Measurement of electroweak Z(νν)γjj production and limits on anomalous quartic gauge couplings in ATLAS

Diana Pyatiizbyantseva

on behalf of the ATLAS Collaboration

NNV Annual meeting

Lunteren, 04 November 2022

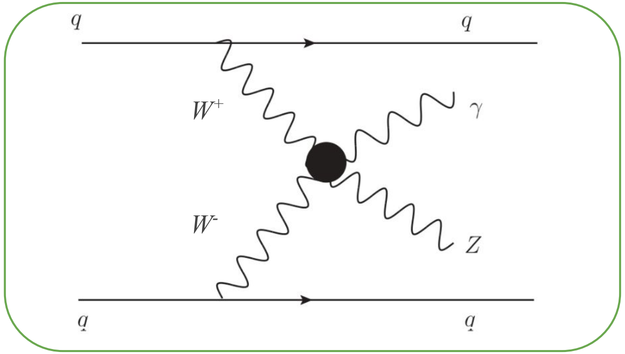
Motivation

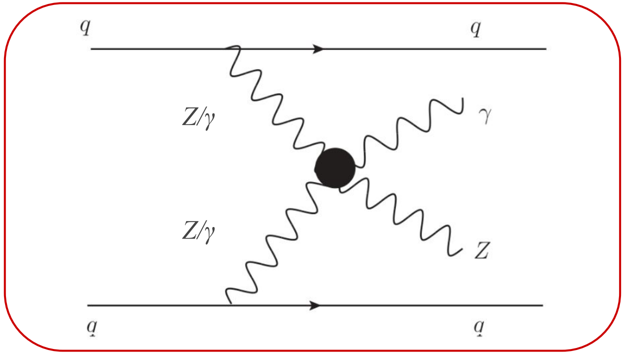
arXiv: **EWK Z(νν̄)γjj production**

- Tests of the electroweak (EWK) symmetry breaking mechanism in the Standard Model (SM).
- Sensitivity to SM quartic gauge couplings (QGCs) and possible anomalous QGCs **(aQGCs)** ⇒ beyond SM (**BSM**) physics.

Neutral QGCs are absent in the SM at tree level, but they can be induced by BSM.

SM





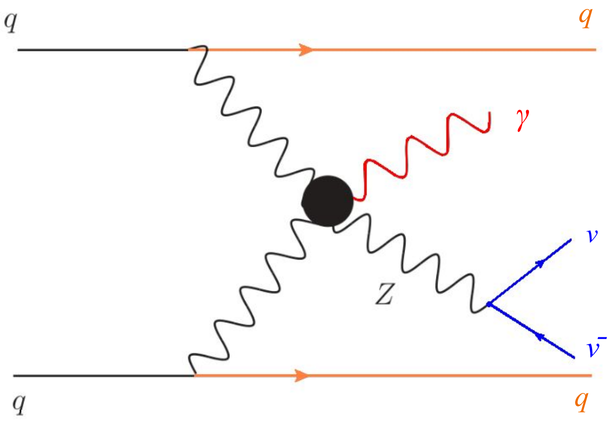
BSM

Higher Γ + better bkg control ⇒ ***Z(νν̄)γjj*** final state – optimal choice between *Z(ll)γjj* and *Z(qq)γjj*

2015–2018 data collected by the ATLAS experiment from *pp* collisions at $\sqrt{s}$ = 13 TeV, 139 fb^{-1}

Definition of the Regions

High-energy phase-space region (sensitive to aQGC)

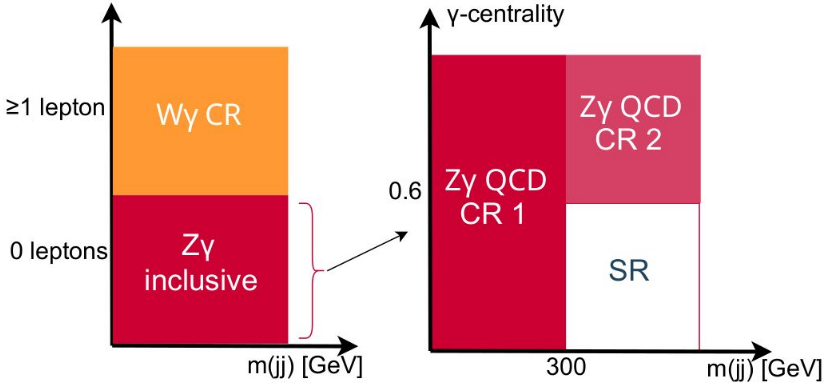


$N_{jets} \geq 2$

one isolated photon
$E_T^{\gamma} > 150$ GeV

$E_T^{miss} > 120$ GeV
lepton veto

Preselection



Wγ CR + **Zγ QCD CR 1**: bkg estimation
Zγ QCD CR 2: m_{jj} mismodelling

Selection optimisation to increase the signal significance: $S = N_{\text{signal}} / \sqrt{N_{\text{signal}} + N_{\text{bkg}}}$

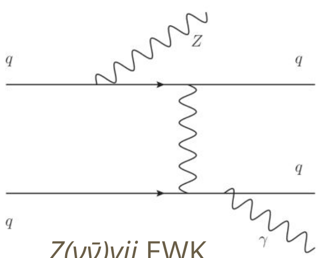
Preselection + additional cuts to suppress bkgs ⇒ **Zγ inclusive region**

Background Composition

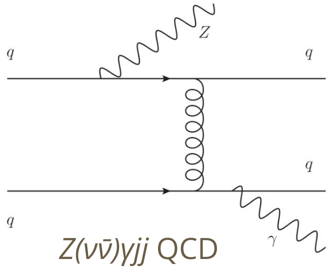
Signal: *Z(νν̄)γjj* EWK

Backgrounds:

- Simultaneous SR+CRs **fit to data:** *Z(νν̄)γjj* QCD, *W(lν)γjj*, and *ttγjj*

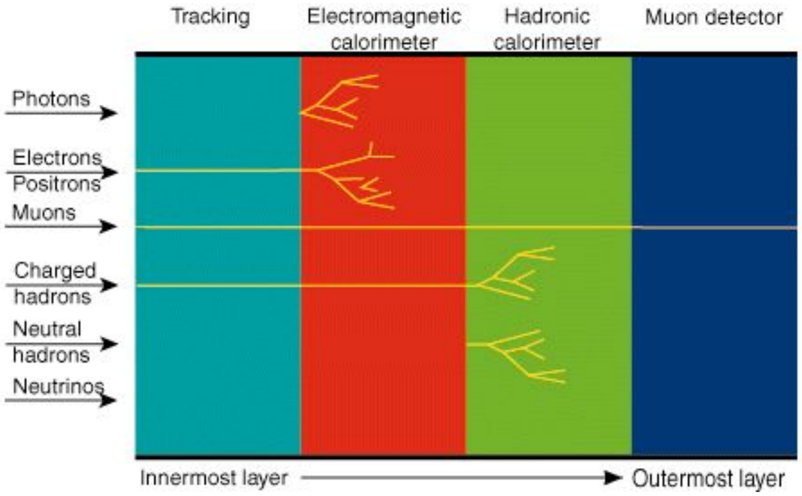


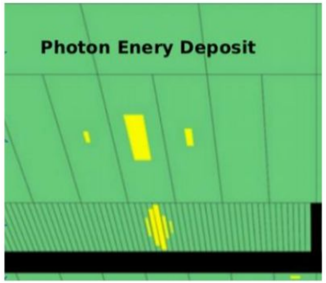
Z(νν̄)γjj EWK

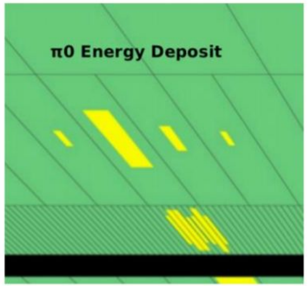


Z(νν̄)γjj QCD

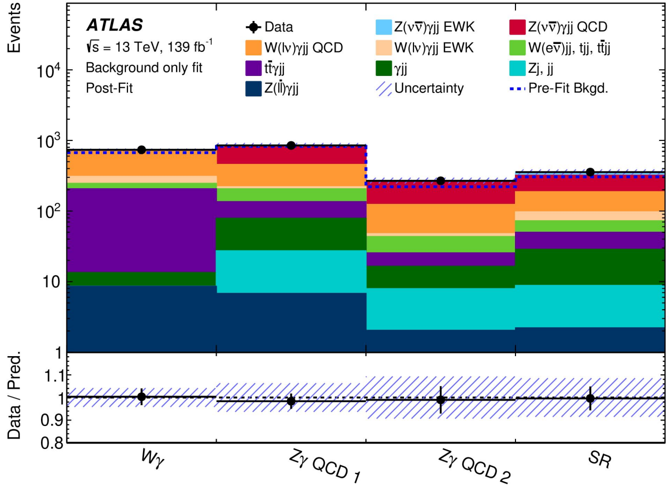
- **Data-driven:** $e \to \gamma$ (tag and probe method), $j \to E_T^{miss}$ and $j \to \gamma$ (2D sideband method), pile-up background ($\Delta z = z_{vtx} - z_{\gamma}$)
- **MC:** *Z(ll)γjj*







Maximum-likelihood Fit



BDT classifier:

- created with the TMVA package
- *Z(νν̄)γjj* EWK and QCD, *W(lν)γjj*, *ttγjj*
- trained in the Zγ inclusive region

Maximum-likelihood fit: the BDT classifier response (SR), m_{jj} (Zγ QCD and Wγ CRs)

$\mu_{Z\gamma EWK}$, $\mu_{Z\gamma QCD}$, $\mu_{W\gamma}$, event yields – estimation in the fit to the observed data:

POI	Value		
	Current analysis	Previous analysis*	Combination
$\mu_{Z\gamma\mathrm{EWK}}$	0.78 ± 0.33	1.04 ± 0.23	0.96 ± 0.18
$\mu_{Z\gamma\mathrm{QCD}}$	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

*Observation for *Z(νν̄)γjj* with $E_T^{\gamma} \in [15; 110]$ GeV

Current analysis: E_T^{γ} > 150 GeV

The largest impact of systematic uncertainties is from the theoretical uncertainties of the *Z(νν̄)γjj* EWK and QCD

Results

- **The observed significance** ($\mu_{Z\gamma EWK}$ = 0, background-only fit to the data): **3.2σ**.

  The expected significance (fit to the Asimov dataset): **3.7σ**.

  The observed (expected) significance of the combined result* is **6.3σ (6.6σ)**.

  *Observation for *Z(νν̄)γjj* with $E_T^{\gamma} \in [15; 110]$ GeV

- **Predicted** with *MadGraph5_aMC@NLO* (interfaced with *Pythia*) at LO, with NLO QCD corrections and scale uncertainties computed with *VBFNLO* **fiducial cross-section**:

$$\sigma^{\text{pred}}_{Z\gamma\text{EWK}} = 0.98 \pm 0.02\,(\text{stat.}) \pm 0.09\,(\text{scale}) \pm 0.02\,(\text{PDF})\ \text{fb}.$$

  Observed fiducial cross-section:

$$\sigma_{Z\gamma\text{EWK}} = 0.77^{+0.25}_{-0.23}\,(\text{stat.})^{+0.22}_{-0.18}\,(\text{syst.})\ \text{fb},$$

  which is consistent with the SM prediction.

Effective Field Theory (EFT)

Model-independent approach – **Effective Field Theory (EFT)**, which parametrises the BSM physics contributions in the Lagrangian:

$$\mathcal{L}_{\mathrm{EFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i^6 + \sum_j \frac{f_j}{\Lambda^4}\mathcal{O}_j^8$$

dim-6 → QGCs, TGCs

dim-8 → aQGCs, no aTGCs

Wilson coefficients:

- f_{M0}/Λ^4, f_{M1}/Λ^4, f_{M2}/Λ^4 (f_{MX} couplings)
- f_{T0}/Λ^4, f_{T5}/Λ^4, f_{T8}/Λ^4, f_{T9}/Λ^4 (f_{TX} couplings)

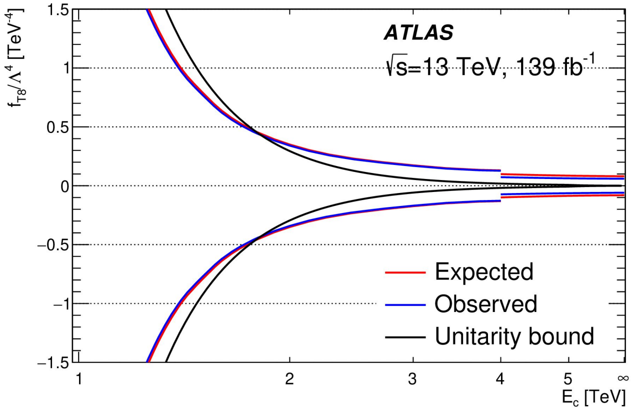
can be probed **only** by the neutral quartic vertices

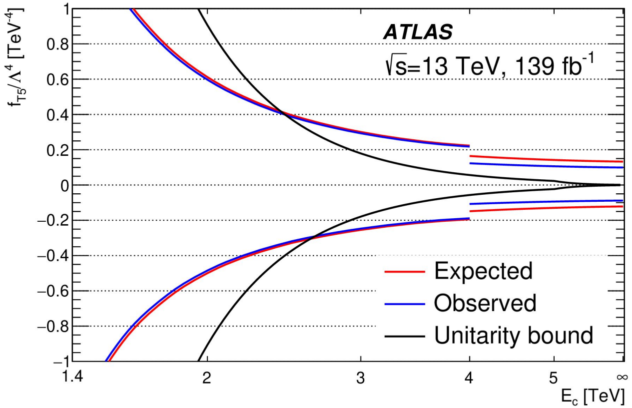
	$\mathcal{O}_{S,0}$, $\mathcal{O}_{S,1}$, $\mathcal{O}_{S,2}$	$\mathcal{O}_{M,0}$, $\mathcal{O}_{M,1}$, $\mathcal{O}_{M,7}$	$\mathcal{O}_{M,2}$, $\mathcal{O}_{M,3}$, $\mathcal{O}_{M,4}$, $\mathcal{O}_{M,5}$	$\mathcal{O}_{T,0}$, $\mathcal{O}_{T,1}$, $\mathcal{O}_{T,2}$	$\mathcal{O}_{T,5}$, $\mathcal{O}_{T,6}$, $\mathcal{O}_{T,7}$	$\mathcal{O}_{T,8}$, $\mathcal{O}_{T,9}$	
$WWWW$	X	X		X			
$WWZZ$	X	X	X	X	X		
$ZZZZ$	X	X	X	X	X	X	
$WWZ\gamma$		X	X	X	X		SM
$WW\gamma\gamma$		X	X	X	X		
$ZZZ\gamma$		X	X	X	X	X	BSM
$ZZ\gamma\gamma$		X	X	X	X	X	BSM
$Z\gamma\gamma\gamma$				X	X	X	BSM
$\gamma\gamma\gamma\gamma$				X	X	X	

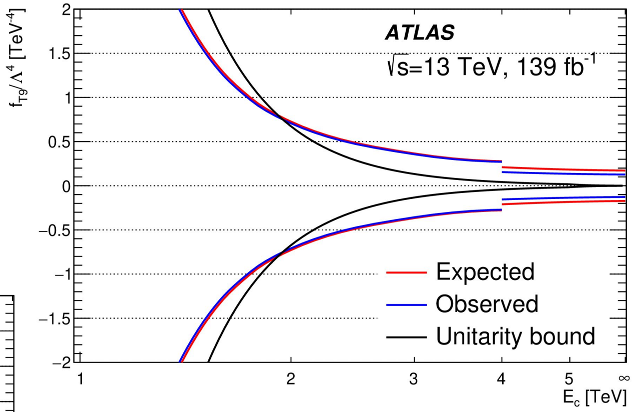
Evolution of the Expected and Observed Limits

Clipping technique: preserve unitarity at high energies.

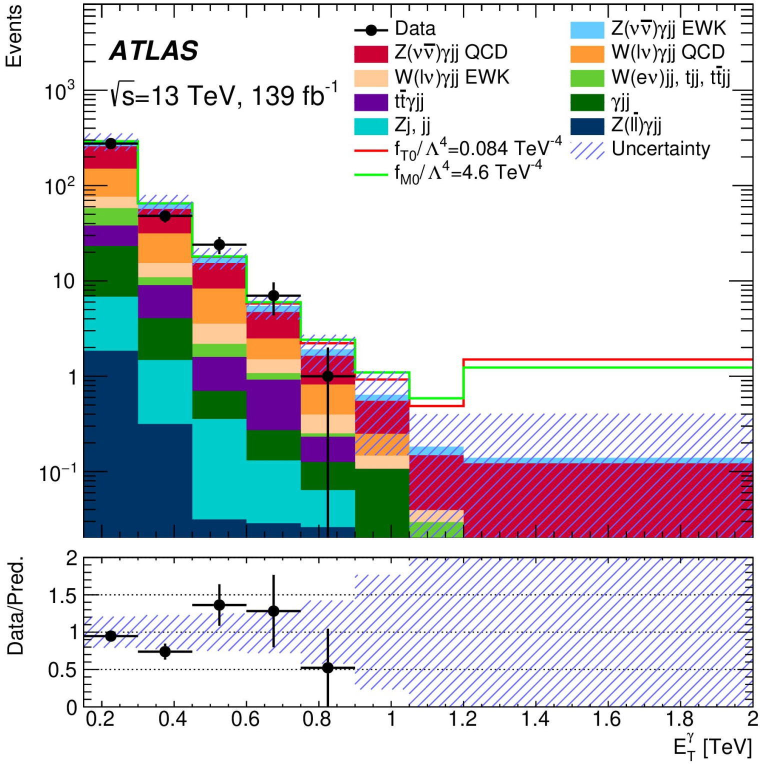
E_c – a cut-off scale: $m_{Z\gamma} > E_c \Rightarrow$ the anomalous signal contribution = 0.







Limits on Anomalous Quartic Gauge Couplings



Non-unitarised limits ($E_c = \infty$):

Coefficient	Observed limit, TeV^{-4}	Expected limit, TeV^{-4}
f_{T0}/Λ^4	$[-9.4, 8.4] \times 10^{-2}$	$[-1.3, 1.2] \times 10^{-1}$
f_{T5}/Λ^4	$[-8.8, 9.9] \times 10^{-2}$	$[-1.2, 1.3] \times 10^{-1}$
f_{T8}/Λ^4	$[-5.9, 5.9] \times 10^{-2}$	$[-8.1, 8.0] \times 10^{-2}$
f_{T9}/Λ^4	$[-1.3, 1.3] \times 10^{-1}$	$[-1.7, 1.7] \times 10^{-1}$
f_{M0}/Λ^4	$[-4.6, 4.6]$	$[-6.2, 6.2]$
f_{M1}/Λ^4	$[-7.7, 7.7]$	$[-1.0, 1.0] \times 10^{1}$
f_{M2}/Λ^4	$[-1.9, 1.9]$	$[-2.6, 2.6]$

Unitarised limits:

Coefficient	E_c, TeV	Observed limit, TeV^{-4}	Expected limit, TeV^{-4}
f_{T0}/Λ^4	1.7	$[-8.7, 7.1] \times 10^{-1}$	$[-8.9, 7.3] \times 10^{-1}$
f_{T5}/Λ^4	2.4	$[-3.4, 4.2] \times 10^{-1}$	$[-3.5, 4.3] \times 10^{-1}$
f_{T8}/Λ^4	1.7	$[-5.2, 5.2] \times 10^{-1}$	$[-5.3, 5.3] \times 10^{-1}$
f_{T9}/Λ^4	1.9	$[-7.9, 7.9] \times 10^{-1}$	$[-8.1, 8.1] \times 10^{-1}$
f_{M0}/Λ^4	0.7	$[-1.6, 1.6] \times 10^{2}$	$[-1.5, 1.5] \times 10^{2}$
f_{M1}/Λ^4	1.0	$[-1.6, 1.5] \times 10^{2}$	$[-1.4, 1.4] \times 10^{2}$
f_{M2}/Λ^4	1.0	$[-3.3, 3.2] \times 10^{1}$	$[-3.0, 3.0] \times 10^{1}$

Comparison of Limits

	$Z(\nu\nu)\gamma jj$ ATLAS	$Z(\ell\ell)\gamma jj$ CMS	$ZZjj$ CMS	$W\gamma jj$ CMS	$WW/WZ/ZZ+jj$ CMS
f_{T0}/Λ^4	**[-0.09, 0.08]**				[-0.12, 0.11]
f_{T5}/Λ^4	**[-0.09, 0.10]**			[-0.5, 0.5]	
f_{T8}/Λ^4	**[-0.06, 0.06]**		[-0.43, 0.43]		
f_{T9}/Λ^4	**[-0.13, 0.13]**	[-0.91, 0.91]			
f_{M0}/Λ^4	[-4.6, 4.6]				**[-0.69, 0.70]**
f_{M1}/Λ^4	[-7.7, 7.7]				**[-2.0, 2.1]**
f_{M2}/Λ^4	**[-1.9, 1.9]**			[-2.8, 2.8]	

*** Bold indicates the most stringent constraint.**

- f_{T5}/Λ^4, f_{T8}/Λ^4, f_{T9}/Λ^4: constraints are **significantly stringent** than those previously published for *Z(ll)γjj*, *ZZjj*, and *Wγjj* CMS analyses.
- f_{T0}/Λ^4, f_{M2}/Λ^4: constraints are **more stringent** than those previously published for *WW/WZ/ZZ+jj* CMS analyses.

Conclusion

***Z(νν̄)γjj* EWK** production (**full Run 2**, the ATLAS experiment, $E_T^{\gamma} > 150$ GeV):

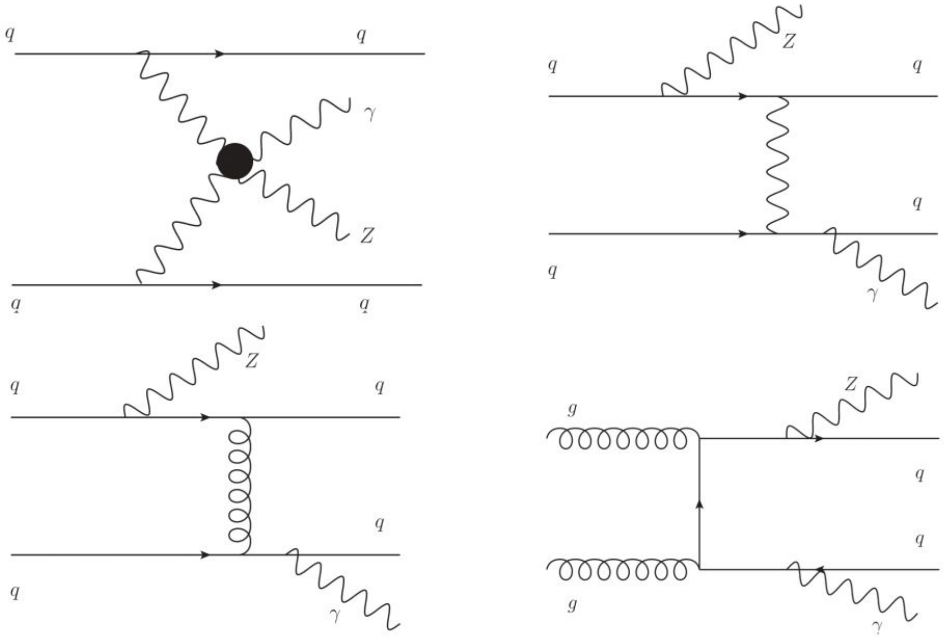
- The resulting observed (expected) **significance** is **3.2σ (3.7σ)** ⇔ **evidence** for this process in boosted photon regime. Signal significance of the **combination** with the previously published ATLAS result is **6.3σ (6.6σ)**.
- Measured fiducial **cross-section** $\mathbf{0.77^{+0.25}_{-0.23}(stat.)^{+0.22}_{-0.18}(syst.)\ fb}$ is in agreement with SM prediction within the uncertainty.
- **Limits on aQGCs** set on EFT dimension-8 operators are **either competitive with or more stringent** than previously published results.

Collecting more data (Run 3), optimising the signal extraction procedure, improving the bkg estimation techniques (better bkg suppression), and taking into account the impact of aQGCs on the bkgs can **increase the sensitivity**!

Thanks for your attention!

Back-up slides

Feynman Diagrams



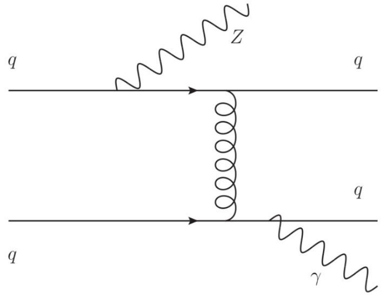
Electroweak *Zγjj* production involving the VBS subprocess (top left) or non-VBS subprocesses (top right) and of QCD *Zγjj* production with gluon exchange (bottom left) or the *s*-channel *gg*–*qq* process (bottom right).

Zγ inclusive region definition

Selections	Cut value
$E_{\mathrm{T}}^{\mathrm{miss}}$	> 120 GeV
E_{T}^{γ}	> 150 GeV
Number of isolated photons	$N_{\gamma} = 1$
Photon isolation	$E_{\mathrm{T}}^{\mathrm{cone40}} < 0.022 E_{\mathrm{T}}^{\gamma} + 2.45$ GeV, $p_{\mathrm{T}}^{\mathrm{cone20}} / E_{\mathrm{T}}^{\gamma} < 0.05$
Number of jets	$N_{\mathrm{jets}} \geq 2$
Lepton veto	$N_e = 0$, $N_{\mu} = 0$
$E_{\mathrm{T}}^{\mathrm{miss}}$ significance	> 12
$\lvert\Delta\phi(\gamma, \vec{p}_{\mathrm{T}}^{\mathrm{miss}})\rvert$	> 0.4
$\lvert\Delta\phi(j_1, \vec{p}_{\mathrm{T}}^{\mathrm{miss}})\rvert$	> 0.3
$\lvert\Delta\phi(j_2, \vec{p}_{\mathrm{T}}^{\mathrm{miss}})\rvert$	> 0.3
$p_{\mathrm{T}}^{\mathrm{SoftTerm}}$	< 16 GeV

$E_{\mathrm{T}}^{\mathrm{miss}}$ significance is calculated as $|\vec{p}_{\mathrm{T}}^{\mathrm{miss}}|^2 / \left(\sigma_{\mathrm{L}}^2 \left(1 - \rho_{\mathrm{LT}}^2\right)\right)$, where σ_{L} is the total variance in the direction longitudinal to the $E_{\mathrm{T}}^{\mathrm{miss}}$, and ρ_{LT} is the correlation coefficient of the longitudinal (L) and transverse (T) measurements [62].

Background Composition



$Z(\nu\bar{\nu})\gamma jj$ QCD

Signal: $Z(\nu\bar{\nu})\gamma jj$ EWK

Background estimation:

- $Z(\nu\bar{\nu})\gamma jj$ QCD (36%)
- $W(l\nu)\gamma jj$ QCD (25%) and EWK (7%)
- $tt\gamma jj$ (6%)

} simultaneous SR+CRs **fit to data** (shape from MC)

- $e\rightarrow\gamma$ ($W(e\nu)$, t, tt, 6%) – tag and probe method ($e\gamma/ee$ pairs)
- $E_T^{miss}\rightarrow j$ (γ+j, 6%) – 2D sideband method (E_T^{miss} significance and $p_T^{SoftTerm}$)
- $j\rightarrow\gamma$ ($Z(\nu\bar{\nu})$, multijet, 2%) – 2D sideband method (photon isolation and ID)
- pile-up background (negligible) – dependence on $\Delta z = z_{vtx} - z_\gamma$

} **data-driven**

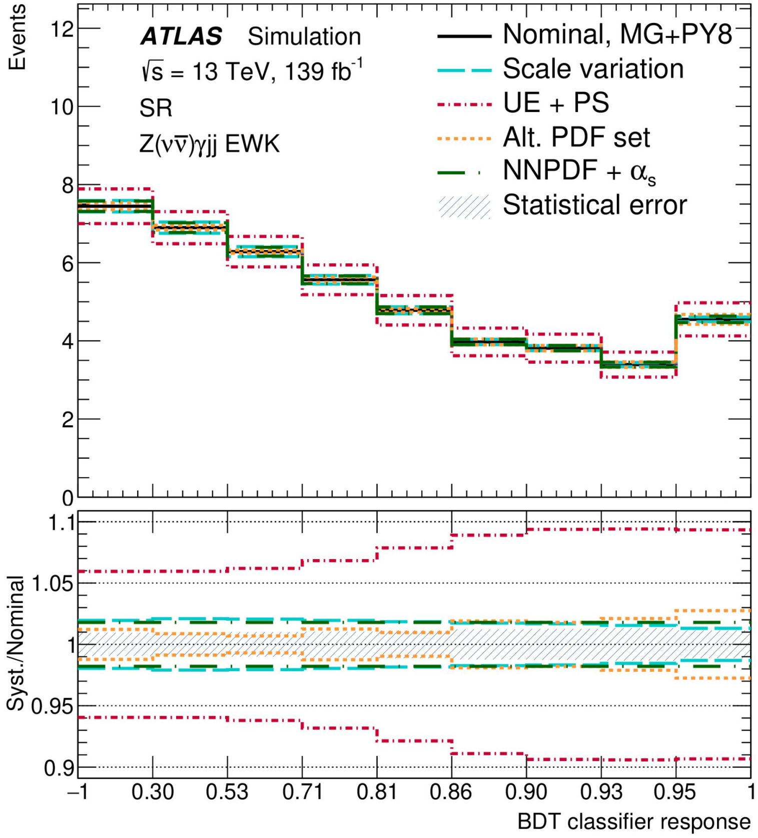
- $Z(ll)\gamma jj$ (< 1%) – **MC**

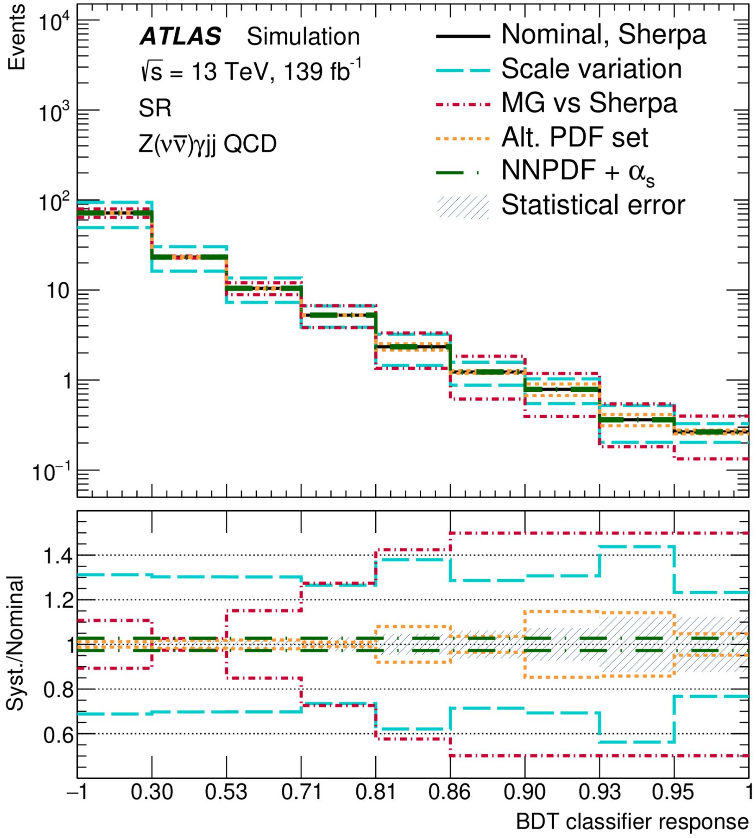
Systematic Uncertainties

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

The largest impact – theoretical uncertainties of the *Z(νν̄)γjj* EWK and QCD

Theoretical Systematic Uncertainties: *Z(νν)γjj* EWK and QCD





BDT Classifier

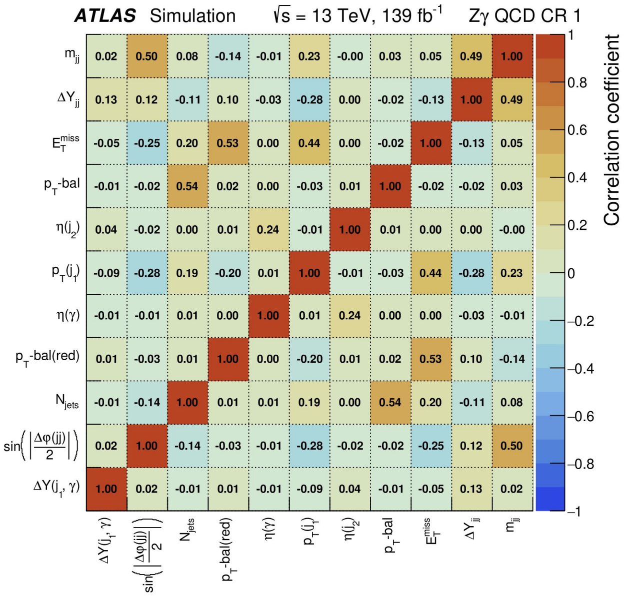
Variables used to create the classifier:

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

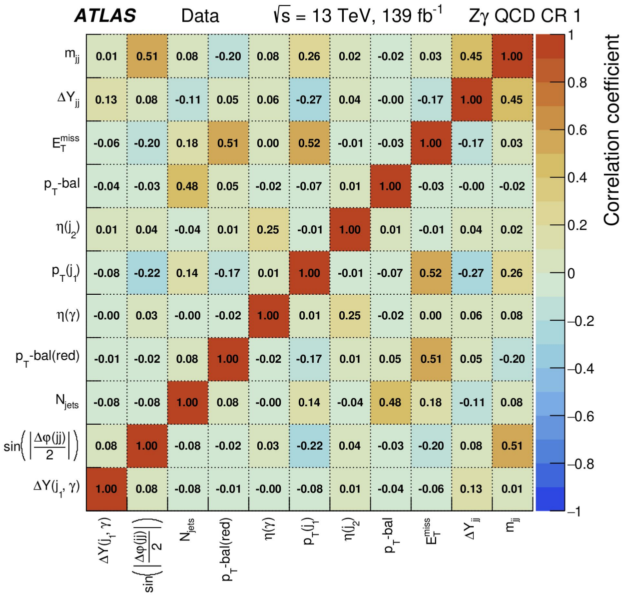
$$\text{The } p_\text{T}\text{-balance} = \frac{|\vec{p}_\text{T}^{\,\text{miss}} + \vec{p}_\text{T}^{\,\gamma} + \vec{p}_\text{T}^{\,j1} + \vec{p}_\text{T}^{\,j2}|}{E_\text{T}^{\text{miss}} + E_\text{T}^{\gamma} + p_\text{T}^{j1} + p_\text{T}^{j2}}.$$

$$\text{The } p_\text{T}\text{-balance (reduced)} = \frac{|\vec{p}_\text{T}^{\,\gamma} + \vec{p}_\text{T}^{\,j1} + \vec{p}_\text{T}^{\,j2}|}{E_\text{T}^{\gamma} + p_\text{T}^{j1} + p_\text{T}^{j2}}.$$

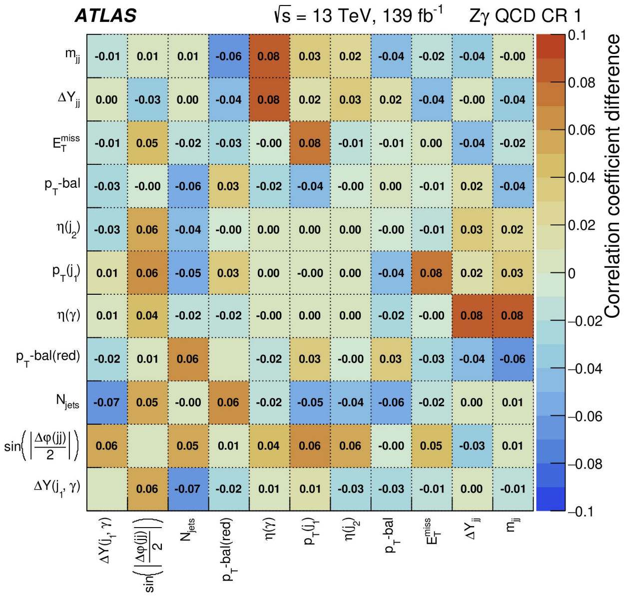
Correlation Coefficients between the Input Variables



MC

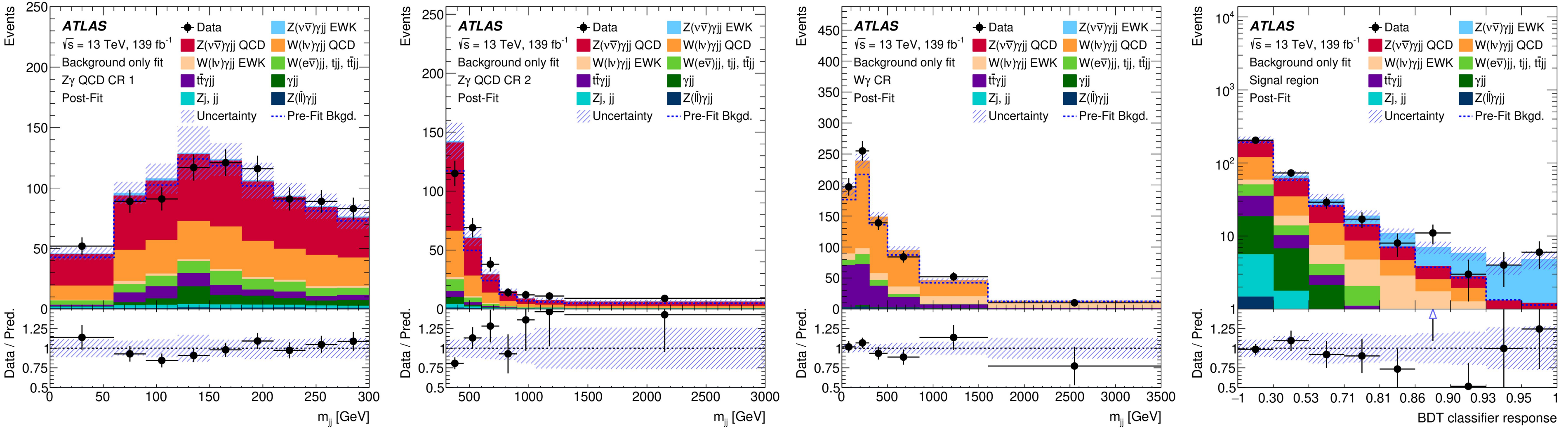


Data



Difference

The Post-fit m_{jj} and BDT Classifier Response Distributions



Event Yields after the Fit to the Data

	$W\gamma$ CR	$Z\gamma$ QCD CR 1	$Z\gamma$ QCD CR 2	Signal region
$Z(\nu\bar{\nu})\gamma jj$ EWK	0.108 ± 0.028	11.0 ± 4.3	4.0 ± 2.2	37 ± 14
$Z(\nu\bar{\nu})\gamma jj$ QCD	1.04 ± 0.46	394 ± 84	143 ± 32	133 ± 39
$W(\ell\nu)\gamma jj$ QCD	425 ± 63	237 ± 71	76 ± 24	91 ± 30
$W(\ell\nu)\gamma jj$ EWK	63 ± 12	14.3 ± 2.7	4.5 ± 1.2	24.6 ± 4.9
$W(e\nu)jj, tjj, t\bar{t}jj$	39.8 ± 2.5	70.1 ± 4.1	17.9 ± 1.3	22.5 ± 1.5
$t\bar{t}\gamma jj$	193 ± 57	57 ± 20	9.1 ± 3.4	21.3 ± 7.6
γjj	4.8 ± 7.4	52 ± 36	8 ± 11	20 ± 17
Zj, jj	0.06 ± 0.66	20 ± 14	5.9 ± 6.9	6.6 ± 7.8
$Z(\ell\bar{\ell})\gamma jj$	8.6 ± 2.5	6.8 ± 2.0	2.04 ± 0.95	2.2 ± 1.3
Total	735 ± 30	863 ± 54	271 ± 25	357 ± 30
Data	737	849	268	356

Fiducial Region Definition

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

$$\gamma\text{-centrality} = \left| \frac{y(\gamma) - 0.5[y(j_1) + y(j_2)]}{y(j_1) - y(j_2)} \right|$$

Evolution of the Expected and Observed Limits