Measurement of dilepton production from photon fusion processes in UPC in Pb+Pb collisions with the ATLAS detector

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INTRODUCTION

➤ **Ultra-peripheral collisions (UPC)** of lead-lead (Pb+Pb) have attracted a lot of attention in the heavy-ion community
  ➤ Very clean environment to study **quantum electrodynamics** (QED) and **photon fluxes** within the Equivalent Photon Approximation (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 prove to be a competitive tool for **searches** for beyond Standard Model (BSM) physics
  ➤ **Non-UPC** $\gamma \gamma \rightarrow \mu^+\mu^-$ events as a **new probe** of the QGP or strong QED fields

➤ 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]
  ➤ **Final** $\gamma \gamma \rightarrow e^+e^-$ [JHEP 06 (2023) 182]
  ➤ **Final** $\gamma \gamma \rightarrow \tau^+\tau^-$ [PRL 131 (2023) 151802]
  ➤ **Final** non-UPC $\gamma \gamma \rightarrow \mu^+\mu^-$ [PRC 107 (2023) 054907]
### Exclusive Dimuons and Dielectrons

<table>
<thead>
<tr>
<th>Data</th>
<th>2015</th>
<th>2018</th>
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<tbody>
<tr>
<td><strong>Int lumi</strong></td>
<td>0.48 nb(^{-1})</td>
<td>1.72 nb(^{-1})</td>
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- **Fiducial**
  - \(p_T^\mu > 4\) GeV
  - \(p_T^\ell\ell < 2\) GeV
  - \(|\eta^\mu| < 2.4\)
  - \(|\eta^\ell| < 2.5\)
  - \(m_{\mu\mu} > 10\) GeV
  - \(m_{ee} > 5\) GeV

| Event candidates | 12k | 30k |

\(\gamma\gamma \rightarrow \mu^+\mu^-\) \(\gamma\gamma \rightarrow e^+e^-\) event candidate

- \(p_T^\gamma = 8.2\) GeV
- \(p_T^e = 7.4\) GeV

**Signal**

- Data 2018
- STARlight+Py8 \(\gamma\gamma \rightarrow e^+e^-\)
- SC4+Py8 dissociative \(e^+e^-\)
- \(Y(nS) \rightarrow e^+e^-, \gamma\gamma \rightarrow \ell^+\ell^-\)
- MC stat. + syst. unc.
**EXCLUSIVE DIMUONS: DIFFERENTIAL CROSS SECTIONS**


- Differential cross sections studied in $m_{\mu\mu}, |y_{\mu\mu}|$, dilepton scattering angle ($|\cos \theta^*|$), photon energy ($k_{\text{min}}, k_{\text{max}}$) and acoplanarity ($\alpha$)
- $m_{\mu\mu}$ measured up to 200 GeV
- Good agreement with STARlight 2.0
- ... but systematic excess of the data at higher $|y_{\mu\mu}|$
EXCLUSIVE DILEPTONS: ACTIVITY IN ZDC

➤ **ZDC** are 140 m away from the IP (|η| > 8.3)

➤ Detect neutral particles (e.g. neutrons, photons)

➤ Inclusive sample of $\gamma\gamma \to \ell^+\ell^-$ is 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)

- **Corrected fractions** of events in the **OnOn** (dielecrons) and **XnOn/XnXn** (dimuons) categories as a function of $m_{\ell\ell}$ in three $|y_{\ell\ell}|$ intervals
  - $f_{OnOn} (f_{XnOn}, f_{XnXn})$ **decreases** (increases) with $m_{\ell\ell}$ and increases (decrease) with $|y_{\ell\ell}|$
  - Results consistent between dielectron and dimuon channels
  - **STARlight** qualitatively describes the impact-parameter dependence of the fluxes, but some systematic differences are observed
EXCLUSIVE DILEPTONS: BACKGROUNDS

- Use **ZDC categories** to constraint **dissociative background** via template method
- Precise evaluation of dissociative background in **SuperChic v4.0 (LPair)** in $e^+e^- (\mu^+\mu^-)$
- In inclusive samples: dimuons - 3%, dielectrons - 4.3%
EXCLUSIVE DIMUONS: ACOPLANARITY

- Differential cross section in acoplanarity for \(0n0n\)
- Comparison to inclusive STARlight and STARlight+Pythia8 scaled to \(0n0n\) from data
- Pure STARlight fails at high \(\alpha\) due to a missing FSR contribution
- STARLight+Pythia8 with QED showering describes \(\alpha > 0.01\) quite well
- However, for \(\alpha < 0.01\) differences in shapes observed which can be attributed to differences in the photon flux of STARlight
EXCLUSIVE DIELECTRONS: CROSS SECTIONS

- Differential cross sections measured in $m_{ee}$, $|y_{ee}|$, $\langle p_T^e \rangle$ and $|\cos \theta^*|$ in the $0n0n$ category
  - STARlight $0n0n$ provides predictions for no neutron production (black dotted line)
  - SuperChic 3.05 doesn’t implement ZDC selections
  - Use measured $0n0n$ fractions with uncertainties to correct both STARlight and SuperChic predictions
- General conclusions similar to the inclusive ZDC case
  - STARlight 2.2 (SuperChic 3.05) systematically lower (higher) than data
  - SuperChic does a better job in the description of shapes
New data triggered developments in **SuperChic v4.2** which brings modeling of ion excitation/de-excitation and emission of neutrons in the forward direction

- See L.H. Harland-Lang arXiv:2303.04826 for more details

- **Good description** of dielectron/dimuon data from ATLAS
Event candidates for $\gamma\gamma \rightarrow \tau^+\tau^- \rightarrow \mu^\pm\nu_\mu\nu_\tau$ track(s) or $\gamma\gamma \rightarrow \tau^+\tau^- \rightarrow \mu^\pm\nu_\mu\nu_\tau e^\pm\nu_e\nu_\tau$
EXCLUSIVE DITAMUS

- **First observation** of τ 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 (semi)leptonic decay modes
  - $\mu 1T$-SR: muon + 1 track (e/µ/hadron)
  - $\mu 3T$-SR: muon + 3 tracks (3 hadrons)
  - $\mu e$-SR: muon + electron

  with $p_T^{\mu} > 4$ GeV, $p_T^{e} > 4$ GeV, $p_T^{trk} > 100$ MeV
  $p_T^{clus} > 1$ GeV ($|\eta| < 2.5$)
  $p_T^{clus} > 100$ MeV ($2.5 < |\eta| < 4.5$)

  - Exclusivity: veto additional clusters ($\mu 1T$-SR and $\mu 3T$-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 ($\text{STARlight + Tauola}$) reweighted to 0n0n with data-driven weights
EXCLUSIVE DITAUS: CONTROL PLOTS

- $\gamma\gamma \rightarrow \tau^+\tau^-$ measured in three channels:
  - $\mu 1T$-SR: muon + 1 track (e/\mu/hadron)
  - $\mu 3T$-SR: muon + 3 tracks (3 hadrons)
  - $\mu e$-SR: muon + electron

- 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

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Main backgrounds:
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Good agreement of SM predictions with data
Signal strength $\mu_{\tau\tau} = \frac{N_{\gamma\gamma\to\tau\tau}^{\text{meas}}}{N_{\gamma\gamma\to\tau\tau}^{\text{SM, pred}}}$ measured using a profile-likelihood fit to the $p_T^\mu$ distribution in the three SRs and $\mu\mu$ control region (2$\mu$-CR)

First observation of tau leptons and $\gamma\gamma \to \tau^+\tau^-$ process with more than 5$\sigma$ significance in HI collisions at the LHC

Result of $\mu_{\tau\tau}$ for each SR assuming $a_\tau$ anomalous magnetic moment from SM are compatible with unity
In addition to 3 SRs, events from 2µ-CR from $\gamma\gamma \rightarrow \mu^+\mu^-$ used in the fit to constrain photon fluxes

Reach a total uncertainty of 5% for the combined $\mu_{\tau\tau}$ dominated by statistical precision
EXCLUSIVE DITAUS: TAU MAGNETIC MOMENT

OPAL 1998
L3 1998
DELPHI 2004
µ1T-SR
µ3T-SR
µe-SR
Combined
Expected

ATLAS
Pb+Pb \( \sqrt{s_{\text{NN}}} = 5.02 \text{ TeV}, 1.44 \text{ nb}^{-1} \)

\[ g = \gamma + \mu + \cdots \]

\[ g = a = \frac{g - 2}{2} \]

| \( a_{\tau} \) extracted in a profile-likelihood fit to the \( p_{T}^{\mu} \) distribution |
| \( \text{HI collisions at the LHC} \) contribute to the hot topic of lepton \( g - 2 \) measurements |
| Templates for different \( a_{\tau} \) built by reweighting signal MC using weights from [PLB 809 (2020) 135682] |
| Constraints on \( a_{\tau} \) similar in precision to those observed by DELPHI at LEP |
NON-UPC DIMUONS: CROSS SECTIONS

\[ \mu^+ \mu^- \text{ studied in non-UPC events} \]

\[ \gamma \gamma \rightarrow \mu^+ \mu^- (A<0.06, k_\perp<150 \text{ MeV}) \]

\[ \text{Cross section measured as a function of centrality} \]

\[ \text{STARlight predictions (solid lines) describe the shape but underestimate the normalisation, likely due to the truncation of photon fluxes for } b < R_A \]

\[ \text{Centrality-dependent broadening of } \alpha \text{ and } k_\perp \text{ is confirmed} \]

\[ \text{Described by QED [PLB 800 (2020) 135089] and PWF [PRD 102 (2020) 094013] calculations} \]

\[ \text{Also the depletion of yields at small } \alpha \text{ and } k_\perp \text{ is found to develop with centrality} \]

\[ \text{PWF does not reproduce the first point} \]
Non-upc dimuons: Moments

- Significant increase in the **mean** and **RMS** values is observed as one goes from UPC to higher centralities.
- **Standard deviation** shows a much slower increase.
- **PWF** predictions reproduce many of the trends, but the mean and RMS values systematically lie below the data.
➤ Hypothesis of centrality-dependent broadening of $k_\perp$ in a **strong magnetic field**

➤ Broadening should vary as the hyperbolic tangent of **rapidity difference** of two muons $|\Delta y| = |y_1 - y_2|$

➤ $k_\perp$ distribution is supposed to depend on the orientation of muon pairs relative to the direction of the **second-order event plane** $|2\Delta \phi| = |2(\phi_{\mu\mu} - \Psi_2)|$

➤ Predicted trends associated with effects of **magnetic fields** on dimuons are **not observed**
TOWARDS RUN-3 DATA ANALYSIS

- ATLAS experiment collected Pb+Pb collisions in October 2023
  - Run 2: 2.2 nb\(^{-1}\) at \(\sqrt{s_{\text{NN}}} = 5.02\) TeV
  - Run 3: 1.7 nb\(^{-1}\) at \(\sqrt{s_{\text{NN}}} = 5.36\) TeV
- **Readout** and **trigger upgrade** of ZDC
- Improved **trigger** strategies for low-\(p_T\) particles
- Significant improvements in low-\(p_T\) **electron reconstruction**
- Provide access to electrons with \(p_T > 1\) GeV

**Trigger**

![Diagram of triggered events]

**Reconstruction**

![Diagram of reconstructed electrons]
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
    ➤ Perhaps suggesting higher order Coulomb effects need to be considered [*JHEP* 2021 (2021) 83]
  ➤ **ZDC** provides constraints for **background** and **impact-parameter dependence**
    ➤ Establish a reference for non-UPC studies and rare processes (e.g. light-by-light)
➤ ATLAS established observation of exclusive **ditau** production in UPC Pb+Pb collisions at the LHC with above 5$\sigma$ significance
  ➤ Data is used to constrain $\alpha_z$ at the LHC with a precision comparable to the best limit from **DELPHI**
  ➤ $\gamma\gamma \rightarrow \mu^+\mu^-$ process is used to probe non-UPC collisions with high precision
    ➤ **Broadening** of acoplanarity and transverse momentum scale distributions with centrality confirmed
    ➤ Also significant **depletion** at close-to-zero $\alpha$ and $k_\perp$ values with centrality is established
    ➤ **Initial-state calculations** quantitatively describe many features
➤ **Run 3** is in progress, new 2023 Pb+Pb data set collected at $\sqrt{s_{NN}} = 5.36$ TeV is on tape
  ➤ **Significant improvements** in instrumentation, trigger and reconstruction efficiency at low-$p_T$ for leptons

➤ All results from ATLAS available at [https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HeavyIonsPublicResults](https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HeavyIonsPublicResults)
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