VBS Measurements at ATLAS

Todd Zenger

On Behalf of the ATLAS Collaboration

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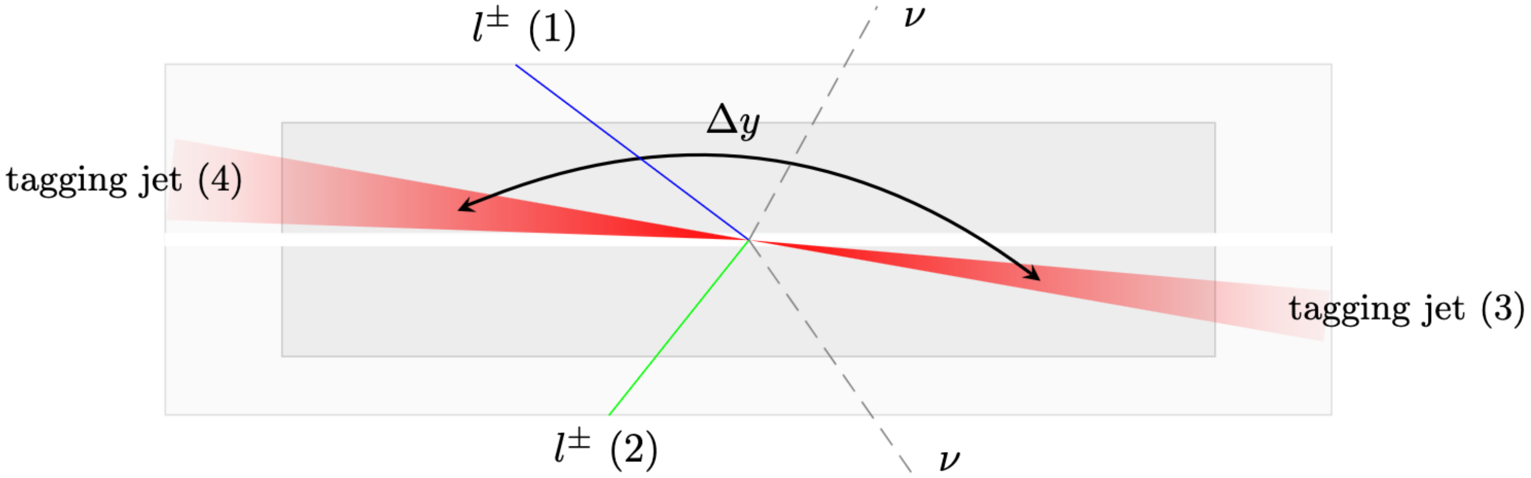
Introduction

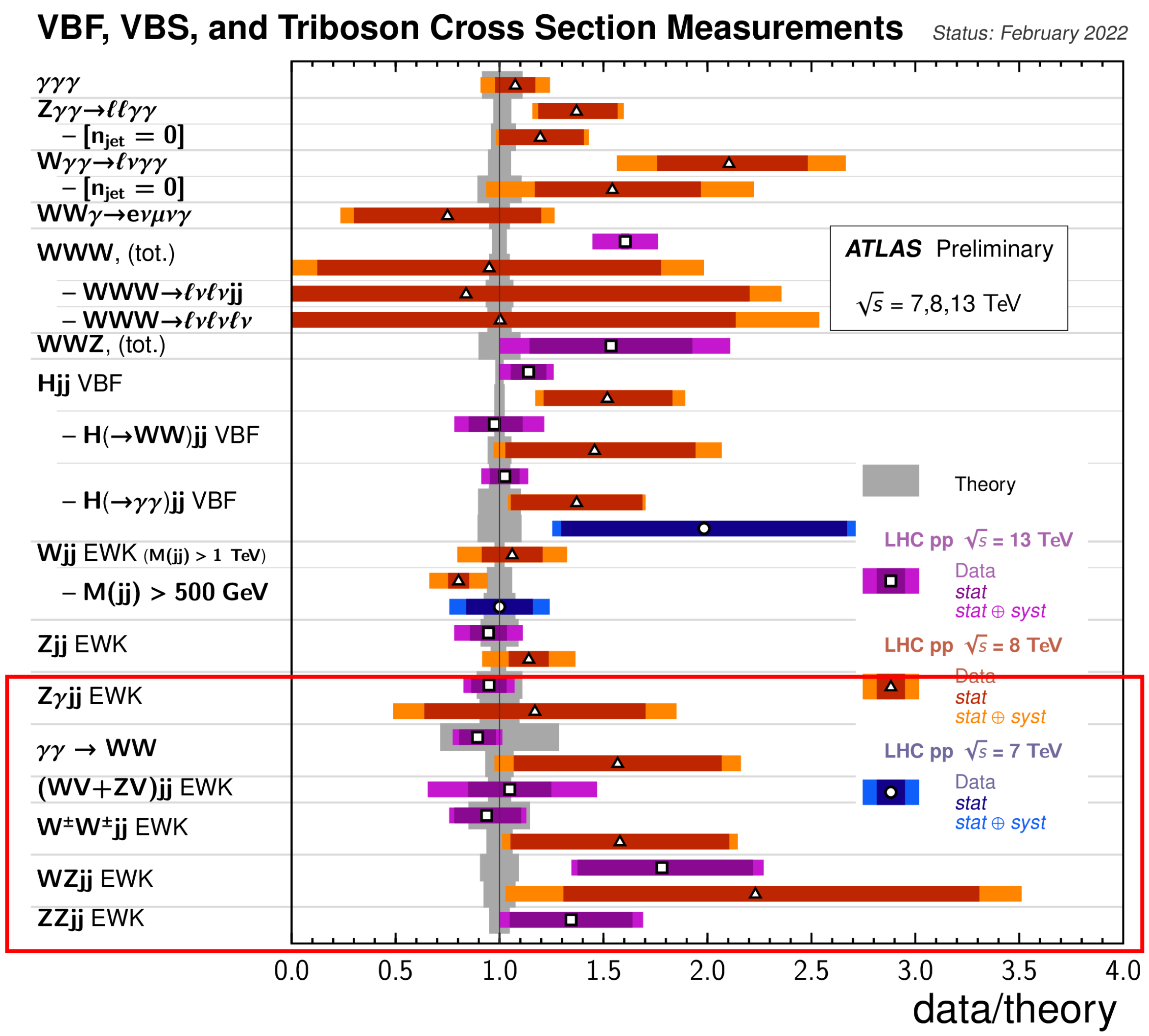
- Probing new VBS processes at ATLAS
- VBS sensitive to EWSB and probes quartic gauge couplings
- VBS features:
  - Two tagging jets with large rapidity separation, Δy
  - Large dijet mass, m_{jj}

Example VBS topology of $W^{\pm}W^{\pm}jj \rightarrow \ell^{\pm}\nu\ell^{\pm}\nu jj$



Overview

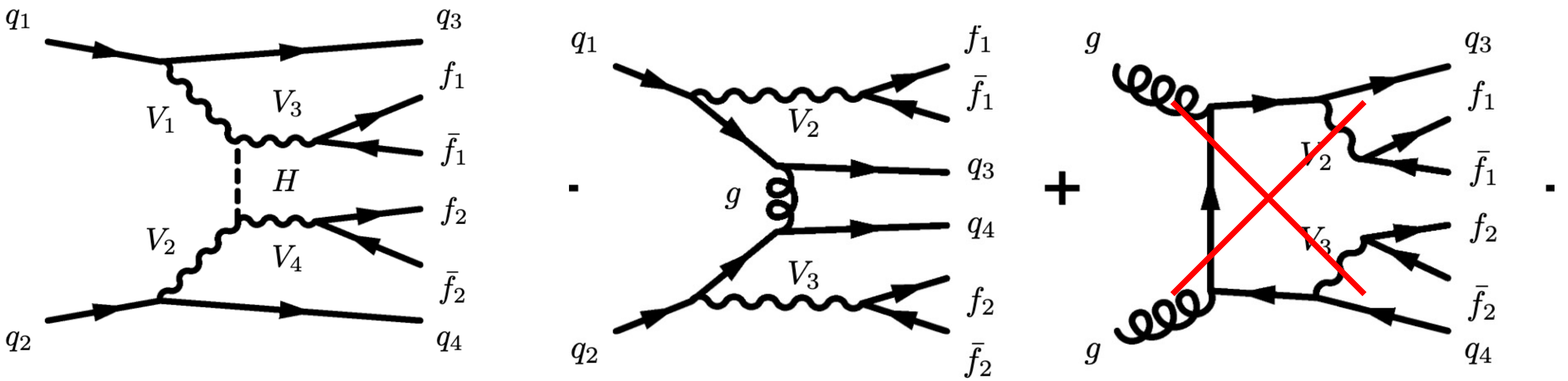
- In this talk: recent ATLAS VBS measurements
  - Same-Sign $W^{\pm}W^{\pm}jj$
  - Opposite-Sign $W^{\pm}W^{\mp}jj$
  - $Z(\ell\ell)\gamma jj$
  - $ZZjj$
- In backup:
  - $Z(\nu\nu)\gamma jj$



ATL-PHYS-PUB-2022-009

Same-Sign $W^{\pm}W^{\pm}jj$

- Largest EW to QCD ratio compared to other VBS interactions
  - No gluon-gluon fusion or quark-gluon QCD VVjj interactions from same-sign WW
- Measure fiducial and differential cross section using $139\ fb^{-1}$ luminosity
- Previous measurement Phys. Rev. Lett. 123 (2019) 161801
  - 6.5σ observation with $36.1\ fb^{-1}$ integrated luminosity

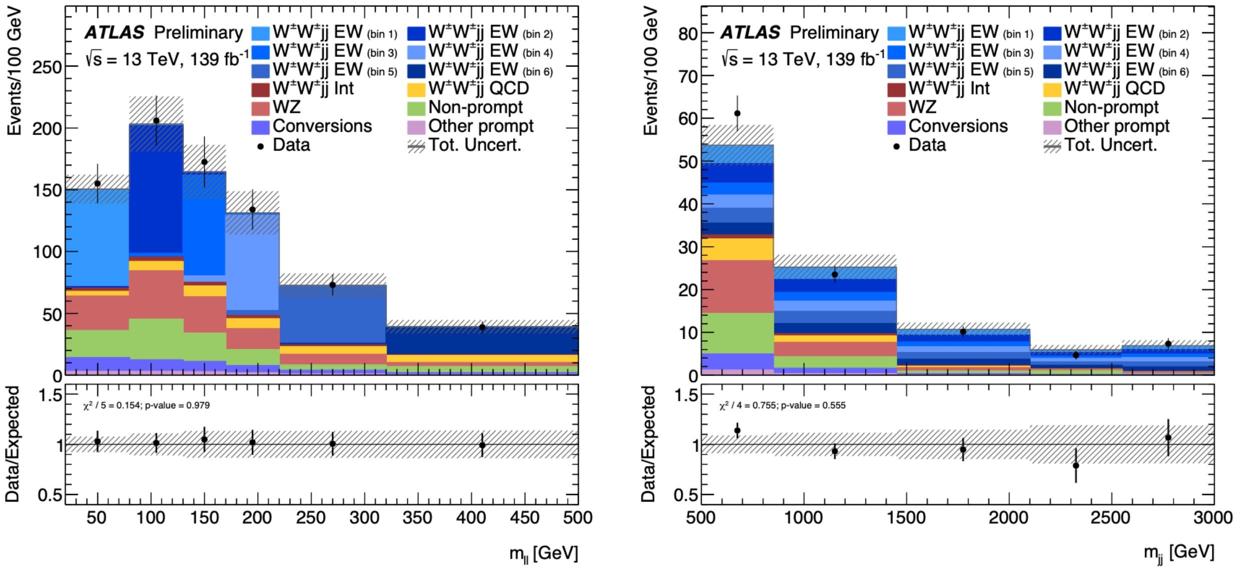


Same-Sign $W^{\pm}W^{\pm}jj$ Results

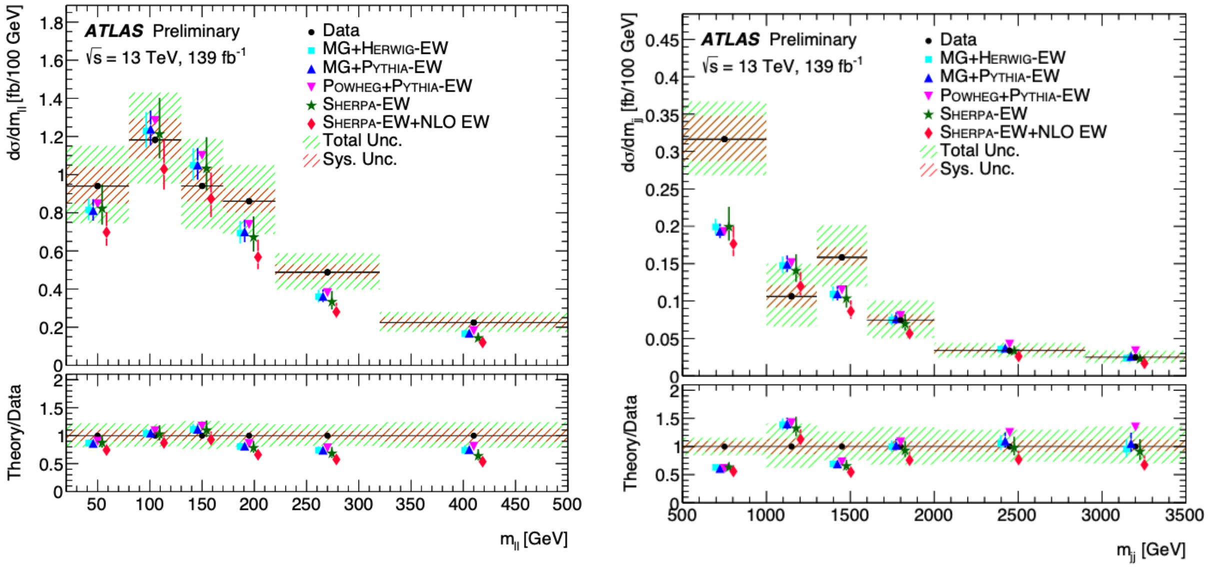
Description	$\sigma_{\text{fid}}^{\text{EW}}$, fb	$\sigma_{\text{fid}}^{\text{EW+Int+QCD}}$, fb
Measured cross section	2.88 ± 0.21 (stat.) ± 0.19 (syst.)	3.35 ± 0.22 (stat.) ± 0.20 (syst.)
MG_aMC@NLO+Herwig	2.53 ± 0.04 (PDF) $\pm^{0.22}_{0.19}$ (scale)	2.93 ± 0.05 (PDF) $\pm^{0.34}_{0.27}$ (scale)
MG_aMC@NLO+Pythia	2.55 ± 0.04 (PDF) $\pm^{0.22}_{0.19}$ (scale)	2.94 ± 0.05 (PDF) $\pm^{0.33}_{0.27}$ (scale)
Sherpa	2.44 ± 0.03 (PDF) $\pm^{0.40}_{0.27}$ (scale)	2.80 ± 0.03 (PDF) $\pm^{0.53}_{0.36}$ (scale)
Powheg Box +Pythia	2.67	–

Fiducial and differential measurements agree with SM

EW $W^{\pm}W^{\pm}$ and inclusive $W^{\pm}W^{\pm}$ differential cross section measured with variables: m_{ll}, m_T, m_{jj}, $N_{gap\ jets}$, ξ_{j3}



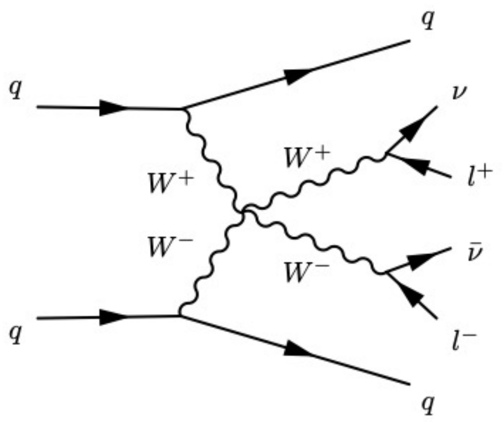
Post-fit distribution of m_{ll} (left) and m_{jj} (right) for differential cross section

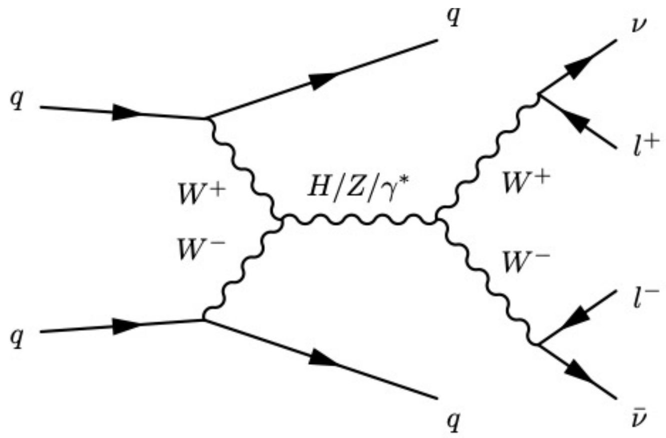


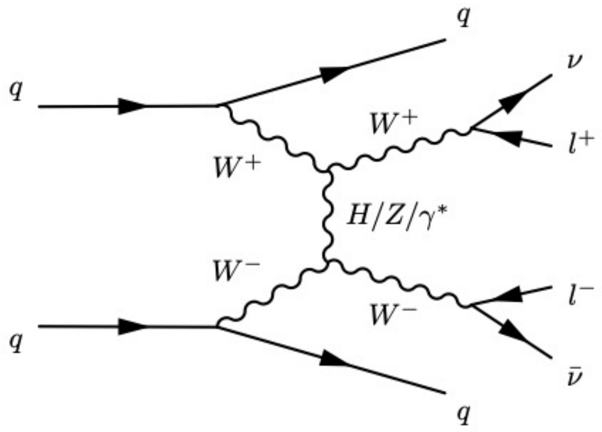
Differential cross section measurement of EW $W^{\pm}W^{\pm}jj$ m_{ll} (left) and m_{jj} (right)

Opposite-Sign $W^{\pm}W^{\mp}jj$

- Choose $W^{\pm}W^{\mp}jj \rightarrow e^{\pm}\nu\mu^{\mp}\nu jj$ for enhanced detector sensitivity compared to same-flavor decays
- Use neural network (NN) to distinguish signal from largest irreducible backgrounds – top quark production and $W^{\pm}W^{\mp}jj$ QCD

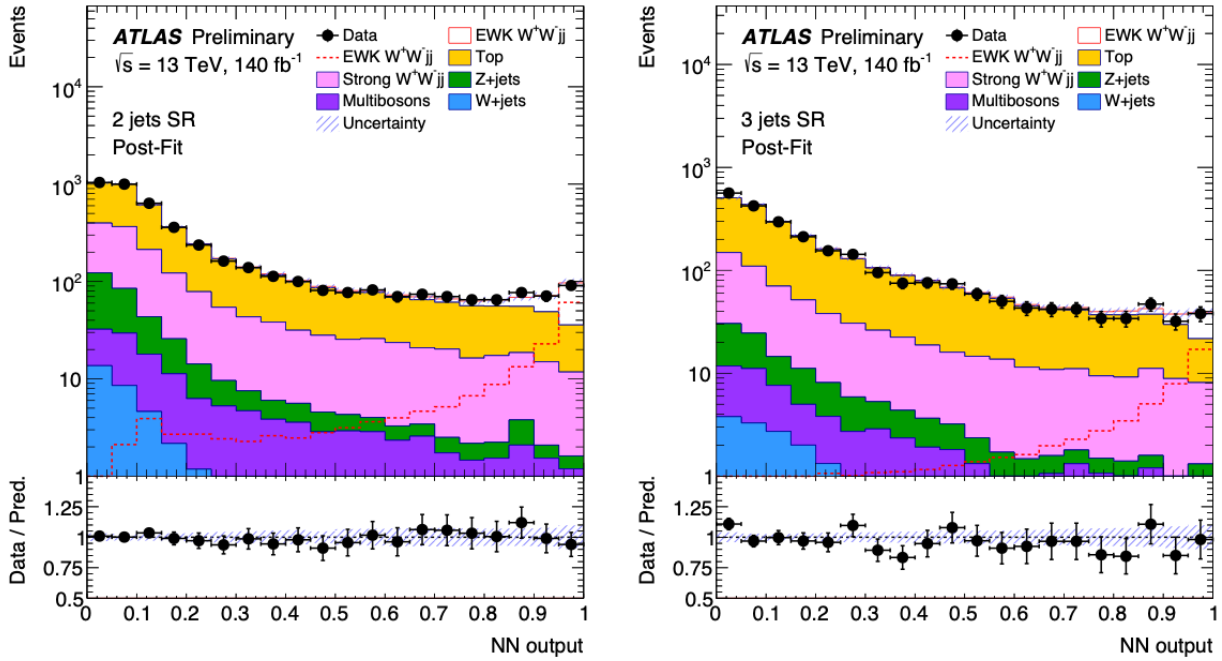




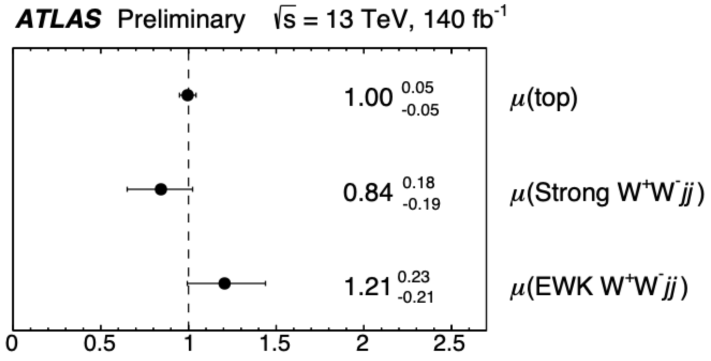


Opposite-Sign $W^{\pm}W^{\mp}jj$ Results

- Set three floating parameters – Strong $W^{\pm}W^{\mp}jj$, EW $W^{\pm}W^{\mp}jj$, top
- Use split SR with two jet regions – 2 jets and 3 jets SRs
- Signal observed with 7.1σ while 6.2σ expected with background only hypothesis
- Cross section measured $2.65^{+0.52}_{-0.48} fb$ observed with $2.20^{+0.14}_{-0.13} fb$ expected from POWHEG BOX 2
- Results agree with SM



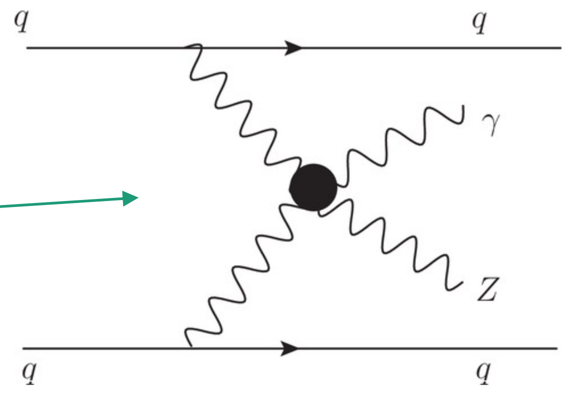
(a) Two jets (b) Three jets

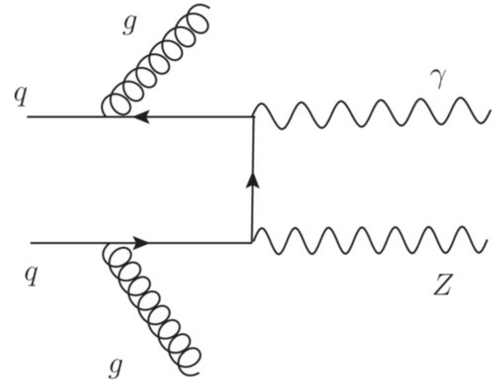


[2305.19142 (Submitted to PLB)](2305.19142)

$Z(\ell\ell)\gamma jj$

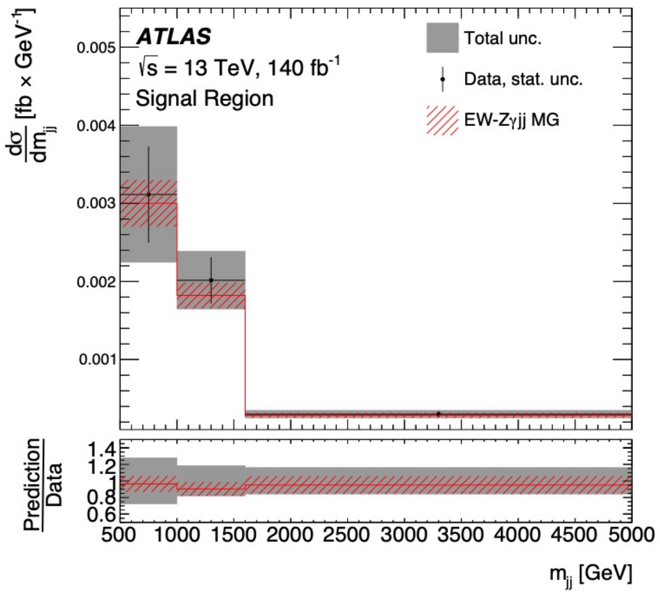
- Interesting due to probing the neutral quartic coupling
- Larger cross section than ZZ EW process
- Measure fiducial and differential fiducial cross section
- Improves previous ATLAS measurement at $36fb^{-1}$ integrated luminosity
  - Phys. Lett. B 803 (2020) 135341
  - 4.1σ evidence



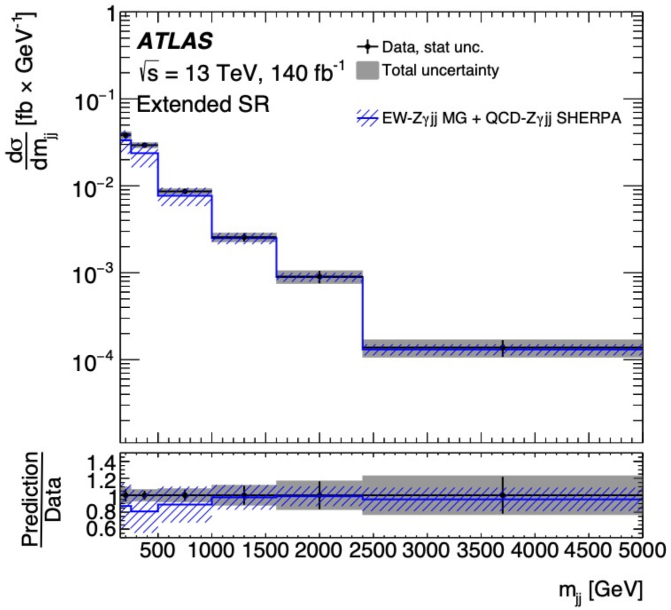


$Z(\ell\ell)\gamma jj$ Results

- Measured differential cross section $Z\gamma jj$ EW and $Z\gamma jj$ inclusive
- $Z\gamma jj$ EW extracted using maximum-likelihood fit with m_{jj}
- First observation of $Z(\ell\ell)\gamma jj$ in ATLAS



$Z\gamma jj$ EW SR: $m_{jj} > 500GeV$, $\zeta < 0.4$



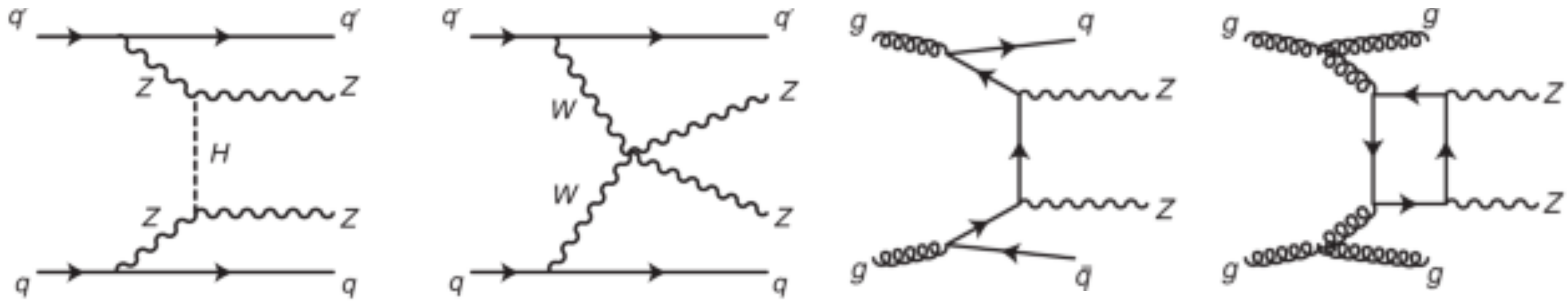
$Z\gamma jj$ inclusive SR: $m_{jj} > 150GeV, \zeta < 0.4$

	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	$^{+12}_{-11}$

	Predicted	Measured
$Z\gamma$ EW cross section	3.5 ± 0.2 fb	3.6 ± 0.5 fb
$Z\gamma$ cross section	$15.7^{+5.0}_{-2.6}$ fb	$16.8^{+2.0}_{-1.8}$ fb

$ZZjj$

- Measure differential cross section of ZZjj EW production
  - $ZZ \to 4\ell$
- ZZjj EW sensitive to $WWZZ$ and WWZ self interaction couplings
- ZZjj QCD sensitive to perturbative calculations
- Previous ZZjj observation paper:
  - Nature Phys. 19 (2023) 237
  - Observed 5.7σ



Nature Phys. 19 (2023) 237

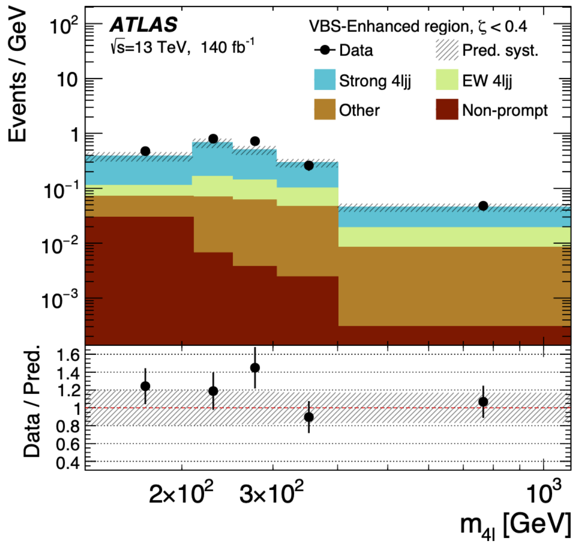
$ZZjj$ Results

- Split signal region into:
  - VBS enhanced ($\zeta < 0.4$)
  - VBS suppressed ($\zeta > 0.4$)

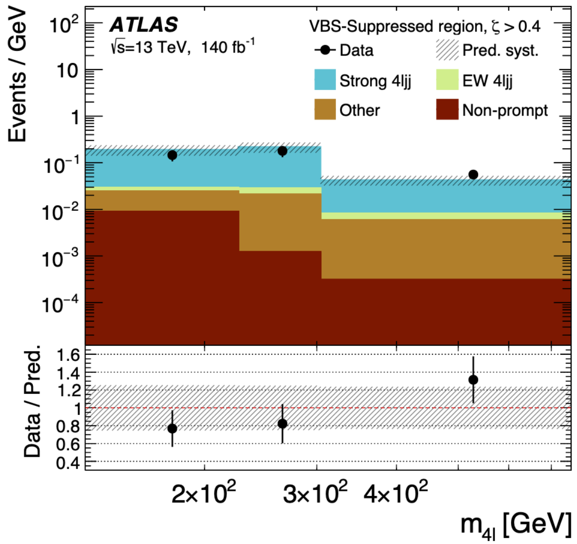
$$\zeta = \left| \frac{[y_{4\ell} - 0.5(y_{j_1} + y_{j_2})]}{\Delta y_{jj}} \right|$$

- Madgraph + Pythia8 strong $4\ell jj$ underestimate cross section in both signal regions
- Sherpa strong $4\ell jj$ in agreement with larger theoretical uncertainties

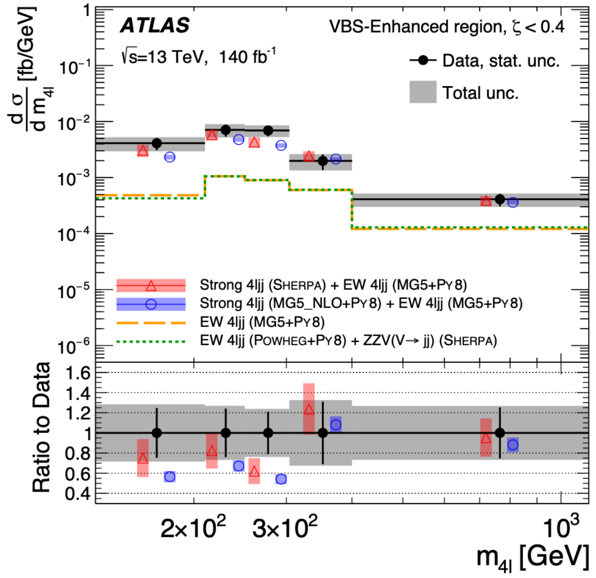
VBS enhanced $\zeta < 0.4$



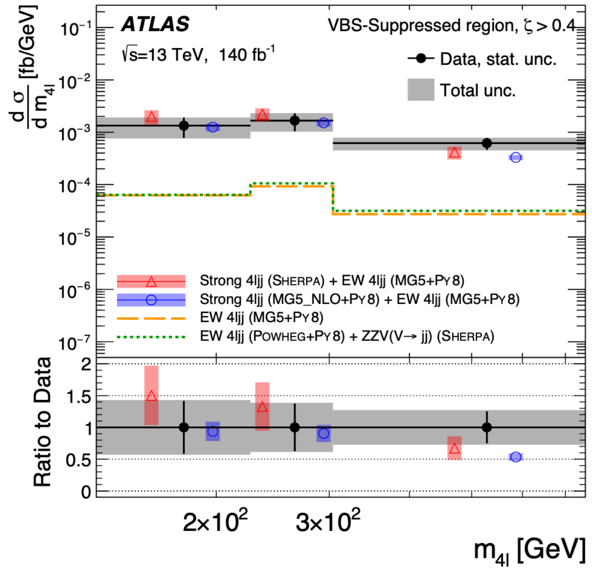
VBS suppressed $\zeta > 0.4$



VBS enhanced $\zeta < 0.4$



VBS suppressed $\zeta > 0.4$



EFT Measurements

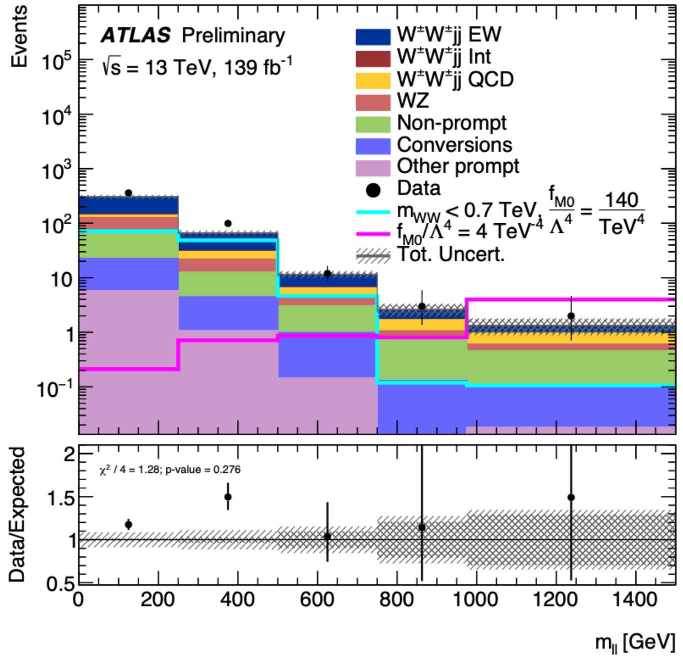
- SM measurements can provide hints of BSM
- New physics can induce anomalous quartic gauge couplings (aQGC)
- Extend SM using effective Lagrangian encoding aQGC
- Non-zero aQGCs violates tree-level unity at sufficiently higher energy scales

$$\mathcal{L}_{EFT} = \mathcal{L}_{SM} + \sum_i \frac{f^i}{\Lambda^4} O^{d=8}$$

$W^{\pm}W^{\pm}jj$ measurement of $f_{M0}/_{\Lambda^4}$

Purple line: EFT contribution with no unitarization applied

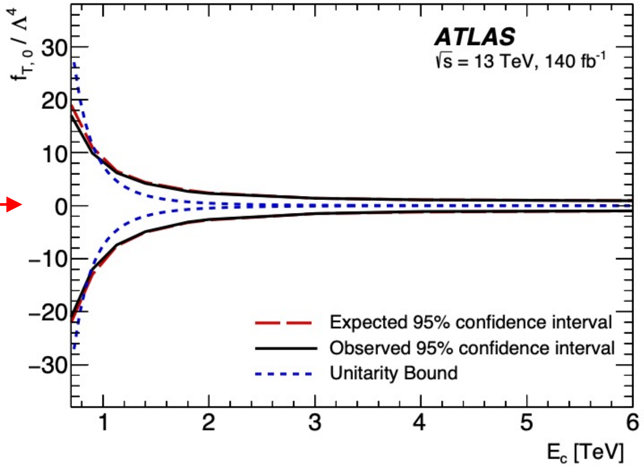
Cyan line: EFT contribution with 700GeV cutoff



EFT Measurement Results

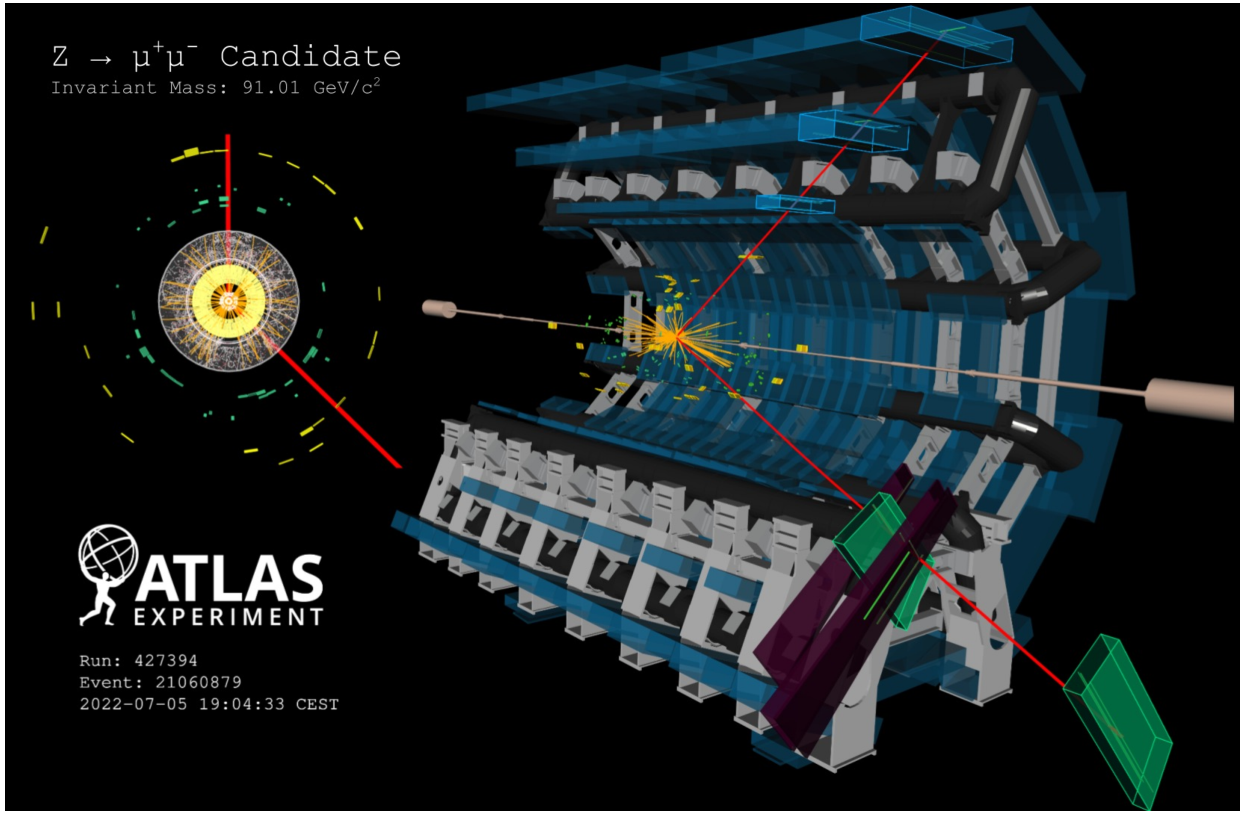
- Results of SM measurements places limits on EFT
- Table below: observed exclusion limits placed on the Wilson coefficients on dimension-8 operators at 95% confidence limit

	$W^\pm W^\pm jj$		$Z(\nu\bar{\nu})\gamma jj$		$ZZjj$	
Parameter	Exp.	Obs.	Exp.	Obs.	Exp.	Obs.
$f_{M0}/\Lambda^4[TeV^{-4}]$	$[-3.9, 3.8]$	$[-4.1, 4.1]$	$[-6.2, 6.2]$	$[-4.6, 4.6]$		
$f_{M1}/\Lambda^4[TeV^{-4}]$	$[-6.3, 6.6]$	$[-6.8, 7.0]$	$[-1.0, 1.0] \times 10^1$	$[-7.7, 7.7]$		
$f_{M2}/\Lambda^4[TeV^{-4}]$			$[-2.6, 2.6]$	$[-1.9, 1.9]$		
$f_{M7}/\Lambda^4[TeV^{-4}]$	$[-9.3, 8.8]$	$[-9.8, 9.5]$				
$f_{S02}/\Lambda^4[TeV^{-4}]$	$[-5.5, 5.7]$	$[-5.9, 5.9]$				
$f_{S1}/\Lambda^4[TeV^{-4}]$	$[-22.0, 22.5]$	$[-23.5, 23.6]$				
$f_{T0}/\Lambda^4[TeV^{-4}]$	$[-0.34, 0.34]$	$[-0.36, 0.36]$	$[-1.3, 1.2] \times 10^{-1}$	$[-9.4, 8.4] \times 10^{-2}$	$[-0.98, 0.93]$	$[-1.00, 0.97]$
$f_{T1}/\Lambda^4[TeV^{-4}]$	$[-0.158, 0.174]$	$[-0.174, 0.186]$			$[-1.2, 1.2]$	$[-1.3, 1.3]$
$f_{T2}/\Lambda^4[TeV^{-4}]$	$[-0.56, 0.70]$	$[-0.63, 0.74]$			$[-2.5, 2.4]$	$[-2.6, 2.5]$
$f_{T5}/\Lambda^4[TeV^{-4}]$			$[-1.2, 1.3] \times 10^{-1}$	$[-8.8, 9.9] \times 10^{-2}$	$[-2.5, 2.4]$	$[-2.6, 2.5]$
$f_{T6}/\Lambda^4[TeV^{-4}]$					$[-3.9, 3.9]$	$[-4.1, 4.1]$
$f_{T7}/\Lambda^4[TeV^{-4}]$					$[-8.5, 8.1]$	$[-8.8, 8.4]$
$f_{T8}/\Lambda^4[TeV^{-4}]$			$[-8.1, 8.0] \times 10^{-2}$	$[-5.9, 5.9] \times 10^{-2}$	$[-2.1, 2.1]$	$[-2.2, 2.2]$
$f_{T9}/\Lambda^4[TeV^{-4}]$			$[-1.7, 1.7] \times 10^{-1}$	$[-1.3, 1.3] \times 10^{-1}$	$[-4.5, 4.5]$	$[-4.7, 4.7]$



Conclusions

- Many new VBS measurements from ATLAS this year!
- Results compatible with standard model
- Placed limits on EFT
- New analyses underway to probe VBS sectors in Run 3

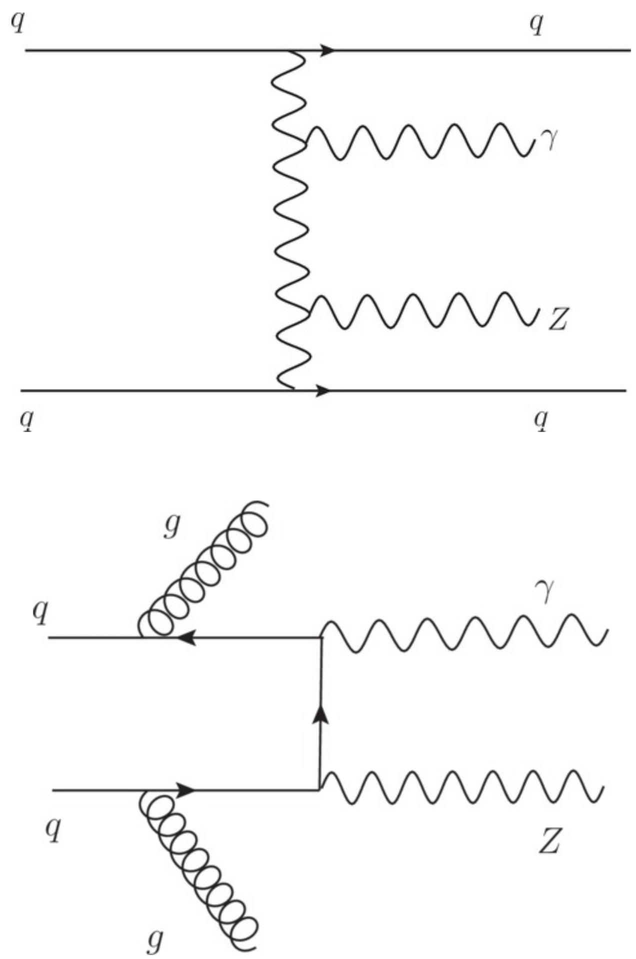


Run 3 2022 $Z \rightarrow \mu\mu$ candidate
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/EventDisplayRun3Collisions

Backup

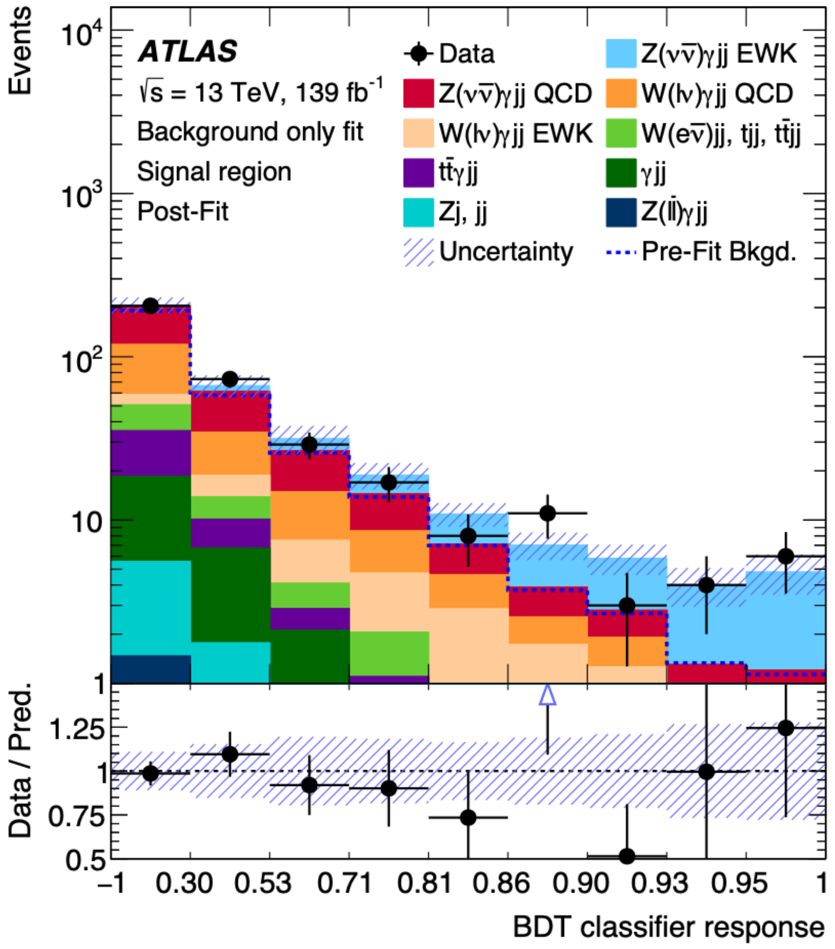
$Z(\nu\nu)\gamma jj$

- Measure Z decaying to two neutrinos
- Larger branching ratio to neutrinos compared to charged leptons
- $E_T^\gamma > 150 GeV$
- Previously observed in low energy phase space orthogonal to this measurement
  - Eur. Phys. J. C 82, 105 (2022)
  - $15 < E_T^\gamma < 110 GeV$
  - Observed with 5.2σ
- Use BDT classifier to separate signal and background



$Z(\nu\nu)\gamma jj$ Results

- Measured EW significance 3.2σ with expected 3.7σ
- Combined measurement with Eur. Phys. J. C 82, 105 (2022) to get EW significance of 6.3σ



POI	Value: Current analysis	Ref. [7]	Combination
$\mu_{Z\gamma\mathrm{EWK}}$	0.78 ± 0.33	1.03 ± 0.25	0.96 ± 0.19
$\mu_{Z\gamma\mathrm{QCD}}$	1.21 ± 0.37	1.02 ± 0.41	1.17 ± 0.27
$\mu_{W\gamma}$	1.02 ± 0.22	1.01 ± 0.20	1.01 ± 0.13

$E_T^\gamma > 150 GeV$ $\quad$ $15 < E_T^\gamma < 110 GeV$

Same-Sign $W^{\pm}W^{\pm}jj$ Strategy

- One signal region and two control regions (WZ 3ℓ and low m_{jj})
- Largest backgrounds:
  - $W + Z/\gamma$ ~22% of SR Yield
    - One lepton escaping detector
    - QCD produced events reweighted with CRs
  - Non-prompt leptons ~12% of SR Yield
    - $W + jets$ and semileptonic $t\bar{t}$
    - Estimated using data-driven methods
  - Electron charge misidentification ~2.2% of SR Yield
    - Z and dileptonic $t\bar{t}$
    - Estimated using data-driven methods

Signal Region Selection

Exactly two signal leptons with $p_{\mathrm{T}} > 27$ 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
$E_{\mathrm{T}}^{\mathrm{miss}} \geq 30$ GeV
At least two jets Leading and subleading jets satisfying $p_{\mathrm{T}} > 65$ GeV and $p_{\mathrm{T}} > 35$ GeV, respectively b-jet veto for jets with $p_{\mathrm{T}} > 20$ GeV and $\lvert\eta\rvert < 2.5$ $m_{\mathrm{jj}} \geq 500$ GeV $\lvert\Delta y_{\mathrm{jj}}\rvert > 2$

WZ Control Region: signal region selection but with:

- 3 leptons
- $m_{jj} > 200GeV$
- $m_{lll} > 106GeV$

Low m_{jj} Control Region: signal region but with $200 < m_{jj} < 500GeV$

Same-Sign $W^{\pm}W^{\pm}jj$ Systematics

Source	Impact [%]
Experimental	
Electron calibration	0.4
Muon calibration	0.5
Jet energy scale and resolution	1.8
$E_{\mathrm{T}}^{\mathrm{miss}}$ 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

Opposite-Sign $W^{\pm}W^{\mp}jj$ Strategy

- One signal region (no b-tagged jets) and one control region (at least one b-tagged jet)
- Use two NNs – one for 2 jets SR and one for 3 jets SR
  - Trained using $W^{\pm}W^{\mp}jj$ EW vs top and $W^{\pm}W^{\mp}jj$ QCD
- Largest Backgrounds:
  - Top quark ~66% of SR Yield
    - Single and pair production
  - $W^{\pm}W^{\mp}jj$ Strong Production ~24% of SR Yield

Signal Region Selection

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

$$\zeta = centrality = \min\left\{\left[\min(\eta_{\ell_1}, \eta_{\ell_2}) - \min(\eta_{j_1}, \eta_{j_2})\right], \left[\max(\eta_{j_1}, \eta_{j_2}) - \max(\eta_{\ell_1}, \eta_{\ell_2})\right]\right\}$$

Opposite-Sign $W^{\pm}W^{\mp}jj$ NN Variables

- 2 Jets:
  - Leading jet p_T
  - Sub-leading jet p_T
  - M_{ll}
  - ζ
  - E_T^{miss} significance
  - $\Delta\eta_{jj}$, two leading jets
  - $\Delta\phi_{jj}$, two leading jets
  - m_{lj}, from two leading leptons and jets
- 3 Jets:
  - Includes all above from 2 jet categories
  - 3rd jet p_T
  - Centrality of 3rd jet

$E_{\mathrm{T}}^{\mathrm{miss}}$ significance is computed as $\frac{|\vec{p}_{\mathrm{T}}^{\,miss}|^2}{\sigma_L^2\times(1-\rho_{LT}^2)}$, where σ_L is the total variance in the direction longitudinal to $E_{\mathrm{T}}^{\mathrm{miss}}$, and ρ_{LT} is the correlation coefficient of the longitudinal (L) and transverse (T) measurements.

$$\text{Third jet centrality} = \left| y_{j_3} - \frac{1}{2} \times \frac{y_{j_1} + y_{j_2}}{y_{j_1} - y_{j_2}} \right|$$

Opposite-Sign $W^{\pm}W^{\mp}jj$ Systematics

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

$Z\gamma(\ell\ell)jj$ Strategy

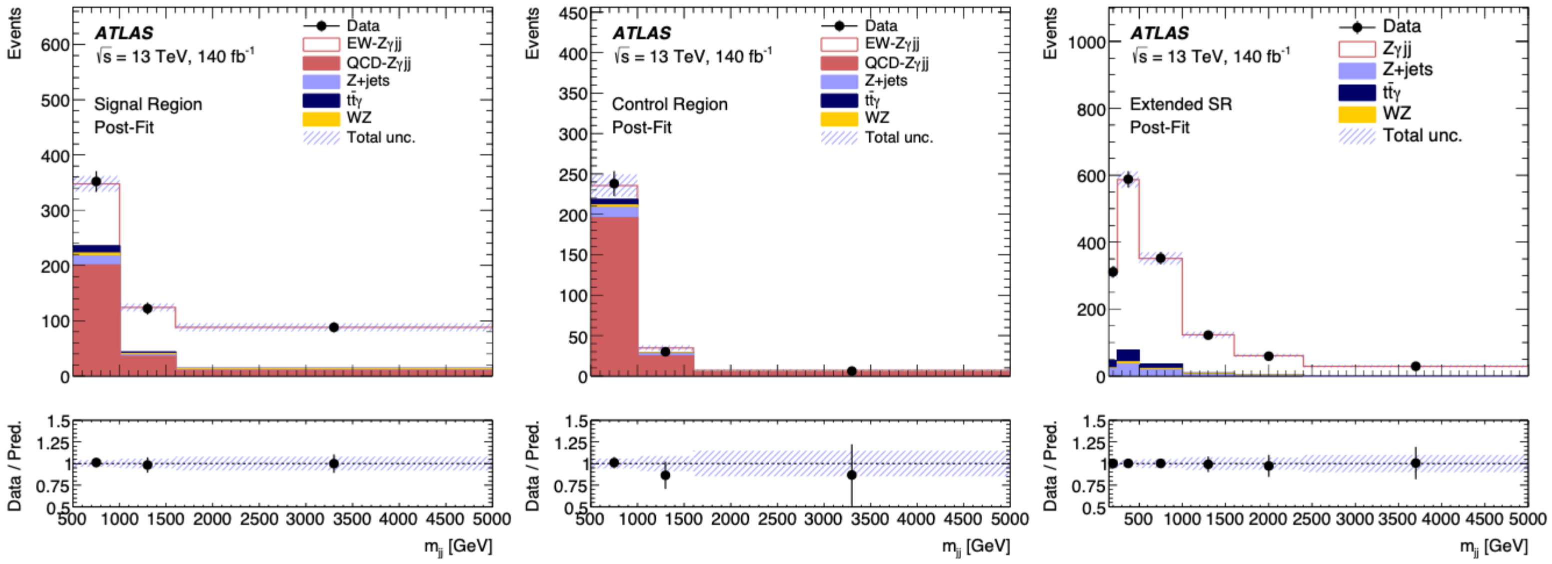
- One SR ($\zeta(Z\gamma) < 0.4$) and one CR ($\zeta(Z\gamma) > 0.4$)
- Estimate $Z\gamma jj$ EW $\sim 48\%$ of SR Yield
- Largest Backgrounds:
  - $Z\gamma jj$ QCD $\sim 44\%$ of SR Yield
  - Z+jets, jet misidentified as photon
  - $t\bar{t}\gamma$
    - checked using data with different lepton flavor

Particle level selection:

Lepton	$p_{\mathrm{T}}^{\ell} > 20, 30(\text{leading})$ GeV, $\lvert\eta_\ell\rvert < 2.5$ $N_\ell \geq 2$
Photon	$E_{\mathrm{T}}^{\gamma} > 25$ GeV, $\lvert\eta_\gamma\rvert < 2.37$ $E_{\mathrm{T}}^{\text{cone20}} < 0.07 E_{\mathrm{T}}^{\gamma}$ $\Delta R(\ell, \gamma) > 0.4$
Jet	$p_{\mathrm{T}}^{j} > 50$ 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 $\zeta(Z\gamma) < 0.4$ $N_{\text{jets}}^{\text{gap}} = 0$

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

$Z\gamma(\ell\ell)jj$ Distributions



Post-fit distributions of m_{jj} in SR (left, $m_{jj} > 500GeV$), CR (center, $m_{jj} > 500GeV$), Extended SR (right, $m_{jj} > 150GeV$)

$Z(\nu\nu)\gamma jj$ Strategy

- Largest Backgrounds:
  - $Z(\nu\nu)\gamma jj$ QCD ~36% of SR Yield
  - $W(\ell\nu)\gamma jj$ QCD ~25% of SR Yield
  - $W(\ell\nu)\gamma jj$ QCD ~7% of SR Yield
  - $t\bar{t}\gamma jj$ ~6% of SR Yield

Table 2: Fiducial region definition.

Selections	Cut value
E_T^{miss}	> 120 GeV
E_T^{γ}	> 150 GeV
Number of isolated photons	$N_\gamma = 1$
Photon isolation	$E_T^{cone40} < 0.022 p_T + 2.45$ GeV, $p_T^{cone20}/p_T < 0.05$
Number of jets	$N_{jets} \geq 2$ with $p_T > 50$ GeV
Overlap removal	$\Delta R(\gamma, \text{jet}) > 0.3$
Lepton veto	$N_e = 0$, $N_\mu = 0$
$\lvert\Delta\phi(\gamma, \vec{p}_T^{miss})\rvert$	> 0.4
$\lvert\Delta\phi(j_1, \vec{p}_T^{miss})\rvert$	> 0.3
$\lvert\Delta\phi(j_2, \vec{p}_T^{miss})\rvert$	> 0.3
m_{jj}	> 300 GeV
γ-centrality	< 0.6

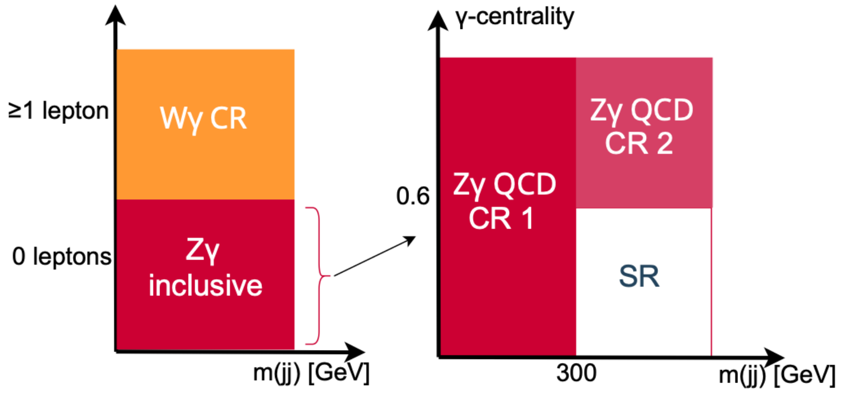


Figure 2: Definition of the regions used in the analysis.

$Z\gamma$ QCD CR1: $Z\gamma$ QCD Yield
$Z\gamma$ QCD CR2: $Z\gamma$ m_{jj} mismodeling check

[6] Photon centrality relative to the two jets with the highest p_T values in the event is defined as $\gamma\text{-centrality} = \left|\frac{y(\gamma)-0.5[y(j_1)+y(j_2)]}{y(j_1)-y(j_2)}\right|$, where $y = 0.5 \times \ln[(E+p_z)/(E-p_z)]$ is the rapidity of the objects (p_z is the z-component of the momentum of a particle).

$Z(\nu\nu)\gamma jj$ Systematics

Source of uncertainty	$\Delta\sigma/\sigma$ [%]
Experimental	
Jets	$-3.2/+3.4$
Electrons and photons	$-0.3/+1.7$
Muons	$-0.4/+0.5$
$E_{\mathrm{T}}^{\mathrm{miss}}$	$-1.8/+2.2$
Pile-up modelling	$-1.7/+3.2$
Trigger efficiency	$-0.9/+2.1$
Luminosity	$-1.2/+2.6$
Theory	
$Z(\nu\bar{\nu})\gamma jj$ EWK/QCD interference	$-0.6/+2.6$
$Z(\nu\bar{\nu})\gamma jj$ EWK process	$-6/+12$
$Z(\nu\bar{\nu})\gamma jj$ QCD process	$-15/+16$
Other processes	$-5.3/+7.7$
Other sources	
Data-driven backgrounds	$-0.9/+1.2$
Pile-up background	$-1.2/+2.6$
$Z(\nu\bar{\nu})\gamma jj$ QCD m_{jj} modelling	$-4.4/+4.4$

$Z(\nu\nu)\gamma jj$ BDT Variables

- m_{jj}
- $\Delta y(j_1, j_2)$
- E_T^{miss}
- p_T-balance
- $\eta(j_2)$
- $\eta(\gamma)$
- $p_T(j_1)$
- p_T-balance (reduced)
- N_{jets}
- $\sin(|\Delta\varphi(j_1, j_2)/2|)$
- $\Delta y(j_1, \gamma)$

[12] The p_{T}-balance $= \frac{|\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}} + \vec{p}_{\mathrm{T}}^{\,\gamma} + \vec{p}_{\mathrm{T}}^{\,j_1} + \vec{p}_{\mathrm{T}}^{\,j_2}|}{E_{\mathrm{T}}^{\mathrm{miss}} + E_{\mathrm{T}}^{\gamma} + p_{\mathrm{T}}^{j_1} + p_{\mathrm{T}}^{j_2}}$.

[13] The p_{T}-balance (reduced) $= \frac{|\vec{p}_{\mathrm{T}}^{\,\gamma} + \vec{p}_{\mathrm{T}}^{\,j_1} + \vec{p}_{\mathrm{T}}^{\,j_2}|}{E_{\mathrm{T}}^{\gamma} + p_{\mathrm{T}}^{j_1} + p_{\mathrm{T}}^{j_2}}$.

$ZZjj$ Strategy

- Select two $\ell^+\ell^-$ pairs with smallest $|m_{\ell\ell} - m_Z|$
- Leptons must satisfy $m_{4\ell} > 130 GeV$
- Largest backgrounds:
    - Prompt backgrounds
        - WWZ, WZ, and $t\bar{t}Z$
        - Modeled with MC
    - Nonprompt backgrounds
        - WZjj and $t\bar{t}$
        - Use data driven estimates

$ZZjj$ Systematics

Source	Uncertainty (%)	
	VBS-enhanced region	VBS-suppressed region
Luminosity	0.8 – 2.1	0.8 – 2.0
Leptons	0.8 – 1.6	1.0 – 1.5
Jets	2.7 – 18	3.4 – 13
Pile-up	0.0 – 2.5	0.0 – 0.7
Backgrounds	0.9 – 9.0	1.2 – 7.0
Theory modelling	0.6 – 7.5	1.2 – 8.8
Unfolding method	0.9 – 12	1.2 – 12
Total systematic	6 – 22	5 – 17