Fiducial and differential cross-section measurements of EW $W\gamma jj$ production at 13TeV with the ATLAS detector

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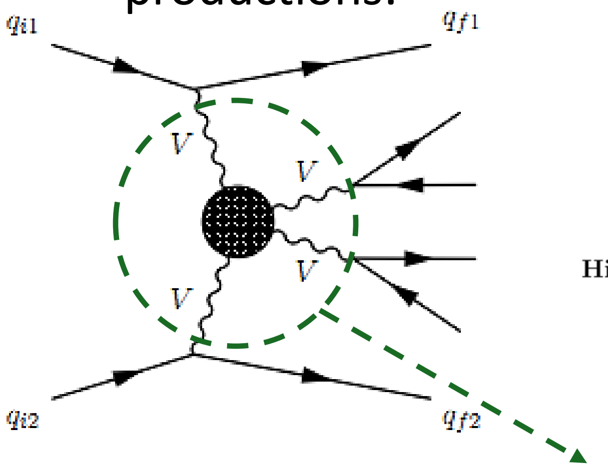
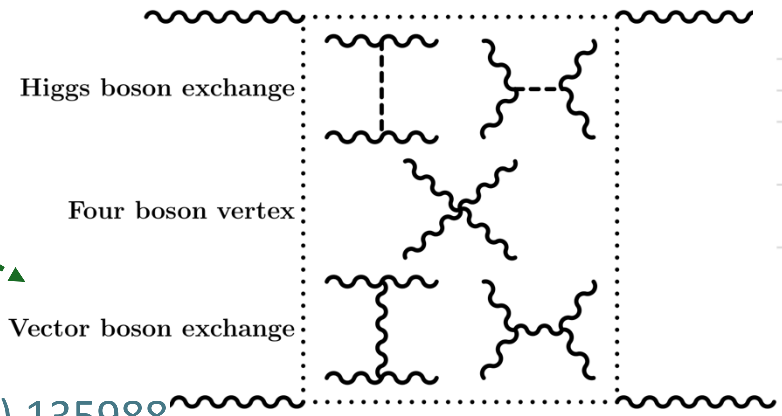
Introduction

- **Vector boson scattering (VBS)** measurements offers an important way to probe electroweak symmetry breaking.
- Sensitive to new physics: **probe aTGC, aQGC …**
- A good probe of the SM in the electroweak (EW) sector. Measure VBS via the corresponding EW productions.

$W\gamma jj$

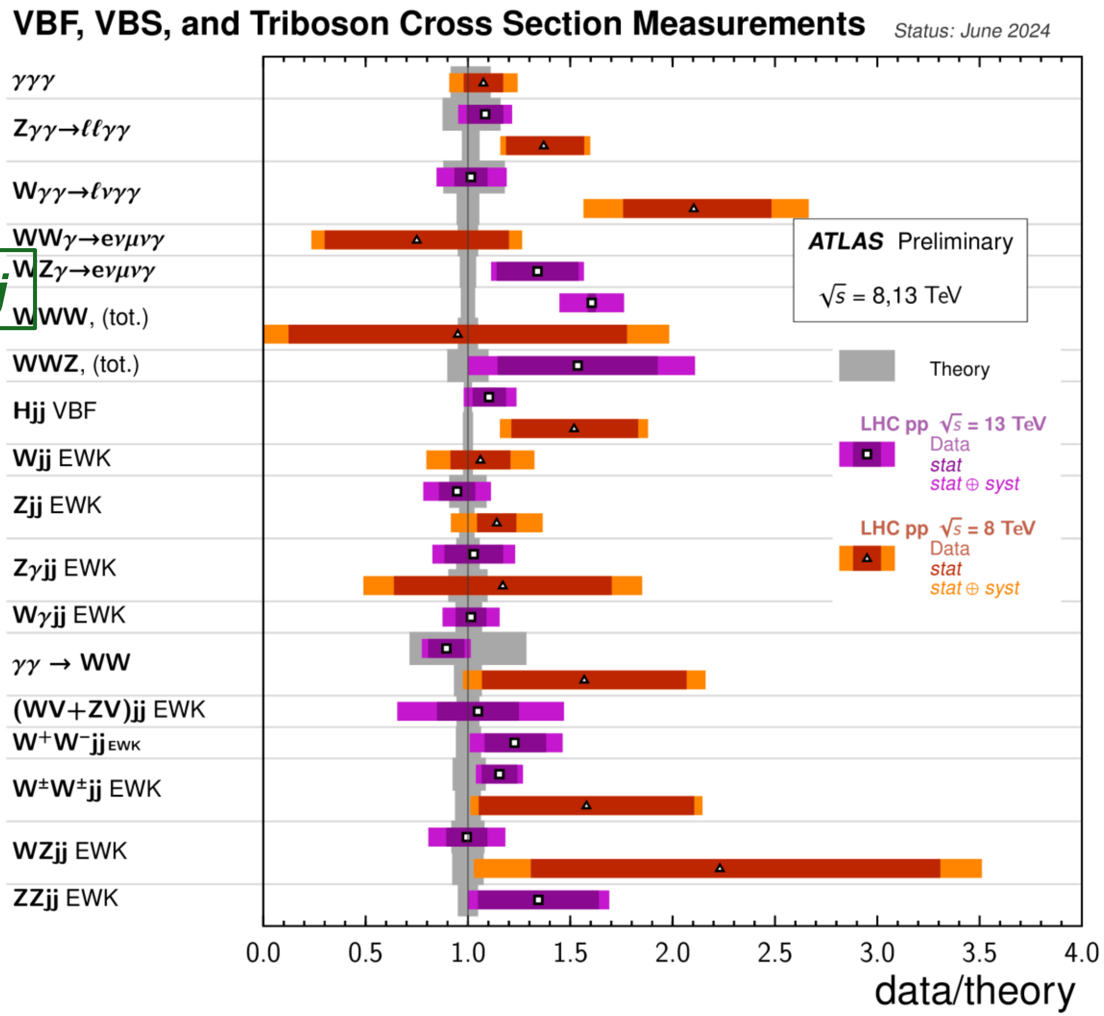


- For VBS processes, many channels have been measured and observed at LHC.



- CMS $W\gamma jj$:

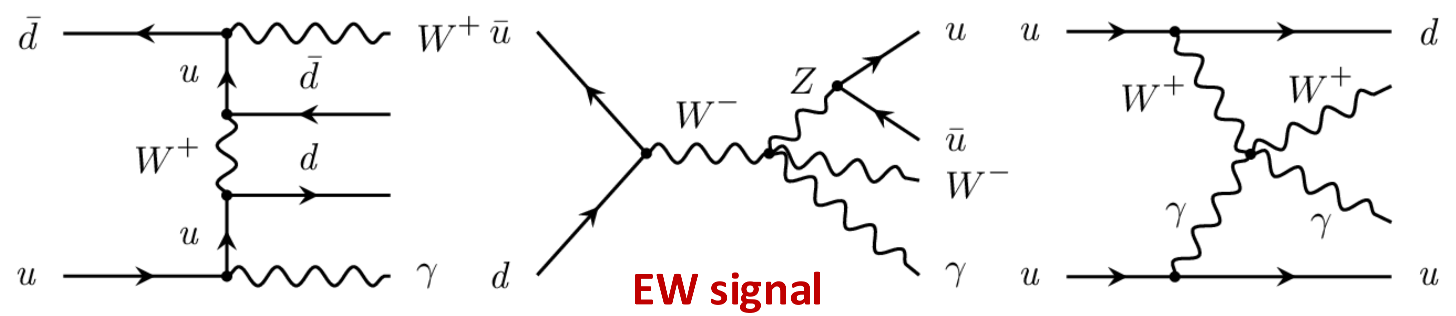
  Phys. Lett. B 811 (2020) 135988
  Phys. Rev. D 108 (2023) 032017



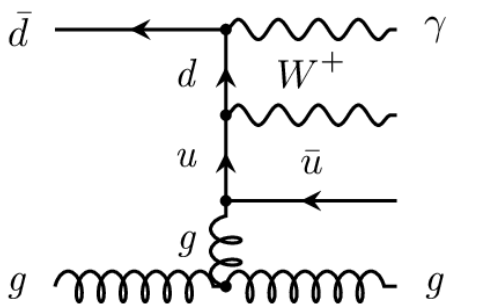
1st observation of EW $W\gamma jj$ at ATLAS.

$W\gamma jj$

- **EW $W(\rightarrow l\nu)\gamma jj$:**
  - **Observation** of EW $W\gamma jj$ production.
  - **Differential cross-section** measurements.
  - Limits on **aQGC**.
- **Full Run2 datasets (140 fb^{-1}).**



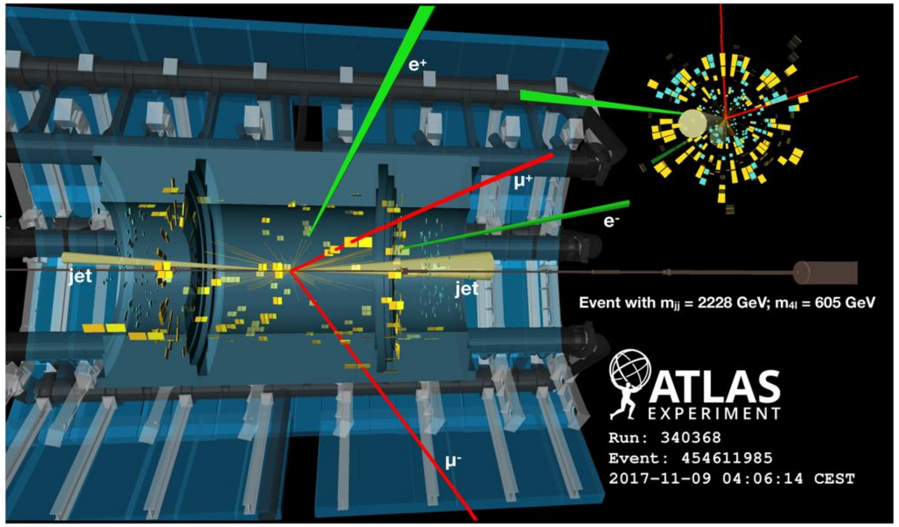
EW signal



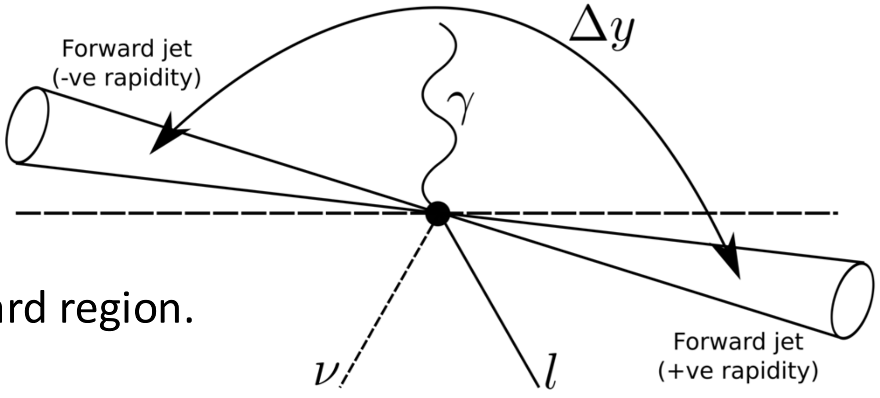
Irreducible QCD background

- VBS topology:

$ZZjj$



Nature Physics 19 (2023) 237-253



$W(\rightarrow l\nu)\gamma jj$

- Perform measurement in **VBS-enhanced** phase space.
  - two energetic jets in the forward and backward region.
  - High m_{jj}, large Δy_{jj}.

Analysis strategy

- **Observation and fiducial cross section measurement**
  - A control region (CR) is defined to constrain the QCD background.
  - Data driven method is used to estimate all non-prompt, fake, pileup backgrounds.
  - Fit the Neural Network (NN) output to extract the signal strength (μ_{EW}).
  - Fiducial cross-section is obtained by correcting the detector effects.

- **Differential cross section measurement**
  - Three CRs are defined to constrain QCD background.
  - Observables: $m_{jj}, p_T^{jj}, p_T^{l}, m_{l\gamma}$(VBS observables, sensitive to aQGC), $\Delta\phi_{jj}, \Delta\phi_{l\gamma}$(Charge conjugation and Parity observables, probe CP structure).
  - EFT interpretation: The six unfold observable distributions are used to constrain dimension-8 (D-8) operators (sensitive to quartic gauge couplings).

$$\Delta\phi_{jj} = \phi_f^j - \phi_b^j \Leftarrow y_f^j > y_b^j$$

$$\Delta\phi_{l\gamma} = \phi_f - \phi_b \Leftarrow y_f > y_b$$

Object & event selection

- **object selection:**

γ	lepton	Jets
- At least 1 tight and isolated γ. - p_T > 22 GeV. - $\lvert\eta\rvert$ < 2.37.	- 1 tight and isolated lepton. - p_T > 30 GeV. - $\lvert\eta\rvert$ < 2.5. - 2nd lepton veto.	- At least 2 jets. - p_T > 50 GeV. - $\lvert\eta\rvert$ < 4.4. - No b-jets (DL1r at 85%WP)

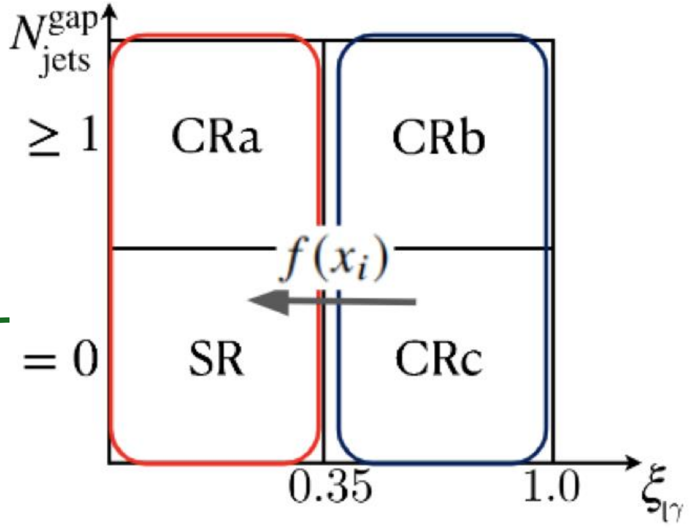
$$\xi_{l\gamma} = \left| y_{l\gamma} - \frac{(y_{j1} + y_{j2})}{2} \middle/ (y_{j1} - y_{j2}) \right|$$

- **Event selection:**
  - m_T^W > 30 GeV.
  - E_T^{miss} > 30 GeV.
  - $|m_{l\gamma} - m_Z|$ > 10 GeV.
  - Standard object overlap removal.

Observation & fiducial cross-section

SR	CR
Δy_{jj} > 2, m_{jj} > 500 GeV	
N_{jets}^{gap} = 0	N_{jets}^{gap} > 0

Differential cross-section



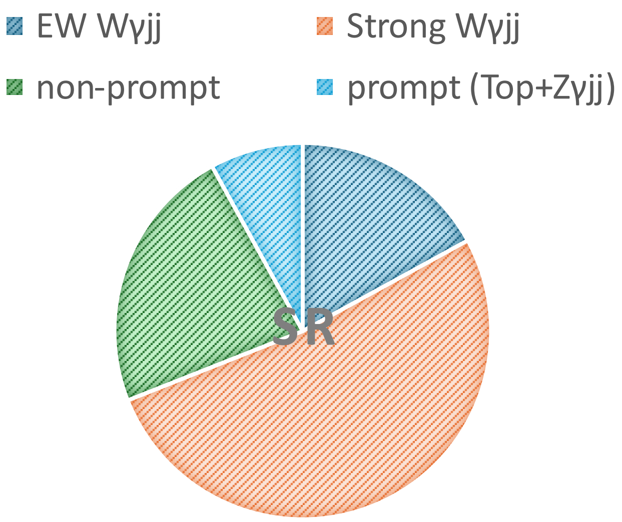
+

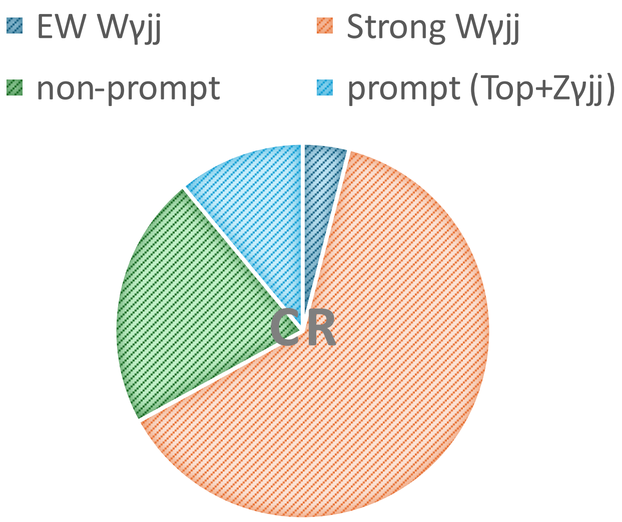
Δy_{jj} > 2
m_{jj} > 1000 GeV

N_{jets}^{gap}:Number of jets in rapidity gap Δy.

Background estimation

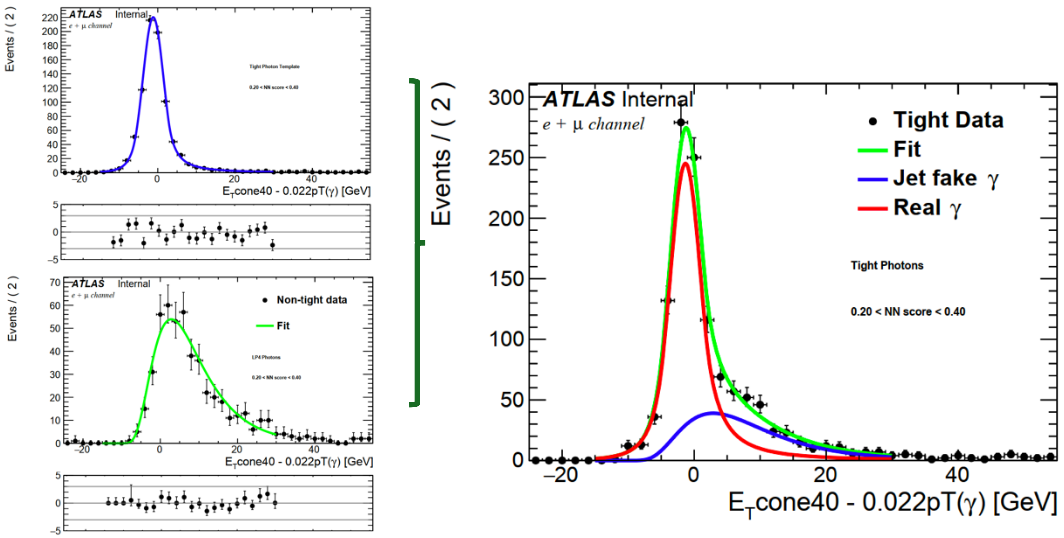
- **QCD background:**
  - Main background.
  - Strong $W\gamma jj$.
  - A control region is defined to constrain the QCD background.
  - Simultaneously fit the NN output in signal region and control region.
- **Prompt background:**
  - Top + $Z\gamma jj$.
  - Estimate by using MC simulation.
- **Non-prompt background:**
  - **Jet fake photon**: Largest non-prompt background (W+jet). A data-driven **template fit** is used.
  - **Jet fake lepton**: Leptons arising from mis-reconstructed jets or in-flight decays of hadrons. **Fake factor** method is used.
  - **Electron fake photon**: Arise from conversions and inefficient calorimeter to track matching (Z+jets & $t\bar{t}$). **Tag & probe** method is used.
  - **Pile-up photon**: A photon originating from one pp interaction is selected alongside a Wjj event from another pp interaction from the same bunch crossing. Data driven method is used.





Background estimation

- **Jet fake photon:**



- Prompt γ isolation shape ← tight ID γ.
- Non-prompt γ isolation shape ← non-tight ID γ.
- Uncertainties: Stat. uncertainty in template & fit, choice of γ ID criteria, real γ subtraction , $E_T^{iso,\gamma}$ modelling.
- ABCD method is used to cross check.

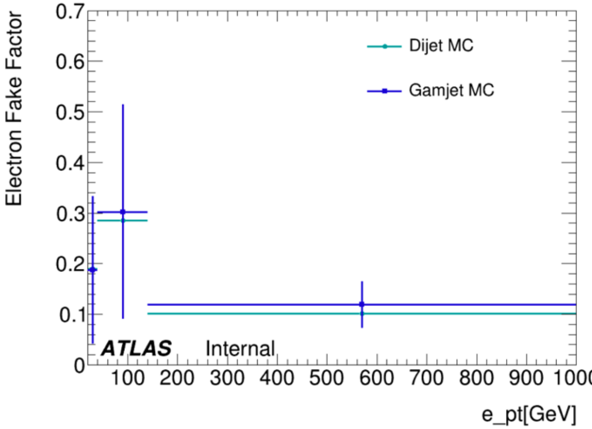
- **Jet fake lepton:**

Fake efficiency: $$\epsilon = \frac{N_e^{tight}}{N_e^{loose}}$$ Fake factor: $$F = \frac{\epsilon}{1-\epsilon}$$

Fake lepton background in SR:

$$N_{fakelep} = F_{e/\mu} \times (N_{e/\mu-data}^{anti-tight} - N_{e/\mu-prompt-lepton}^{anti-tight})$$

- Dijet sample is used to get fake factors. A closure test has performed between dijet and gamjet samples.
- Fake factor with different p_T and η bins are measured.

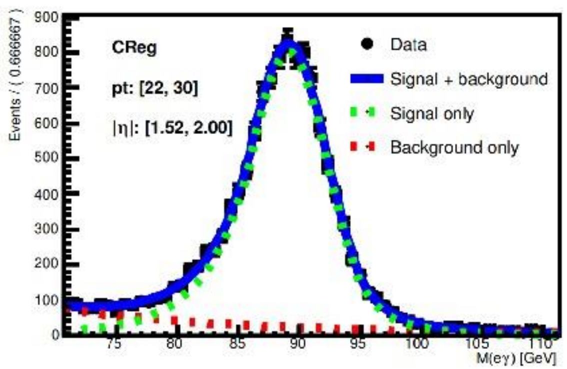


- Uncertainties: Stat., jet composition uncertainty (γ + jet vs dijet), variation of selection cuts, prompt lepton subtraction with different QCD MC samples, variation of p_T, η binning of fake factor, background subtraction in dijet region.

Background estimation

- **Electron fake photon:**
  - Fake and real enriched regions defined by the presence of a probe electron or a probe photon.
  - Fake rate: $$F_{e\to\gamma} = \frac{N_{\gamma}^{reco}\epsilon_{\gamma}}{N_{e}^{reco}\epsilon_{e}}$$

    $\epsilon_{\gamma}, \epsilon_{e}$:the identification efficiency for γ and e.
  - Estimated under Z peak: $|M_Z - M_{e\gamma}| < 10$ using a signal + background fit



$$F_{e\to\gamma} = \frac{N_{e\gamma}}{2N_{ee}} = \frac{S_{e\gamma}+B_{e\gamma}}{2(S_{ee}+B_{ee})} = \frac{S_{e\gamma}+S_{e\gamma}(\frac{1}{S/B})}{2(S_{ee}+S_{ee}(\frac{1}{S/B}))} = \frac{S_{e\gamma}}{2S_{ee}}\frac{(1+\frac{1}{S/B})}{(1+\frac{1}{S/B})} = \frac{S_{e\gamma}}{2S_{ee}}$$

  - uncertainties: Stat., variation of fit range, integration range, p_T, η binning, different fit function in the fit.

- **Pile-up photon**

  Pile-up fraction:

$$f_{PU} = \frac{N_{data}^{|\Delta z|>50mm} - N_{MC}^{|\Delta z|>50mm} * C}{N_{data} * 0.32}$$

  C is a normalization factor derived by comparing the MC to data.

  - Only converted photons with hits in the silicon tracker are used to ensure good resolution.
  - Real photon purity is applied to fake fraction to avoid double counting pileup jets with fake photons.
  - $f_{pu} = (1.7 \pm 1.6)\%$ in SR.

- **Event yields:**

	$\mathrm{SR}^{\mathrm{fid}}\left(N_{\mathrm{jets}}^{\mathrm{gap}}=0\right)$	$\mathrm{CR}^{\mathrm{fid}}\left(N_{\mathrm{jets}}^{\mathrm{gap}}>0\right)$
EW $W\gamma jj$	520 ± 141	120 ± 49
Strong $W\gamma jj$	1550 ± 830	1970 ± 950
Non-prompt	692 ± 57	698 ± 58
Top quark processes	109 ± 18	183 ± 37
EW + strong $Z\gamma jj$	128 ± 34	163 ± 77
Total	3000 ± 830	3140 ± 960
Data	3341	3143

Observation & fiducial cross-section

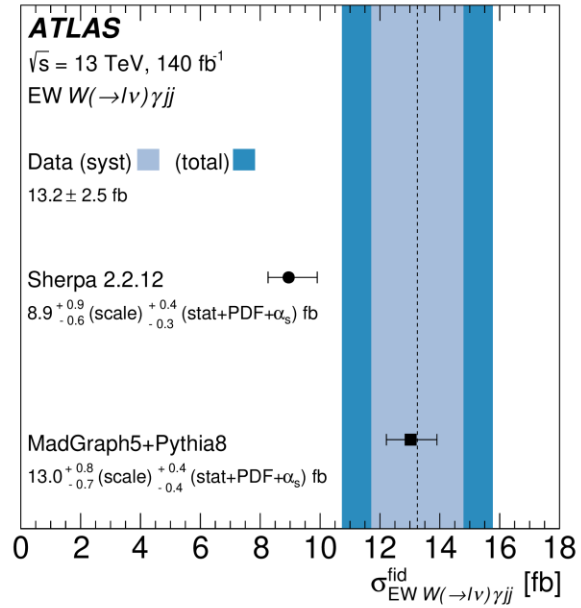
- **Signal extraction:**
  - Simultaneously fit the NN output in signal region and control region.
  - Two floating normalization factors: μ_{EW} & μ_{strong}.

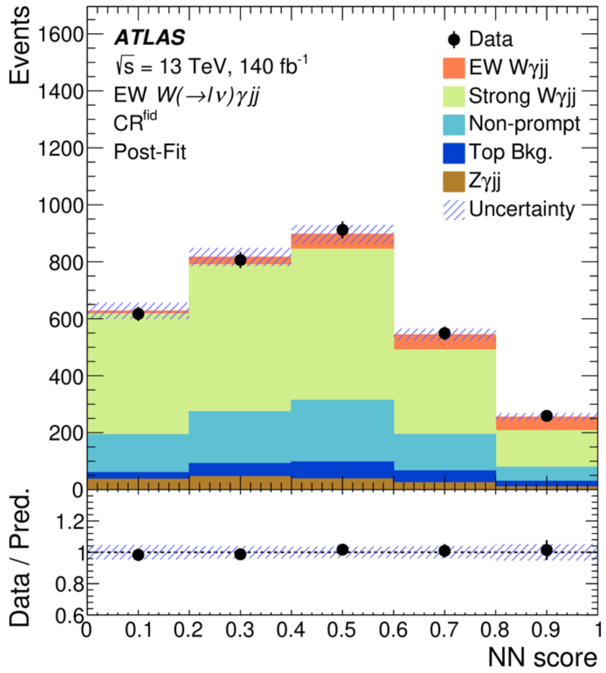
- **Observation:**
  - $\mu_{EW} = 1.5 \pm 0.5.$
  - Observed (expected) significance: ***9.0σ (6.3σ)***   **1st observation at ATLAS!**

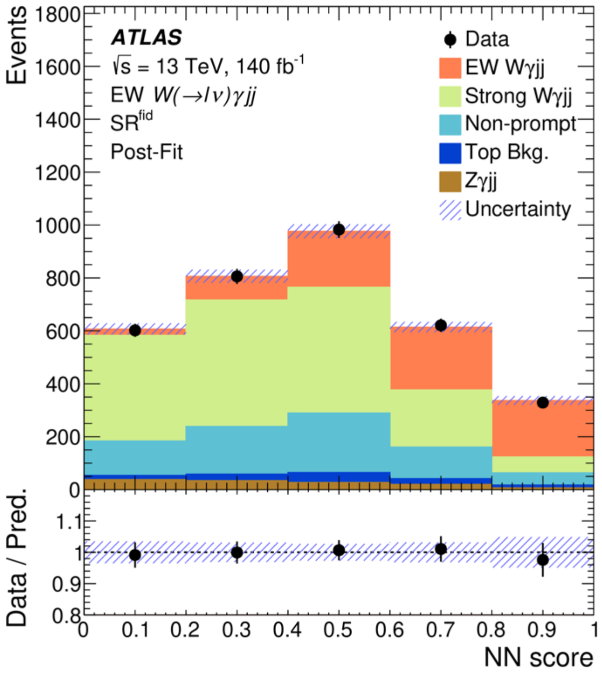
- **Fiducial cross-section:**

$$\sigma^{\text{fid}}_{\text{EW } W\gamma jj} = \frac{N_{\text{EW } W\gamma jj}}{L \cdot C_{\text{EW } W\gamma jj}}$$

$$C_{EW\ W\gamma jj} = \frac{N^{reco.}}{N^{fid.}}$$







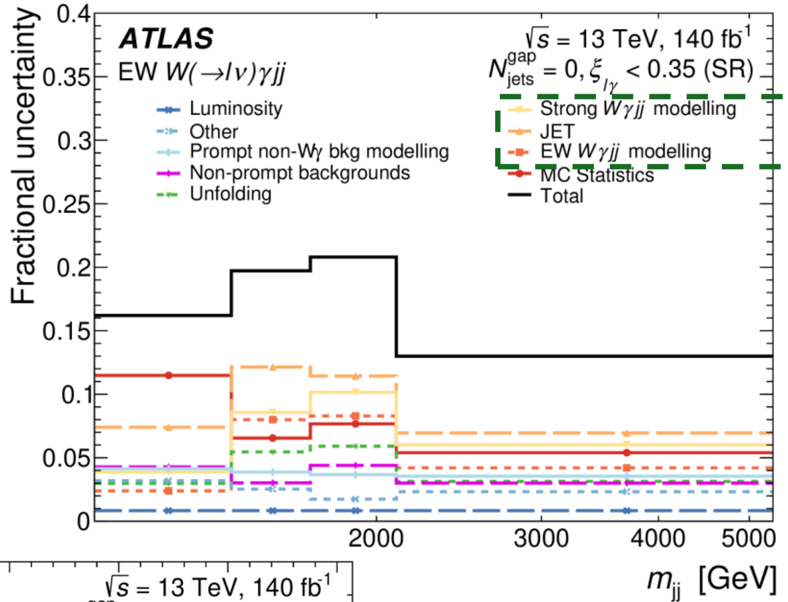
Uncertainty Source	Fractional Uncertainty [%]
MC Statistics	11
Jets	8
Lepton, photon, pile-up	8
EW $W\gamma jj$ modelling	7
Data Statistics	6
Strong $W\gamma jj$ modelling	6
Non-prompt background	2
Luminosity	2
Other Background modelling	2
$E_{\text{T}}^{\text{miss}}$	1

Dominant

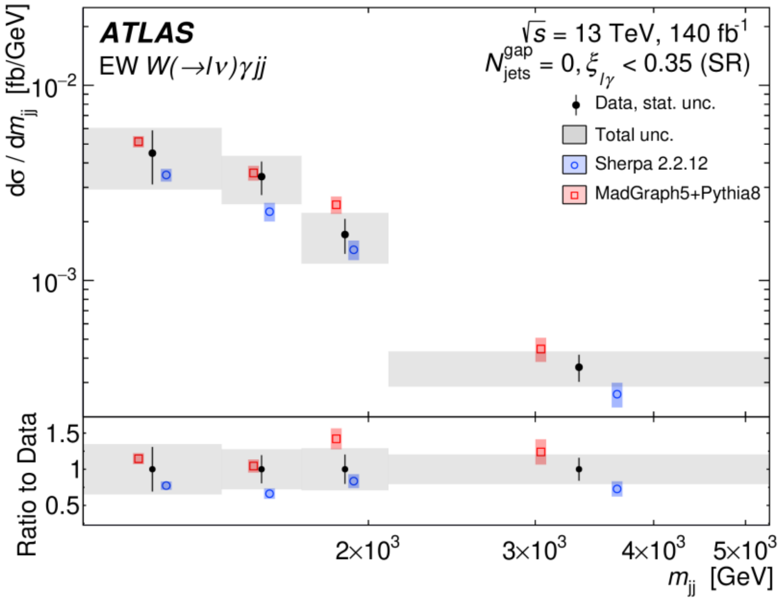
Large JES & JER

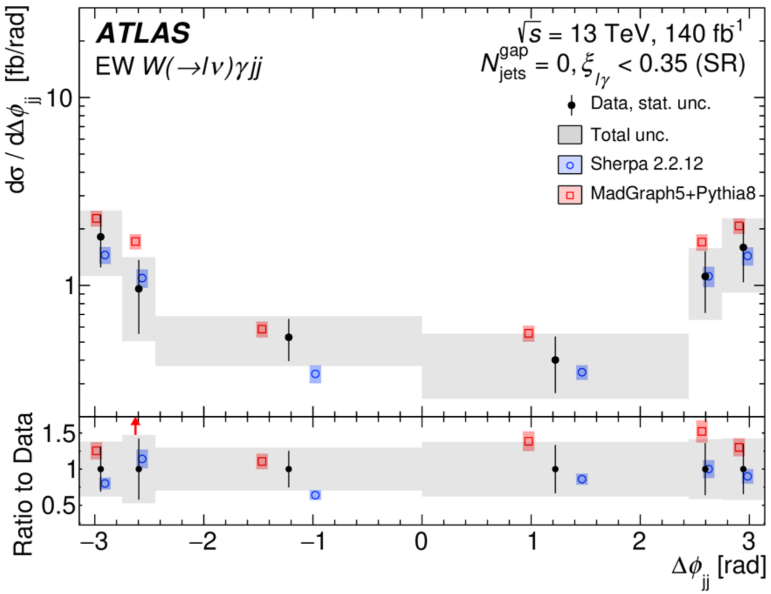
Differential cross-section

- **Signal extraction:**
  - SR + 3CRs: defined by N_{jets}^{gap} & $\xi_{l\gamma}$.
  - Observables: $m_{jj}, p_T^{jj}, p_T^l, m_{l\gamma}, \Delta\phi_{jj}, \Delta\phi_{l\gamma}$.
  - Simultaneously fit in signal and control regions with bin by bin reweighting of signal and QCD components in each region.
  - The extracted yields are unfolded to produce differential cross sections.



Dominated uncertainties





- **Differential cross-section:**
  - The predictions from both MadGraph5+Pythia8 and Sherpa are in agreement with the data within uncertainties.

EFT interpretation

- The effective Lagrangian:

Wilson coefficients → $f_j^{(8)}$; dimension-8 operators → $O_j^{(8)}$

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_j \frac{f_j^{(8)}}{\Lambda^4} O_j^{(8)}$$

energy scale of new physics → Λ^4

- The differential cross-section can be decomposed into 3 terms:

$$|\mathcal{M}|^2 = |\mathcal{M}_{\text{SM}}|^2 + 2Re(\mathcal{M}^*_{\text{SM}}\mathcal{M}_{\text{D-8}}) + |\mathcal{M}_{\text{D-8}}|^2$$

scales linearly w/ $f_j^{(8)}$ → $2Re(\mathcal{M}^*_{\text{SM}}\mathcal{M}_{\text{D-8}})$

scales quadratically w/ $f_j^{(8)}$ → $|\mathcal{M}_{\text{D-8}}|^2$

- $W\gamma jj$:
  - Sensitive to potential anomalous quartic couplings of $WW\gamma\gamma$ & $WW\gamma Z$.
  - p_T^{jj} (most sensitive to tensor-type operators), p_T^l (most sensitive to mixed-scalar operators).
  - Constraints on the f_{T3} and f_{T4} operators: **1st such limits at the LHC**.

	Coefficients [TeV^{-4}]	Observable	$M_{W\gamma}$ cut-off [TeV]	Expected [TeV^{-4}]	Observed [TeV^{-4}]
Tensor-type operators	f_{T0}/Λ^4	p_T^{jj}	-	[-2.4,2.4]	[-1.7,1.8]
	f_{T1}/Λ^4	p_T^{jj}	-	[-1.5,1.6]	[-1.1,1.2]
	f_{T2}/Λ^4	p_T^{jj}	-	[-4.4,4.7]	[-3.1,3.5]
	f_{T3}/Λ^4	p_T^{jj}	-	[-3.3,3.5]	[-2.4,2.6]
	f_{T4}/Λ^4	p_T^{jj}	-	[-3.0,3.0]	[-2.2,2.2]
	f_{T5}/Λ^4	p_T^{jj}	1.1	[-9.9,9.9]	[-7.5,7.5]
	f_{T6}/Λ^4	p_T^{jj}	1.3	[-7.4,7.6]	[-5.2,5.4]
	f_{T7}/Λ^4	p_T^{jj}	-	[-3.8,3.9]	[-2.7,2.8]
Mixed-scalar operators	f_{M0}/Λ^4	p_T^l	-	[-38,37]	[-38,37]
	f_{M1}/Λ^4	p_T^l	-	[-57,58]	[-41,42]
	f_{M2}/Λ^4	p_T^l	0.8	[-110,110]	[-88,82]
	f_{M3}/Λ^4	p_T^l	1.1	[-100,110]	[-73,77]
	f_{M4}/Λ^4	p_T^l	1.0	[-118,111]	[-89,83]
	f_{M5}/Λ^4	p_T^l	1.3	[-57,80]	[-32,77]
	f_{M7}/Λ^4	p_T^l	-	[-96,95]	[-69,68]

Coefficients [TeV^{-4}]	Observable	Expected [TeV^{-4}]	Observed [TeV^{-4}]
f_{T0}/Λ^4	p_T^{jj}	[-2.4, 2.4]	[-1.8, 1.8]
f_{T1}/Λ^4	p_T^{jj}	[-1.5, 1.6]	[-1.1, 1.2]
f_{T2}/Λ^4	p_T^{jj}	[-4.4, 4.7]	[-3.1, 3.5]
f_{T3}/Λ^4	p_T^{jj}	[-3.3, 3.5]	[-2.4, 2.6]
f_{T4}/Λ^4	p_T^{jj}	[-3.0, 3.0]	[-2.2, 2.2]
f_{T5}/Λ^4	p_T^{jj}	[-1.7, 1.7]	[-1.2, 1.3]
f_{T6}/Λ^4	p_T^{jj}	[-1.5, 1.5]	[-1.0, 1.1]
f_{T7}/Λ^4	p_T^{jj}	[-3.8, 3.9]	[-2.7, 2.8]
f_{M0}/Λ^4	p_T^l	[-28, 28]	[-24, 24]
f_{M1}/Λ^4	p_T^l	[-43, 44]	[-37, 38]
f_{M2}/Λ^4	p_T^l	[-10, 10]	[-8.6, 8.5]
f_{M3}/Λ^4	p_T^l	[-16, 16]	[-13, 14]
f_{M4}/Λ^4	p_T^l	[-18, 18]	[-15, 15]
f_{M5}/Λ^4	p_T^l	[-17, 14]	[-14, 12]
f_{M7}/Λ^4	p_T^l	[-78, 77]	[-66, 65]

Summary

- **1st observation** of EW $W\gamma jj$ at ATLAS.
  - $\mu_{EW} = 1.5 \pm 0.5.$
  - Observed (expected) significance: ***9.0σ (6.3σ).***
- Measurements of EW $W\gamma jj$ **fiducial** and **differential cross-section** are reported.
  - $\sigma_{EW}^{fid} = 13.2 \pm 2.5\ fb.$
  - **Differential cross-sections are measured** as functions of six kinematic observables.
  - The data are corrected for detector effects of inefficiency and resolution using an iterative Bayesian **unfolding** method.
  - These differential measurements are used to **search for anomalous quartic boson interactions** using D-8 operators in the context of an effective field theory.
  - The first LHC constraints on f_{T3} and f_{T4} are presented.
- Publication: Eur. Phys. J. C 84 (2024) 1064

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谢谢！

Particle level definition

Object	Selection requirements
Dressed muons	$p_T > 30$ GeV and $\|\eta\| < 2.5$
Dressed electrons	$p_T > 30$ GeV and $\|\eta\| < 2.47$ (excluding $1.37 < \|\eta\| < 1.52$)
Isolated photons	$E_T^\gamma > 22$ GeV and $\|\eta\| < 2.37$ (excluding $1.37 < \|\eta\| < 1.52$) and $E_T^{iso} < 0.2E_T^\gamma$
Jets	At least two jets with $p_T > 50$ GeV and $\|y\| < 4.4$, b−jet veto
Missing transverse momentum	$E_T^{miss} > 30$ GeV and $m_T^W > 30$ GeV
VBS topology	$N_\ell = 1$, $N_\gamma \geq 1$, $\|m_{\ell\gamma} - m_Z\| > 10$ GeV
	$\Delta R_{min}(\ell, j) > 0.4$, $\Delta R_{min}(\gamma, j) > 0.4$, $\Delta R_{min}(\ell, \gamma) > 0.4$
	$\Delta R_{min}(j_1, j_2) > 0.4$, $\Delta\phi_{min}(E_T^{miss}, j) > 0.4$
	$N_{jets} \geq 2$, $p_T^{j1}, p_T^{j2} > 50$ GeV
	$m_{jj} > 500$ GeV, $\|\Delta y_{jj}\| > 2$
Fiducial measurement	VBS topology
Differential measurement	VBS topology $\oplus$ ($m_{jj} > 1000$ GeV, $N_{jets}^{gap} = 0$, and $\xi_{W\gamma} < 0.35$)

MC samples

Signal. Sh-2.2.11 Nominal, MG5 systematic

Irreducible bkg. Sh-2.2.11 Nominal, MG5 systematic

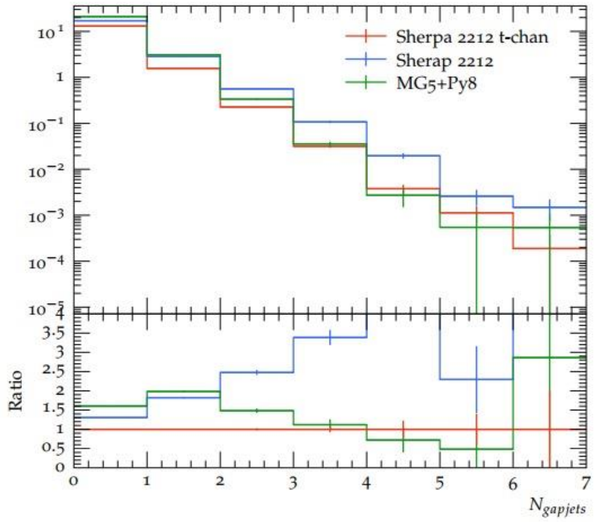
Reducible prompt bkgs.

Non-prompt backgrounds used for DD fakes estimates

Process	Prompt/Non-prompt	Generator	ME Accuracy	PDF	Shower & Hadronization	Parameter Tune
EW Wγjj	Prompt	Madgraph5	LO	NNPDF3.1 LO	Pythia8+EvtGen	A14
		Sherpa 2.2.12	LO	NNPDF3.0 NLO	Sherpa	Default
QCD Wγjj	Prompt	Sherpa 2.2.11	NLO	NNPDF3.0 NLO	Sherpa	default
		Madgraph5	NLO	NNPDF3.0 NLO	Pythia8+EvtGen	A14
EW Zγjj	Prompt	Madgraph5	LO	NNPDF3.1 LO	Pythia8+EvtGen	A14
QCD Zγjj	Prompt	Sherpa 2.2.11	NLO	NNPDF3.0 NLO	Sherpa	default
$t\bar{t}\gamma$	Prompt	Madgraph5	LO	NNPDF2.3 LO	Pythia8+EvtGen	A14
$tW\gamma$	Prompt	Madgraph5	LO	NNPDF3.0 NLO	Pythia8+EvtGen	A14
$tq\gamma$	Prompt	Madgraph5	LO	NNPDF3.0 NLO	Herwig7+EvtGen	Default
Single Top	Prompt	Powheg	NLO	NNPDF3.0 NLO	Pythia8+EvtGen	A14
W+jets	Non-Prompt	Sherpa 2.2.11	NLO	NNFDF3.0 NNLO	Sherpa	Default
Z+jets	Non-Prompt	Sherpa 2.2.11	NLO	NNPDF3.0 NNLO	Sherpa	Default
Diboson	Non-Prompt	Sherpa 2.2.12	NLO	NNPDF 3.0 NNLO	Sherpa	Default
Dijet	Non-Prompt	Pythia8	LO	NNPDF2.3 LO	Pythia8+EvtGen	A14
EW Wjj	Non-Prompt	Sherpa 2.2.1	LO	NNPDF3.0 NNLO	Sherpa	default
EW Zjj	Non-Prompt	Sherpa 2.2.1	LO	NNPDF3.0 NNLO	Sherpa	default
$t\bar{t}$	Non-Prompt	Powheg	NLO	NNPDF3.0 NLO	Pythia8+EvtGen	A14
tW	Non-Prompt	Powheg	NLO	NNPDF3.0 NLO	Pythia8+EvtGen	A14

MadGraph & Sherpa signal comparison

- The difference certainly comes from having the **3rd jet included in the matrix element in Sherpa**.
- Diagrams with gluon emission from the incoming or outgoing quarks interfere destructively, resulting in a suppression of centrally produced jets. (More details)
- Sherpa sample predicts more hadronic activity in the gap between the two leading jets.



$$\eta^*_{j3} = \eta_{j3} - \frac{\eta_{j1} + \eta_{j2}}{2}$$