Iwona Grabowska-Bold (AGH UST, Kraków)
for the ATLAS Collaboration

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ATLAS measurements of photon-photon fusion processes in Pb+Pb collisions
INTRODUCTION

➤ **Ultra-peripheral collisions (UPC)** of lead-lead (Pb+Pb) are gaining more and more interest in the heavy-ion community
  ➤ Very clean environment to study **quantum electrodynamics (QED)**
  ➤ Precision tool to study **photon fluxes** within the EPA framework
  ➤ $Z^4(\approx 4.5 \times 10^7)$ **enhancement** of cross sections in Pb+Pb wrt proton-proton (pp) collisions
  ➤ **Zero Degree Calorimeters (ZDC)** offer control over backgrounds and impact-parameter dependence
  ➤ $\gamma\gamma$ collisions are considered a tool to **search** for **beyond Standard Model (BSM)** physics

➤ The following results from 5.02 TeV UPC Pb+Pb collisions from **ATLAS** are discussed:
  ➤ **Final** $\gamma\gamma \rightarrow \mu^+\mu^-$ [PRC 104 (2021) 024906]
  ➤ **Preliminary** $\gamma\gamma \rightarrow e^+e^-$ [ATLAS-CONF-2022-025]
  ➤ **Final** $\gamma\gamma \rightarrow \tau^+\tau^-$ [arXiv:2204.13478] **NEW**
  ➤ **Final** light-by-light scattering and ALP search [JHEP 03 (2021) 243]
  ➤ **Not covered:**
    ➤ Non-UPC $\gamma\gamma \rightarrow \mu^+\mu^-$ [ATLAS-CONF-2019-051] - major update coming soon
EXCLUSIVE DIMUONS AND DIELECTRONS

<table>
<thead>
<tr>
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<th>$\gamma\gamma \rightarrow \mu^+\mu^-$</th>
<th>$\gamma\gamma \rightarrow e^+e^-$</th>
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<td>Data</td>
<td>2015</td>
<td>2018</td>
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<td>Int lumi</td>
<td>0.48 nb$^{-1}$</td>
<td>1.72 nb$^{-1}$</td>
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<td>Fiducial</td>
<td>$p_T^{\mu} &gt; 4$ GeV \quad</td>
<td>$p_T^e &gt; 2.5$ GeV \quad</td>
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<tr>
<td>Event candidates</td>
<td>12k</td>
<td>30k</td>
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Background
- Dissociative LPair (3%)
- Dissociative SuperChic v4.0 (4%)

Dissociative background uses **template fitting** to $\alpha$.
- Contribution from FSR important to have a good description of $\alpha$ distribution (STARlight+Pythia8).

**Signal**

**Background**
Differential cross sections studied in $m_{\mu\mu}$, $|y_{\mu\mu}|$, $|\cos \theta^*|$, $k_{\text{min}}$, $k_{\text{max}}$, $\alpha$

- $m_{\mu\mu}$ measured up to 200 GeV
- Good agreement with STARlight 2.0
EXCLUSIVE DIMUONS: DIFFERENTIAL CROSS SECTIONS

- Differential cross sections studied in \( m_{\mu\mu}, |y_{\mu\mu}|, |\cos\theta^*|, k_{\text{min}}, k_{\text{max}}, \alpha \)
- Good agreement with STARlight 2.0
- … but systematic excess of the data at higher \(|y_{\mu\mu}|\)

EXCLUSIVE MUONS: ACTIVITY IN ZDC

➤ ZDC are 140 m away from the IP (|η| > 8.3)
  ➤ Detect neutral particles (e.g. neutrons, photons)
  ➤ Inclusive sample of γγ → ℓ⁺ℓ⁻ can be divided into three categories
    ➤ 0n0n: no activity in neither ZDC arm
    ➤ Xn0n: activity in one ZDC arm
    ➤ XnXn: activity in both ZDC arms
➤ Fractions of events falling to each category f_{0n0n}, f_{Xn0n}, f_{XnXn} are measured
  ➤ After subtracting backgrounds and accounting for electromagnetic pileup
➤ Each category probes different impact parameters (b)

**EXCLUSIVE DIMUONS: FORWARD ACTIVITY**

- **Raw and corrected fractions** of events in **Xn0n** and **XnXn** categories as a function of $|y_{\mu\mu}|$ (left) and $m_{\mu\mu}$ (right)

  - Corrected fractions are lower after accounting for electromagnetic pileup
  - $f_{Xn0n}, f_{XnXn}$ decrease with $|y_{\mu\mu}|$ and increase with $m_{\mu\mu}$
  - STARlight describes the shapes well but overestimates the value

EXCLUSIVE DIELECTRONS: 0N0N CROSS SECTIONS

Differential cross sections measured in $m_{ee}$, $|y_{ee}|$, $\langle p_T^e \rangle$ and $|\cos \theta^*|$ in the 0n0n category

- STARlight provides predictions for neutron production (black dotted line)
- Use measured 0n0n fractions with uncertainties to correct both STARlight and SuperChic predictions

General conclusions similar to the inclusive ZDC case

- STARlight 3.13 (SuperChic 3.05) systematically lower (higher) than data
- SuperChic does a better job in description of shapes
Event candidate for $\gamma\gamma \rightarrow \tau^+\tau^- \rightarrow e^+\nu_e\nu_{\tau}\mu^-\nu_{\mu}\nu_{\tau}$
EXCLUSIVE DITAUS

- **NEW** First observation of $\tau$ leptons in A+A collisions in 2018 UPC Pb+Pb collisions of 1.44 nb$^{-1}$
- Exclusive ditau production $\gamma\gamma \rightarrow \tau^+\tau^-$ with **semileptonic decay** modes
  - $\mu1T$-SR: muon + 1 track (e/$\mu$/hadron)
  - $\mu3T$-SR: muon + 3 tracks (3 hadrons)
  - $\mu e$-SR: muon + electron

with $p_T^{\mu} > 4$ GeV, $p_T^e > 4$ GeV, $p_T^{\text{trk}} > 100$ MeV

$p_T^{\text{clus}} > 1$ GeV ($|\eta| < 2.5$)

$p_T^{\text{clus}} > 100$ MeV ($2.5 < |\eta| < 4.5$)

- Exclusivity: veto additional clusters ($\mu1T$-SR and $\mu3T$-SR only) and tracks
- Total of $\sim 650$ events across all SRs
- Only data in the 0n0n category used to suppress photonuclear/hadronic backgrounds
- Simulation (**STARlight**+**Tauola**) reweighted to 0n0n with data-driven weights

[arXiv:2204.13478]
Main backgrounds:

- $\gamma\gamma \rightarrow \mu^+\mu^- (\gamma)$ and photonuclear

In general little background contributions in all three SR (15%)

- Good agreement of SM predictions with data
Measure $\gamma\gamma \to \tau^+\tau^-$ signal strength $\mu_{\tau\tau} = \frac{N_{\gamma\gamma\to \tau\tau}^{\text{meas}}}{N_{\gamma\gamma\to \tau\tau}^{\text{SM, pred}}} \text{ and } a_{\tau}$ using profile likelihood fit to the $p_T^{\mu}$ distribution in the three SRs and $2\mu$-CR.

Result of $\mu_{\tau\tau}$ for each SR assuming $a_{\tau}$ from SM compatible with unity.
Measure $a_\tau = \frac{g - 2}{2}$ using profile likelihood fit to the $p_T^{\mu}$ distribution in the three SRs and 2µ-CR

Templates built for different $a_\tau$ values by reweighting signal MC using weights from [PLB 809 (2020) 135682]

Expected 95% CL limits from the combined fit: $-0.039 < a_\tau < 0.020$

Observed 95% CL limits: $a_\tau \in (-0.058, -0.012) \cup (-0.006, 0.025)$
  - Double-interval structure due to interference of SM and BSM amplitudes

Constraints on $a_\tau$ similar to those observed by DELPHI
Light-by-light scattering is a rare fundamental QED process

- Observed in a direct way at the LHC for the first time [PRL 123 (2019) 052001]
- About 100 event candidates in combined 2015+2018 (full Run 2) UPC Pb+Pb data

Cross sections measured in the fiducial region $E_T^γ > 2.5$ GeV, $m_{γγ} > 5$ GeV, $|η^γ| < 2.4, p_T^{γγ} < 1$ GeV

- Differential in $m_{γγ}, |y_{γγ}|, |cos θ^*|, (p_T^{γ1} + p_T^{γ2})/2$

- Good agreement in shape, differences in the normalisation

Distribution of $m_{\gamma\gamma}$ used to search for ALP in $6 < m_{\gamma\gamma} < 100$ GeV range using a cut-and-count method

- Signal: $\gamma\gamma \rightarrow a \rightarrow \gamma\gamma$, BR$(a \rightarrow \gamma\gamma)$=100%
- Background: LbyL, $\gamma\gamma \rightarrow e^+e^-$, central exclusive production of $gg \rightarrow \gamma\gamma$

- 95% CL limits on $\sigma$ and coupling $1/\Lambda_a$
  - Largest deviation of $2.1\sigma$ at $m_{\gamma\gamma} \sim 10$ GeV
  - The most stringent limit established for ALP masses between 6-100 GeV
SUMMARY AND OUTLOOK

➤ ATLAS provides precision results on $\gamma\gamma \rightarrow \ell^+\ell^-$ with $\ell = e, \mu, \tau$ from UPC Pb+Pb collisions recorded in Run 2
  ➤ Measured cross sections reveal systematic differences with STARlight and SuperChic calculations
    ➤ SuperChic gets the spectral shape right but generally over predicts, suggesting recent discussions on higher order Coulomb effects [JHEP 2021 (2021) 83]
  ➤ Dimuon and dielectron channels limited by systematic uncertainties
  ➤ ZDC provides constraints for background and impact-parameter dependence
  ➤ FSR needs to be accounted for to get a good description of data
➤ ATLAS shows a first final measurement of exclusive ditau production in UPC Pb+Pb collisions at the LHC with above $5\sigma$ significance
  ➤ Data is used to constrain $a_\tau$ at the LHC
  ➤ Precision is comparable to the DELPHI best limit from the LEP era
➤ Final light-by-light measurement from ATLAS available from the full Run 2 Pb+Pb data
  ➤ Input to the first combination of ATLAS+CMS data at the LHC [arXiv:2204.02845] NEW
➤ UPC Pb+Pb proves to provide constraints for BSM physics
  ➤ Most stringent limits on ALP production for $6 < m_a < 100$ GeV established
➤ Data taking is about to start in LHC Run 3
  ➤ Expect to double integrated luminosity at the end of 2022, a factor of 3.5 more after Run 3

➤ All results from ATLAS available at https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HeavylonsPublicResults
BACK-UP SLIDES
Three main components: inner tracker, electromagnetic (EM) and hadronic (HAD) calorimeters, and muon system

**Electrons**: inner tracker, EM calo

\[ p_T^e > 20 \ (25) \ \text{GeV for} \ Z \ (W^\pm) \]

**Muons**: inner tracker, muon system

\[ p_T^\mu > 20 \ (25) \ \text{GeV for} \ Z \ (W^\pm) \]

**Charged particles**: inner tracker

\[ p_T^{\text{ch}} > 100 \ \text{MeV} \]

**Neutrons**: Zero Degree Calorimeter

\[ |\eta| > 8 \]

\[ |\eta^{\ell, \text{ch}}| \lesssim 2.5 \]
EXCLUSIVE DIMUONS

- Data set from 2015 Pb+Pb collisions of 0.49 nb\(^{-1}\)
- Production measured in the fiducial region defined by:
  \[ p_T^{\mu} > 4 \text{ GeV}, |\eta^{\mu}| < 2.4, m_{\mu\mu} > 10 \text{ GeV} \text{ and } p_T^{\mu\mu} < 2 \text{ GeV} \]
- About 12k event candidates
- Background from single-dissociative processes (3%) subtracted using a template fitting to the acoplanarity \( \alpha \) distribution
  - Contribution from FSR important to have a good description of \( \alpha \) distribution (STARlight+Pythia8)

\[ \text{Signal} \quad \text{Background} \]

- \[ \text{Pb} \quad \text{Pb} \quad \text{Pb} \quad \text{Pb} \quad \text{Pb} \quad \text{Pb} \quad \text{Pb} \quad \text{Pb}\]
- \[ \mu^- \quad k_2 \quad k_1 \quad \mu^+ \quad \mu^- \quad k_2 \quad k_1 \quad \mu^+ \]
- \[ \text{Pb} \quad \text{Pb} \quad \text{Pb} \quad \text{Pb} \quad \text{Pb} \quad \text{Pb} \quad \text{Pb} \quad \text{Pb}\]
- \[ \gamma \quad \mu^- \quad k_1 \quad \mu^+ \quad \mu^- \quad k_1 \quad \mu^+ \]
- \[ p \text{ (in Pb)} \quad \text{Pb}^* + X \]
EXCLUSIVE DIELECTRONS

- Data set from 2018 UPC Pb+Pb collisions of 1.72 nb\(^{-1}\)
- Production measured in the fiducial region defined by: \(p_T^e > 2.5\) GeV, \(|\eta^e| < 2.5\), \(m_{ee} > 5\) GeV and \(p_T^{ee} < 2\) GeV
- About 30k event candidates
- Dissociative background (~4%) evaluated using improved template fitting to the acoplanarity distribution
  - SuperChic 4.0 used
  - Other backgrounds: \(\Upsilon\) and \(\gamma\gamma \rightarrow \tau^+\tau^-\)
- Systematic uncertainties dominate (10%)

[ATLAS-CONF-2022-025]
Differential cross sections measured in $m_{ee}$, $|y_{ee}|$, $\langle p_T^e \rangle$ and $|\cos \theta^*|$ for the inclusive ZDC sample

- **STARlight 3.13** (SuperChic 3.05) systematically lower (higher) than data
- Fairly good description of shapes
Final result on LbyL scattering ($\gamma\gamma \rightarrow \gamma\gamma$) from ATLAS

- Fundamental QED process with a tiny cross section
  - Prior to the LHC, tested indirectly (anomalous magnetic moment of the electron and muon)
- Sensitive to new physics
  - Possible contributions from new particles beyond SM
  - Anomalous gauge couplings

Earlier results at the LHC:


Several improvements introduced in the final publication:

- All Run-2 Pb+Pb data (2015+2018): 2.2 nb$^{-1}$
- Improved luminosity calibration: 3.2% uncertainty
- Lower photon $E_T$ threshold ($E_T > 2.5$ GeV)
- Differential cross sections
- Search for axion-like particles (ALP)
EXCLUSIVE DIMUONS

Run: 287038
Event: 71765109
2015-11-30 23:20:10 CEST

Dimuons UPC Pb+Pb 5.02 TeV

➤ Very clean dimuon event
➤ Only two photons in the detector