Photon+V measurements in ATLAS

Dimitrii Krasnopevtsev on behalf of ATLAS collaboration
Moscow NRNU MEPhI

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Outline

- Motivation
- Photon identification in ATLAS
- Photon+V measurements with 8 TeV
  - NEW Zγ vector boson scattering (VBS)
  - Zγ(γ) production
  - NEW WVγ production
- Anomalous triple gauge coupling (aTGC)
- Anomalous quartic gauge coupling (aQGC)
- Summary

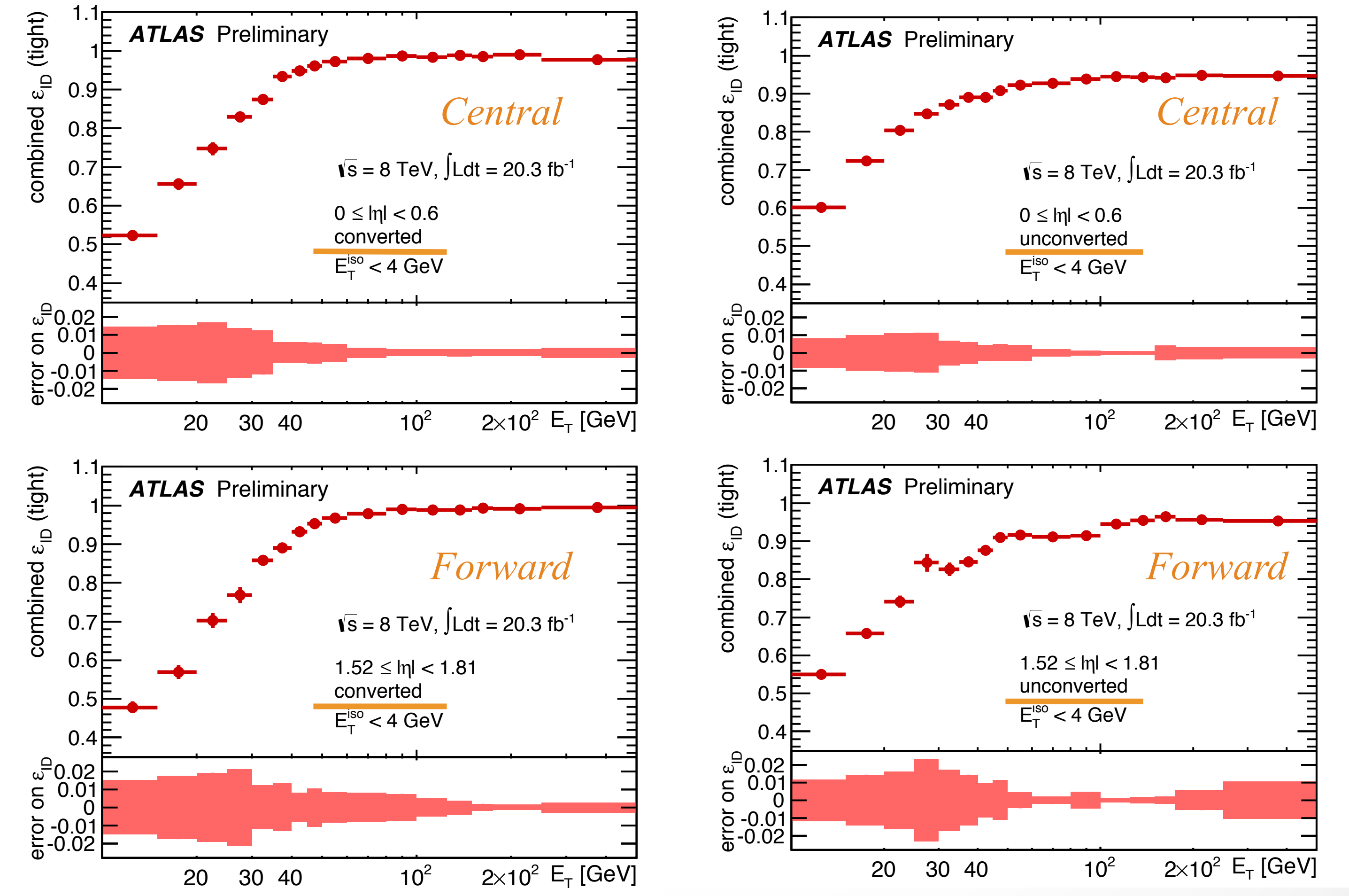
Importance of Photon+V measurements

- To test the electroweak sector of the Standard Model with high accuracy using multi-boson production cross section measurements.
- To probe the $SU(2)_L \times U(1)_Y$ gauge symmetry of the electroweak theory that determines the structure and self-couplings of the vector bosons.
- To search for signs of new physics using anomalous triple and quartic gauge-boson couplings studies.

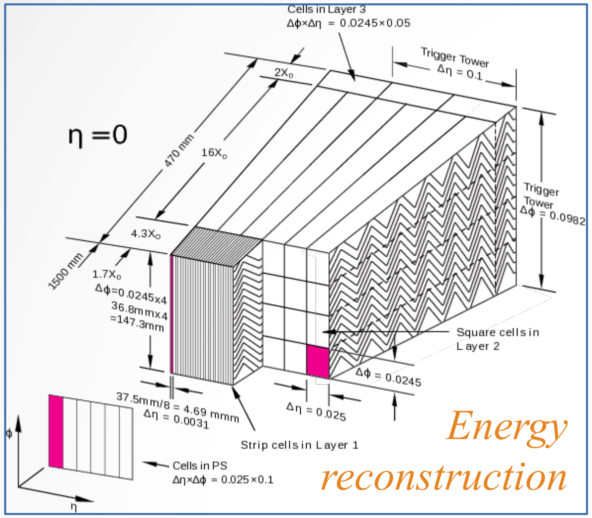
Last but not least:
SM multi-boson production is a background for Higgs and exotic searches. Precision Photon+V measurements help to tune Monte-Carlo, which describes some of these backgrounds.

Photons in ATLAS

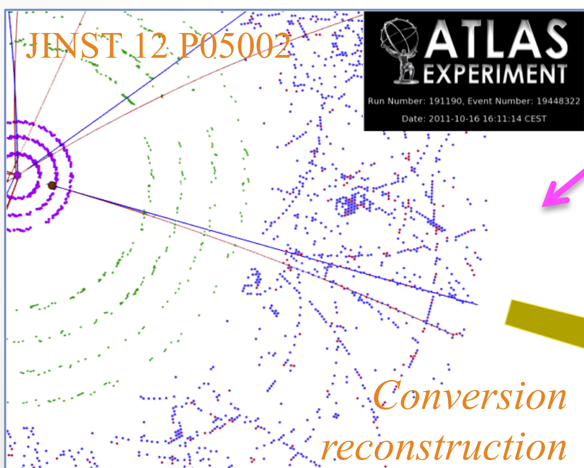
- ATLAS uses Electromagnetic calorimeter and Inner Detector system to reconstruct photons with high efficiencies. Both photons that do or do not convert to electron-positron pairs are reconstructed in ATLAS.
- The jet suppression is about 10^4 along with a high identification efficiency for photons:



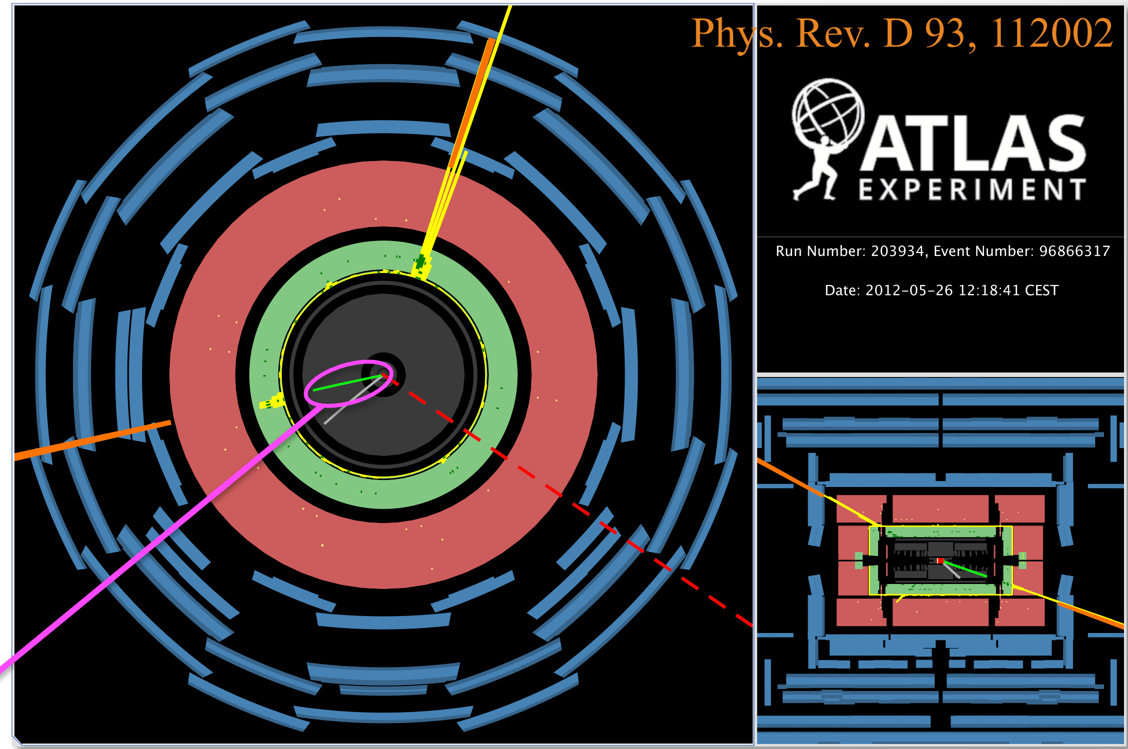
Multi-boson production



Sketch of a barrel module of the ATLAS electromagnetic calorimeter



Close-up view of hits and reconstructed tracks in the ID

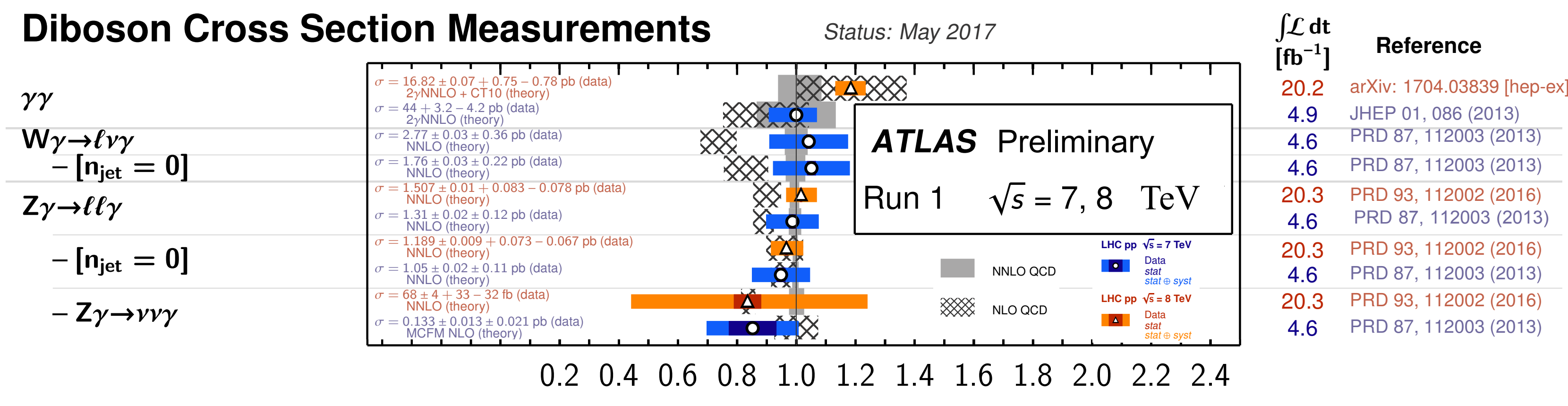


Z(νν) production in association with one converted and one unconverted photons (orange lines)

Photon+V measurements with 8 TeV

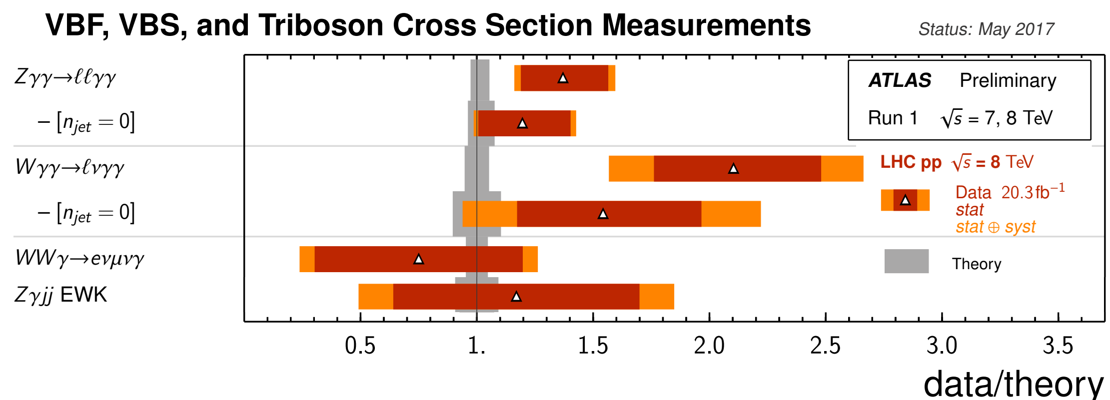
Standard Model cross sections (σ) for Vγ production in ATLAS were measured with high accuracy already with 7 TeV data. Proton-proton collisions at 8 TeV **allowed to improve some measurements…**

$$\sigma = \frac{Obs. - Bkg.}{Eff. \times \int L\,dt}$$



Agreement between data and NNLO theory predictions!

…and to study rare processes of Zγ scattering and triboson productions.

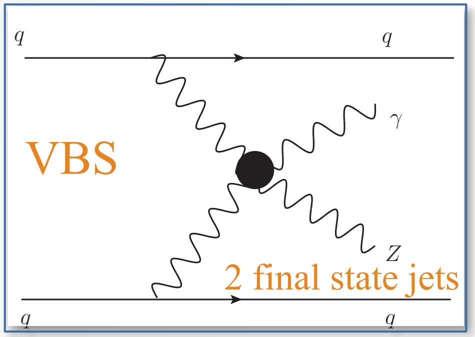


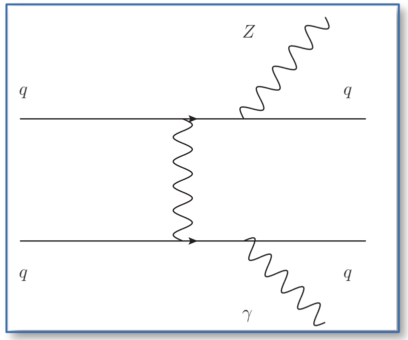
arXiv:1705.01966

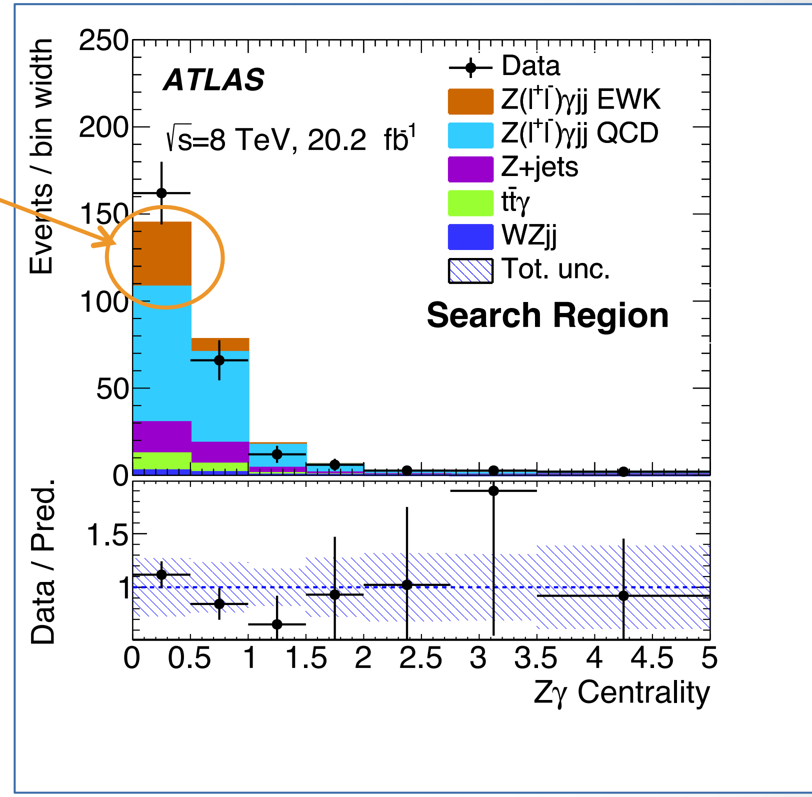
Zγ VBS

EWK component:

- jets with wide rapidity separation.
- large dijet invariant mass (m_{jj}).
- production with high centrality (small values of ζ).

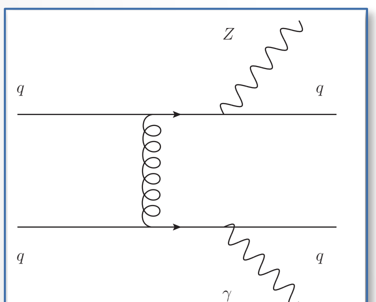


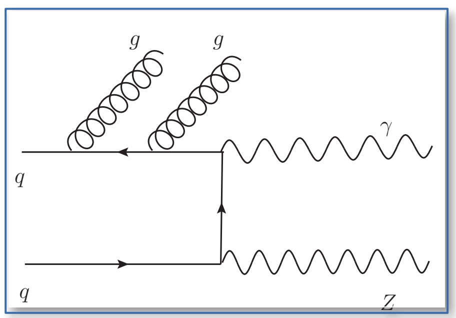




$$\zeta \equiv \left|\frac{\eta - \bar{\eta}_{jj}}{\Delta\eta_{jj}}\right| \quad \text{with} \quad \bar{\eta}_{jj} = \frac{\eta_{j_1} + \eta_{j_2}}{2}, \quad \Delta\eta_{jj} = \eta_{j_1} - \eta_{j_2}$$

QCD component:





Z(ll)γ – cross section measurements, aQGC limits setting.
Z(νν)γ – aQGC limits setting.

arXiv:1705.01966

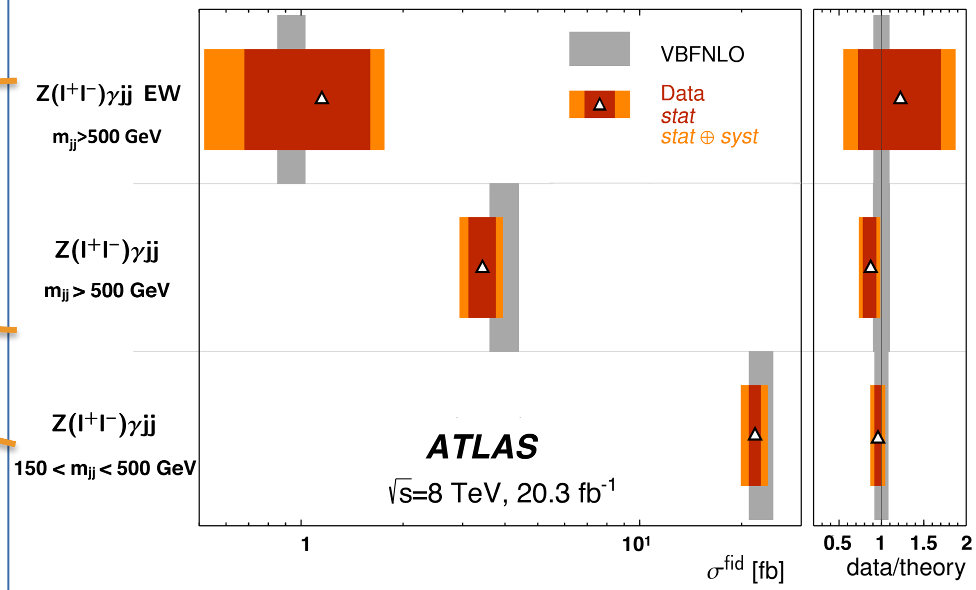
Zγ VBS

Basic selection for charged channel:

$E_T^{\gamma} > 15$ GeV, two OS same flavor leptons with $E_T > 25$ GeV, $N_{jets} \geq 2$, $m_{ll} > 40$ GeV, $m_{ll} + m_{ll\gamma} > 182$ GeV.

Two regions were studied:

- **Search region** with max. VBS contribution was used for σ_{EWK}, $\sigma_{EWK+QCD}$ measurements.
- **Control region** with max. QCD contribution was used for QCD normalization in search region and also for $\sigma_{EWK+QCD}$ measurements.



The significance of the observed EWK production signal is 2σ (1.8σ expected)

Zγ production

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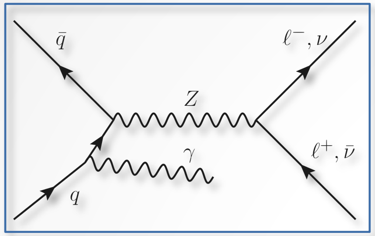
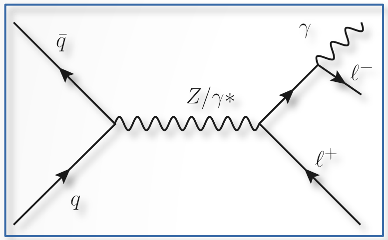


Initial state radiation (ISR) photon



Final state radiation (FSR) photon

Basic selection:

Events with $N_{jets} \geq 0$ and $N_{jets} = 0$ were studied (jet $p_T > 30$ GeV).

$Z(ll)\gamma$: $E_T^{\gamma} > 15$ GeV, two OS leptons with $p_T > 25$ GeV, $m_{ll} > 40$ GeV.

$Z(\nu\nu)\gamma$: $E_T^{\gamma} > 130$ GeV (trigger 120 GeV), $E_T^{miss} > 100$ GeV.

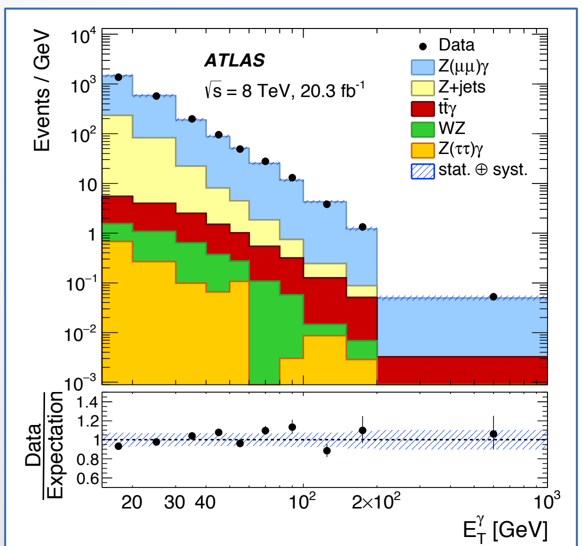
$$E_T^{miss} = E_{x(y)}^{miss,e} + E_{x(y)}^{miss,\gamma} + E_{x(y)}^{miss,jets} + E_{x(y)}^{miss,SoftTerm} + E_{x(y)}^{miss,\mu}$$

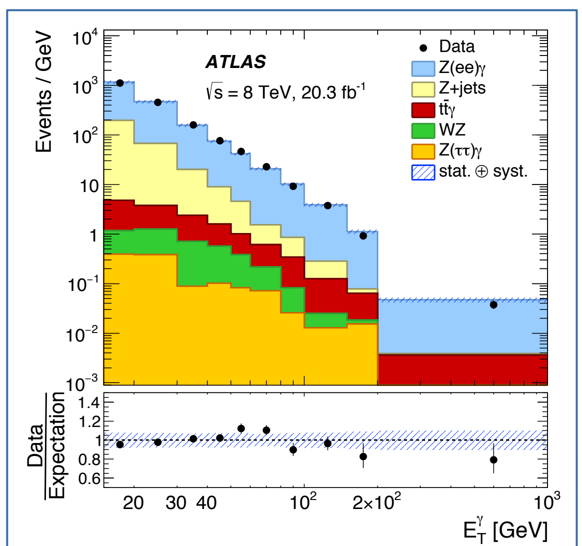
Major backgrounds were estimated from data:

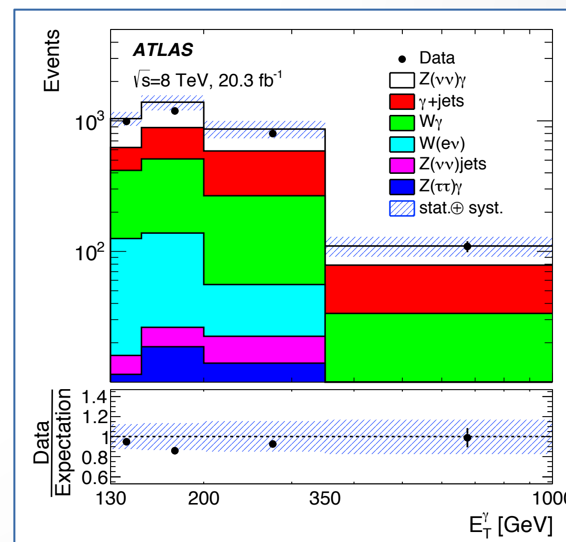
Z+jets for $Z(ll)\gamma$.

γ+jets and W(lν)γ for $Z(\nu\nu)\gamma$.

Photon E_T spectrums:







High level of agreement

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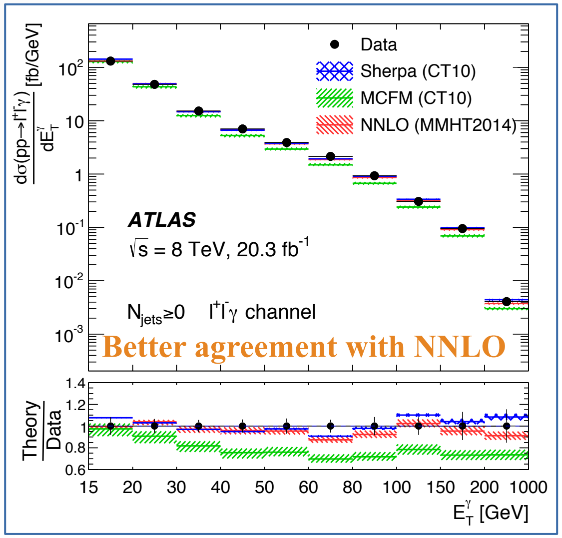
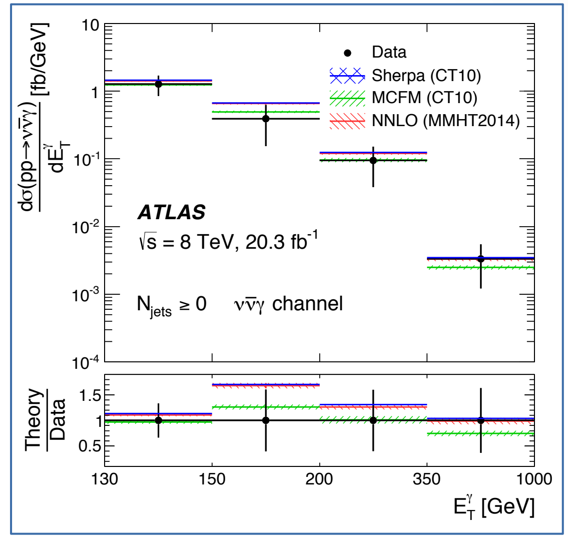
$Z\gamma$ production

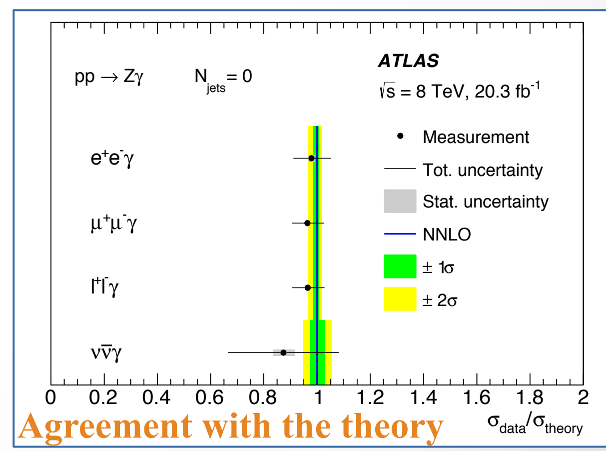
An unfolding procedure was performed to remove measurement inefficiencies and resolution effects from the observed distributions.





Cross section measurements:

Channel	Measurement [fb]	MCFM Prediction [fb]	NNLO Prediction [fb]
	$N_{\text{jets}} \geq 0$		
$e^+e^-\gamma$	$1510 \pm 15(\text{stat.})^{+91}_{-84}(\text{syst.})^{+30}_{-28}(\text{lumi.})$	1345^{+66}_{-82}	1483^{+19}_{-37}
$\mu^+\mu^-\gamma$	$1507 \pm 13(\text{stat.})^{+78}_{-73}(\text{syst.})^{+29}_{-28}(\text{lumi.})$		
$\ell^+\ell^-\gamma$	$1507 \pm 10(\text{stat.})^{+78}_{-73}(\text{syst.})^{+29}_{-28}(\text{lumi.})$		
$\nu\bar{\nu}\gamma$	$68 \pm 4(\text{stat.})^{+33}_{-32}(\text{syst.}) \pm 1(\text{lumi.})$	68.2 ± 2.2	$81.4^{+2.4}_{-2.2}$
	$N_{\text{jets}} = 0$		
$e^+e^-\gamma$	$1205 \pm 14(\text{stat.})^{+84}_{-75}(\text{syst.}) \pm 23(\text{lumi.})$	1191^{+71}_{-89}	1230^{+10}_{-18}
$\mu^+\mu^-\gamma$	$1188 \pm 12(\text{stat.})^{+68}_{-63}(\text{syst.})^{+23}_{-22}(\text{lumi.})$		
$\ell^+\ell^-\gamma$	$1189 \pm 9(\text{stat.})^{+69}_{-63}(\text{syst.})^{+23}_{-22}(\text{lumi.})$		
$\nu\bar{\nu}\gamma$	$43 \pm 2(\text{stat.}) \pm 10(\text{syst.}) \pm 1(\text{lumi.})$	$51.0^{+2.1}_{-2.3}$	$49.21^{+0.61}_{-0.52}$



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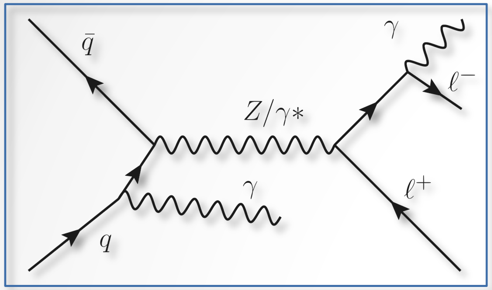
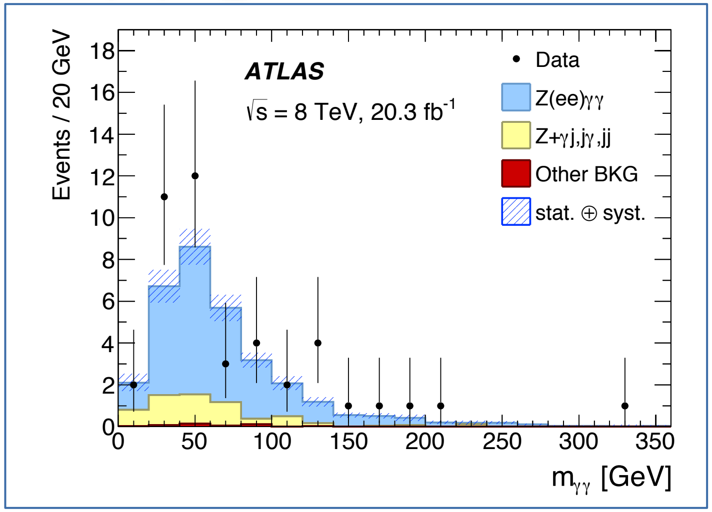
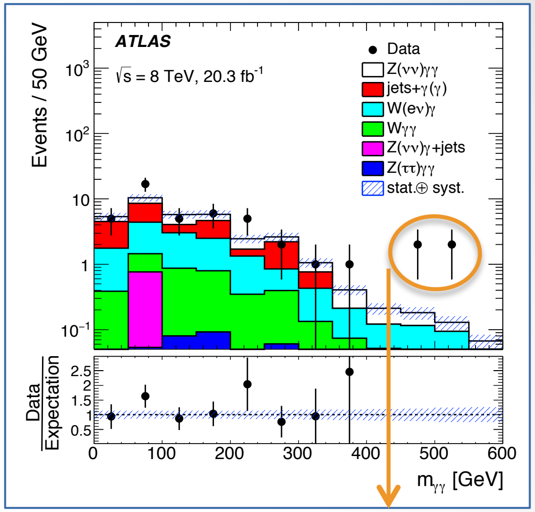
Zγγ production



Mixed ISR+FSR channel





Looking forward to new data

Selection:

$Z(ll)\gamma\gamma$: similar as for one photon channel.

$Z(\nu\nu)\gamma\gamma$: $E_T^{\gamma} > 22$ GeV (trigger 20 GeV), $E_T^{miss} > 110$ GeV.

Major backgrounds estimated from data:

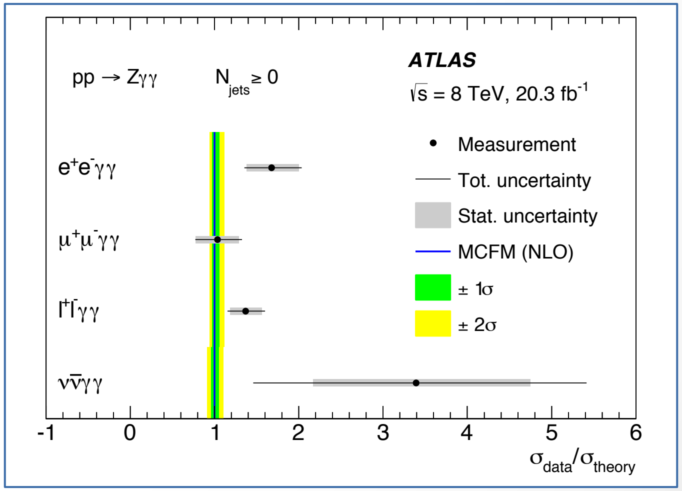
$Z(ll)\gamma\gamma$: $Z(\gamma)$+jets.

$Z(\nu\nu)\gamma\gamma$: $\gamma(\gamma)$+jets; W(eν)γ.

Cross section:

$Z(ll)\gamma\gamma$: **significance is greater 6σ.**

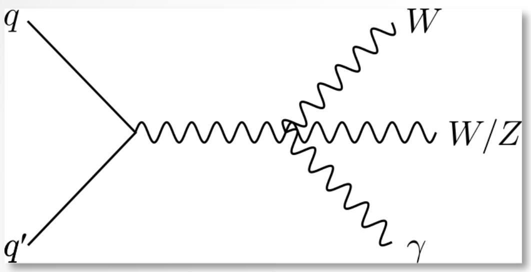
$Z(\nu\nu)\gamma\gamma$: **measured for the first time at LHC.**



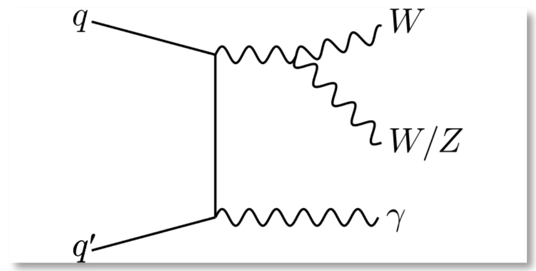
The measurements are statistically limited, but the data and SM predictions agree within 1.5σ stat. error

WWγ production (fully-leptonic)

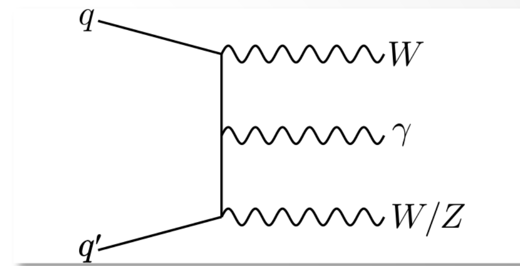
The quartic vertex



Trilinear vertex



Radiative processes



- WWγ events are studied solely in the eνμνγ final state.
- eνeνγ and μνμνγ channels have low sensitivity because of large Zγ backgrounds.

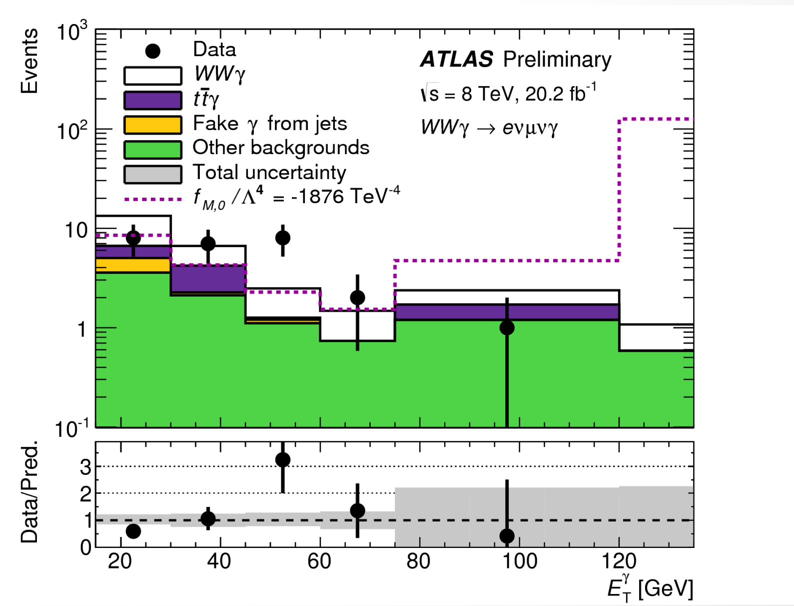
Basic selection:

$E_T^{\gamma} > 15$ GeV, $p_T^{e,\mu} > 20$ GeV, $N_{jets}=0$ ($p_T > 25$ GeV), $E_T^{miss} > 50$ GeV, $m_{ll} > 50$ GeV.

Measured cross section (**significance of 1.4σ**):

$$\sigma_{\text{fid}}^{e\nu\mu\nu\gamma} = (1.53 \pm 0.92(\text{stat.}) \pm 0.46(\text{syst.}))\ \text{fb}$$

Agreement with NLO predictions by VBFNLO: (2.02 ± 0.10) fb

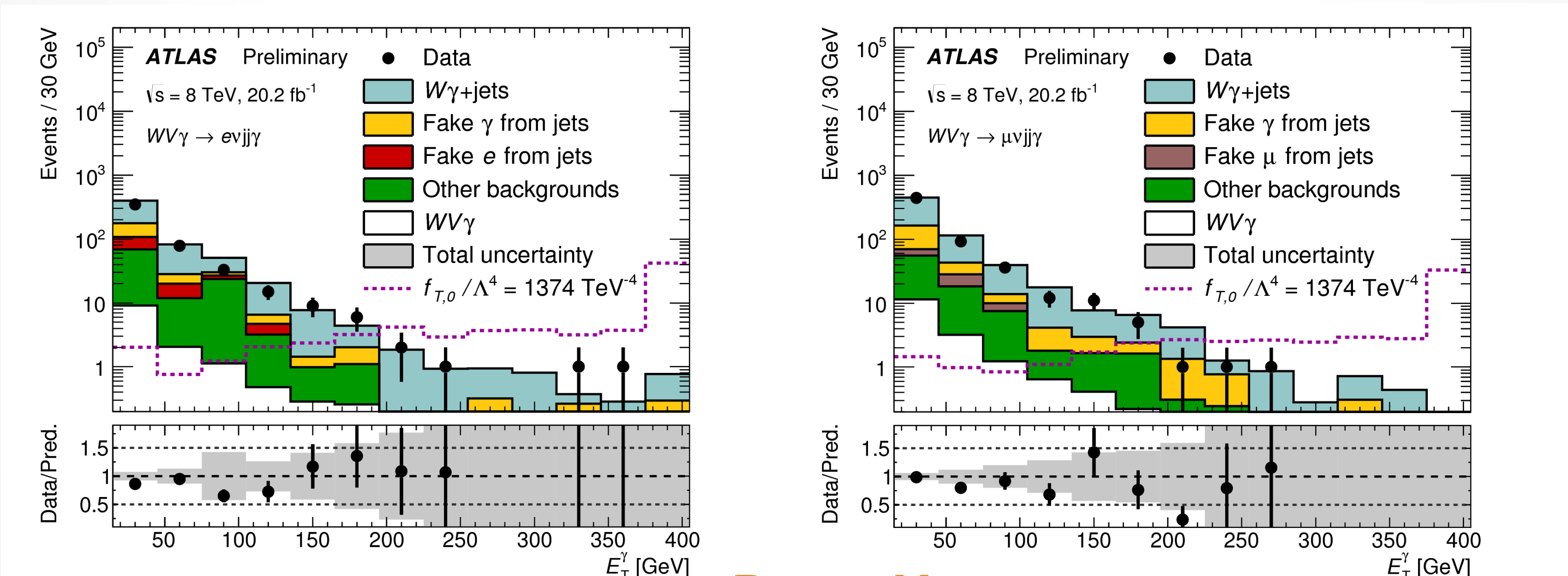


WVγ production (semi-leptonic)

WVγ events with one leptonically decaying W boson and one hadronically decaying W or Z boson are studied: **eνjjγ, μνjjγ**.

Basic selection:

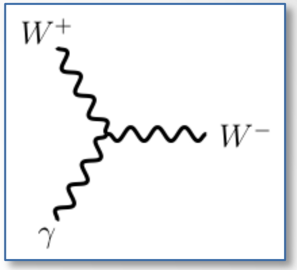
$E_T^{\gamma} > 15$ GeV, $p_T^{e,\mu} > 25$ GeV, $N_{jets} \geq 2$ (no b –jets), $E_T^{miss} > 30$ GeV, $m_T > 50$ GeV, $70 < m_{ll} < 100$ GeV.



Reasonable agreement

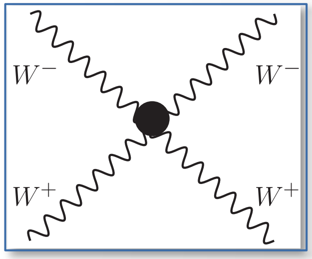
Upper exclusion limits on eνjjγ, μνjjγ and lνjjγ production cross-section were set.
Results are as low as 2.5 x Standard Model expectation.

Triple and quartic gauge couplings

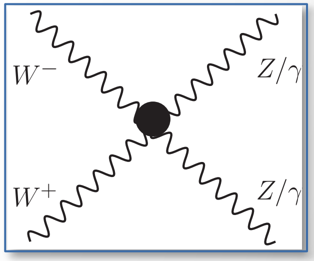


- Non-Abelian nature of $SU(2)_L \times U(1)_Y$ allows for self-couplings of the gauge bosons in fermions interactions: triple and quartic gauge couplings.

Allowed in SM

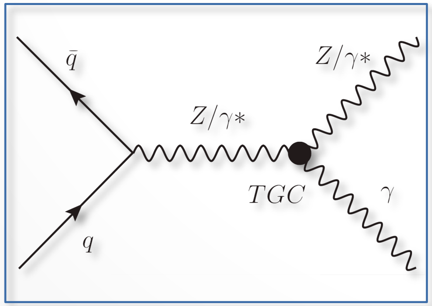


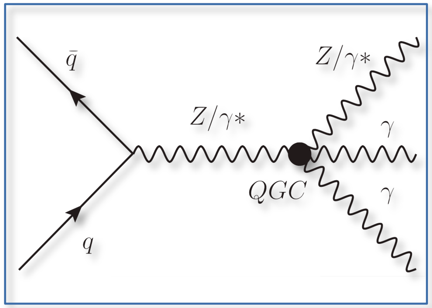
- Allowed are vertices with charged gauge couplings: WWZ, WWγ, WWWW, WWZZ, WWZγ, WWγγ.



- Neutral boson gauge couplings are forbidden at tree level in the SM, but can arise in theories beyond the SM via anomalous couplings. Limits on anomalous couplings will provide constraints on many exotic models.

Forbidden





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Zγ production and aTGC

Vertex approach was used to study aTGC.
Anomalous ZZγ vertex function:

$$\Gamma^{\alpha\beta\mu}_{Z\gamma Z}(q_1,q_2,P) = \frac{P^2 - q_1^2}{M_Z^2}\left[h_1^Z(q_2^\mu g^{\alpha\beta} - q_2^\alpha g^{\mu\beta}) + \frac{h_2^Z}{M_Z^2}P^\alpha(P\cdot q_2 g^{\mu\beta} - q_2^\mu P^\beta) + h_3^Z\varepsilon^{\mu\alpha\beta\rho}q_{2\rho} + \frac{h_4^Z}{M_Z^2}P^\alpha\varepsilon^{\mu\beta\rho\sigma}P_\rho q_{2\sigma}\right]$$

For Zγγ:

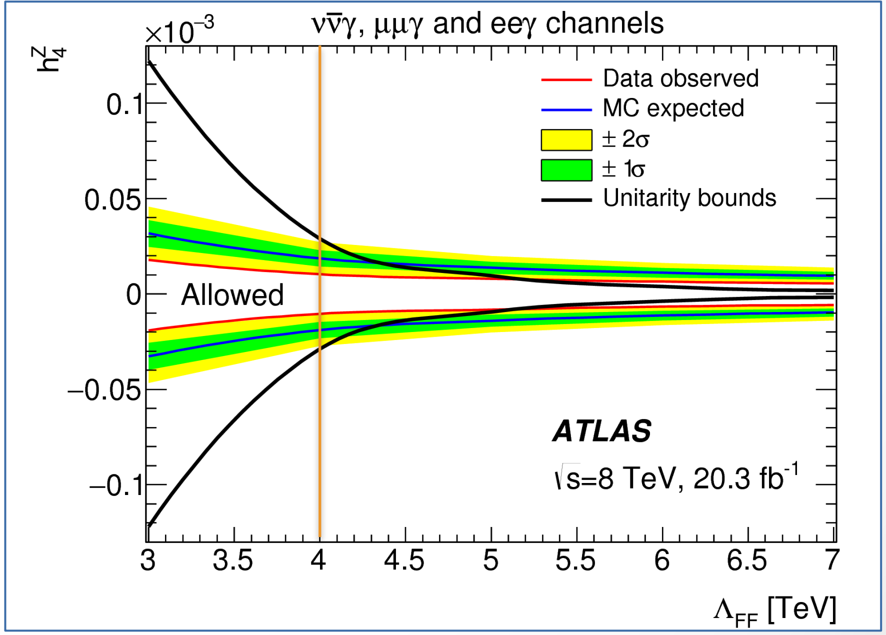
$$\frac{P^2 - q_1^2}{M_Z^2} \to \frac{P^2}{M_Z^2},\, h_i^Z \to h_i^\gamma,\, i = 1,2,3,4.$$

CP-conversing parameters $h_{3,4}^V$ and CP-violating $h_{1,2}^V$ do not interfere and their sensitivities are nearly identical. **$h_{3,4}^V$ were studied in this analysis.**

Unitarity preservation at high energies:

$$h_3^V(\hat{s}) = h_3^V/(1+\hat{s}/\Lambda_{FF}^2)^n$$

Λ_{FF} - form factor energy scale.
Unitarized scheme: Λ_{FF} = 4 TeV.
Violation scheme: $\Lambda_{FF} = \infty$.



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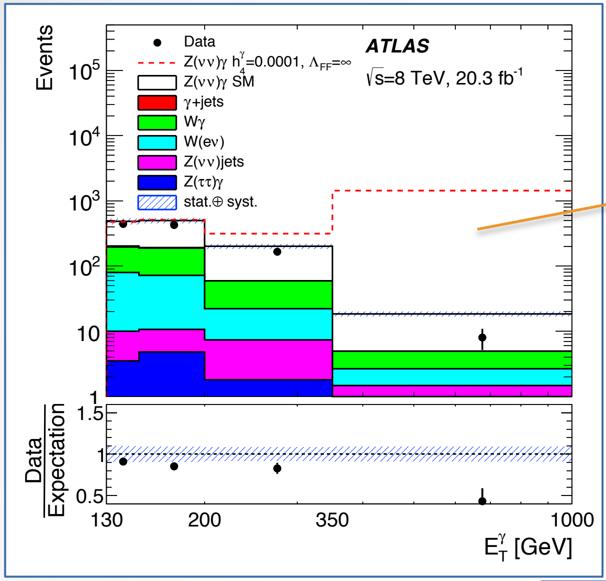
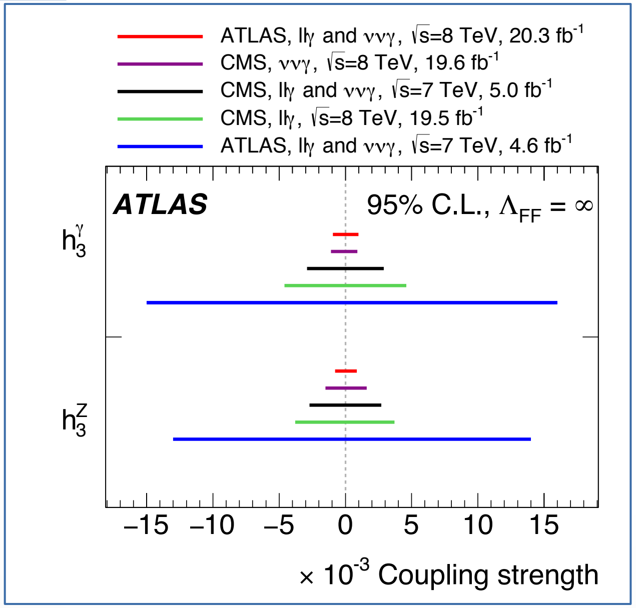
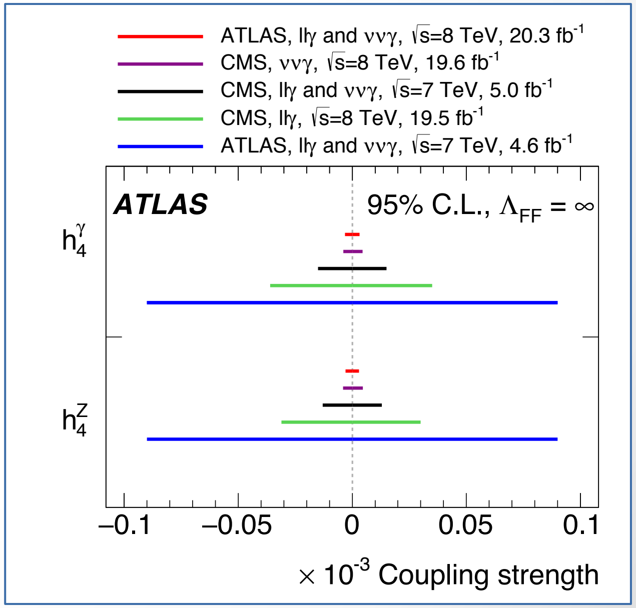
aTGC limits from Zγ production



Dominant contribution from aTGC is expected for region with high-E_T photons:
$ll\gamma$: $E_T(\gamma) > 250$ GeV.
$\nu\nu\gamma$: $E_T(\gamma) > 400$ GeV.





Non-unitarized intervals:

- LHC limits are several orders better than LEP, Tevatron.
- ATLAS limits for these parameters are the strongest at LHC.

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Zγγ production and aQGC

Effective field theory with higher-dimensional operators is adopted to parameterize the anomalous couplings. It uses EFT Lagrangian:

$$\mathcal{L} = \mathcal{L}^{SM} + \underbrace{\sum_i \frac{c_i}{\Lambda^2} O_i}_{\text{aTGC}} + \underbrace{\sum_j \frac{f_j}{\Lambda^4} O_j}_{\text{aQGC}}$$

$O_{i(j)}$ – dimension-6(8) operators
Λ [mass] - energy scale of the new physics
f_i - numerical coefficients used to set limits

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

These constants were studied.

Unitarity preservation at high energies with energy dependent Form Factor:

$$f \rightarrow \left(1 + \frac{s}{\Lambda_{\mathrm{FF}}^2}\right)^{-n} \times f$$

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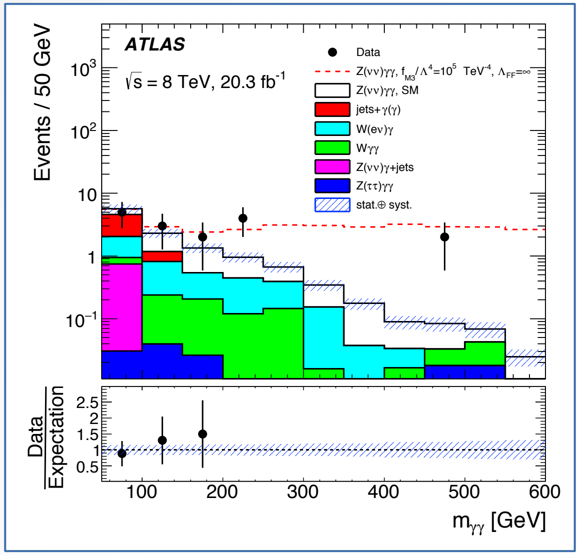
aQGC limits from Zγγ production

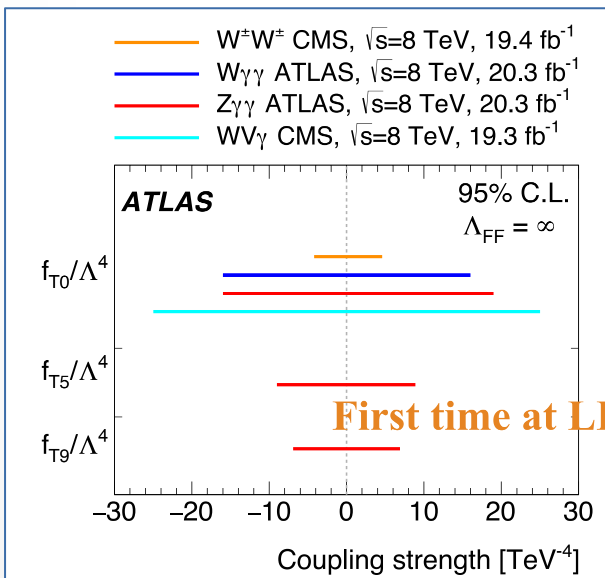


To maximize aQGC sensitivity regions with high $m_{\gamma\gamma}$ were considered:

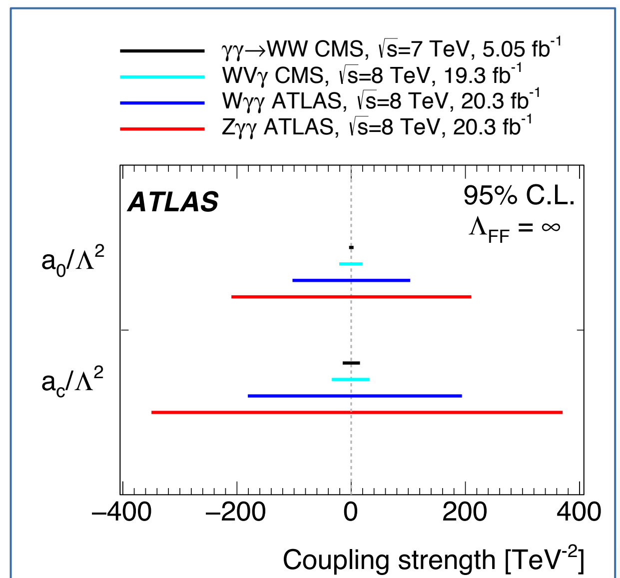
***llγγ*: $m_{\gamma\gamma}$ > 200 GeV.**

νν*γγ*: $m_{\gamma\gamma}$ > 300 GeV.

Non-unitarized intervals:



First time at LHC

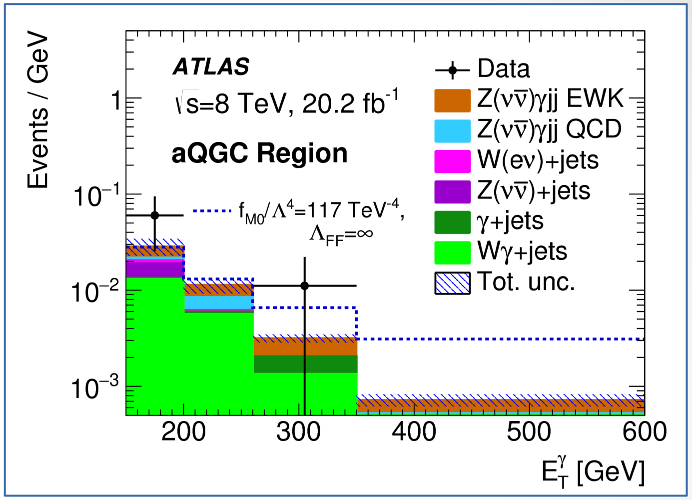


$$\frac{f_{M2}}{\Lambda^4} = \frac{a_0}{\Lambda^2}\frac{2}{g^2v^2}$$
$$\frac{f_{M3}}{\Lambda^4} = -\frac{a_c}{\Lambda^2}\frac{2}{g^2v^2}$$

aQGC from Zγ VBS

The neutrino channel provides best expected limits for all studied operators. Combination with charged channels improves results by 5-10%.

Basic selection for neutral channel:
$N_{jets} \geq 1$, $E_T^{\gamma} > 150$ GeV, $E_T^{miss} > 100$ GeV, angular cuts.



Non-unitarized limits:

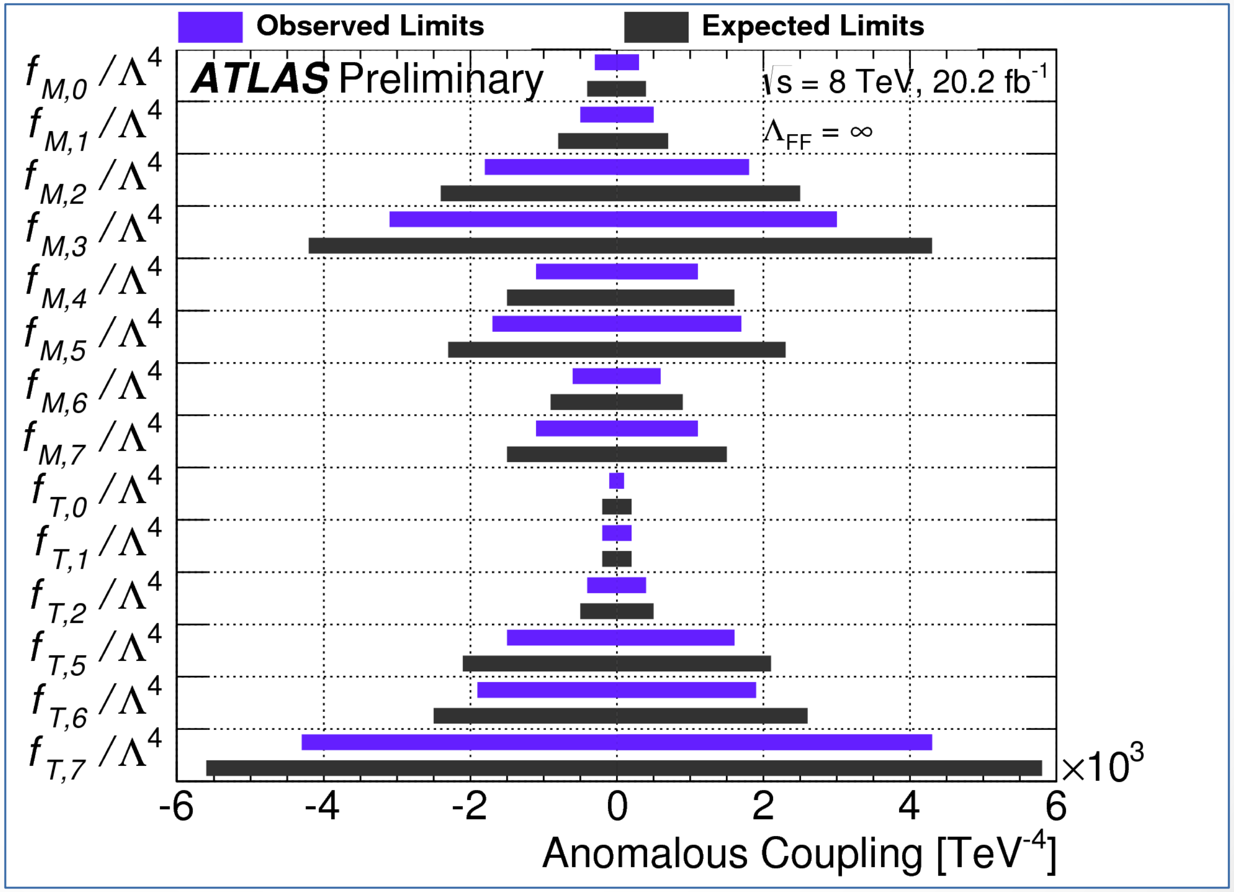
	Limits 95% CL	Measured [TeV^{-4}]	Expected [TeV^{-4}]
ATLAS $Z(\to \ell\bar{\ell}/\nu\bar{\nu})\gamma$-EWK	f_{T9}/Λ^4	[−3.9, 3.9]	[−2.7, 2.8]
	f_{T8}/Λ^4	[−1.8, 1.8]	[−1.3, 1.3]
	f_{T0}/Λ^4	[−3.4, 2.9]	[−3.0, 2.3]
	f_{M0}/Λ^4	[−76, 69]	[−66, 58]
	f_{M1}/Λ^4	[−147, 150]	[−123, 126]
	f_{M2}/Λ^4	[−27, 27]	[−23, 23]
	f_{M3}/Λ^4	[−52, 52]	[−43, 43]
CMS $Z(\to \ell\bar{\ell})\gamma$-EWK	f_{T9}/Λ^4	[−4.0, 4.0]	[−6.0, 6.0]
	f_{T8}/Λ^4	[−1.8, 1.8]	[−2.7, 2.7]
	f_{T0}/Λ^4	[−3.8, 3.4]	[−5.1, 5.1]
	f_{M0}/Λ^4	[−71, 75]	[−109, 111]
	f_{M1}/Λ^4	[−190, 182]	[−281, 280]
	f_{M2}/Λ^4	[−32, 31]	[−47, 47]
	f_{M3}/Λ^4	[−58, 59]	[−87, 87]
CMS $W(\to \ell\nu)\gamma$-EWK	f_{T0}/Λ^4	[−5.4, 5.6]	[−3.2, 3.4]
	f_{M0}/Λ^4	[−77, 74]	[−47, 44]
	f_{M1}/Λ^4	[−125, 129]	[−72, 79]
	f_{M2}/Λ^4	[−26, 26]	[−16, 15]
	f_{M3}/Λ^4	[−43, 44]	[−25, 27]

ATLAS obtained stronger limits with combined measurements of $ll\gamma$ and $\nu\nu\gamma$ channels.

aQGC limits from WVγ production

- Effective field theory was used for these studies.
- To maximize aQGC sensitivity regions with high – E_T photons were considered.
- First exclusion limits on the coupling parameters f_{M4}, f_{M5}, f_{T6} and f_{T7}.

Non-unitarized limits:



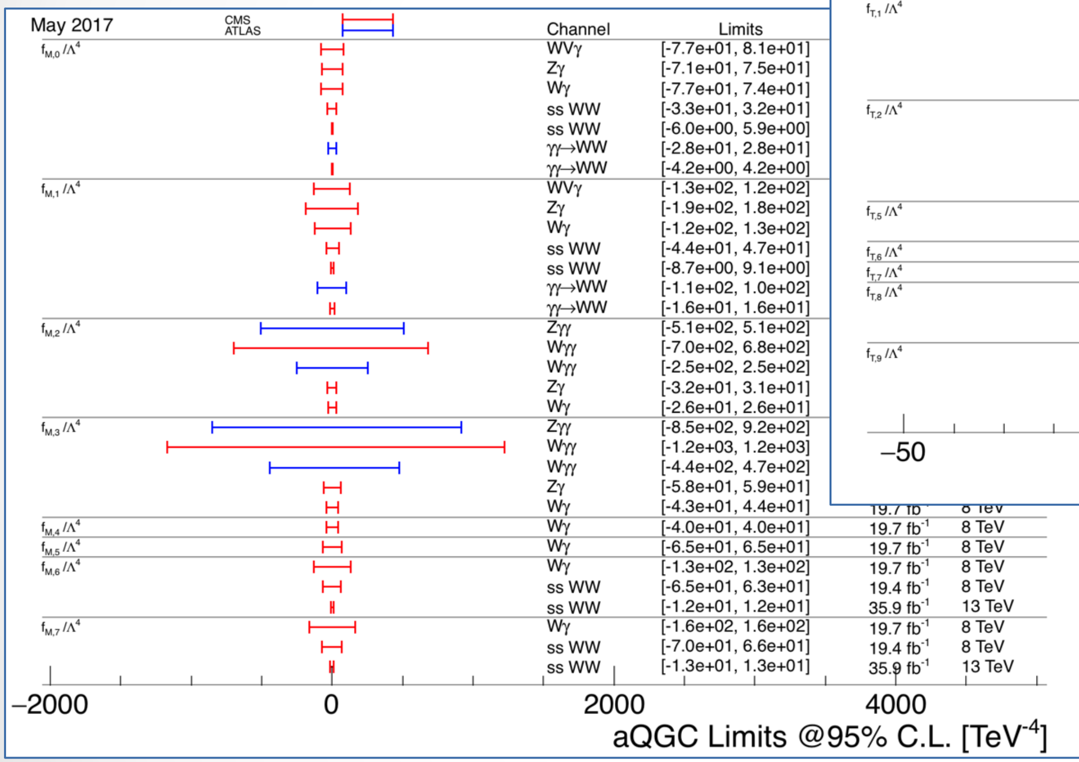
Summary

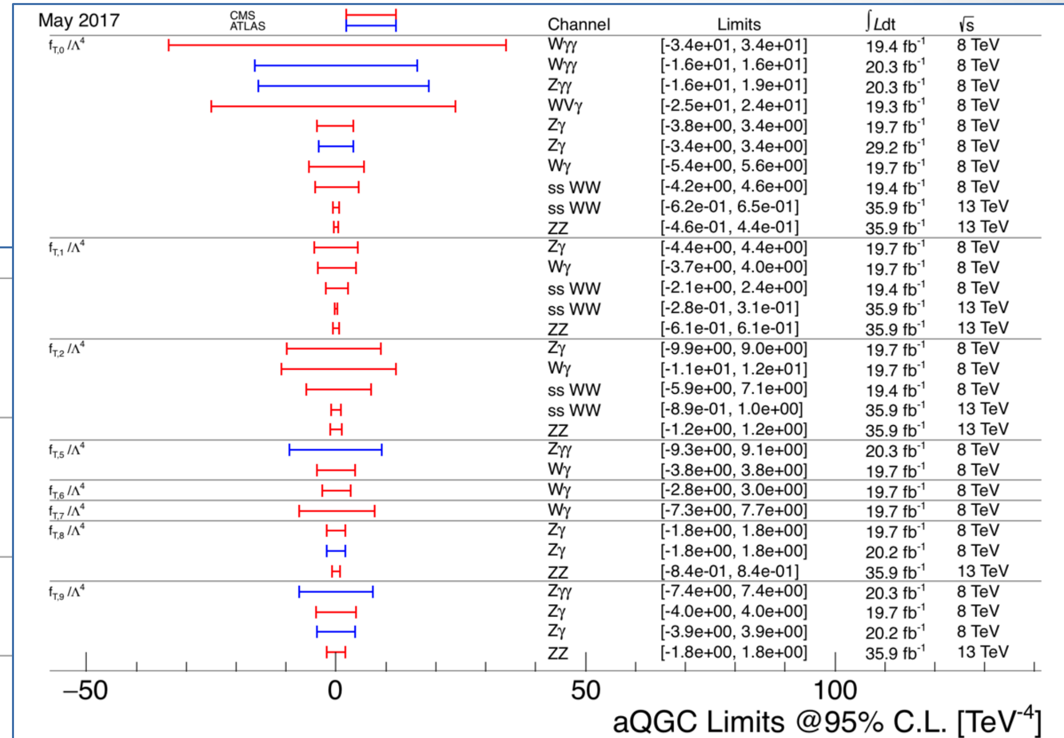
- ATLAS provides great possibilities to study $V\gamma(\gamma)$ productions in high energy proton-proton collisions with previously unattainable accuracy.
- All measurements reported here demonstrate an agreement with Standard Model predictions.
- No evidence for physics beyond the SM was found in anomalous boson triple and quartic couplings.
- New energies at LHC open frontiers to the new research areas. $V\gamma$ studies with 13 TeV data are in progress now and more results will come soon.

Thank you
for your attention!

Backup

aQGC limits summary





- **No evidence for physics beyond the Standard Model.**
- **ATLAS and CMS aQGC limits are of the same order.**

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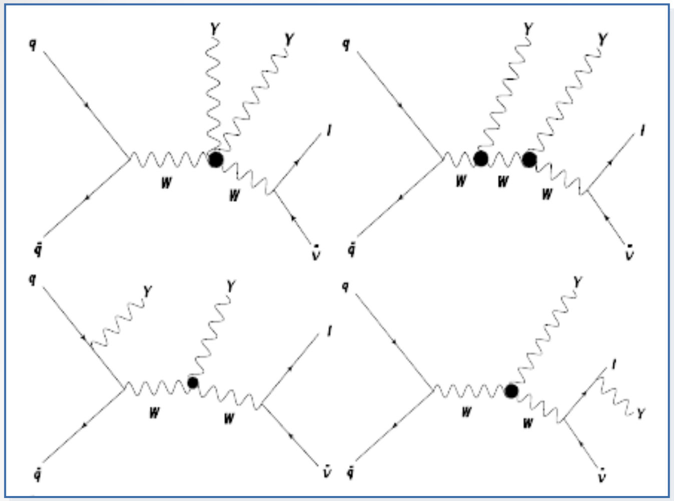
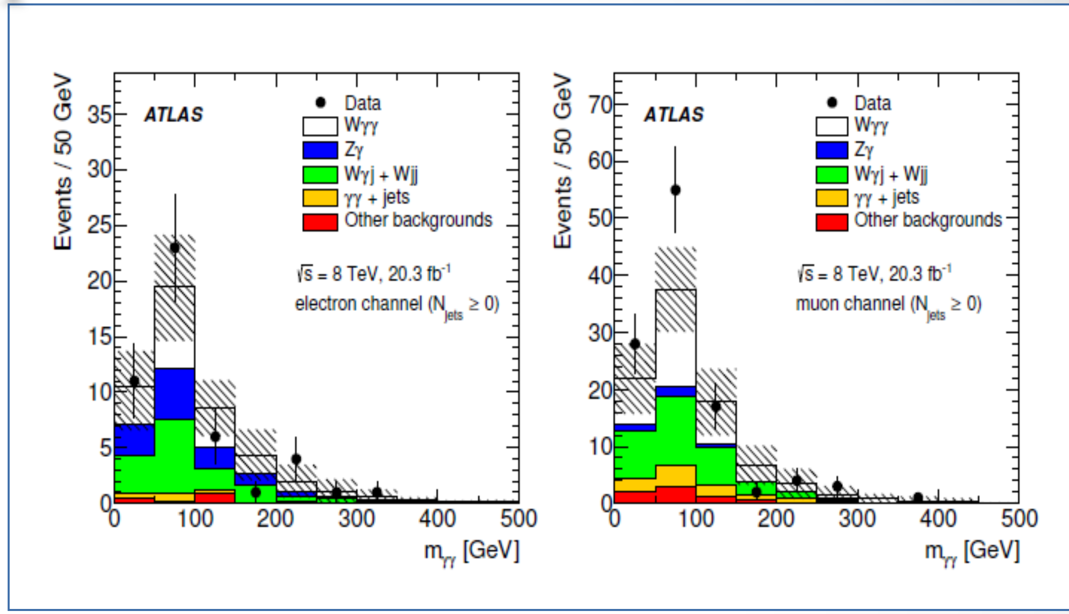
Wγγ production





- Signature: two isolated photons and W decays into leptons (isolated lepton + missing energy).
- The largest background from jets fake photons or leptons are estimated using data.

First measurement of triboson process in ATLAS!

	σ^{fid} [fb]	σ^{MCFM} [fb]
Inclusive ($N_{\text{jet}} \geq 0$)		
$\mu\nu\gamma\gamma$	$7.1\ ^{+1.3}_{-1.2}$ (stat.) ± 1.5 (syst.) ± 0.2 (lumi.)	2.90 ± 0.16
$e\nu\gamma\gamma$	$4.3\ ^{+1.8}_{-1.6}$ (stat.) $^{+1.9}_{-1.8}$ (syst.) ± 0.2 (lumi.)	
$\ell\nu\gamma\gamma$	$6.1\ ^{+1.1}_{-1.0}$ (stat.) ± 1.2 (syst.) ± 0.2 (lumi.)	
Exclusive ($N_{\text{jet}} = 0$)		
$\mu\nu\gamma\gamma$	3.5 ± 0.9 (stat.) $^{+1.1}_{-1.0}$ (syst.) ± 0.1 (lumi.)	1.88 ± 0.20
$e\nu\gamma\gamma$	$1.9\ ^{+1.4}_{-1.1}$ (stat.) $^{+1.1}_{-1.2}$ (syst.) ± 0.1 (lumi.)	
$\ell\nu\gamma\gamma$	$2.9\ ^{+0.8}_{-0.7}$ (stat.) $^{+1.0}_{-0.9}$ (syst.) ± 0.1 (lumi.)	

Results

- Above **3σ significance** for SM Wγγ process for combined results.
- Cross sections are higher by 1.9σ than SM NLO prediction in inclusive case, better agreement in exclusive case.

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aQGC limits from Wγγ production

- **Anomalous quartic couplings limits are set for exclusive case.**
- $M_{\gamma\gamma} > 300$ GeV.
- Limits better or similar to LEP and D0.