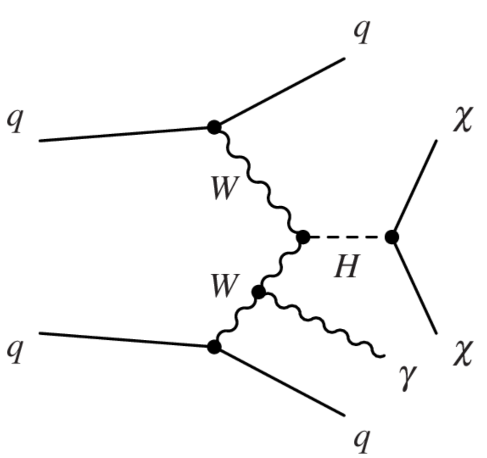
- Fiducial cross-sections measured for both EW Zγjj and EW+QCD Zγjj

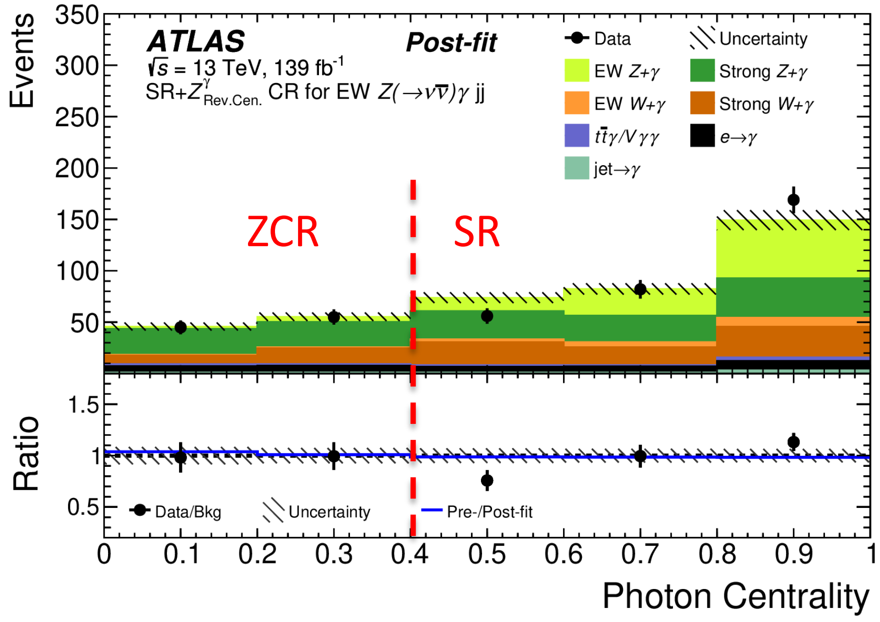
σ(Zγjj)	Measured	Predicted
EW	4.49 ± 0.40 (stat.) ± 0.42 (syst.) fb	4.73 ± 0.01 (stat.) ± 0.15 (PDF)$^{+0.23}_{-0.22}$ (scale) fb
EW+QCD	20.6 ± 0.6 (stat.)$^{+1.2}_{-1.0}$ (syst.) fb	20.4 ± 0.1 (stat.) ± 0.2 (PDF)$^{+2.6}_{-2.0}$ (scale) fb

Consistent with LO, MadGraph5_aMC@NLO predictions

Observation of EW Z(→$\nu\nu$)γjj production

- Analysis originally designed to search for VBF H(→invisible)γ — EPJC 82 (2022) 105
- Dominant backgrounds: QCD Z(→$\nu\nu$)γ+jets and W(→$l\nu$)γ+jets
  - Wγ +jets: using CRs with one selected lepton
  - Z(→$\nu\nu$)γ: reversing the C_γ requirement



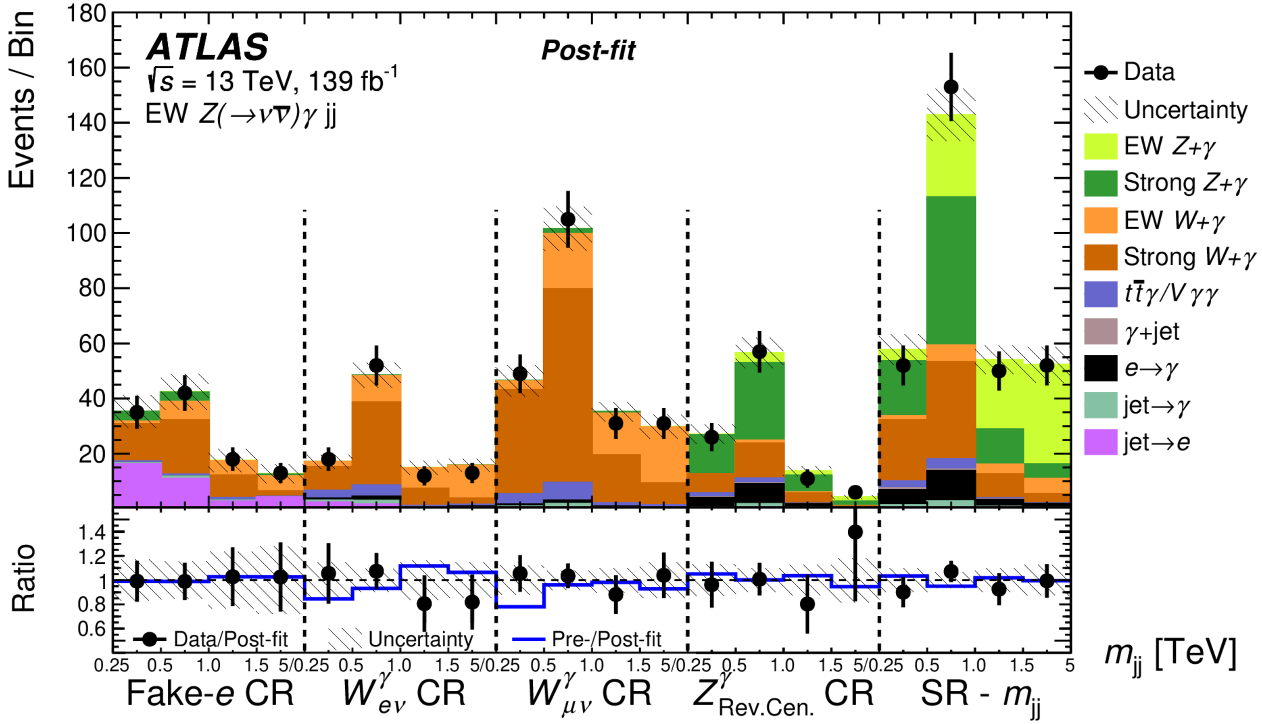


$$C_\gamma = \exp\left[-\frac{4}{(\eta_1-\eta_2)^2}\left(\eta_\gamma - \frac{\eta_1+\eta_2}{2}\right)^2\right]$$

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

Observation of EW $Z(\rightarrow\nu\nu)\gamma jj$ production

- Events are categorized into 4 m_{jj} bins
- Signal extracted from simultaneous fit of SRs and CRs
- EW $Z(\rightarrow\nu\nu)\gamma jj$ observed at 5.1σ

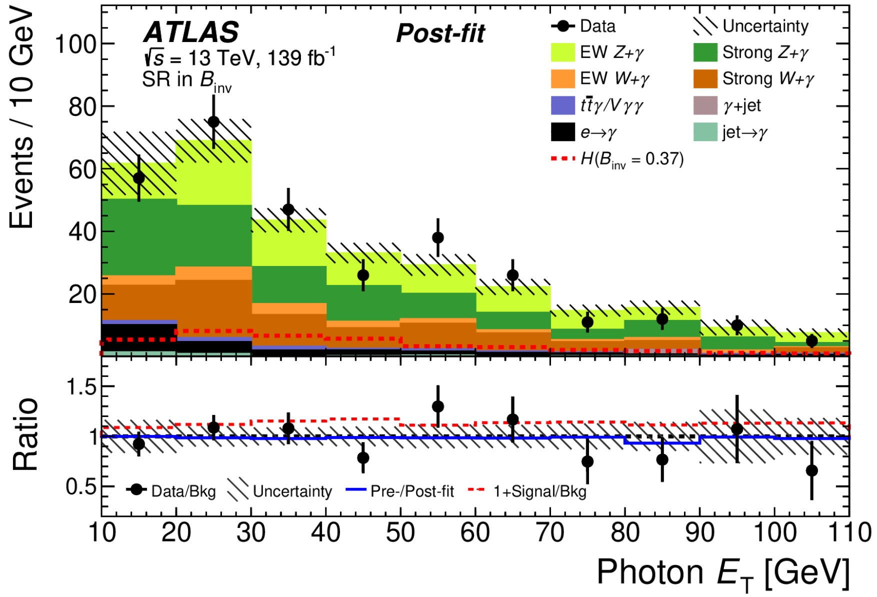


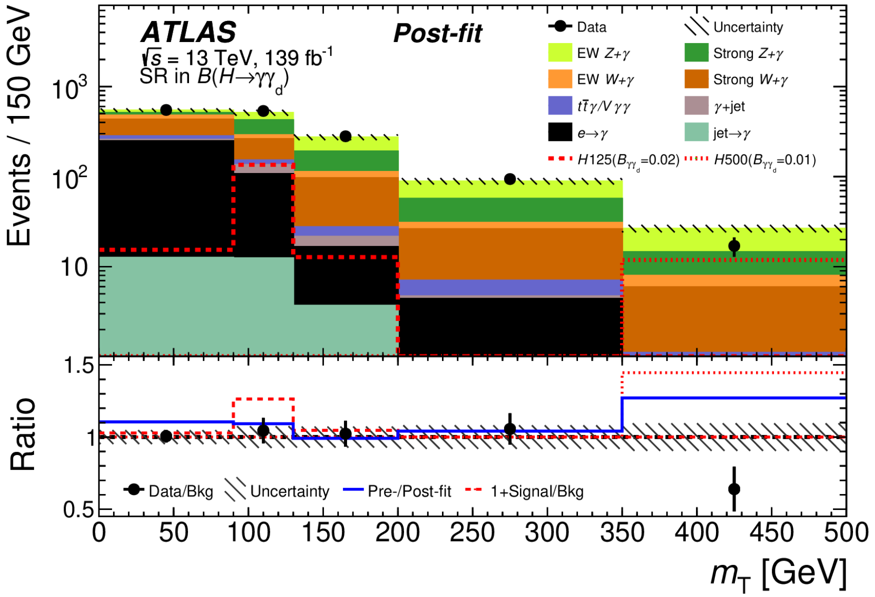
$\mu_{Z\gamma_{EW}}$	$\beta_{Z\gamma_{strong}}$	$\beta_{W\gamma}$
1.03 ± 0.25	1.02 ± 0.41	1.01 ± 0.20

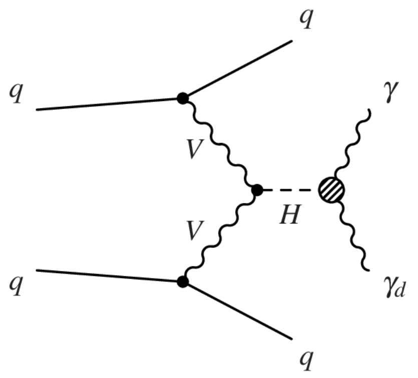
Source	1σ Uncertainty on $\mu_{Z\gamma_{EW}}$
Jet scale and resolution	0.076
$V\gamma$ + jets theory	0.067
pile-up	0.040
Photon	0.035
$e\rightarrow\gamma$, jet$\rightarrow e,\gamma$ Bkg.	0.035
Lepton	0.027
E_T^{miss}	0.023
Signal theory shape	0.020
Signal theory acceptance	0.12
Data stats.	0.16
$W\gamma$ + jets/$Z\gamma$ + jets Norm.	0.073
MC stats.	0.063
Total	0.25

Observation of EW Z(→$\nu\nu$)γjj production

- Measured fiducial cross-section: 1.31 ± 0.20(stat) ± 0.20(syst) fb
- Predictions:
  - 1.27 ± 0.01(stat) ± 0.17(scale) ± 0.03(pdf) fb
  - LO from MadGraph and 0.3% NLO QCD K-factor correction from VBFNLO
- The observation of EW production of $Z(\rightarrow \nu\nu)\gamma jj$ lays the groundwork for BSM searches
  - Invisible Higgs and H→$\gamma\gamma_d$





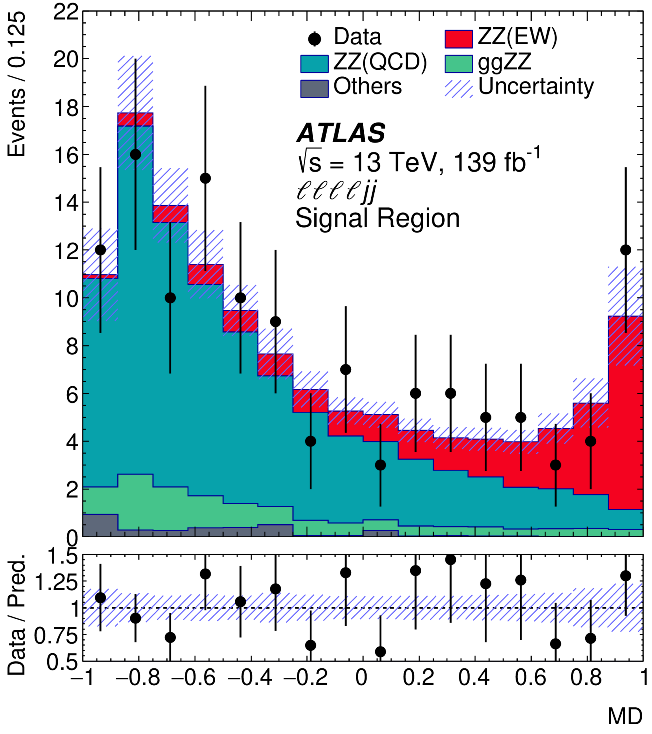


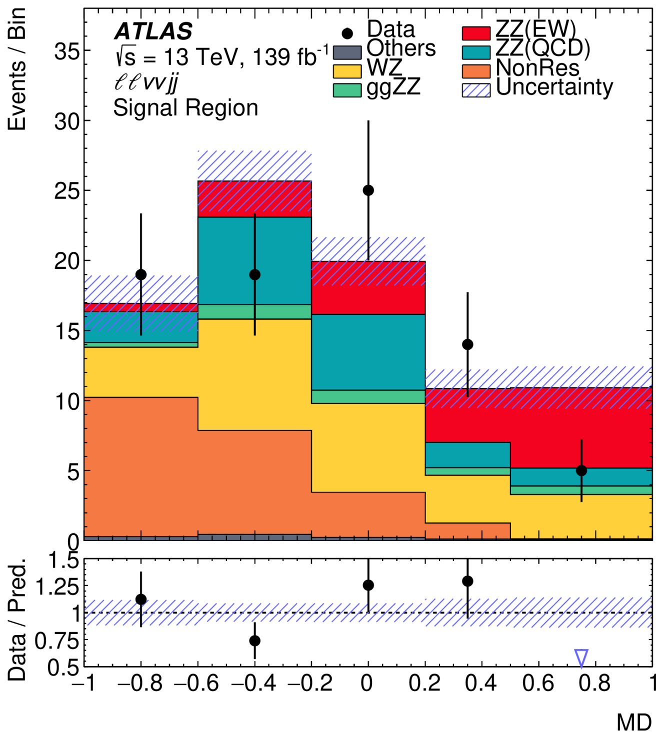
Observation of EW ZZjj production

arXiv:2004.10612

- Two final states 4l and 2l2v used and combined
  - Very low rates, but clean final states in 4l
- Using BDT to separate EW and QCD ZZjj
- CRs used to constrain the QCD ZZjj

	$\mu_{\rm EW}$	$\mu_{\rm QCD}^{\ell\ell\ell\ell jj}$	Significance Obs. (Exp.)
$\ell\ell\ell\ell jj$	1.5 ± 0.4	0.95 ± 0.22	$5.5\ (3.9)\ \sigma$
$\ell\ell\nu\nu jj$	0.7 ± 0.7	–	$1.2\ (1.8)\ \sigma$
Combined	1.35 ± 0.34	0.96 ± 0.22	$5.5\ (4.3)\ \sigma$





Fiducial cross-sections measured for the inclusive EW+QCD ZZjj production

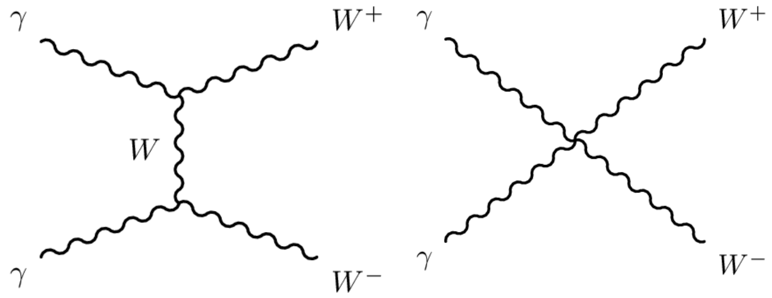
EW+QCD	Measured	Predicted
llljj	1.27 ± 0.14 fb	1.14 ± 0.04(stat) ± 0.20(theo)
llvvjj	1.22 ± 0.35 fb	1.07 ± 0.01(stat) ± 0.12(theo)

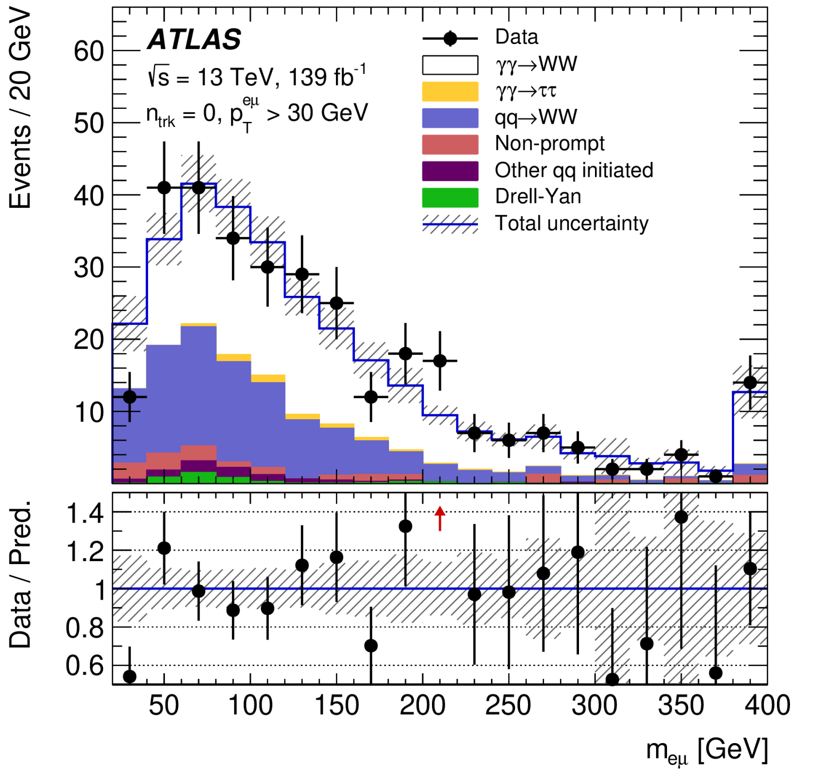
EW: LO MadGraph
QCD: Sherpa 0,1j@NLO+2,3j@LO

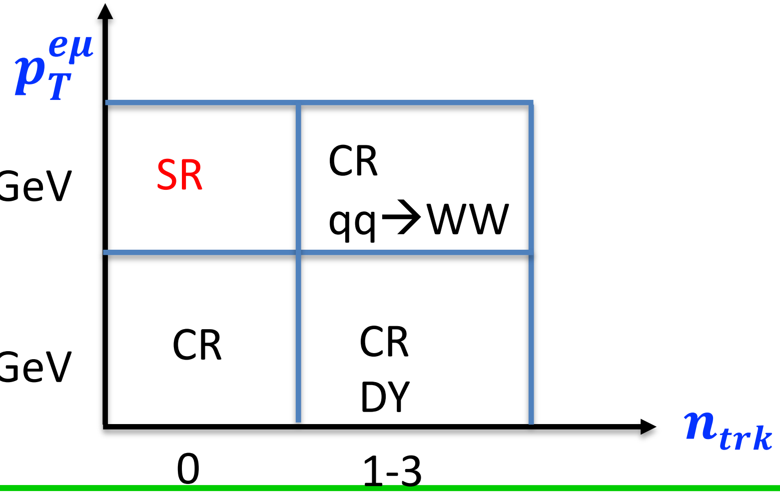
Observation of $\gamma\gamma \rightarrow W^{\pm}W^{\mp}$ production

PLB 816 (2021) 136190

- At LO, only involves diagrams with TGCs and QGCs
- Signal includes both elastic and dissociative contributions
- Only WW→$e\nu\mu\nu$ used to suppress the background
  - CRs used to constrain qq→WW and Drell-Yan
  - ee and $\mu\mu$ events used to constrain $\gamma\gamma \rightarrow ll/WW$ [3.59 ± 0.15]
- Measured fiducial cross-section:
  - σ(γγ→WW) = 3.13 ± 0.31(stat) ± 0.28(sys) fb (8.4 σ)
  - Consistent with SM predictions



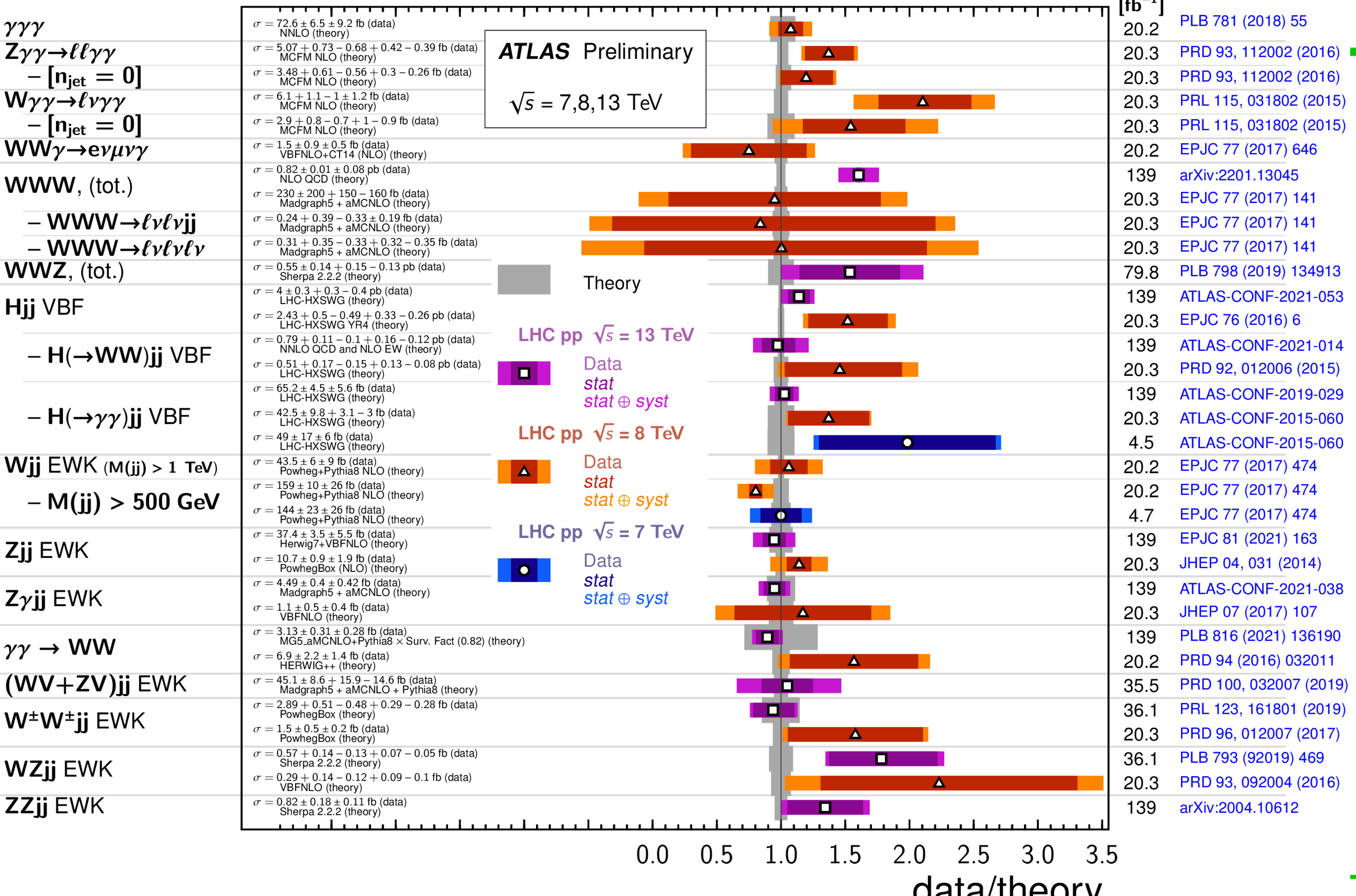




ATL-PHYS-PUB-2022-009

VBF, VBS, and Triboson Cross Section Measurements

Status: February 2022



Summary

- VBS/VBF processes are essential probes to unveil the nature of the Higgs mechanism
  - Also sensitive to new physics that modifies TGCs, QGCs and HVV couplings
    - Sensitivity grows with $\sqrt{\hat{s}}$
- Comprehensive program within ATLAS to measure EW Vjj and VVjj productions
  - Entering from the discovery phase to the precision measurement phase
  - Large theory uncertainties in many channels
  - Background modelling is also key to precisely measure these processes

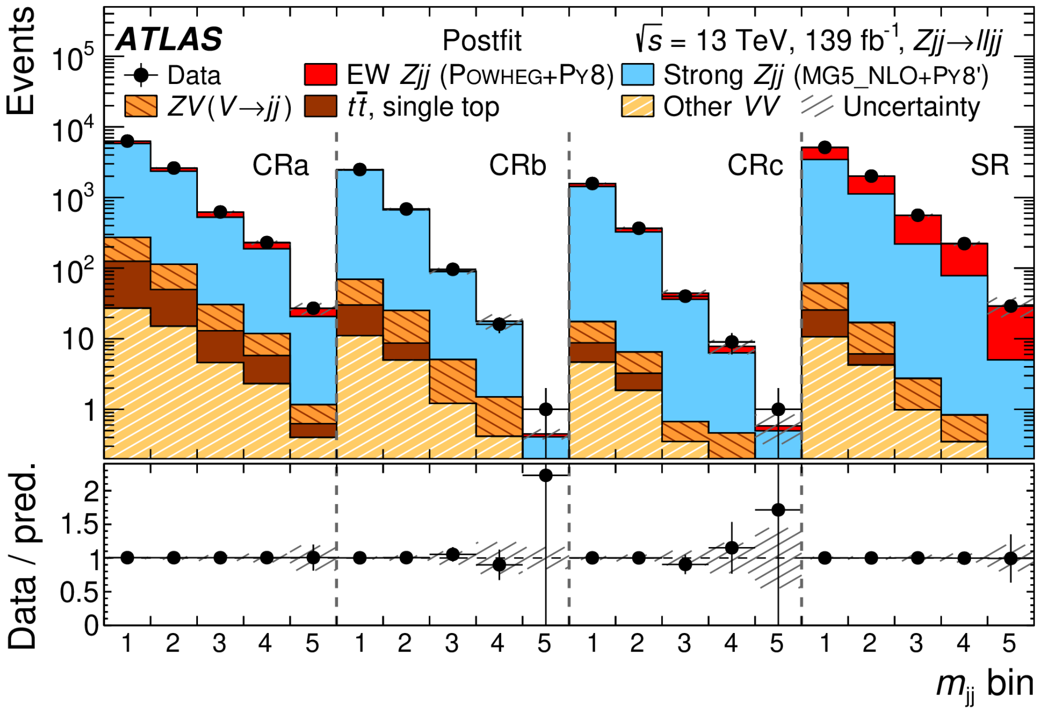
See also:
EFT interpretations by Evgeny, May 16

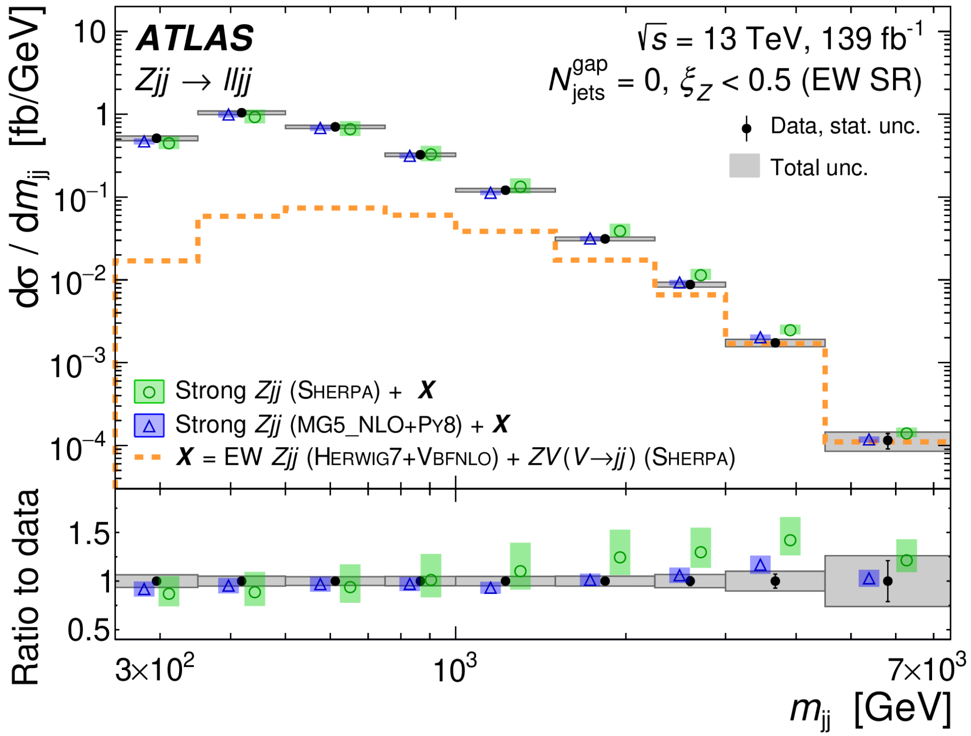
Backup

Differential measurements of EW Zjj production

EPJC81(2021)163

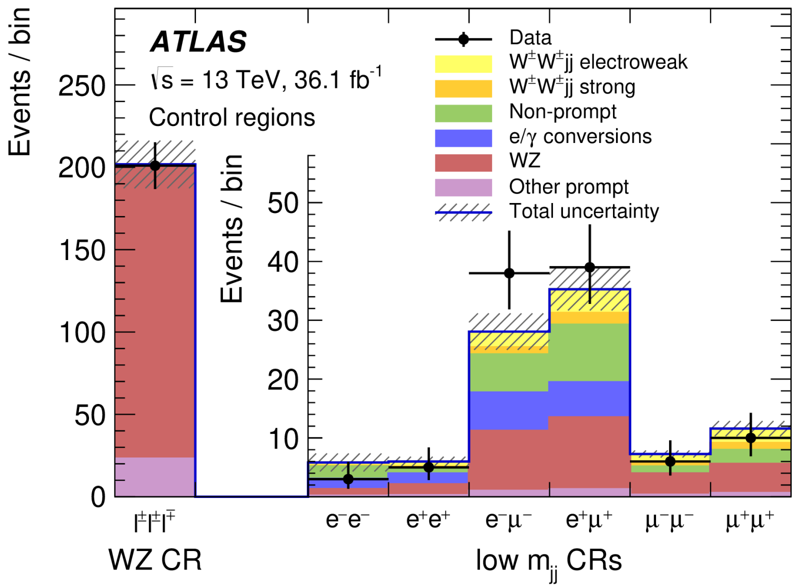
- Probe VBF production and triple gauge couplings
- QCD Zjj background constrained in each bin of observable using control regions
- Poor modelling of m_{jj} by MC event generators → corrected using data
- Differential cross-sections measured in m_{jj}, $|\Delta y_{jj}|$, $p_T ll$ and $\Delta\phi_{jj}$
  - Using bin-by-bin EW Zjj signal strengths

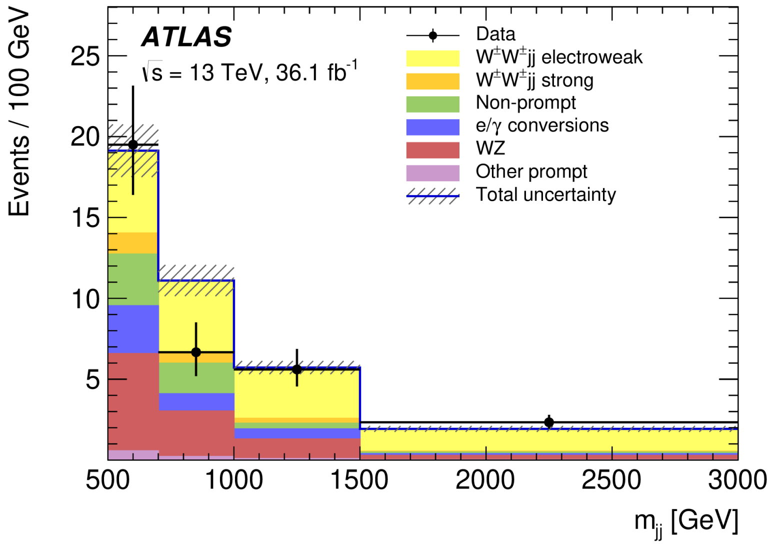


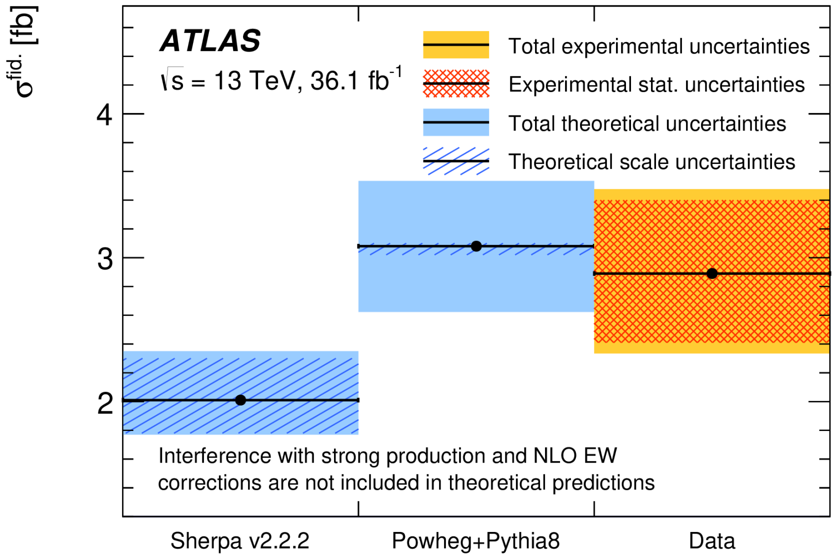


Electroweak W±W±jj production

- Highest signal to background ratio among all VBS measurements
- Same-sign dilepton final states
- Data-driven estimation for non-prompt and charge-flip background
- Control regions for WZ and QCD W±W±jj

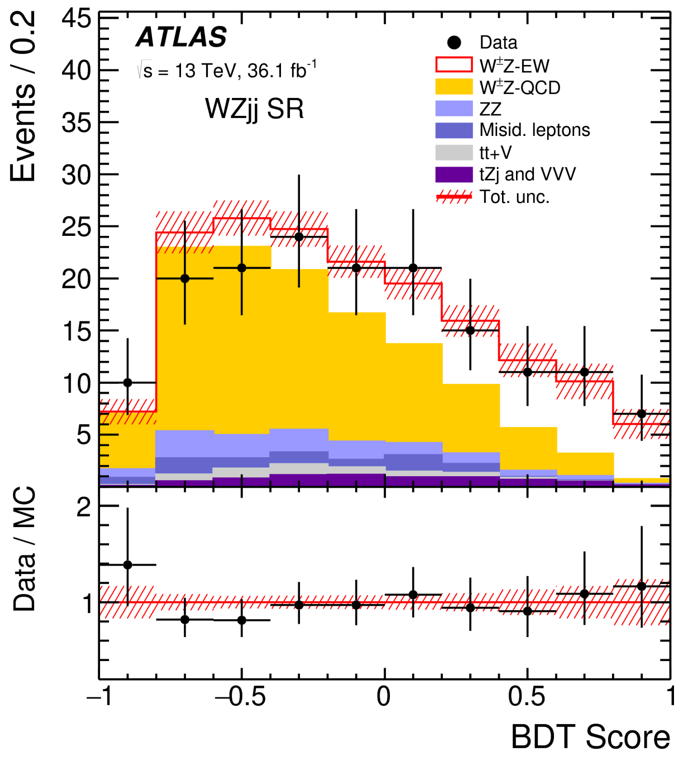




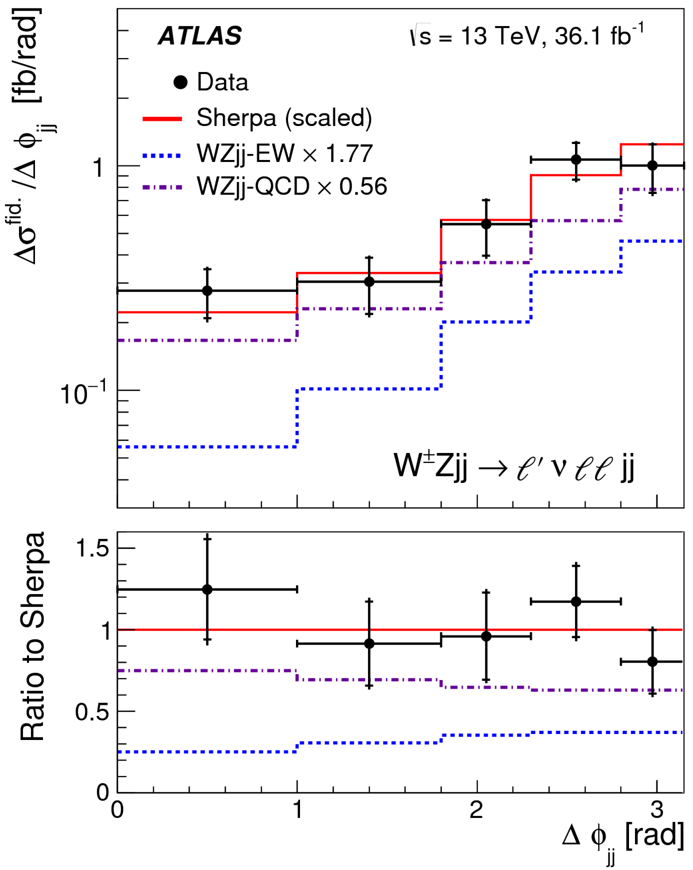


Electroweak WZ(→ $lvll$)jj production

- BDT used to discriminate between EW signal and QCD background
- QCD WZjj constrained using a CR
- Differential cross-sections measured for the inclusive EW+QCD WZ(→ $lvll$)jj production



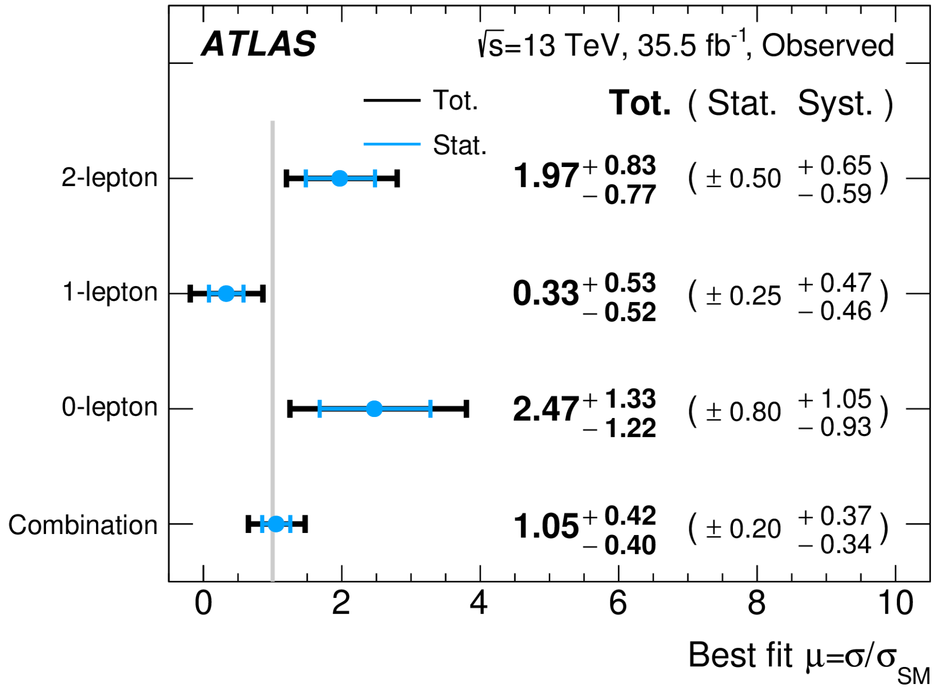
Observed significance: 5.3 σ
(expected: 3.2 σ)



EW VVjj Production in semileptonic final states

- Analysis performed in three lepton channels
  - 0-lepton ($\nu\nu qq$), 1-lepton ($l\nu qq$) and 2-lepton ($llqq$)
- Do not distinguish between W→qq' and Z→qq
  - allow for both boosted (one large-radius jet) and resolved (two small-radius jets) topologies
- 6 separate BDTs are trained for 0/1/2 lepton and boosted and resolved regions

PRD100(2019)032007



Observed significance: 2.7 σ
Expected significance: 2.5 σ

Observation of $\gamma\gamma \rightarrow W^{\pm}W^{\mp}$ production

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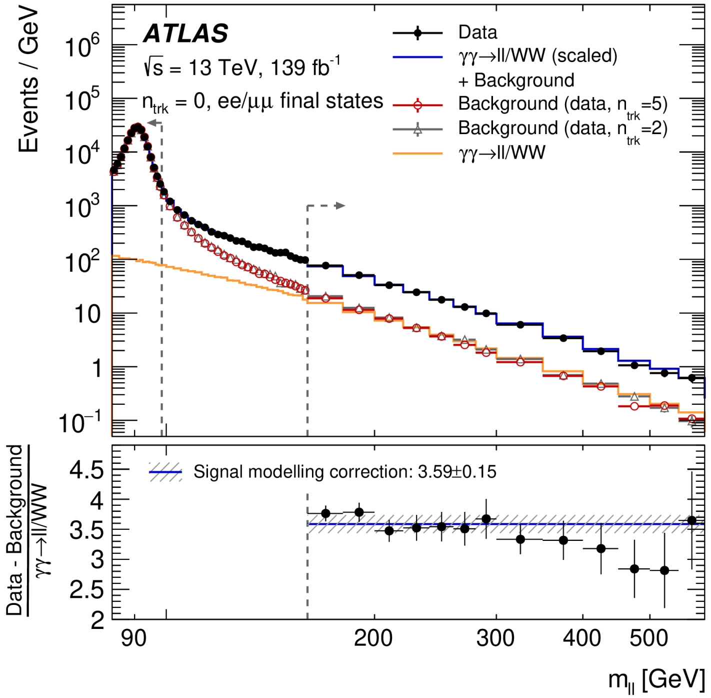

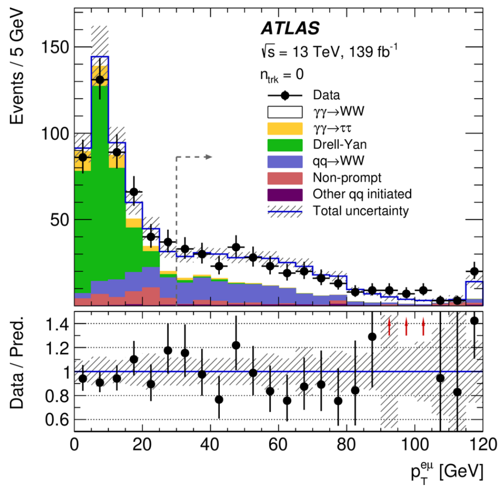

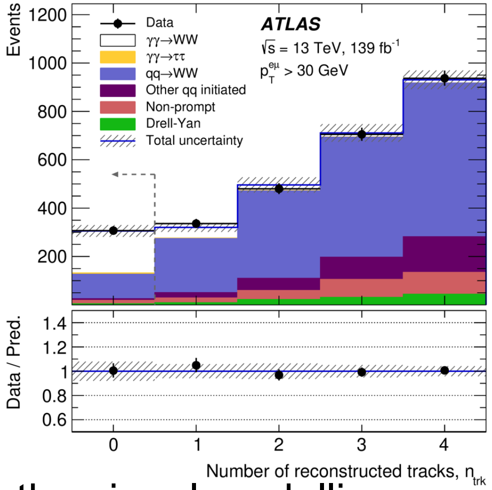

Source of uncertainty	Impact [% of the fitted cross section]
Experimental	
Track reconstruction	1.1
Electron energy scale and resolution, and efficiency	0.4
Muon momentum scale and resolution, and efficiency	0.5
Misidentified leptons, systematic	1.5
Misidentified leptons, statistical	5.9
Other background, statistical	3.2
Modelling	
Pile-up modelling	1.1
Underlying-event modelling	1.4
Signal modelling	2.1
WW modelling	4.0
Other background modelling	1.7
Luminosity	1.7
Total	8.9

The distribution of $m_{\ell\ell}$ in the region where the signal modelling correction is extracted as the ratio of the yield of $\gamma\gamma \rightarrow \ell\ell$ and $\gamma\gamma \rightarrow WW$ processes passing the exclusivity requirement of $n_{track}=0$ to the yield of the simulated elastic process only.