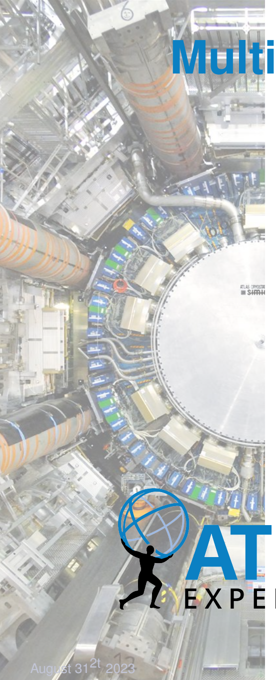

Multiboson physics with photons in ATLAS

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on behalf of the ATLAS collaboration

MBI 2023 Conference

August 29th - September 1st

ATLAS EXPERIMENT

University of Victoria

Overview

- What will be covered
  - $W Z \gamma$ CERN-EP-2023-095
  - $W \gamma\gamma$ CERN-EP-2023-037
  - $Z \gamma\gamma$ Eur. Phys. J. C 83 (2023) 539
  - $Z \gamma$ JHEP 03 (2020) 054
- What will not be covered
  - EFT interpretation of $Z\gamma\gamma$
    - see Michael Schmitt's talk on EFT searches in multiboson final states in ATLAS and CMS from Wednesday
  - EW production (VBS/VBF):

$Z(\rightarrow \ell\ell)\gamma jj$	ATLAS-CONF-2021-038 ($m_{jj} > 150\,\text{GeV}$)
	STDM-2018-36 ($m_{jj} > 500\,\text{GeV}$)
$Z(\rightarrow \nu\nu)\gamma jj$	EPJC 82 (2022) 105
	JHEP 06 (2023) 082

Motivation

- Triboson final states are rare and some are only now becoming accessible at the LHC
- Probe of non-Abelian self couplings of the electroweak gauge bosons in the Standard Model (SM)
  - Sensitive to anomalous Quartic Gauge Coupling (aQGC) operators
  - Can be used to set limits within Effective Field Theory (EFT) parameters
- Backgrounds to SM processes like $ZH(\rightarrow \gamma\gamma)$ and $WH(\rightarrow \gamma\gamma)$ that will become accessible during run 3

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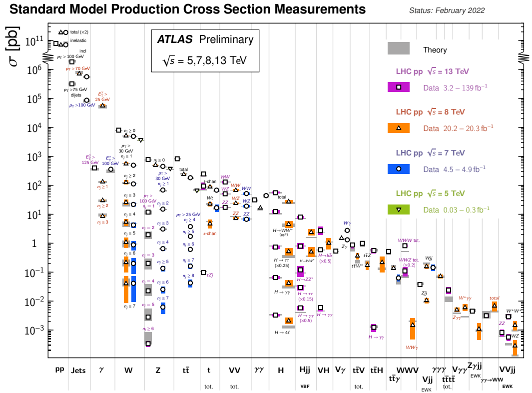
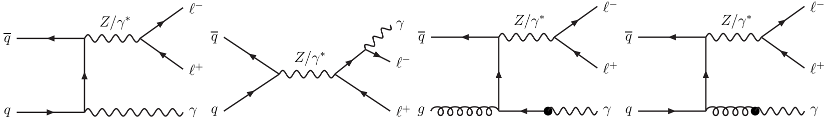


$Z\gamma$ Production

- Process studied is $Z(\to \ell\ell)\gamma$ where $\ell = e, \mu$

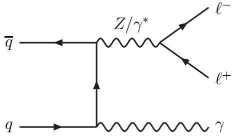


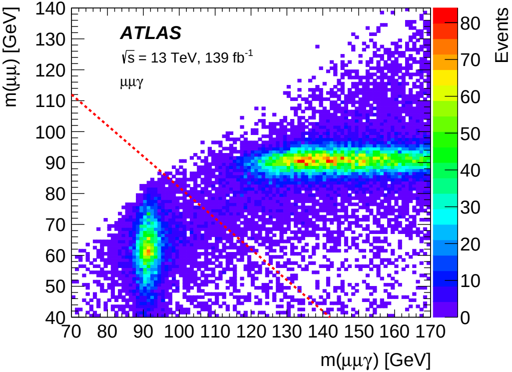
- Signal modeled using `Sherpa 2.2.4` with the `NNPDF3.0 NNLO` PDF set with $m_{\ell\ell} > 10\,\text{GeV}$
- Can be used to search for new physics effects such as the direct coupling of Z bosons to photons.
- Important for searches for
  - the decay $H \to Z\gamma$ of the Higgs boson
  - other resonances in the $Z\gamma$ channel where non-resonant $Z\gamma$ production is a major background

$Z\gamma$ Event Selection

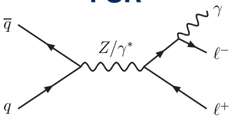
- Includes large contributions from FSR from the leptons

ISR





FSR

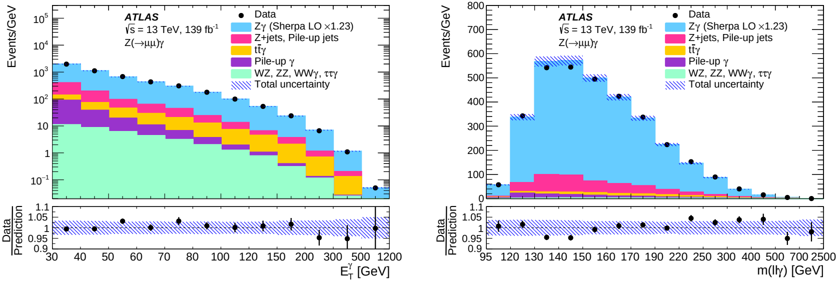


- Increase sensitivity to EW couplings by selecting events with

$$m_{\ell\ell} + m_{\ell\ell\gamma} \geq 2m_Z$$

$Z\gamma$ Background Estimation

- Major backgrounds include:
  - $Z+$jets and pile-up backgrounds, estimated using a data-driven method.
  - Remaining backgrounds are estimated using MC simulated samples:
    - Prompt photon: $t\bar{t}\gamma$, $Z(\rightarrow \tau\tau)\gamma$ and $WW\gamma$
    - $e \rightarrow \gamma$: $WZ \rightarrow \ell\ell\ell\nu$ and $ZZ \rightarrow \ell\ell\ell\ell$



$Z\gamma$ Cross-Section

Photons	Electrons/Muons
$E_{\mathrm{T}}^{\gamma} > 30$ GeV	$p_{\mathrm{T}}^{\ell} > 30, 25$ GeV
$\lvert\eta^{\gamma}\rvert < 2.37$	$\lvert\eta^{\ell}\rvert < 2.47$
$E_{\mathrm{T}}^{\mathrm{cone0.2}}/E_{\mathrm{T}}^{\gamma} < 0.07$	dressed leptons
$\Delta R(\ell,\gamma) > 0.4$	
Event selection	
$m(\ell\ell) > 40\,GeV$	
$m(\ell\ell) + m(\ell\ell\gamma) > 182\,GeV$	

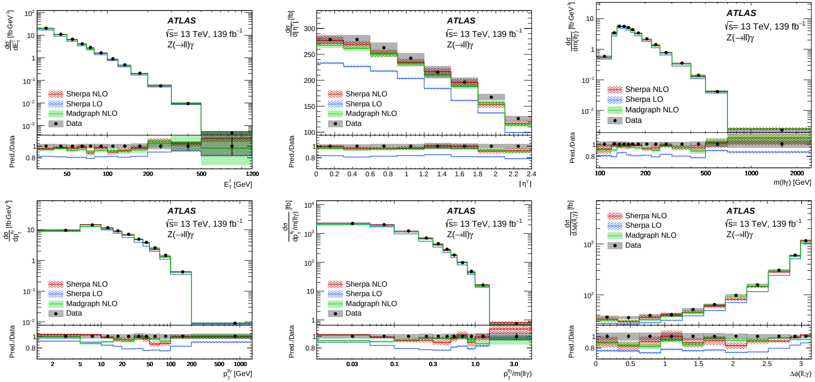
- The $\ell^{\pm}\ell^{\mp}\gamma$ cross-section is measured in a fiducial phase-space region defined by particle level requirements.

	Cross-section [fb]		
$e^+e^-\gamma$	530.4	$\pm$ 9.0 (uncorr)	$\pm$ 11.7 (corr) $\pm$ 9.0 (lumi)
$\mu^+\mu^-\gamma$	535.0	$\pm$ 6.1 (uncorr)	$\pm$ 11.5 (corr) $\pm$ 9.1 (lumi)
$\ell^+\ell^-\gamma$	533.7	$\pm$ 5.1 (uncorr)	$\pm$ 11.6 (corr) $\pm$ 9.1 (lumi)
SHERPA LO	438.9	$\pm$ 0.6 (stat)	
SHERPA NLO	514.2	$\pm$ 5.7 (stat)	
MADGRAPH NLO	503.4	$\pm$ 1.8 (stat)	
MATRIX NLO	444.2	$\pm$ 0.1 (stat)	$\pm$ 4.3 (C_{theory}) $\pm$ 8.8 (PDF) $^{+16.8}_{-18.9}$ (scale)
MATRIX NNLO	518.9	$\pm$ 2.0 (stat)	$\pm$ 5.1 (C_{theory}) $\pm$ 10.8 (PDF) $^{+16.4}_{-14.9}$ (scale)
MATRIX NNLO $\times$ NLO EW	513.5	$\pm$ 2.0 (stat)	$\pm$ 2.7 (C_{theory}) $\pm$ 10.8 (PDF) $^{+16.4}_{-14.9}$ (scale)
MATRIX NNLO + NLO EW	518.3	$\pm$ 2.0 (stat)	$\pm$ 2.7 (C_{theory}) $\pm$ 10.8 (PDF) $^{+16.4}_{-14.9}$ (scale)

- The overall precision of the measurement is 2.9% (about 2X better than ATLAS $\sqrt{s} = 8\,\mathrm{TeV}$ result)

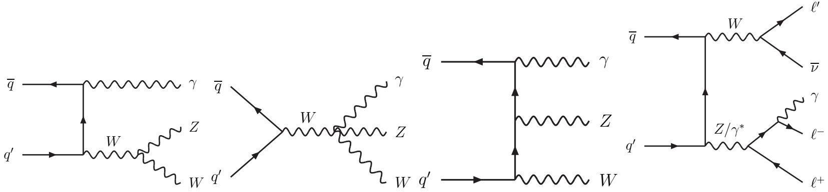
$Z\gamma$ Differential Cross-Section

- The $\ell^{\pm}\ell^{\mp}\gamma$ differential cross-section in extracted for six variables using an iterative Bayesian method.
  - $E_{\rm T}^{\gamma}$, $|\eta^{\gamma}|$, $m(\ell\ell\gamma)$, $p_{\rm T}^{\ell\ell\gamma}$, $p_{\rm T}^{\ell\ell\gamma}/m(\ell\ell\gamma)$ and $\Delta\phi(\ell\ell,\gamma)$



$WZ\gamma$ Production

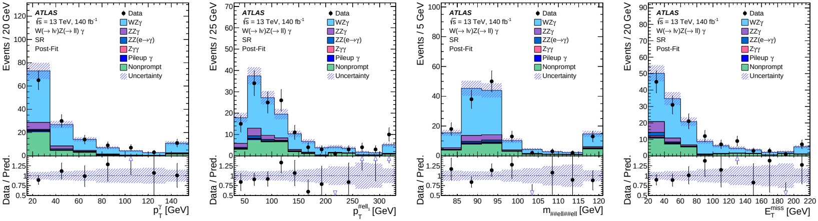
- Process being generated is $WZ\gamma \to \ell^{\pm}\nu\ell^{\pm}\ell^{\pm}\gamma$ where $\ell = e, \mu$



- Signal modeled using `Sherpa 2.2.11` and the `NNPDF3.0nnlo` PDF set with the requirement $m_{\ell\ell} > 20$ GeV.
- Events where the photon is radiated from a lepton are also considered signal
- Sensitive to the quartic interactions between EW gauge bosons
- Can be used to indirectly study physics beyond the Standard Model (BSM)

$WZ\gamma$ Background Estimation

- Major backgrounds:
  - Nonprompt lepton or photon from a hadronic decay or a jet misidentified as a photon:
    - $Z(\rightarrow \ell\ell)\gamma$, $t\bar{t}\gamma$, WZ, and ZZ
    - These backgrounds are estimated using a data-driven method
  - Other backgrounds include:
    - $ZZ\gamma$ and $ZZ(e \rightarrow \gamma)$
    - These backgrounds are modeled using MC simulated samples.
    - The normalization for these backgrounds are determined in separate CRs enriched in these events.



$WZ\gamma$ Cross-Section

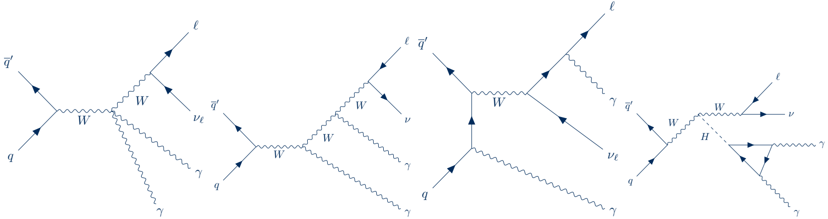
- $WZ\gamma$ cross section is measured in a fiducial phase-space region.

	Photons	Leptons (e, μ)	Neutrino
$\|\eta\|$	$\|\eta^{\gamma}\| < 2.37$	$\|\eta^{\ell}\| < 2.5$	–
p_{T}	$p_{\mathrm{T}}^{\gamma} > 15\,GeV$	$p_{\mathrm{T}}^{\ell_1,\,\ell_2,\,\ell_3} > 30, 20, 20\,GeV$	$p_{\mathrm{T}}^{\nu} > 20\,GeV$
Isolation	$E_{\mathrm{T}}^{\mathrm{cone0.2}}/p_{\mathrm{T}}^{\gamma} < 0.07$	–	–
ℓ_Z assignment	for $eee/\mu\mu\mu$ channels, choose smallest $\|m_{\ell\ell} - m_Z\|$		
ΔR	$\Delta R(\ell, \gamma) > 0.4$		
Z invariant mass	$m_{\ell\ell} > 81\,GeV$		

- The measured fiducial cross-section is
$\sigma_{\text{fid}} = 2.01 \pm 0.30$ (stat) $\pm\ 0.16$ (syst) fb
where the significance of the measurement is 6.3 (5.0) σ measured(expected)
- The dominate uncertainty is due to statistical uncertainty at 15%
- The largest systematic uncertainties are due to the statistics in the CRs used to determine the $ZZ\gamma$ and $ZZ(e \to \gamma)$ normalizations

$W\gamma\gamma$ Production

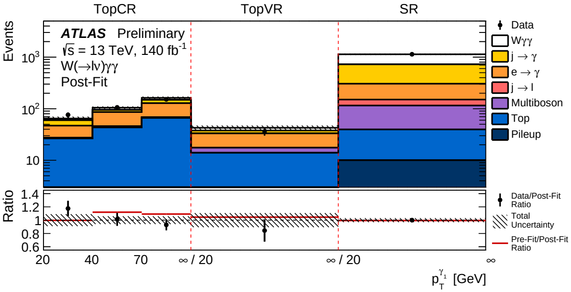
- The process being studied is $W(\rightarrow \ell\nu)\gamma\gamma$ where $\ell = e, \mu$.



- The signal sample is modeled with `Sherpa 2.2.10` with the `NNPDF3.0nnlo` PDF set
- This process is
  - sensitive to triple and quardic gauge boson couplings
  - an important background to to other measurements such as $WH(\rightarrow \gamma\gamma)$
- $WH(\rightarrow \gamma\gamma)$ is considered a background to isolate contributions sensitive to EW gauge boson interactions.

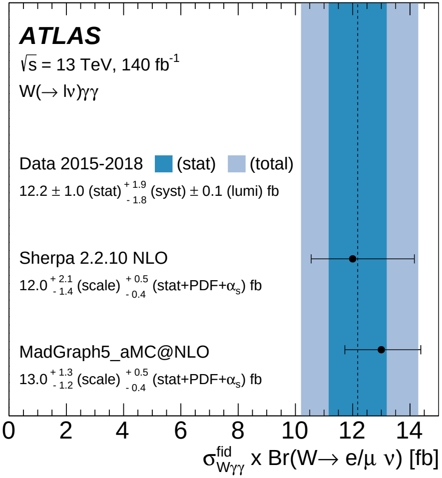
$W\gamma\gamma$ Background Estimation

- Nonprompt photon estimated using data-driven methods
  - jet or neutral hadron decay being misidentified as a photon ($j \to \gamma$), electrons being misidentified as a photon ($e \to \gamma$), and pileup
- Nonprompt leptons from hadronic decay ($j \to \ell$) estimated using a data-driven method
- Other backgrounds are estimated using MC simulated samples
  - Multiboson: $WH(\gamma\gamma)$, $WW\gamma$, $Z\gamma\gamma$
  - Top: $t\bar{t}\gamma$, $tW\gamma$, $tq\gamma$ (normalization constrained in separate CR)



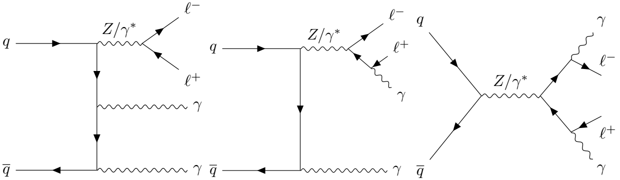
$W\gamma\gamma$ Cross-Section

- The cross-section is measured in a particle level fiducial phase-space region.
- The measured fiducial cross-section is 12.2 ± 1.0 (stat) $\pm\ ^{+1,9}_{-1,8}$ (syst) $\pm\ 0.1$ (lumi) fb
  with a statistical significance of 5.6 σ
- The leading systematic uncertainties are
  - $j \to \gamma$ background estimate (12%)
  - Photon efficiency (4.5%)



$Z\gamma\gamma$ Production

- The process being studied is $Z(\rightarrow \ell\ell)\gamma\gamma$ where $\ell = e, \mu$.

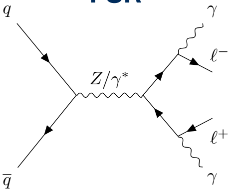


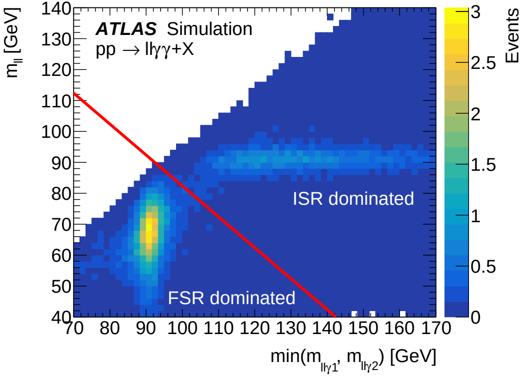
- The signal is modeled using `Sherpa 2.2.10` with the `NNPDF3.0nnlo` PDF set
- Sensitive to neutral quartic gauge couplings
- Important background for $ZH(\rightarrow \gamma\gamma)$
- $ZH(\rightarrow \gamma\gamma)$ is considered a background

$Z\gamma\gamma$ Event Selection

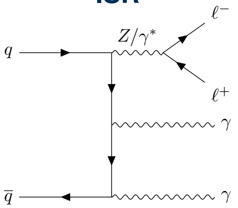
- Includes large contributions from FSR from the leptons

FSR





ISR



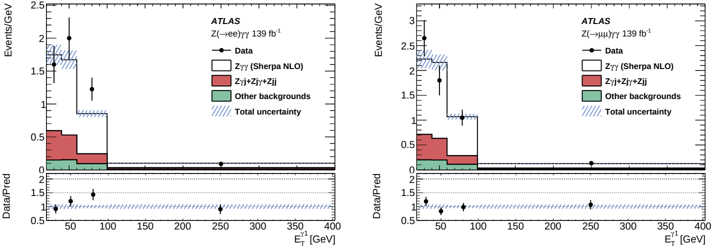
- Increase sensitivity to EW couplings by selecting events with

$$m_{\ell\ell} + min(m_{\ell\ell\gamma_1}, m_{\ell\ell\gamma_2}) \geq 2m_Z$$

$Z\gamma\gamma$ Background Estimation

- Major backgrounds include:
  - jets misidentified as photons ($j \to \gamma$) is estimated using a data-driven method
  - Other backgrounds are estimated using MC cimulated samples
    - $t\bar{t}\gamma\gamma$, $Z(\to \ell\ell)H(\to \gamma\gamma)$
    - $e \to \gamma$: $ZZ \to \ell\ell\ell\ell$, $WZ\gamma$
    - Pileup: $Z\gamma + \gamma$, $Z + \gamma\gamma$

Detector level distributions

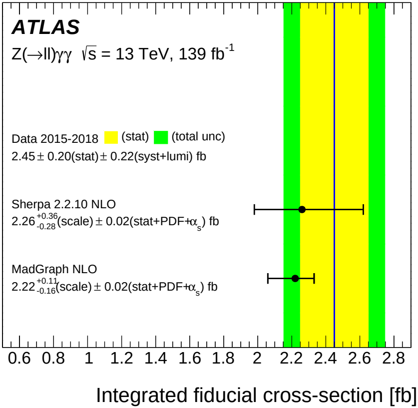


$Z\gamma\gamma$ Cross-Section

- The $Z(\rightarrow \ell\ell)\gamma\gamma$ cross section is determined in a fiducial phase-space region

Photons	Leptons
$p_T^\gamma > 20$ GeV	$p_T^{\ell 1} > 30$ GeV, $p_T^{\ell 2} > 20$ GeV
$\lvert\eta^\gamma\rvert < 2.37$	$\lvert\eta^\ell\rvert < 2.47$
$E_T^{iso}/p_T^\gamma < 0.07$	dressed leptons
Event	
$\Delta R(\gamma,\ell) > 0.4$, $\Delta R(\gamma,\gamma) > 0.4$	
$m_{\ell\ell} > 40$ GeV	
$m_{\ell\ell} + \min(m_{\ell\ell\gamma_1}, m_{\ell\ell\gamma_2}) > 2m_Z$	

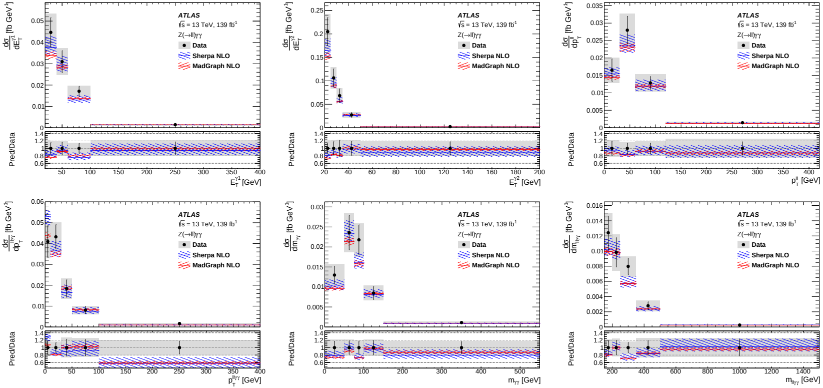
- The measured fiducial cross-section is 2.45 ± 0.20 (stat) $\pm$ 0.22 (syst) fb
- The cross-section measurement uncertainty is dominated by statistical uncertainty.



- The largest systematic uncertainty is
  - $j \rightarrow \gamma$ backgrounds (7.6%)
  - Pileup reweighting (2.9%)
  - Photon efficiency (2.6%)

$Z\gamma\gamma$ Differential Cross-Section

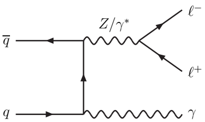
- The $Z(\rightarrow \ell\ell)\gamma\gamma$ differential cross-section in extracted for six variables using an iterative Bayesian method.
  - $E_{\mathrm{T}}^{\gamma 1}$, $E_{\mathrm{T}}^{\gamma 2}$, $p_{\mathrm{T}}^{\ell\ell}$, $p_{\mathrm{T}}^{\ell\ell\gamma\gamma}$, $m_{\gamma\gamma}$, and $m_{\ell\ell\gamma\gamma}$



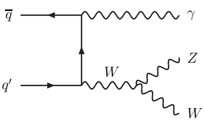
Summary

- New observation of $WZ\gamma$ and $W\gamma\gamma$
- First differential cross section for $Z\gamma\gamma$
- Good agreement between data and the SM prediction observed.

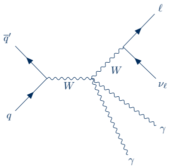
$Z\gamma$



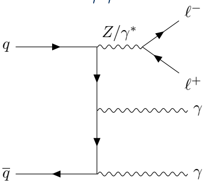
$WZ\gamma$



$W\gamma\gamma$



$Z\gamma\gamma$



Questions?