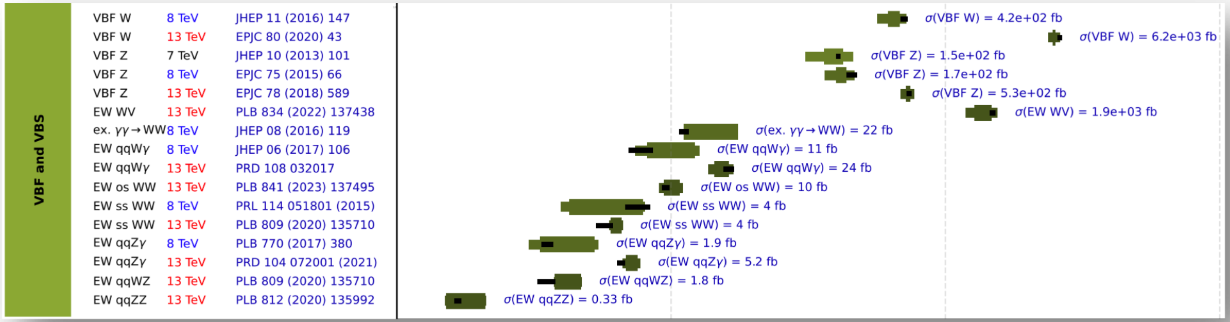
VBS: 3 slides of comparison

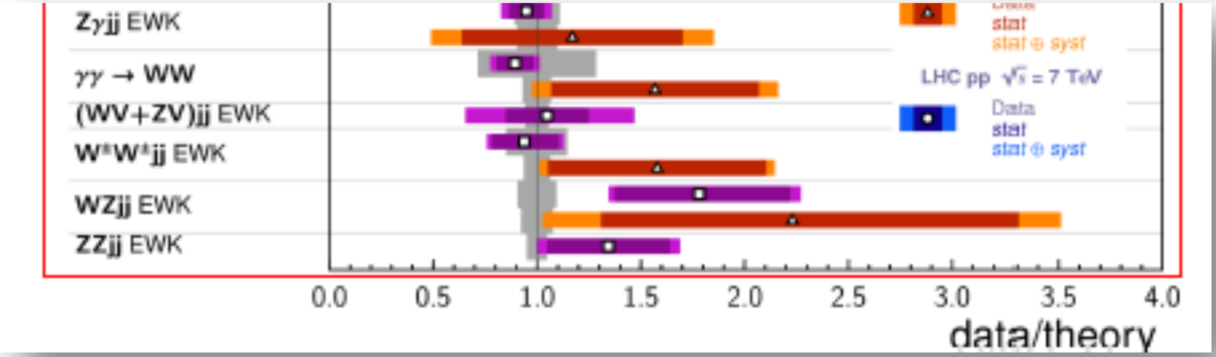
1. WWjj opposite-sign (OS) leptons
2. WWjj with same-sign (SS)
3. W/Z + γ

* Newest results reported, full Run 2 statistics and leptonic channels (cleanest ones)

CMS



ATLAS EXPERIMENT

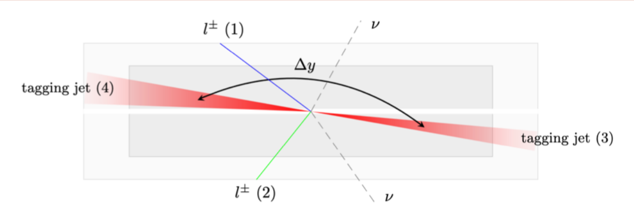


Elisabetta Gallo (DESY and University of Hamburg)

DESY. CLUSTER OF EXCELLENCE QUANTUM UNIVERSE

UH Universität Hamburg DER FORSCHUNG | DER LEHRE | DER BILDUNG

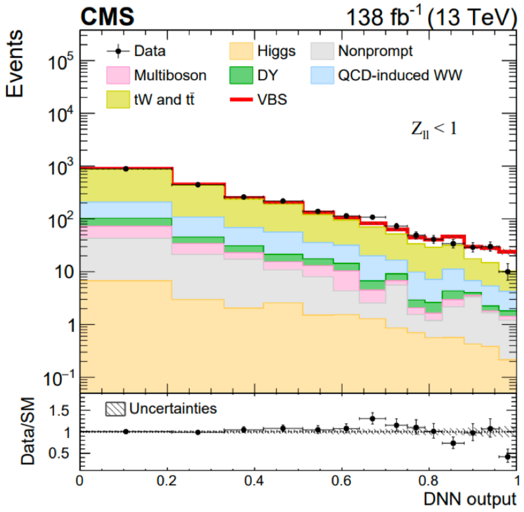
W^+W^- jj in two leptons, OS



PLB 841 (2023) 137495

Obs.+xsec

- Both ee/$\mu\mu$, $e\mu$, *observation* 5.6 σ (5.0 σ expected)



$e\mu$

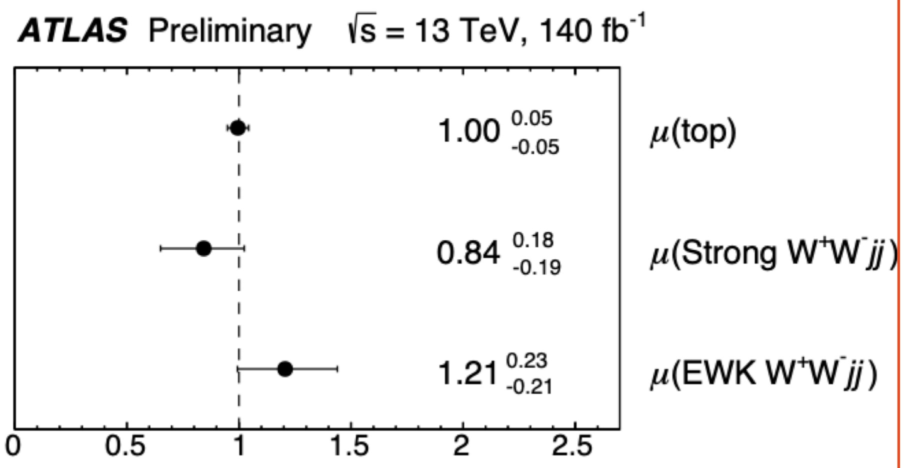
$$\sigma_{fid} = 10.2 \pm 2.0 \text{ fb @LO}$$
$$\sigma_{fid}^{theo} = 9.1 \pm 0.6 \text{ fb @LO}$$

cross-section in fiducial region (13% stat, 14% syst.)

ATLAS-CONF-2023-039

Obs. + xsec

- Only $e\mu$, split SR in 2, 3 jets
- Observation 7.1 σ (6.2 σ expected)
- Top well constrained in the fit from a CR



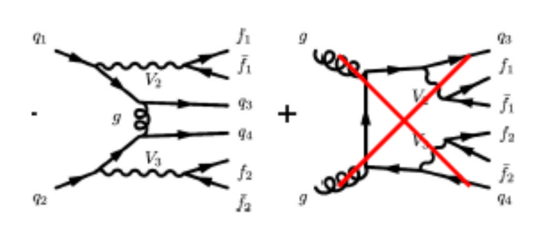
EWK WWjj 12% stat out of 18% total uncertainty, similar to CMS, but slightly better with just one channel. Slightly better experimental uncertainties?

- Sensitive channel, both experiment observation, in agreement with SM
- Top main backgrounds, especially challenging in $e\mu$, constrained in both by CR with b-jets
- ATLAS splitting 2,3 jets. gains sensitivity of 1 σ

-> but still better with only $e\mu$ channel

- Uncertainties dominated by statistical and theoretical
- Question: Can we find a common fiducial region to compare CMS-ATLAS?

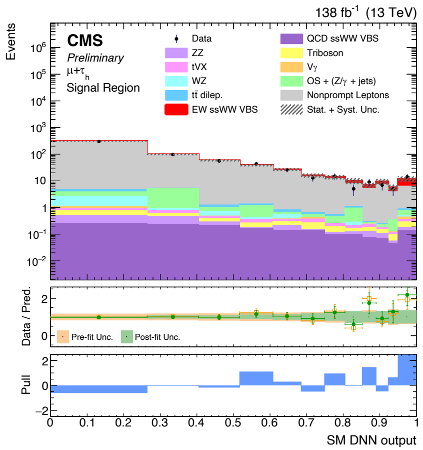
WW jj in two leptons, SS



[CMS-PAS-SMP-22-008](CMS-PAS-SMP-22-008)

SS leptons, one as hadronic tau: 2.7 σ

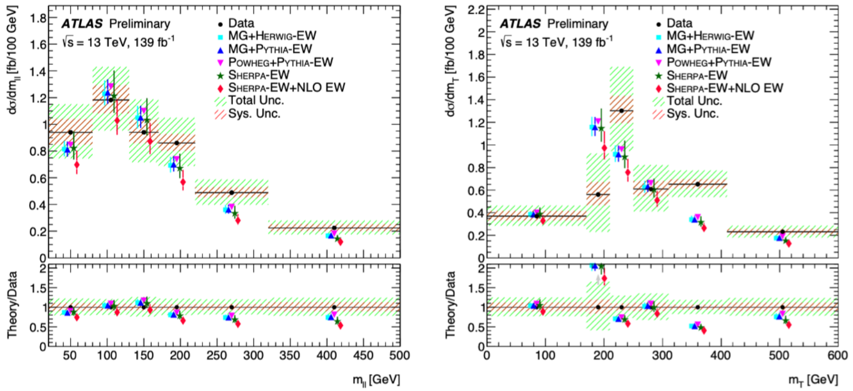
- Largest background jets faking τ_h , estimated from data
- EW 2.7 σ (1.9 σ expected), but first measurement of this kind
- Still statistics limited



ATLAS-CONF-2023-023

e or μ: Obs.+ xsec+ BSM

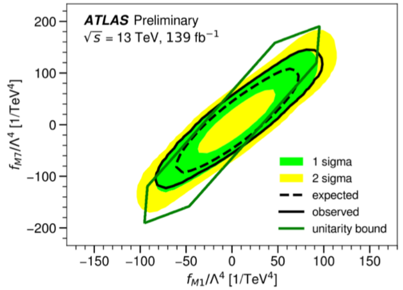
- Largest EWK to QCD ratio, 52% purity
- Already observed in 2016 data, now moving to fiducial/differential cross sections
- Predictions generally OK, a bit lower especially for NLO, m_T not well reproduced



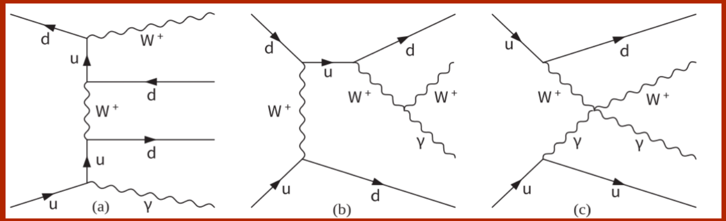
Also observed by CMS ($W_L W_L$) [PLB 812 (2021) 136018](PLB 812 (2021) 136018)

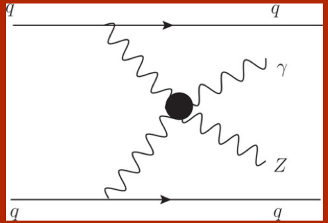
- Golden channel SS e or μ provides the best sensitivity
- Moving to differential cross sections and BSM limits (aQGC, dim-8 EFTs)
- τ_h still statistically limited, large jet-fake background, but interesting to try it

- EFT interpretation



W or Z + γ jj

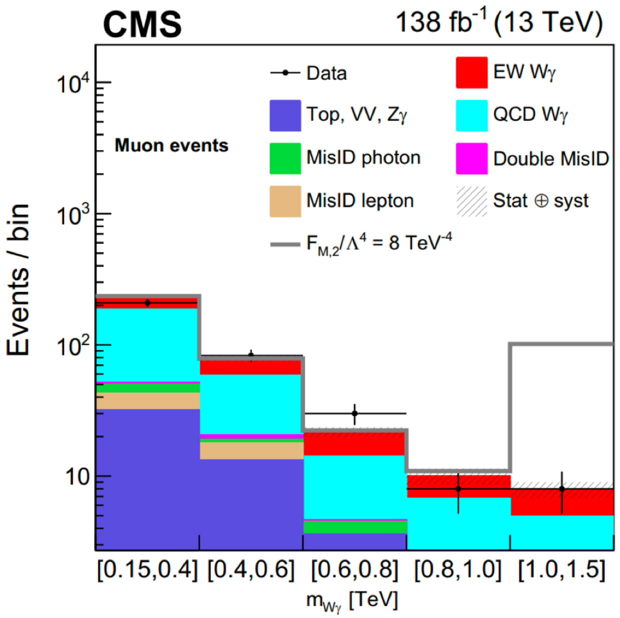




[PRD 108 (2023) 032017](PRD 108 (2023) 032017)

W γjj Obs. + diff xsec + EFT-dim8

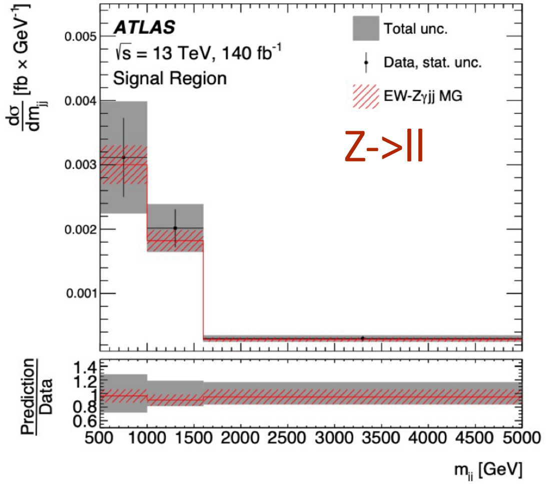
- EWK W γjj process 6.0σ observed (6.8σ *expected)*
- QCD W γjj is the dominant background
- Photon background challenge



arXiv:2305.19142

$Z\gamma jj$ Obs. + xsec + diff

- $Z\gamma jj$ in dilepton + neutrino channel, observed process, differential cross section in ll
- Sensitive to neutral quartic coupling



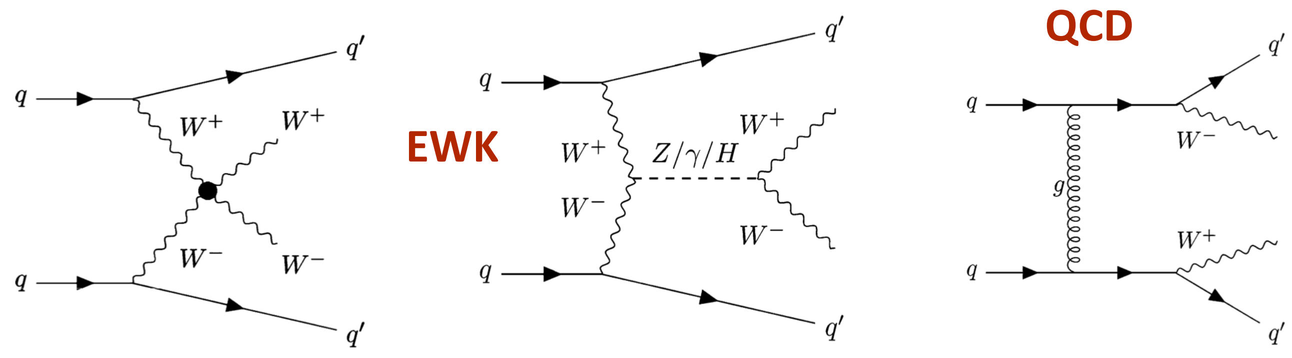
	Data stat.	MC stat.	Background	Reco	EW mod.	QCD mod.	Total
$\Delta\sigma_{EW}/\sigma_{EW}$ [%]	±9	±1	±1	±4	$^{+8}_{-6}$	±2	±13
$\Delta\sigma_{Z\gamma}/\sigma_{Z\gamma}$ [%]	±3	±1	±2	$^{+4}_{-3}$	$^{+7}_{-6}$	±9	$^{+12}_{-11}$

- Improved sensitivity in ATLAS $Z\gamma jj$ by adding the neutrino channel
- Both allow differential cross sections and aQGC interpretations
- Also dim-8 EFT operators

- ATLAS also ZZjj in 4l, full reconstruction of final state, less stat.
- VBS combined fit for EFT parameters in the future. Exploit Run2+Run 3 combinations, think of trigger strategies

Backup

W^+W^- jj in two leptons, OS



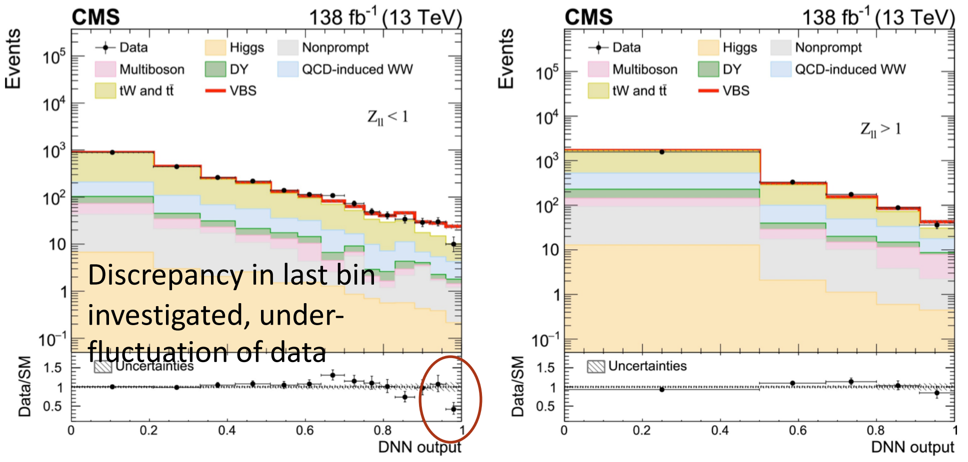
- Two OS leptons (electrons or muons), with dilepton mass $m_{\ell\ell} > 50$ GeV and transverse momentum $p_T^{\ell\ell} > 30$ GeV, are selected with the tight selections described in Refs. [50], [51]. The thresholds for the highest and second-highest p_T leptons are 25 and 13 GeV, respectively. Events with an additional lepton with $p_T > 10$ GeV are rejected;
- p_T^{miss} > GeV;
  20
- At least two jets with $p_T > 30$ GeV, $m_{jj} > 300$ GeV, and $|\Delta\eta_{jj}| > 2.5$.

Table 1: Summary of the event categorization on top of signal candidates preselection. In each region, same-flavor final states share the same kinematic requirements.

Region	Final state	Requirements	Subregion
SR	eμ/μe	$m_T > 60$ GeV $m_{\ell\ell} > 50$ GeV no b jet with $p_T > 20$ GeV	$Z_{\ell\ell} < 1$ $Z_{\ell\ell} > 1$
	ee	$m_{\ell\ell} > 120$ GeV $p_T^{miss} > 60$ GeV no b jet with $p_T > 20$ GeV	$Z_{\ell\ell} < 1$ $Z_{\ell\ell} > 1$
	μμ		$Z_{\ell\ell} < 1$ $Z_{\ell\ell} > 1$
$t\bar{t}$ + tW CR	eμ/μe	$m_{\ell\ell} > 50$ GeV at least one b jet with $p_T > 20$ GeV	
	ee	$m_{\ell\ell} > 120$ GeV $p_T^{miss} > 60$ GeV at least one b jet with $p_T > 20$ GeV	
	μμ		
DY CR	eμ/μe	$m_T < 60$ GeV $50\,\text{GeV} < m_{\ell\ell} < 80$ GeV no b jet with $p_T > 20$ GeV	
	ee	$\lvert m_{\ell\ell} - m_Z\rvert < 15$ GeV $p_T^{miss} > 60$ GeV no b jet with $p_T > 20$ GeV	$\lvert\Delta\eta_{jj}\rvert < 5$ $\lvert\Delta\eta_{jj}\rvert > 5$
	μμ		$\lvert\Delta\eta_{jj}\rvert < 5$ $\lvert\Delta\eta_{jj}\rvert > 5$

Uncertainty source	Value
QCD-induced W^+W^- normalization	5.3%
$t\bar{t}$ scale variation	5.1%
VBS signal scale variation	5.0%
$t\bar{t}$ normalization	4.9%
b tagging	3.5%
Trigger corrections	3.3%
DY normalization	2.9%
Jet energy scale + resolution	2.6%
Unclustered p_T^{miss}	2.4%
QCD-induced W^+W^- scale variation	2.1%
Integrated luminosity	2.0%
Muon efficiency	2.0%
Pileup	1.8%
Electron efficiency	1.5%
Underlying event	1.3%
Parton shower	1.0%
Other	<1%
Total systematic uncertainty	13.1%
Total statistical uncertainty	14.9%

Process	SR eμ $Z_{\ell\ell}$ < 1	SR eμ $Z_{\ell\ell}$ > 1	SR ee - μμ $Z_{\ell\ell}$ < 1	SR ee - μμ $Z_{\ell\ell}$ > 1
DATA	2441	2192	1606	1667
Signal + background	2396.8 ± 98.5	2239.6 ± 106.0	1590.4 ± 49.4	1660.5 ± 43.6
Signal	169.1 ± 20.2	69.9 ± 8.4	98.0 ± 6.5	38.3 ± 2.5
Background	2227.7 ± 96.4	2169.7 ± 105.6	1492.4 ± 48.9	1622.1 ± 43.5



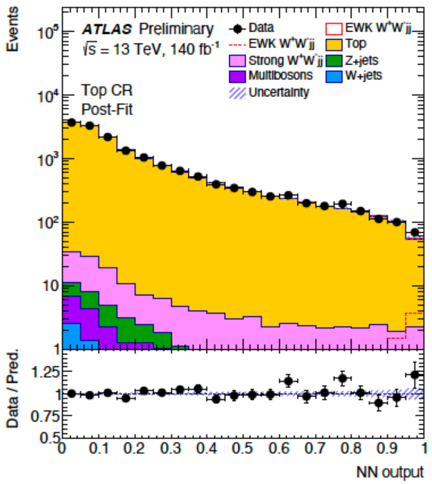
W^+W^- jj in two leptons, OS

Category	Requirements
Leptons	$p_T > 27$ GeV $\lvert\eta\rvert < 2.47$ excluding $1.37 < \lvert\eta\rvert < 1.52$ (electrons) $\lvert\eta\rvert < 2.5$ (muons) Identification: `TightLH` (electrons), `Tight` (muons) Isolation: `Gradient` (electrons), `Tight_FixedRad` (muons) $\lvert d_0/\sigma_{d_0}\rvert < 5$ (electrons), $\lvert d_0/\sigma_{d_0}\rvert < 3$ (muons) $\lvert z_0 \sin\theta\rvert < 0.5$ mm
b-jets	$p_T > 20$ GeV and $\lvert\eta\rvert < 2.5$ (`DL1r` *b*-tagging with 85% efficiency)
Jets	$p_T > 25$ GeV and $\lvert\eta\rvert < 4.5$
Events	One electron and one muon with opposite electric charges No additional lepton with $p_T > 10$ GeV, `Loose` isolation, `TightLH/MediumLH` (electrons) and `Loose` (muons) identification $\zeta > 0.5$ $m_{e\mu} > 80$ GeV $E_T^{miss} > 15$ GeV Two or three jets No *b*-jet

Table 1: Selection cuts on physics objects and events that define the signal region.

Sources	$\frac{\sqrt{(\Delta\mu)^2-(\Delta\mu')^2}}{\mu}$ (%)
Monte Carlo statistical uncertainty	7.7
Top quark theoretical uncertainties	6.3
Signal theoretical uncertainties	5.8
Jet experimental uncertainties	4.9
Strong W^+W^-jj theoretical uncertainties	1.3
Luminosity	0.8
Mis-identified lepton uncertainty	0.5
b-tagging	0.4
Lepton experimental uncertainties	0.1
Others	0.3
Data statistical uncertainty	12.3
Top quark normalisation uncertainty	4.9
Strong W^+W^-jj normalisation uncertainty	2.2
Total uncertainty	18.5

Process	Event yields $n_{jets} = 2$	$n_{jets} = 3$
EWK W^+W^-jj	158 ± 27	54 ± 13
Top quark	2885 ± 214	1851 ± 131
Strong W^+W^-jj	1214 ± 256	514 ± 121
W+jets	37 ± 97	19 ± 48
Z+jets	216 ± 62	65 ± 25
Multiboson	101 ± 5	42 ± 3
SM prediction	4610 ± 77	2546 ± 48
Data	4610	2533



WW jj in two leptons, SS with one tau

Table 1: Definition of the SR and four CRs. All regions are disjoint. The SR and three CRs (Nonprompt, $t\bar{t}$, OS) are selected from an inclusive lepton trigger; the QCD enriched CR (last row) is selected from a jet-based trigger.

Region	1 ℓ, 1 τ_h, no additional "loose" ℓ		
	same-sign (ℓ, τ_h)	p_T^{miss} >50 GeV	additional requirements
SR	✓	×	M_{jj} >500 GeV
Nonprompt CR	✓	×	
$t\bar{t}$ CR	×	✓	b-tagged jet ("medium")
OS CR	×	✓	b-tagged jet veto ("loose")
QCD-enriched CR	1 "loose" e, μ, or τ_h, no add. leptons, p_T^{miss} ≤50 GeV, $M_T(\ell, p_T^{miss})$ <50 GeV		

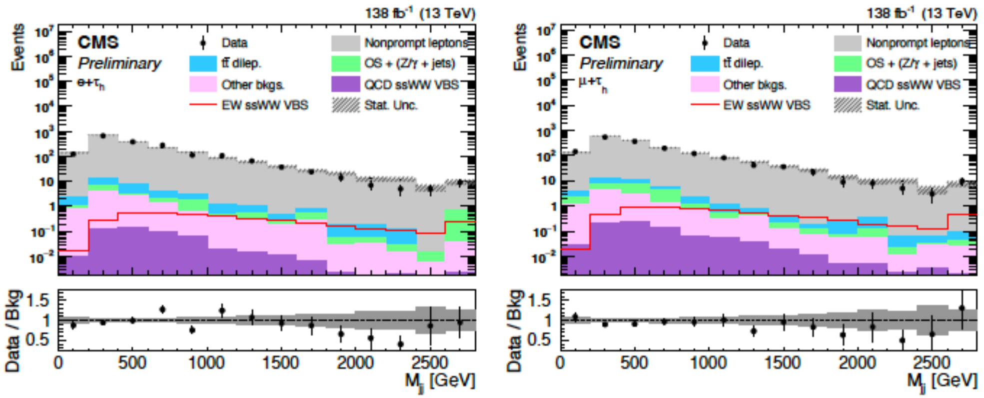


Figure 2: Distributions in the invariant mass of the di-jet system for the data and the pre-fit background prediction for the (left) $e + \tau_h$ and (right) $\mu + \tau_h$ nonprompt CRs. The overflow count is included in the last bin. The solid red line shows the expectation for the EW ssWW signal.

Table 2: The impact of each systematic uncertainty on the signal strength μ as extracted from the fit to measure the SM ssWW VBS signal with the DNN output distributions. Upper and lower uncertainties are given for the various sources.

Uncertainty source	$+\Delta\mu$	$-\Delta\mu$
Theory (PDF, QCD-scale, ISR, and FSR)	+0.157	−0.099
Non-prompt estimation	+0.136	−0.125
$t\bar{t}$ normalization	+0.051	−0.023
Prefiring	+0.105	−0.059
Luminosity	+0.079	−0.092
b-tagging and mistagging	+0.007	−0.004
Jet energy scale and resolution, Pile-up jet ID	+0.079	−0.097
Pileup	+0.152	−0.162
LO-to-NLO VBS corrections	+0.043	−0.025
Unclustered energy	+0.003	−0.010
Hadronic tau energy scale and DEEPTAU	+0.154	−0.152
Charge misidentification	+0.005	−0.010
Lepton reconstruction, identification, and isolation	+0.005	−0.024
MC statistical	+0.324	−0.322
Total systematic uncertainty	+0.344	−0.302
Data statistical uncertainty	+0.522	−0.477
Total uncertainty	+0.625	−0.564

WW jj in two leptons, SS

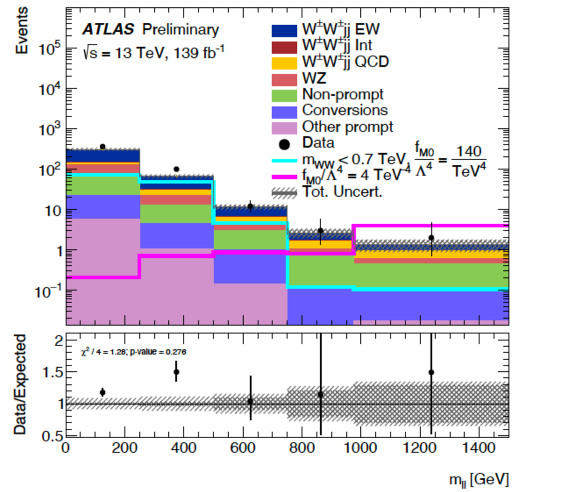
The signal region (SR) event selection is summarised in Table 2. The expected purity of the EW (QCD, Int) $W^{\pm}W^{\pm}jj$ process in the SR is 52% (5.4%, 1.7%).

Table 2: Signal region event selection.

Exactly two signal leptons with $p_T > 27$ GeV and the same electric charge with $\lvert\eta\rvert < 2.5$ for muons and with $\lvert\eta\rvert < 2.47$ excluding $1.37 \leq \lvert\eta\rvert \leq 1.52$ for electrons with $\lvert\eta\rvert < 1.37$ in the ee channel
$m_{\ell\ell'} \geq 20$ GeV 3rd lepton veto $\lvert m_{ee} - m_Z\rvert > 15$ GeV in the ee-channel
$E_T^{miss} \geq 30$ GeV
At least two jets Leading and subleading jets satisfying $p_T > 65$ GeV and $p_T > 35$ GeV, respectively b-jet veto for jets with $p_T > 20$ GeV and $\lvert\eta\rvert < 2.5$ $m_{jj} \geq 500$ GeV $\lvert\Delta y_{jj}\rvert > 2$

$$m_T = \sqrt{\left(E_T^{\ell\ell} + E_T^{miss}\right)^2 - \left|\vec{p}_T^{\,\ell\ell} + \vec{E}_T^{miss}\right|^2},$$

Source	Impact [%]
Experimental	
Electron calibration	0.4
Muon calibration	0.5
Jet energy scale and resolution	1.8
E_T^{miss} scale and resolution	0.2
b-tagging inefficiency	0.7
Background, misid. leptons	3.1
Background, charge misrec.	0.8
Pileup modelling	0.2
Luminosity	1.9
Modelling	
EW $W^{\pm}W^{\pm}jj$, shower, scale, PDF & α_s	0.8
EW $W^{\pm}W^{\pm}jj$, QCD corrections	3.5
EW $W^{\pm}W^{\pm}jj$, EW corrections	0.8
Int $W^{\pm}W^{\pm}jj$, shower, scale, PDF & α_s	0.1
QCD $W^{\pm}W^{\pm}jj$, shower, scale, PDF & α_s	2.3
QCD $W^{\pm}W^{\pm}jj$, QCD corrections	0.9
Background, WZ scale, PDF & α_s	0.2
Background, WZ reweighting	1.7
Background, other	1.0
Model statistical	1.8
Experimental and modelling	6.7
Data statistical	7.4
Total	10.0



$W\gamma jj$

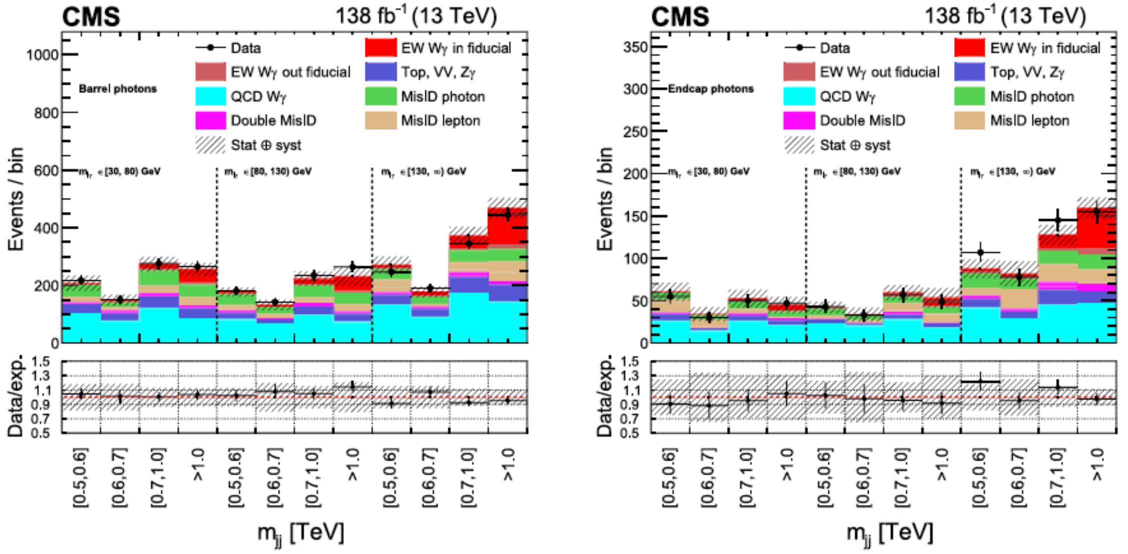


FIG. 3. 2D distributions used in the fit for the total EW $W\gamma$ cross section measurement. The hatched bands represent the combined statistical and systematic uncertainties in the predicted yields. The vertical bars on the data points represent the statistical uncertainties of data. The expectation is shown after the fit to the data. EW $W\gamma$ inside (outside) fiducial region stands for the events of EW $W\gamma$ falling inside (outside) the fiducial region defined in Sec. IX.

$$\sigma^{\text{fid}}_{\text{EW}} = 23.5 \pm 2.8(\text{stat})^{+1.9}_{-1.7}(\text{theo})^{+3.5}_{-3.4}(\text{syst})\,\text{fb} = 23.5^{+4.9}_{-4.7}\ \text{fb}.$$

TABLE II. Exclusion limits at the 95% CL for each aQGC coefficient, derived from the $m_{W\gamma}$ distribution, assuming all other coefficients are set to zero. Unitarity bounds corresponding to each operator are also listed. All coupling parameter limits are in TeV^{-4}, while U_{bound} values are in TeV.

Expected limit	Observed limit	U_{bound}
$-5.1 < f_{M,0}/\Lambda^4 < 5.1$	$-5.6 < f_{M,0}/\Lambda^4 < 5.5$	1.7
$-7.1 < f_{M,1}/\Lambda^4 < 7.4$	$-7.8 < f_{M,1}/\Lambda^4 < 8.1$	2.1
$-1.8 < f_{M,2}/\Lambda^4 < 1.8$	$-1.9 < f_{M,2}/\Lambda^4 < 1.9$	2.0
$-2.5 < f_{M,3}/\Lambda^4 < 2.5$	$-2.7 < f_{M,3}/\Lambda^4 < 2.7$	2.7
$-3.3 < f_{M,4}/\Lambda^4 < 3.3$	$-3.7 < f_{M,4}/\Lambda^4 < 3.6$	2.3
$-3.4 < f_{M,5}/\Lambda^4 < 3.6$	$-3.9 < f_{M,5}/\Lambda^4 < 3.9$	2.7
$-13 < f_{M,7}/\Lambda^4 < 13$	$-14 < f_{M7}/\Lambda^4 < 14$	2.2
$-0.43 < f_{T,0}/\Lambda^4 < 0.51$	$-0.47 < f_{T,0}/\Lambda^4 < 0.51$	1.9
$-0.27 < f_{T,1}/\Lambda^4 < 0.31$	$-0.31 < f_{T,1}/\Lambda^4 < 0.34$	2.5
$-0.72 < f_{T,2}/\Lambda^4 < 0.92$	$-0.85 < f_{T,2}/\Lambda^4 < 1.0$	2.3
$-0.29 < f_{T,5}/\Lambda^4 < 0.31$	$-0.31 < f_{T,5}/\Lambda^4 < 0.33$	2.6
$-0.23 < f_{T,6}/\Lambda^4 < 0.25$	$-0.25 < f_{T,6}/\Lambda^4 < 0.27$	2.9
$-0.60 < f_{T,7}/\Lambda^4 < 0.68$	$-0.67 < f_{T,7}/\Lambda^4 < 0.73$	3.1

Z γjj and ZZjj

Table 2: Summary of selection criteria applied at particle level.

Lepton	$p_T^\ell > 20, 30(\text{leading})$ GeV, $\lvert\eta_\ell\rvert < 2.5$ $N_\ell \geq 2$
Photon	$E_T^\gamma > 25$ GeV, $\lvert\eta_\gamma\rvert < 2.37$ $E_T^{\text{cone20}} < 0.07 E_T^\gamma$ $\Delta R(\ell, \gamma) > 0.4$
Jet	$p_T^j > 50$ GeV, $\lvert y_j\rvert < 4.4$ $\lvert\Delta y\rvert > 1.0$ $m_{jj} > 150$ GeV or $m_{jj} > 500$ 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 $\zeta(Z\gamma) < 0.4$ $N_{\text{jets}}^{\text{gap}} = 0$

$$\mu_{\text{EW}} = 1.02 \pm 0.09\ (\text{stat}) \pm 0.09\ (\text{syst}) = 1.02^{+0.13}_{-0.12}.$$

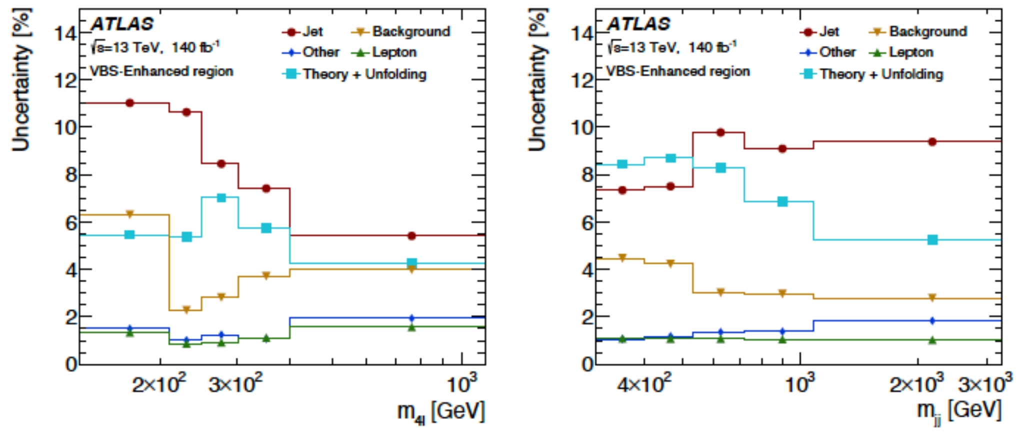


Figure 3: Systematic uncertainties in the differential cross section for $4\ell jj$ production in the VBS-enhanced region as a function of $m_{4\ell}$ (left) and m_{jj}(right).

Table 3: The breakdown of the systematic uncertainties in the *EW-Zγjj* and *Zγjj* cross-sections. The EW modelling component includes interference, parton shower, underlying event, PDF and QCD scale uncertainties in the *EW-Zγjj* process. The QCD modelling component includes merging scale, resummation scale, PDF and QCD scale uncertainties in the *QCD-Zγjj* process.

	Data stat.	MC stat.	Background	Reco	EW mod.	QCD mod.	Total
$\Delta\sigma_{EW}/\sigma_{EW}$ [%]	±9	±1	±1	±4	$^{+8}_{-6}$	±2	±13
$\Delta\sigma_{Z\gamma}/\sigma_{Z\gamma}$ [%]	±3	±1	±2	$^{+4}_{-3}$	$^{+7}_{-6}$	±9	$^{+12}_{-11}$

From talk at EPS 2023 M. Presilla

Recent results

CMS

PROCESS	RESULTS	REFERENCE
polarized ssWW	W_LW_L measurement	PLB 812 (2020) 136018
ZZ (4ljj)	4.0 σ + dim-8 EFT limits	PLB 812 (2021) 135992
osWW (2l2vjj)	Observation + XS	PLB 841 (2023) 137495
★ ssWW to τ_h	2.7 σ	CMS-PAS-SMP-22-008
Wγ	Observation, differential XS + dim-8 EFT	PLB 811 (2020) 135988 + arXiv:2212.12592
VBS Zγ	Observation	PRD.104.072001
★ VV semi-leptonic	WVjj evidence with full Run2 data	PLB 834 (2022) 137438
Wpp (4jpp)	Dim-6/8 QGCs (100/fb CMS+TOTEM)	JHEP 07 (2023) 229

ATLAS EXPERIMENT

PROCESS	RESULTS	REFERENCE
Zγ (2vγjj)	Observation + dim-8 EFT	JHEP 06 (2023) 082
Zγ (2lγjj)	Observation + XS + differential XS	arXiv:2305.19142 ★
ZZ (4ljj)	Diff. XS+ dim-8 EFT	ATLAS-CONF-2023-024 ★
osWW (2l2vjj)	Observation + XS	ATLAS-CONF-2023-039 ★
ssWW + WZ	Combined EFT interpretation (36/fb)	ATL-PHYS-PUB-2023-002
ssWW	Diff. XS + BSM +EFT interpretation	ATLAS-CONF-2023-023 ★
ZZ (4ljj, 2vjj)	Observation	Nature Phys. 19 (2023) 237

★ Focus of this talk