Julius-Maximilians-UNIVERSITÄT WÜRZBURG

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Study of electroweak production of $W(\ell\nu)Z(\ell\ell)\gamma$ events in the Run-2 and Run-3 proton-proton collision data of the ATLAS detector

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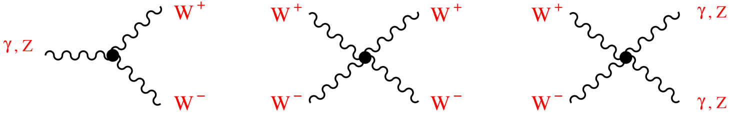
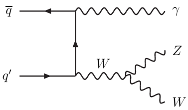
Introduction

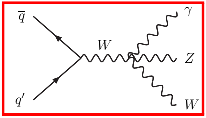


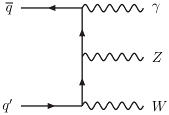
- Standard Model Lagrangian is symmetric under $SU(2)_L \otimes U(1)_Y \rightarrow$ non-abelian gauge structure predicts triple and quartic gauge self-interactions
- Coupling strength fixed by $SU(2)_L \otimes U(1)_Y$ gauge symmetry
- Measurement can provide a powerful test of non-abelian gauge structure
- Deviations from the SM prediction can indicate additional interactions

Run-2 $WZ\gamma$ measurement

- SM gauge structure can be probed in EW multiboson measurements
- Particularly interesting: $WZ\gamma$ production $\rightarrow$ Access to $WWZ\gamma$ coupling
- Test of Composite Higgs models possible
- $WZ\gamma$ production observed by ATLAS collaboration at the LHC using $\mathcal{L} = (140.1 \pm 1.2)\,\text{fb}^{-1}$ proton-proton collision data at $\sqrt{s} = 13\,\text{TeV}$ (PhysRevLett.132.021802)





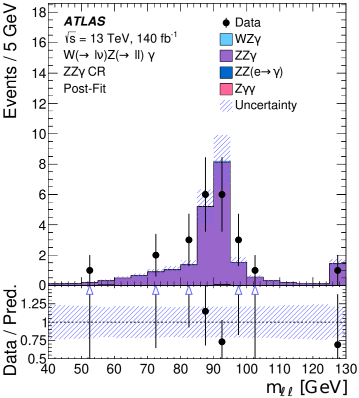


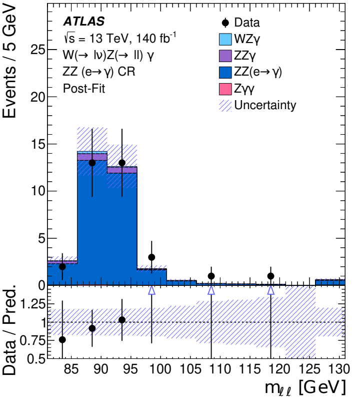
Run-2 $WZ\gamma$ measurement: Event selection

- Signature: $e^+e^-/\mu^+\mu^- + e^\pm/\mu^\pm + \gamma$
- SR selection: Focus on rejecting FSR/including events only with a hard-scatter photon $\rightarrow WWZ\gamma$ not well isolated

	SR definition
Lepton veto	no additional leptons with $p_T^{\ell_4} > 10\,\text{GeV}$
Z lepton assignment	smallest $\lvert m_{\ell\ell} - m_Z \rvert$
$ZZ(e \rightarrow \gamma)$ rejection	$\lvert m(e_W, \gamma) - m_Z \rvert > 10\,\text{GeV}$
Missing p_T	$E_T > 20\,\text{GeV}$
ΔR	$\Delta R(\ell, \gamma) > 0.4$, $\Delta R(e, \mu) > 0.2$
Z candidate	$m_{\ell\ell} > 81\,\text{GeV}$

Non-prompt background: $Z\gamma\gamma$, $WZ+X$, $ZZ+X$, $t\bar{t}\gamma$
→ Estimated using data-driven "Fake factor" method
Irreducible background: ZZ, $ZZ\gamma$
→ Dedicated CRs





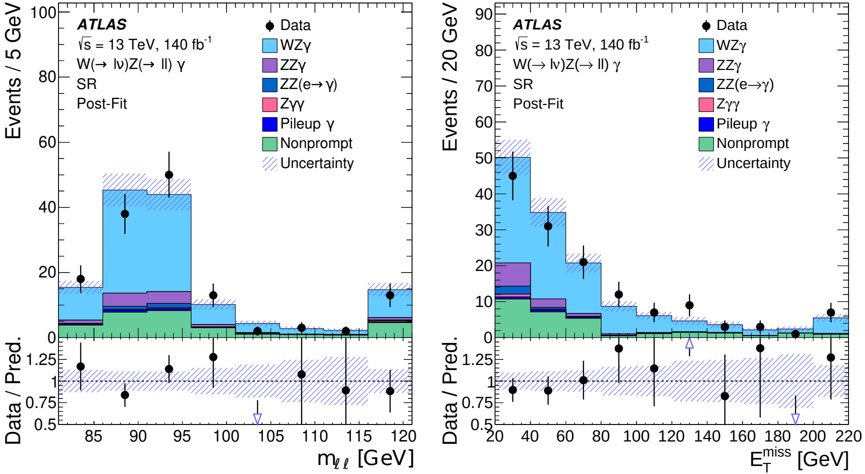
Run-2 $WZ\gamma$ measurement: Results

Binned log-likelihood fit of $WZ\gamma$ SR and $ZZ\gamma + ZZ$ CRs (3 bin fit)

- $\mu_{WZ\gamma} = 1.34 \pm 0.20\,(\text{stat}) \pm 0.10\,(\text{syst}) \pm 0.07\,(\text{theory})$
- $\sigma_{WZ\gamma} = 2.01 \pm 0.30\,(\text{stat}) \pm 0.16\,(\text{syst})$ fb
- Observation of $WZ\gamma$ at 6.3σ (expected 5.0σ)

Process	SR	$ZZ\gamma$ CR	$ZZ(e \to \gamma)$ CR
$WZ\gamma$	92 ± 15	0.21 ± 0.07	0.56 ± 0.14
$ZZ\gamma$	10.7 ± 2.3	23 ± 5	1.8 ± 0.4
$ZZ(e \to \gamma)$	3.0 ± 0.6	0.028 ± 0.020	30 ± 6
$Z\gamma\gamma$	1.05 ± 0.32	0.15 ± 0.06	0.29 ± 0.10
Nonprompt background	30 ± 6	-	-
Pileup γ	1.9 ± 0.7	-	-
Total yield	139 ± 12	23 ± 5	33 ± 6
Data	139	23	33

Run-2 $WZ\gamma$ measurement: Kinematic distributions



Goals of my PhD project

Analyse $WZ\gamma$ production with the following improvements compared to Run-2:

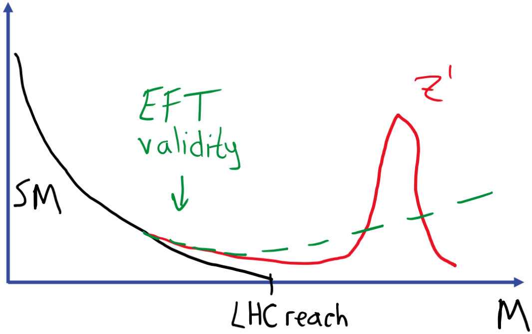
- Differential cross-section measurement of triboson $WZ\gamma$ production using Run-2 and Run-3 data $\rightarrow$ reduced statistical uncertainty due to larger dataset
- Probe EW gauge structure by setting constraints on anomalous quartic gauge couplings (aQGC) using EFT interpretation
- At later stage: Test Composite Higgs models

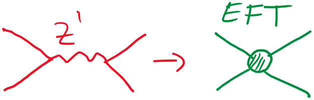
Introduction to effective field theory (EFT)

- Effective field theories allow us to quantify agreement/disagreement
- Add operators to the Lagrangian with mass dimension $\Delta_i > 4$:

$$\mathcal{L} = \mathcal{L}_{\mathsf{SM}} + \sum_i \frac{g_i}{\Lambda^{\Delta_i - 4}} \mathcal{O}_i$$

- Λ represents the energy scale of new physics
- g_i: Wilson coefficients
- EFT is valid for $E \ll \Lambda$





Eboli model

Eboli model (arXiv:1604.03555v1): 21 CP conserving operators of mass dimension 8 for aQGC

Scalar operators only

$$\mathcal{O}_{S,0} = \left[(D_\mu\Phi)^\dagger D_\nu\Phi\right] \times \left[(D^\mu\Phi)^\dagger D^\nu\Phi\right]$$

$$\mathcal{O}_{S,1} = \left[(D_\mu\Phi)^\dagger D^\mu\Phi\right] \times \left[(D_\nu\Phi)^\dagger D^\nu\Phi\right]$$

$$\mathcal{O}_{S,2} = \left[(D_\mu\Phi)^\dagger D_\nu\Phi\right] \times \left[(D^\nu\Phi)^\dagger D^\mu\Phi\right]$$

Mixed operators

$$\mathcal{O}_{M,0} = \mathrm{Tr}\left[\widehat{W}_{\mu\nu}\widehat{W}^{\mu\nu}\right] \times \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right] \quad , \quad \mathcal{O}_{M,1} = \mathrm{Tr}\left[\widehat{W}_{\mu\nu}\widehat{W}^{\nu\beta}\right] \times \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right] \quad ,$$

$$\mathcal{O}_{M,2} = \left[B_{\mu\nu}B^{\mu\nu}\right] \times \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right] \quad , \quad \mathcal{O}_{M,3} = \left[B_{\mu\nu}B^{\nu\beta}\right] \times \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right] \quad ,$$

$$\mathcal{O}_{M,4} = \left[(D_\mu\Phi)^\dagger \widehat{W}_{\beta\nu} D^\mu\Phi\right] \times B^{\beta\nu} \quad , \quad \mathcal{O}_{M,5} = \left[(D_\mu\Phi)^\dagger \widehat{W}_{\beta\nu} D^\nu\Phi\right] \times B^{\beta\mu} + \mathrm{h.c.} \quad ,$$

$$\mathcal{O}_{M,7} = \left[(D_\mu\Phi)^\dagger \widehat{W}_{\beta\nu}\widehat{W}^{\beta\mu} D^\nu\Phi\right] \quad .$$

Field strength tensor operators only

$$\mathcal{O}_{T,0} = \mathrm{Tr}\left[\widehat{W}_{\mu\nu}\widehat{W}^{\mu\nu}\right] \times \mathrm{Tr}\left[\widehat{W}_{\alpha\beta}\widehat{W}^{\alpha\beta}\right] \quad , \quad \mathcal{O}_{T,1} = \mathrm{Tr}\left[\widehat{W}_{\alpha\nu}\widehat{W}^{\mu\beta}\right] \times \mathrm{Tr}\left[\widehat{W}_{\mu\beta}\widehat{W}^{\alpha\nu}\right]$$

$$\mathcal{O}_{T,2} = \mathrm{Tr}\left[\widehat{W}_{\alpha\mu}\widehat{W}^{\mu\beta}\right] \times \mathrm{Tr}\left[\widehat{W}_{\beta\nu}\widehat{W}^{\nu\alpha}\right] \quad , \quad \mathcal{O}_{T,5} = \mathrm{Tr}\left[\widehat{W}_{\mu\nu}\widehat{W}^{\mu\nu}\right] \times B_{\alpha\beta}B^{\alpha\beta}$$

$$\mathcal{O}_{T,6} = \mathrm{Tr}\left[\widehat{W}_{\alpha\nu}\widehat{W}^{\mu\beta}\right] \times B_{\mu\beta}B^{\alpha\nu} \quad , \quad \mathcal{O}_{T,7} = \mathrm{Tr}\left[\widehat{W}_{\alpha\mu}\widehat{W}^{\mu\beta}\right] \times B_{\beta\nu}B^{\nu\alpha}$$

$$\mathcal{O}_{T,8} = B_{\mu\nu}B^{\mu\nu}B_{\alpha\beta}B^{\alpha\beta} \quad , \quad \mathcal{O}_{T,9} = B_{\alpha\mu}B^{\mu\beta}B_{\beta\nu}B^{\nu\alpha} \; .$$

Contributions of operators to various QGC

	$O_{S,0}$ $O_{S,1}$ $O_{S,2}$	$O_{M,0}$ $O_{M,1}$ $O_{M,7}$	$O_{M,2}$ $O_{M,3}$ $O_{M,4}$ $O_{M,5}$	$O_{T,0}$ $O_{T,1}$ $O_{T,2}$	$O_{T,5}$ $O_{T,6}$ $O_{T,7}$	$O_{T,8}$ $O_{T,9}$
WWWW	√	√		√		
WWZZ	√	√	√	√	√	
WWγZ		√	√	√	√	
WW$\gamma\gamma$		√	√	√	√	
ZZZZ	√	√	√	√	√	√
ZZZγ		√	√	√	√	√
ZZ$\gamma\gamma$		√	√	√	√	√
Z$\gamma\gamma\gamma$				√	√	√
$\gamma\gamma\gamma\gamma$				√	√	√

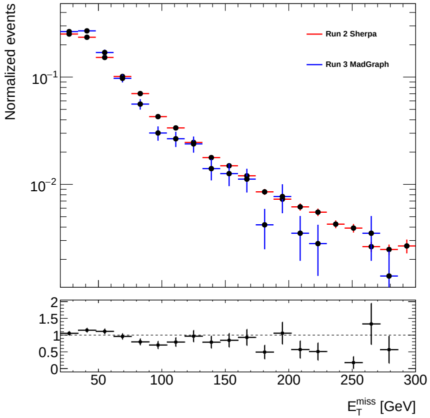
Monte Carlo sample production

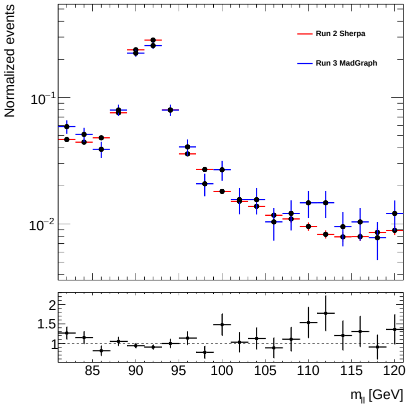
Production of Monte Carlo samples

- Crucial samples for the analysis currently not available for Run-3
  - $\ell\nu\ell\ell\gamma$: $WZ\gamma$ signal sample
  - $\ell\ell\ell\ell\gamma$: Irreducible $ZZ\gamma$ background
  - $t\bar{t}\gamma$: Important non-prompt background
- Produced LO samples $\mathcal{O}(100k)$ for $\ell\nu\ell\ell\gamma/WZ\gamma$ using MadGraph+Pythia8
- Testing samples at the particle level using a slightly modified selection

	Photons	Leptons (e, μ)	Neutrino
$\lvert\eta\rvert$	$\lvert\eta^{\gamma}\rvert < 2.37$	$\lvert\eta^{\ell}\rvert < 2.47$	–
p_{T}	$p_{\mathrm{T}}^{\gamma} > 15\,\mathrm{GeV}$	$p_{\mathrm{T}}^{\ell_1,\ell_2,\ell_3} > 30, 20, 20\,\mathrm{GeV}$	$p_{\mathrm{T}}^{\nu} > 20\,\mathrm{GeV}$
isolation	$E_{\mathrm{T}}^{\mathrm{cone0.2}}/p_{\mathrm{T}}^{\gamma} < 0.07$	–	–
	prompt	prompt, dressed	prompt
ΔR		$\Delta R(\ell,\gamma) > 0.4$	
ℓ_Z assignment		minimise $\lvert m_{\ell\ell} - m_Z\rvert$	
$m_{\ell\ell}$		$m_{\ell\ell} > 81\,\mathrm{GeV}$	

Kinematic distributions of MC samples





EFT sample production

- Current phase space selection not does not target quartic gauge coupling in isolation→ compare kinematic distributions of EFT samples to SM samples to find sensitive regions
- Need EFT samples with varying Wilson coefficients → decompose matrix element into quadratic and interference terms and adapt MC weight accordingly

$$\sigma \propto |\mathcal{A}_{\mathsf{SM}} + \sum_i c_i \mathcal{A}_i|^2$$

$$= |\mathcal{A}_{\mathsf{SM}}|^2 + \sum_i c_i 2\mathrm{Re}(\mathcal{A}^*_{\mathsf{SM}} A_i) + \sum_i c_i^2 |\mathcal{A}_i|^2 + \sum_{i,j,i\neq j} c_i c_j 2\mathrm{Re}(\mathcal{A}_i^* \mathcal{A}$$

- Last term can be omitted when only varying one coefficient
- Create in total 2×13 samples: quadratic and interference term for 13 relevant operators

	$O_{S,0}$ $O_{S,1}$ $O_{S,2}$	$O_{M,0}$ $O_{M,1}$ $O_{M,7}$	$O_{M,2}$ $O_{M,3}$ $O_{M,4}$ $O_{M,5}$	$O_{T,0}$ $O_{T,1}$ $O_{T,2}$	$O_{T,5}$ $O_{T,6}$ $O_{T,7}$	$O_{T,8}$ $O_{T,9}$
WWγZ		$\surd$	$\surd$	$\surd$	$\surd$	

Summary

- $WZ\gamma$ production probes the electroweak gauge structure, including the $WWZ\gamma$ quartic interaction
- $WZ\gamma$ production observed at ATLAS with Run-2 data
- Goal: Differential measurement with a phase space adapted to quartic gauge coupling sensitivity
- EFT samples for the 13 operators contributing to $WWZ\gamma$ in production
- Next: Compare kinematic distributions and identify observables with enhanced sensitivity to aQGCs

Backup

SR and CR selection

	SR definition	$ZZ\gamma$ CR definition	$ZZ(e\to\gamma)$ CR definition
Lepton veto	no additional leptons with $p_{\mathrm{T}}^{\ell_4} > 10\ GeV$	one additional lepton with $p_{\mathrm{T}}^{\ell_4} > 10\ GeV$	same as SR
Z-leptons assignment	smallest $\lvert m_{\ell\ell} - m_Z\rvert$	same as SR	same as SR
ΔR	$\Delta R(\ell,\gamma) > 0.4, \quad \Delta R(\mu, e) > 0.2$	same as SR	same as SR
$ZZ(e \to \gamma)$ rejection	$\lvert m(e_W,\gamma) - m_Z\rvert > 10\ GeV$	same as SR	$\lvert m(e_W,\gamma) - m_Z\rvert < 10\,GeV$
Missing p_{T}	$E_{\mathrm{T}}^{\mathrm{miss}} > 20\ GeV$	no requirement	$E_{\mathrm{T}}^{\mathrm{miss}} < 20\ GeV$
Z candidate mass	$m_{\ell\ell} > 81\,GeV$	$m_{\ell\ell} > 40\,GeV$	same as SR

Systematic uncertainties

Sources	Relative uncertainty [%]
Photon identification and isolation efficiency	2.5
Electron identification, isolation, reconstruction efficiency	0.3
Electron–photon resolution and energy scale	0.6
Muon identification, isolation, reconstruction, momentum resolution and scale	2.4
Missing E_{T} resolution and energy scale	0.3
Lepton fake factor	1.9
Photon fake factor	2.2
Prompt lepton modelling in loose-lepton region	2.2
Prompt photon leakage factor in loose-photon region	0.9
Pile-up γ background	0.9
Signal PDF and α_s, QCD Scales	1.1
Integrated luminosity	0.9
$Z\gamma\gamma$ cross-section	0.2
Signal MC statistics	1.2
Background MC statistics	0.4
Data statistics in loose-lepton and/or loose-photon region	5.4
Total systematic uncertainty	7.7
$ZZ\gamma$ and $ZZ(e \to \gamma)$ normalisation	2.6
Data statistics	14.8
Total statistical uncertainty	15.1