Photon$+V$ measurements in ATLAS

Dimitrii Krasnopevtsev on behalf of ATLAS collaboration
Moscow NRNU MEPhI
Outline

- Motivation
- Photon identification in ATLAS
- Photon+V measurements with 8 TeV
  - $Z\gamma$ vector boson scattering (VBS)
  - $Z\gamma(\gamma)$ production
  - $WV\gamma$ 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 $\text{SU}(2)_L \times \text{U}(1)_Y$ 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.
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

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

Energy reconstruction

Conversion reconstruction

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

- Phys. Rev. D 93, 112002
- JINST 12 P05002

Sketch of a barrel module of the ATLAS electromagnetic calorimeter
Photon+V measurements with 8 TeV

Standard Model cross sections ($\sigma$) for $V\gamma$ production in ATLAS were measured with high accuracy already with 7 TeV data. Proton-proton collisions at 8 TeV allowed to improve some measurements...

Diboson Cross Section Measurements

<table>
<thead>
<tr>
<th>Process</th>
<th>Status: May 2017</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma\gamma$</td>
<td></td>
</tr>
<tr>
<td>$W\gamma\to\ell\gamma$</td>
<td>$n_{\text{jet}} = 0$</td>
</tr>
<tr>
<td>$Z\gamma\to\ell\ell\gamma$</td>
<td>$n_{\text{jet}} = 0$</td>
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</tbody>
</table>

Agreement between data and NNLO theory predictions!

VBF, VBS, and Triboson Cross Section Measurements

...and to study rare processes of $Z\gamma$ scattering and triboson productions.

\[ \sigma = \frac{\text{Obs.} - \text{Bkg.}}{\text{Eff.} \times \int L \, dt} \]
**Zγ VBS**

**EWK component:**
- jets with wide rapidity separation.
- large dijet invariant mass ($m_{jj}$).
- production with high centrality (small values of $\zeta$).

**QCD component:**

**Z(\ell\ell)γ** – cross section measurements, aQGC limits setting.
**Z(νν)γ** – aQGC limits setting.
**Basic selection for charged channel:**

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

Two regions were studied:

- **Search region** with max. VBS contribution was used for \( \sigma_{\text{EWK}}, \sigma_{\text{EWK}+\text{QCD}} \) measurements.

- **Control region** with max. QCD contribution was used for QCD normalization in search region and also for \( \sigma_{\text{EWK}+\text{QCD}} \) measurements.

The significance of the observed EWK production signal is \( 2\sigma \) (\( 1.8\sigma \) expected).
Zγ production

**Basic selection:**
Events with \( N_{\text{jets}} \geq 0 \) and \( N_{\text{jets}} = 0 \) 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), \( E_T^{\text{miss}} > 100 \) GeV.

\[
E_T^{\text{miss}} = E_T^{\text{miss, e}} + E_T^{\text{miss, \gamma}} + E_T^{\text{miss, jets}} + E_T^{\text{miss, SoftTerm}} + E_T^{\text{miss, \mu}}
\]

**Major backgrounds were estimated from data:**
\( Z + \text{jets} \) for \( Z(ll)\gamma \).  
\( \gamma + \text{jets} \) and \( W(l\nu)\gamma \) for \( Z(\nu\nu)\gamma \).

**Photon \( E_T^{\gamma} \) spectrums:**

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**High level of agreement**
Z\gamma production

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

Cross section measurements:

<table>
<thead>
<tr>
<th>Channel</th>
<th>Measurement [fb]</th>
<th>MCFM Prediction [fb]</th>
<th>NNLO Prediction [fb]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(N_{\text{jets}} \geq 0)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(e^+e^-\gamma)</td>
<td>1510 ±15(stat.)^{+91}<em>{-84}(syst.)^{+30}</em>{-28}(lumi.)</td>
<td>1345^{+66}_{-82}</td>
<td>1483^{+19}_{-37}</td>
</tr>
<tr>
<td>(\mu^+\mu^-\gamma)</td>
<td>1507 ±13(stat.)^{+78}<em>{-73}(syst.)^{+28}</em>{-25}(lumi.)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(\ell^+\ell^-\gamma)</td>
<td>1507 ±10(stat.)^{+78}<em>{-73}(syst.)^{+29}</em>{-25}(lumi.)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(\nu\bar{\nu}\gamma)</td>
<td>68 ±4(stat.)^{+13}_{-12}(syst.) ±1(lumi.)</td>
<td>68.2±2.2</td>
<td>81.4^{+2.4}_{-2.2}</td>
</tr>
<tr>
<td></td>
<td>(N_{\text{jets}} = 0)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(e^+e^-\gamma)</td>
<td>1205 ±14(stat.)^{+84}_{-75}(syst.) ±23(lumi.)</td>
<td>1191^{+71}_{-80}</td>
<td>1230^{+10}_{-18}</td>
</tr>
<tr>
<td>(\mu^+\mu^-\gamma)</td>
<td>1188 ±12(stat.)^{+69}<em>{-63}(syst.)^{+23}</em>{-20}(lumi.)</td>
<td>1191^{+71}_{-80}</td>
<td>1230^{+10}_{-18}</td>
</tr>
<tr>
<td>(\ell^+\ell^-\gamma)</td>
<td>1189 ±9(stat.)^{+69}<em>{-63}(syst.)^{+23}</em>{-20}(lumi.)</td>
<td>1191^{+71}_{-80}</td>
<td>1230^{+10}_{-18}</td>
</tr>
<tr>
<td>(\nu\bar{\nu}\gamma)</td>
<td>43 ±2(stat.) ±10(syst.) ±1(lumi.)</td>
<td>51.0^{+2.1}_{-2.3}</td>
<td>49.21^{+0.61}_{-0.52}</td>
</tr>
</tbody>
</table>
Zγγ production

Selection:
Z(ll)γγ: similar as for one photon channel.
Z(νν)γγ: E_Tγ > 22 GeV (trigger 20 GeV), E_Tmiss > 110 GeV.

Major backgrounds estimated from data:
Z(ll)γγ: Z(γ)+jets.
Z(νν)γγ: γ(γ)+jets; W(νγ).

Cross section:
Z(ll)γγ: significance is greater 6σ.
Z(νν)γγ: 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 evμνγ final state.
- evνγ and μνμγ channels have low sensitivity because of large Zγ backgrounds.

**Basic selection:**

\[ E_T^{\gamma} > 15 \text{ GeV}, \quad p_T^{e,\mu} > 20 \text{ GeV}, \quad N_{\text{jets}} = 0 \quad (p_T > 25 \text{ GeV}), \]

\[ E_{T\text{miss}} > 50 \text{ GeV}, \quad m_{ll} > 50 \text{ GeV}. \]

**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: \( (2.02 \pm 0.10) \text{ fb} \)
Wγ events with one leptonically decaying W boson and one hadronically decaying W or Z boson are studied: evjjγ, µvjjγ.

**Basic selection:**
\[ \mathbb{E}_T \gamma > 15 \text{ GeV}, \ p_{T e,\mu} > 25 \text{ GeV}, \ N_{\text{jets}} \geq 2 \text{ (no } b\text{-jets)}, \ \mathbb{E}_{\text{miss}} > 30 \text{ GeV}, \ m_T > 50 \text{ GeV}, \ 70 < m_{ll} < 100 \text{ GeV}. \]

Upper exclusion limits on evjjγ, µvjjγ and lvjjγ production cross-section were set. Results are as low as 2.5 x Standard Model expectation.
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 are vertices with charged gauge couplings: $WWZ, WW\gamma, WWWW, WWZZ, WWZ\gamma, WW\gamma\gamma$.

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.
Vertex approach was used to study aTGC.

Anomalous $ZZ\gamma$ vertex function:

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

For $Z\gamma\gamma$:

$$\frac{p^2 - q_i^2}{M_Z^2} \rightarrow \frac{p^2}{M_Z^2}, h_i^Z \rightarrow h_i^\gamma, i = 1, 2, 3, 4.$$ 

Unitarity preservation at high energies:

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

$\Lambda_{FF}$ - form factor energy scale.

Unitarized scheme: $\Lambda_{FF} = 4$ TeV.

Violation scheme: $\Lambda_{FF} = \infty$.

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.
Non-unitarized intervals:

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

Dominant contribution from aTGC is expected for region with high-$E_T$ photons:

\[ l\ell\gamma: E_T^{\gamma} > 250 \text{ GeV}. \]

\[ \nu\nu\gamma: E_T^{\gamma} > 400 \text{ GeV}. \]
Effective field theory with higher-dimensional operators is adopted to parameterize the anomalous couplings. It uses EFT Lagrangian:

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

$O_{i(j)}$ – dimension-6(8) operators

$\Lambda$ [mass] - energy scale of the new physics

$f_i$ - numerical coefficients used to set limits

These constants were studied.

Unitarity preservation at high energies with energy dependent Form Factor:

$$f \rightarrow \left(1 + \frac{s}{\Lambda_{FF}^2}\right)^{-n} \times f$$
To maximize aQGC sensitivity regions with high $m_{\gamma\gamma}$ were considered:

- $ll\gamma\gamma$: $m_{\gamma\gamma} > 200$ GeV.
- $\nu\nu\gamma\gamma$: $m_{\gamma\gamma} > 300$ GeV.

Non-unitarized intervals:

First time at LHC
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:**
\( N_{\text{jets}} \geq 1, E_{T}^{\gamma} > 150 \text{ GeV}, E_{T}^{\text{miss}} > 100 \text{ GeV}, \) angular cuts.

**Non-unitarized limits:**

<table>
<thead>
<tr>
<th>Operators</th>
<th>ATLAS ( Z(\rightarrow \ell\ell/\nu\bar{\nu})\gamma\text{-EWK} )</th>
<th>CMS ( Z(\rightarrow \ell\ell)\gamma\text{-EWK} )</th>
<th>CMS ( W(\rightarrow \ell\nu)\gamma\text{-EWK} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( f_{T9}/\Lambda^4 )</td>
<td>([-3.9, 3.9])</td>
<td>([-4.0, 4.0])</td>
<td>([-5.4, 5.6])</td>
</tr>
<tr>
<td>( f_{T8}/\Lambda^4 )</td>
<td>([-1.8, 1.8])</td>
<td>([-1.8, 1.8])</td>
<td>([-7.7, 74])</td>
</tr>
<tr>
<td>( f_{T0}/\Lambda^4 )</td>
<td>([-3.4, 2.9])</td>
<td>([-3.8, 3.4])</td>
<td>([-125, 129])</td>
</tr>
<tr>
<td>( f_{M0}/\Lambda^4 )</td>
<td>([-76, 69])</td>
<td>([-71, 75])</td>
<td>([-125, 129])</td>
</tr>
<tr>
<td>( f_{M1}/\Lambda^4 )</td>
<td>([-147, 150])</td>
<td>([-190, 182])</td>
<td>([-77, 74])</td>
</tr>
<tr>
<td>( f_{M2}/\Lambda^4 )</td>
<td>([-27, 27])</td>
<td>([-32, 31])</td>
<td>([-125, 129])</td>
</tr>
<tr>
<td>( f_{M3}/\Lambda^4 )</td>
<td>([-52, 52])</td>
<td>([-58, 59])</td>
<td>([-43, 44])</td>
</tr>
</tbody>
</table>

\( \Lambda_{\text{F}} = \infty \)

ATLAS obtained stronger limits with combined measurements of \( ll\gamma \) and \( \nu\nu\gamma \) channels.
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:

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/STDM-2016-05/
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
No evidence for physics beyond the Standard Model.

ATLAS and CMS aQGC limits are of the same order.
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.

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.

First measurement of triboson process in ATLAS!

<table>
<thead>
<tr>
<th></th>
<th>σ^ind [fb]</th>
<th>σ^MCFM [fb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inclusive (N_{Jet} ≥ 0)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>μνγγ</td>
<td>7.1 ±1.3 (stat.) ±1.5 (syst.) ±0.2 (lumi.)</td>
<td></td>
</tr>
<tr>
<td>eνγγ</td>
<td>4.3 ±1.8 (stat.) ±1.8 (syst.) ±0.2 (lumi.)</td>
<td>2.90 ±0.16</td>
</tr>
<tr>
<td>ℓνγγ</td>
<td>6.1 ±1.0 (stat.) ±1.2 (syst.) ±0.2 (lumi.)</td>
<td></td>
</tr>
<tr>
<td>Exclusive (N_{Jet} = 0)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>μνγγ</td>
<td>3.5 ±0.9 (stat.) ±1.1 (syst.) ±0.1 (lumi.)</td>
<td>1.88 ±0.20</td>
</tr>
<tr>
<td>eνγγ</td>
<td>1.9 ±1.4 (stat.) ±1.3 (syst.) ±0.1 (lumi.)</td>
<td></td>
</tr>
<tr>
<td>ℓνγγ</td>
<td>2.9 ±0.8 (stat.) ±0.9 (syst.) ±0.1 (lumi.)</td>
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</tr>
</tbody>
</table>

PHOTON2017, May 22-26, Geneva
Anomalous quartic couplings limits are set for exclusive case.

- $M_{\gamma\gamma} > 300$ GeV.
- Limits better or similar to LEP and D0.