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Measurements of quartic coupling and vector boson scattering in ATLAS

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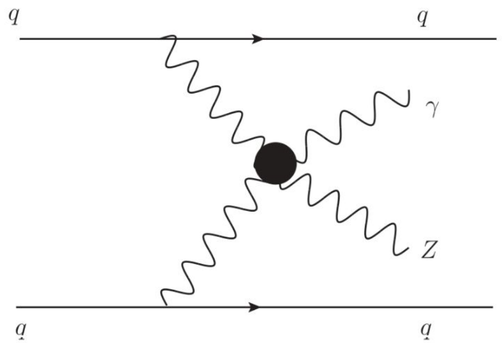
Motivation

Analysis: **EWK $Z(\nu\bar{\nu})\gamma jj$ production**

Vector boson scattering (VBS), $V\,V \rightarrow V\,V$ ($V = W/Z/\gamma$):

- EWK *VVjj* processes;
- Tests of the ESB mechanism;
- Sensitivity to SM **QGCs** and possible aQGCs → BSM.



Final state *Zγjj*: neutral QGCs (absent in the SM at tree level, can be induced by BSM).

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

higher branching ratio → *$Z(ll)\gamma jj$*

better background control → *$Z(\rightarrow hadrons)\gamma jj$*

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

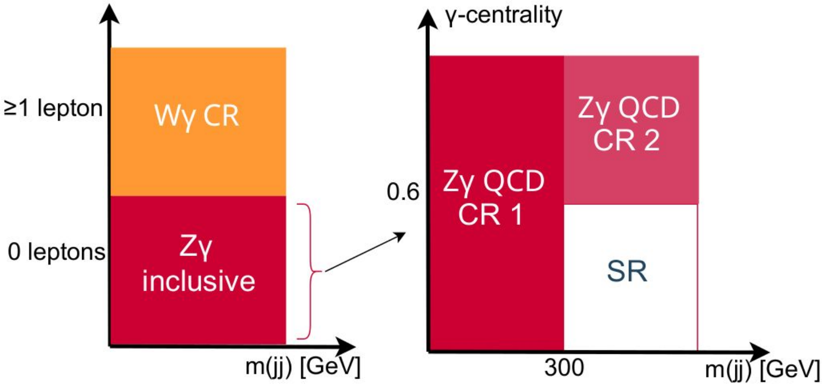
Definition of the Regions

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

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

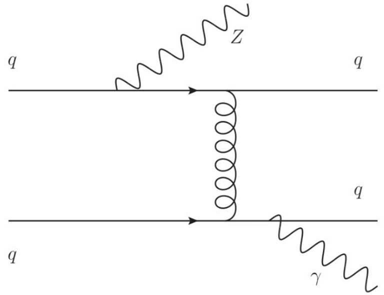
Zγ inclusive region:

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



Wγ CR: normalisation of *Wγjj* QCD+EWK with *ttγjj*
Zγ QCD CR 1: *Z(νν̄)γjj* QCD bkg
Zγ QCD CR 2: check for m_{jj} mismodelling

Background Composition



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

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

Background estimation:

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

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

- $e\rightarrow\gamma$ ($W(e\nu)$, t, tt, 6%) – Z-peak method ($e\gamma/ee$ pairs)
- $E_T^{miss}\rightarrow j$ ($\gamma+j$, 5.5%) – ABCD method (E_T^{miss} significance and $p_T^{SoftTerm}$)
- $j\rightarrow\gamma$ ($Z(\nu\bar{\nu})$, multijet, 2%) – ABCD method (photon isolation and ID)
- pile-up background (negligible) – $\Delta z = z_{vtx} - z_\gamma$

} **data-driven**

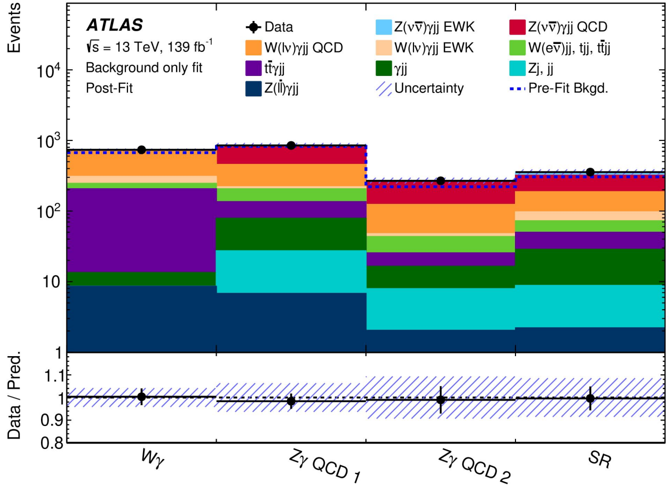
- $Z(ll)\gamma jj$ (< 1%) – **MC**

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

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^γ ∈ [15; 110] GeV**

Current analysis: **E_T^γ > 150 GeV**

Results

- **The observed significance** ($\mu_{Z\gamma EWK}$ = 0, a 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:

$$\sigma_{Z\gamma\text{EWK}} = 0.77^{+0.34}_{-0.30}\ \text{fb}.$$

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:

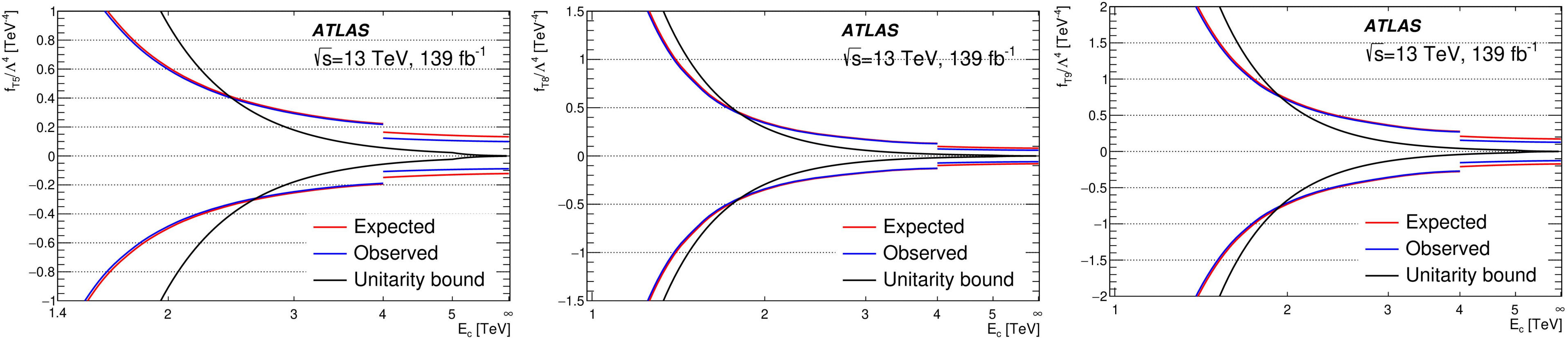
- $f_{\mathrm{M0}}/\Lambda^4$, $f_{\mathrm{M1}}/\Lambda^4$, $f_{\mathrm{M2}}/\Lambda^4$ (f_{MX} couplings)
- $f_{\mathrm{T0}}/\Lambda^4$, $f_{\mathrm{T5}}/\Lambda^4$, $f_{\mathrm{T8}}/\Lambda^4$, $f_{\mathrm{T9}}/\Lambda^4$ (f_{TX} couplings)

$f_{\mathrm{T8}}/\Lambda^4$, $f_{\mathrm{T9}}/\Lambda^4$: can be probed **only** by the neutral quartic vertices

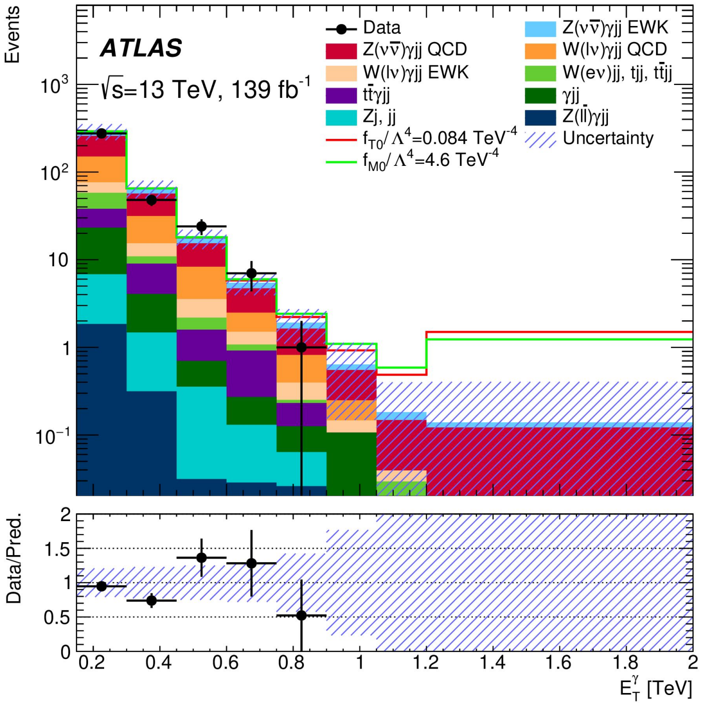
Evolution of the Expected and Observed Limits

Clipping technique: preserve unitarity at high energies. The anomalous signal contribution is set to zero for $m_{Z\gamma} > E_c$, where E_c is a cut-off scale, based on the unitarity bounds for a given limit value calculated from partial-wave unitarity constraints.

***E*$_c$ < 4 TeV regime:** $E_T^\gamma > 600$ GeV (400 GeV) for f_{TX} (f_{MX}) couplings
***E*$_c$ > 4 TeV regime:** $E_T^\gamma > 900$ GeV
***E*$_c$ = ∞** ⇔ no clipping technique



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	$[-3.3, 3.2] \times 10^{1}$	$[-3.0, 3.0] \times 10^{1}$

The constraints are **either competitive with or more stringent** than those previously published by CMS collaboration for *Zγjj*, *Wγjj*, *VVjj* analyses (channel + statistics).

Conclusion

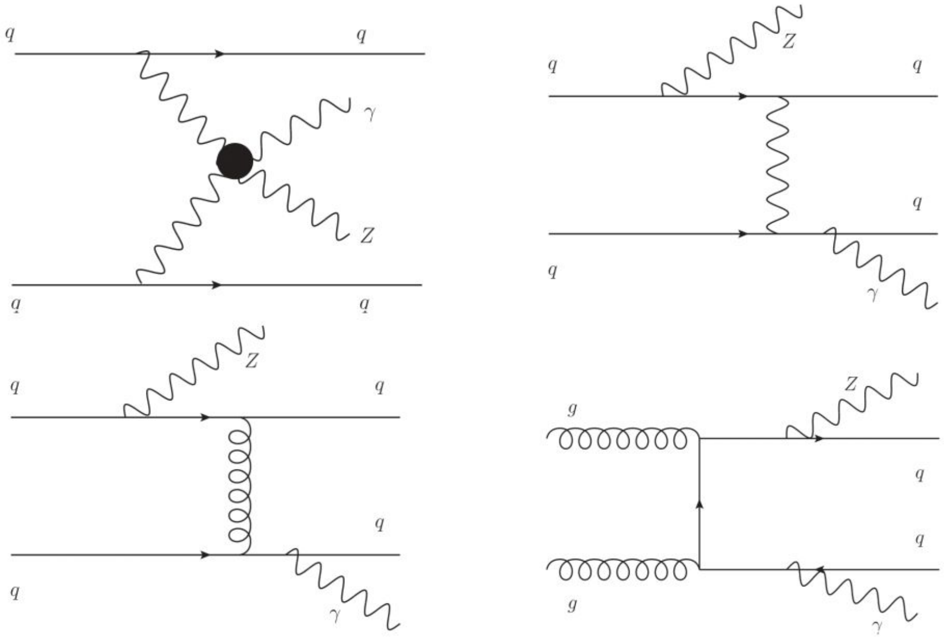
***$Z(\nu\bar{\nu})\gamma jj$* EWK** (E_T^{γ} > 150 GeV), data collected by the ATLAS experiment (*pp* collisions at **$\sqrt{s}$ = 13 TeV** , 2015–2018, **139 fb^{-1}**:

- Dominant bkgs – a simultaneous SR+CRs **fit to data** and **data-driven techniques**.
- **Maximum-likelihood fit** over the BDT classifier distribution ⇒ signal significance is **3.2σ (3.7σ)** ⇔ **evidence** for this process in boosted photon regime.
- **Measured fiducial cross-section** $\mathbf{0.77^{+0.34}_{-0.30}}$ **fb** – in agreement with SM predictions (MadGraph5_aMC@NLO) at NLO in perturbative QCD.
- Signal significance of the **combination** with previously published ATLAS result is **6.3σ (6.6σ)**.
- **Limits on aQGCs** set on EFT dimension-8 operators are **either competitive with or more stringent** than those previously published by CMS. The constraints on the f_{T5}/Λ^4, f_{T8}/Λ^4, and f_{T9}/Λ^4 operators are **significantly stronger** than results previously published by ATLAS and CMS.

Thanks for your attention!

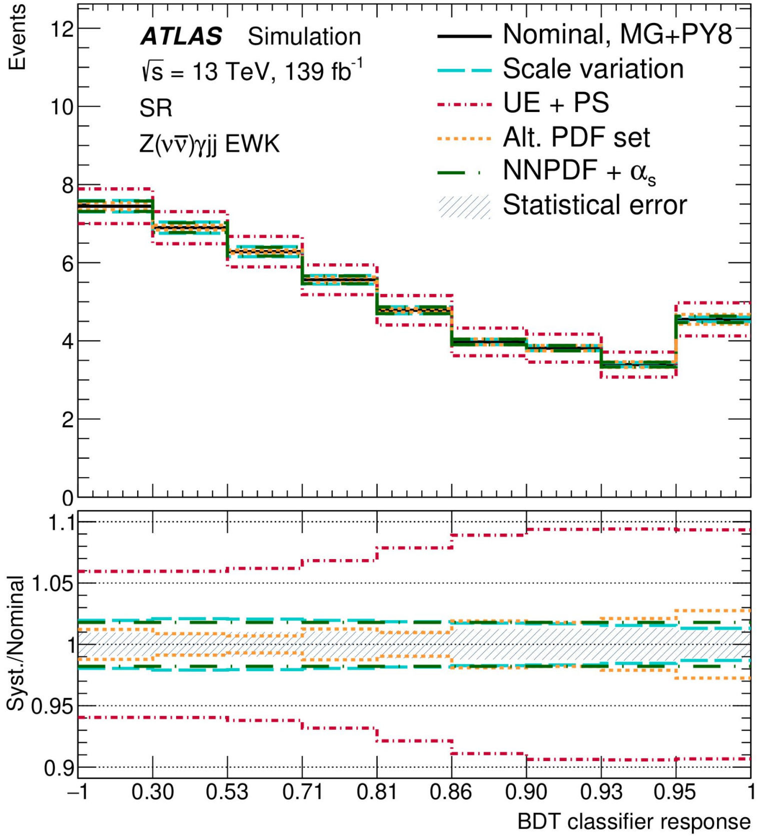
Back-up slides

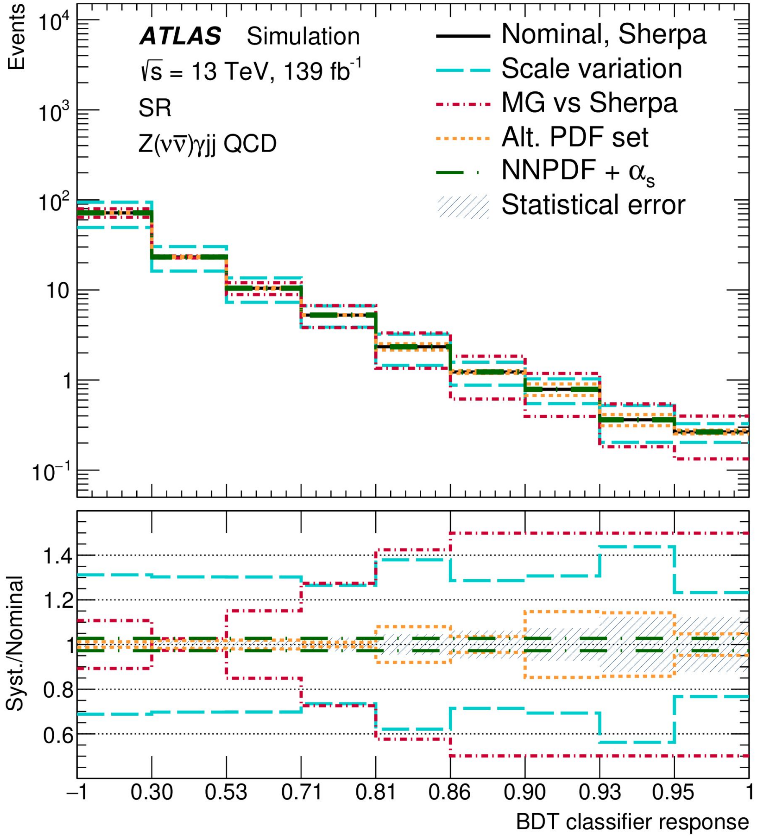
Feynman Diagrams



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).

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





BDT Classifier

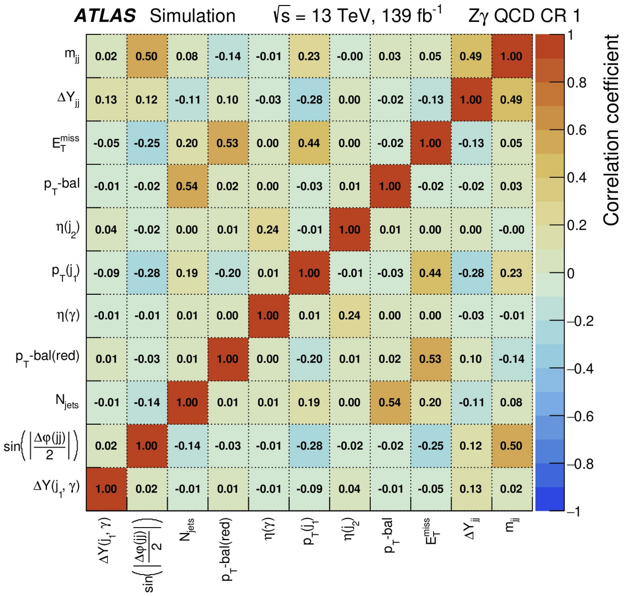
Variables used to create the classifier:

- 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}
- $sin(|\Delta\phi(j_1, j_2)/2|)$
- $\Delta y(j_1, \gamma)$

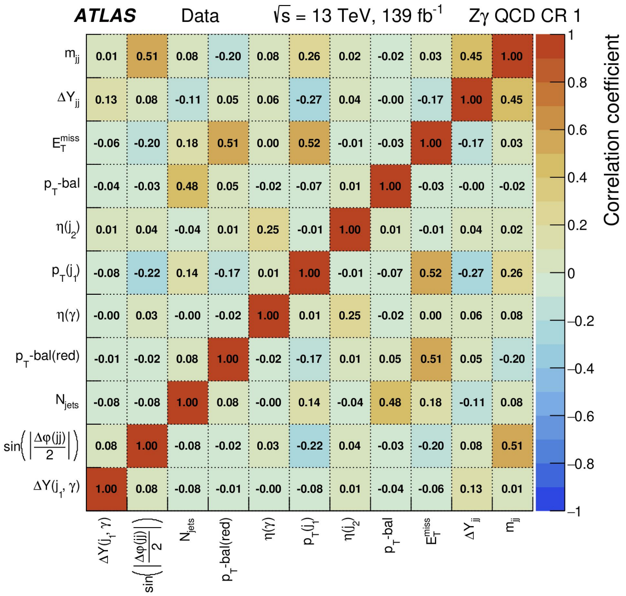
$$\text{The } p_{\mathrm{T}}\text{-balance} = \frac{|\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}} + \vec{p}_{\mathrm{T}}^{\,\gamma} + \vec{p}_{\mathrm{T}}^{\,j1} + \vec{p}_{\mathrm{T}}^{\,j2}|}{E_{\mathrm{T}}^{\mathrm{miss}} + E_{\mathrm{T}}^{\gamma} + p_{\mathrm{T}}^{j1} + p_{\mathrm{T}}^{j2}}.$$

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

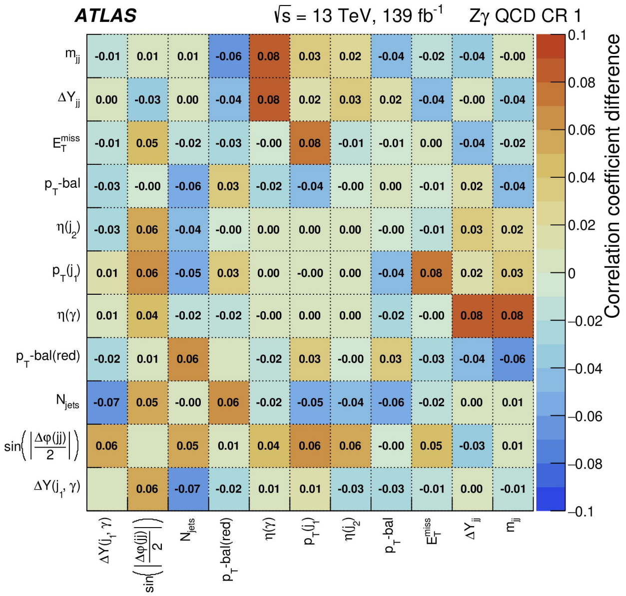
Correlation Coefficients between the Input Variables



MC

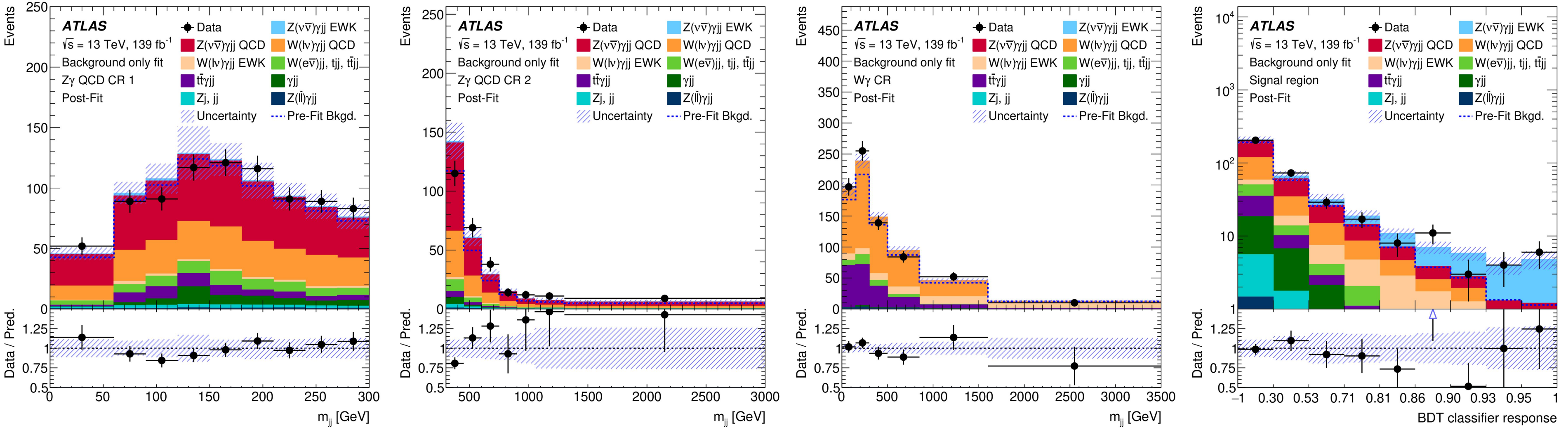


Data



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

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

$E_{\mathrm{T}}^{\mathrm{miss}}$ 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

Evolution of the Expected and Observed Limits