Measurements of Ultra-Peripheral Collisions with ATLAS

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Ultra-Peripheral Collisions

• At the LHC, ion beams are accompanied by large equivalent photon flux
  – Photons that can be emitted by entire nucleus are enhanced by $Z^2$
    \[ k_{\perp \gamma} \sim \frac{\hbar c}{2R_N} \sim 15 \text{ MeV}, \\ k_{z \gamma} = \gamma_{\text{boost}} \times k_{\perp \gamma} \sim 40 \text{ GeV} \]

• Reactions possible at large impact parameter
  – Event characteristics are qualitatively different than usual AA collisions

• Substantial rate for two photon reactions
  – Mostly exclusive processes
  – Opportunity to study light-by-light scattering

• Can study nPDFs with photo-nuclear jet production
  – Very clean probe of target, a la DIS
ATLAS Detector

Slide from M. Dyndal’s QM2017 talk
$\gamma\gamma \rightarrow \mu^+\mu^-$: Measurement

- Important baseline for other UPC measurements
  - Control over photon flux and its relationship to nuclear breakup modes

- Analysis: ATLAS-CONF-2016-025
  - Two opposite signed muons $p_T > 4$ GeV, $|\eta| < 2.4$ and $m_{\mu\mu} > 10$ GeV
  - Reconstructed vertex with zero additional tracks
  - 12069 total di-muon pairs

- Comparison to STARlight 1.1 (EPA+LO QED)

- Total cross section:
  - $\sigma_{\text{meas.}} = 32.2 \pm 0.3$ (stat.) $\pm 4.0$ (syst.) $\mu$b
  - $\sigma_{\text{starlight}} = 31.6 \mu$b
\( \gamma \gamma \rightarrow \mu^+\mu^- \): Cross Sections

- Both \( d\sigma/dM_{\mu\mu} \) and \( d\sigma/dY_{\mu\mu} \) in reasonably good agreement with prediction
\[ \gamma \gamma \rightarrow \mu^+ \mu^- : \text{Acoplanarity} \]

- Background or QED radiation?
  - Influences systematics
- Could use theoretical input for how much of broadening comes from radiation
\( \gamma \gamma \rightarrow \gamma \gamma \): Measurement

- Process is forbidden in classical electrodynamics but is a basic prediction of QED
- Has not been directly observed*
  - As particle-like scattering of two photons of well-defined momenta
- Process also sensitive to quartic gauge couplings and potentially new BSM particles
$\gamma \gamma \rightarrow \gamma \gamma$: Results

- **ATLAS paper:** [arxiv:1702.01625](https://arxiv.org/abs/1702.01625), $4.4 \sigma$ obs (3.8 SM)
- **Cross section:** $\sigma_{\text{meas.}} = 70 \pm 20$ (stat.)$\pm17$(syst.) nb
- $E_{T\gamma} > 3$ GeV, $|\eta_\gamma| < 2.37$
- $m_{\gamma\gamma} < 6$ GeV, $p_{T\gamma\gamma} < 2$ GeV, $Aco = 1-\Delta\phi/\pi < 0.01$

![Graphs showing signal selection with and without Aco requirement](image-url)
• Recent CTEQ analysis of nuclear PDFs with comparisons to other fits

• “Old” problem of the low-$x$ behavior
  - Large uncertainties
  - Not so much progress because little/no new data
Measurement Coverage

Figure adapted from EPPS16
1612.05741 [hep-ph]
Measurement Coverage

Figure adapted from EPPS16
1612.05741 [hep-ph]

ATLAS Preliminary
2015 Pb+Pb data, 0.38 nb⁻¹
\( \sqrt{s_{NN}} = 5.02 \text{ TeV}, 0nXn \)
anti-\( k_t, R = 0.4 \) jets
\( p_T^{\text{had}} > 20 \text{ GeV}, m_{\text{jets}} > 35 \text{ GeV} \)
\( 0.0001 < z_f < 0.05 \)

Not unfolded for detector response

ATLAS-CONF-2017-011
Event Topology: “Direct”

Photon participates directly in hard scattering

Nucleus intact
No neutrons

“0n”
Rapidity gap

No rapidity gap

Nucleus breaks up
Multiple neutrons

“Xn”
Event Topology: “Resolved”

Nucleus intact
No neutrons

“On”

Gap partially filled

No rapidity gap

Nucleus breaks up
Multiple neutrons

“Xn”

Depends on hadronic/partonic structure of photon

Rapidity
The Measurement: Event Selection

• Using 2015 Pb+Pb data; √s_{NN}=5.02 TeV
  – Events selected with ZDC (+jet) triggers, 0.38 nb⁻¹

• Use ZDC to select “0nXn” events (fiducial)
  – No correction for photon emitter breakup

• Physics backgrounds
  – Ordinary Pb+Pb jet production
    ▶ Remove with minimum gap requirement in γ direction: \( \Sigma_\gamma \Delta \eta > 2 \)
  – Central diffraction, \( \gamma \gamma \rightarrow e^+e^-, \tau^+\tau^-, q\bar{q} \)
    ▶ Not usually 0nXn
    ▶ Remove with maximum gap requirement in A direction: \( \Sigma_A \Delta \eta < 3 \)
  – Cross sections corrected for inefficiency introduced by gap requirements
Event topology: 0nXn

- Events selected ZDC "XOR" trigger
- Red: photon-going direction, 0n
- Black: nuclear direction, Xn
Event Topology: Gaps vs Multiplicity

- **Left:** $\Sigma_\gamma \Delta\eta$ vs $N_{\text{trk}}$ for $0nXn$
  - See clear difference between events with, w/o gaps
- **Right:** comparison of $N_{\text{trk}}$ distributions for events with ($\Sigma_\gamma \Delta\eta > 2$) and without ($\Sigma_\gamma \Delta\eta < 1$) gaps.
The Measurement: Jets and Kinematics

• Measure differential cross sections as vs of $H_T$, $x_A$ and $z_\gamma$:

$$m_{jets} \equiv \left( \sum E_i - \left| \sum \vec{p}_i \right| \right)^{1/2}$$

$$y_{jets} \equiv \pm \frac{1}{2} \ln \left| \frac{\sum E_i + \sum p_{z_i}}{\sum E_i - \sum p_{z_i}} \right|$$

$$H_T \equiv \sum p_{T_i}$$

$$x_A = \frac{m_{jets}}{\sqrt{s}} e^{-y_{jets}}$$

$$z_\gamma = \frac{m_{jets}}{\sqrt{s}} e^{+y_{jets}}$$

Sign of $z/\eta/y$ defined to be positive in $\gamma$ direction

- $p_T^{lead} > 20$ GeV
- $|\eta| < 4.4$
- $p_T^{sublead} > 15$ GeV
- $m_{jets} > 35$ GeV

• Event-level observables generalize to $n$ jet final states

• In $2 \rightarrow 2$ scattering limit:
  - $x_A \rightarrow x$ of struck parton in nucleus
  - $z_\gamma \rightarrow x_\gamma y_\gamma$
  - $H_T \rightarrow 2Q$

• No unfolding; measured cross sections compared to MC
  - Use symbol $\tilde{\sigma}$
• Pythia 6 can be used in “mu/gamma p” mode to simulate photo-nuclear processes
  – Contains mixture of direct and resolved processes
    ▶ Does not have right photon flux
• STARlight capable of providing nuclear photon flux
  – Needs to be integrated over target
  – For small $b$, additional hadronic interactions cause nuclei to break up
    ▶ No longer UPC events
    ▶ Cannot separate photo-nuclear processes from “normal” AA collisions
• Used modified STARlight to calculate weights applied on per-event basis to Pythia sample
Monte Carlo Re-weighting

- Re-weighted Pythia in good (not perfect) agreement with data

\[ \frac{1}{N_{\text{evt}}} \frac{dN}{dz} \gamma \]

**ATLAS** Preliminary

\( \sqrt{s_{\text{NN}}} = 5.02 \text{ TeV}, 0nXn \)

anti-\( k_t \), \( R = 0.4 \) jets

\( p_T^{\text{lead}} > 20 \text{ GeV}, m_{\text{jets}} > 35 \text{ GeV} \)

Data/MC ratio

Not unfolded for detector response
Data-MC Comparisons

\[ \frac{1}{N_{\text{evt}}} \frac{dN}{d\Sigma \Delta \eta} \]

\[ \frac{1}{N_{\text{evt}}} \frac{dN}{dy_{\text{jets}}} \]

**ATLAS Preliminary**

Pb+Pb 2015, 0.38 nb\(^{-1}\)

\[ \sqrt{s_{NN}} = 5.02 \text{ TeV}, \, 0nXn \]

anti-\(k_t\), \( R = 0.4 \text{ jets} \)

\( p_{T}^{\text{lead}} > 20 \text{ GeV}, \, m_{\text{jets}} > 35 \text{ GeV} \)

\begin{itemize}
  \item **Good description of gap quantity**
    \begin{itemize}
      \item Comfortable w/ MC-based corrections
    \end{itemize}
  \item **Positive rapidity in photon direction**
    \begin{itemize}
      \item See backward shift because \( z_\gamma < x_A \)
    \end{itemize}
\end{itemize}

Not unfolded for detector response
2-D Cross Sections

- Acceptance in \((z_\gamma, x_A)\) strongly dependent on minimum jet system mass
  - Determined by minimum \(p_T\) in analysis
  - Easiest way to get to low \(x_A\) is large \(z_\gamma\)
Corrections and Systematics

• Correct for inefficiency introduced by event selection requirements
  - ZDC inefficiency: can lose 0\text{n}1\text{n} contribution
    ▶ On average: $0.98 \pm 0.01$
  - “EM pileup”: extra neutrons from EM dissociation
    ▶ $5 \pm 0.5 \%$ on overall normalization
  - Signal events removed by gap requirement
    ▶ Evaluated in MC sample
    ▶ $\sim 1\%$ effect except at very large $z_{\gamma}$

• Luminosity: 6.1\% uncertainty

• Jet response: energy scale and resolution uncertainties
Results: $H_T$ Dependence

**Slices of $x_A$**

- Not in systematic bands: overall normalization systematic of 6.2%
- Not exactly same as $F_2(x,Q^2)$
  - Still has $\sim 1/Q^4$ and $z\gamma$ dependence in cross section
  - Don’t expect to see scaling explicitly

**ATLAS Preliminary**
- 2015 Pb+Pb data, 0.38 nb$^{-1}$
- $\sqrt{s}_{NN} = 5.02$ TeV, 0nXn

- $p_T^{lead} > 20$ GeV
- $m_{jets} > 35$ GeV

- $0.0023 < x_A < 0.0049$
- $0.0049 < x_A < 0.01 \times 10^{-2}$
- $0.01 < x_A < 0.022 \times 10^{-4}$
- $0.022 < x_A < 0.048 \times 10^{-6}$
- $0.048 < x_A < 0.1 \times 10^{-8}$
- $0.1 < x_A < 0.22 \times 10^{-10}$
- $0.22 < x_A < 0.47 \times 10^{-12}$

Not unfolded for detector response

Data

Pythia+STARlight scaled to data
Results: $z_\gamma$ Dependence

- Largest disagreement with model at large and small $z_\gamma$ where reweighting is most significant
- Can extend to lower $x_A$ by going to higher $z_\gamma$
Results: $x_A$ Dependence

**ATLAS Preliminary**
2015 Pb+Pb data, 0.38 nb$^{-1}$
$\sqrt{s_{NN}} = 5.02$ TeV

**anti-$k_T$, $R=0.4$ jets**

- $p_T^{\text{lead}} > 20$ GeV
- $m_{\text{jets}} > 35$ GeV

### Slices of $H_T$

**Data**

- $42 < H_T < 50$ GeV
- $50 < H_T < 59$ GeV (x $10^{-1}$)
- $59 < H_T < 70$ GeV (x $10^{-2}$)
- $70 < H_T < 84$ GeV (x $10^{-3}$)
- $84 < H_T < 100$ GeV (x $10^{-4}$)
- $100 < H_T < 119$ GeV (x $10^{-5}$)
- $119 < H_T < 141$ GeV (x $10^{-6}$)
- $141 < H_T < 168$ GeV (x $10^{-7}$)
- $168 < H_T < 200$ GeV (x $10^{-8}$)

**Pythia+STARlight**

Scaled to data

Not unfolded for detector response

### Slices of $z_\gamma$

**Data**

- $0.0002 < z_\gamma < 0.0003$
- $0.0003 < z_\gamma < 0.0006$ (x $10^{-2}$)
- $0.0006 < z_\gamma < 0.0012$ (x $10^{-4}$)
- $0.0012 < z_\gamma < 0.0022$ (x $10^{-6}$)
- $0.0022 < z_\gamma < 0.0042$ (x $10^{-8}$)
- $0.0042 < z_\gamma < 0.0077$ (x $10^{-10}$)
- $0.0077 < z_\gamma < 0.0144$ (x $10^{-12}$)
- $0.0144 < z_\gamma < 0.0269$ (x $10^{-14}$)

**Pythia+STARlight**

Scaled to data

Not unfolded for detector response

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ATLAS Preliminary
2015 Pb+Pb data, 0.38 nb$^{-1}$
$\sqrt{s_{NN}} = 5.02$ TeV, 0nXn

- $0.4$ jets
- $\gamma > 20$ GeV
- $T_p > 35$ GeV

**Results:**

- Not unfolded for detector response

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Preliminary
• Presented a measurement of photo-nuclear jet production
  – Qualitatively different than normal jet production in hadronic collisions
  – Expected features— rapidity gaps and neutron distributions— observed in the data

• Measurement needs to be unfolded
  – Lots of experience with this

• More rigorous comparisons to theory

• Input into new nPDF analyses
  – Domain of $x/Q^2$ not covered by previous data

• Connects to day 1 measurements at EIC
Questions/Remarks

• Given recent nPDF analyses, would this data actually be used in a fit?
  - e.g. recent EPPS16 analysis ignores potentially useful data like inclusive jet production

• Should we be presenting measurements of (e.g. unfolding) something closer to the structure function?

• Role of direct vs resolved photon contributions
  - Description of photon structure required for extraction of nPDF
  - How should this be handled in measurement?
Extras
Event topology: 0nXn

- Events selected ZDC "XOR" trigger
- Red: photon-going direction, 0n
- Black: nuclear direction, Xn
Event topology (experimental)

\[ \Sigma \Delta \eta = a + b + c \]

-\( y \) \hspace{1cm} +\( y \)

Traditional “edge gap”

\( \Sigma \Delta \eta \) in ZDC

\( \Delta \eta^{\text{edge}} \) in ZDC

N neutrons in ZDC\( _A \)

0 neutrons in ZDC\( _\gamma \)

Photon-going direction

\( \phi \)

\( \phi \)

\( \phi \)

\( \phi \)
Event topology (experimental)

- $\Sigma \Delta \eta = a + b + c$

- ZDC requirement: “0nXn” topology
- Minimum $\Sigma \gamma \Delta \eta$ requirement: $\Sigma \gamma \Delta \eta > 2$
- Maximum $\Sigma A \Delta \eta<$ requirement: $\Sigma A \Delta \eta < 3$
• **Left:** jet $p_T$ spectra

• **Right:** leading - sub-leading $\Delta \phi$ distributions for different numbers of jets
Event topology: gaps

- Left: compare $\Sigma \Delta \eta$ to forward edge gaps
  - See effect of resolved photons in split gaps
    $\Sigma \gamma \Delta \eta > \Delta \eta_{\text{edge}}$

- Right: $\Sigma \gamma \Delta \eta$ vs $\Sigma A \Delta \eta$
  - backgrounds (e.g. $\gamma \gamma \rightarrow e^+e^-$) for large $\Sigma \gamma \Delta \eta$
Data-driven corrections are performed to account for di

This measurement uses

where factor of 2 has been inserted to account for the symmetry of the Pb+Pb collision system. The cross section for

As discussed above, the experimentally accessible part of the photo-nuclear cross section only receives

The events used for this analysis were reconstructed using a configuration of the ATLAS software typically

5.1 Reconstruction

5 Analysis

The total cross section is obtained by multiplying by

As those applied in minimum-bias measurements

Apply per-event weight to Pythia sample

From STARlight

\[ w(E) \equiv \frac{dN_{\gamma}^{\text{eff}}}{dE} \bigg/ \frac{dN_{\gamma}^{\text{PYTHIA}}}{dE} \]

Flux used by Pythia
Jet system distributions

- Distributions of the primary ingredients to the kinematic variables used in cross-section
- Data-MC description very good for variables sensitive to transverse dynamics
Event topology (idealized)

**Direct**
- Nucleus intact
- No neutrons
- Rapidity gap
- No rapidity gap
- Nucleus breaks up
- Multiple neutrons

**Resolved**
- Nucleus intact
- No neutrons
- Gap partially filled
- No rapidity gap
- Nucleus breaks up
- Multiple neutrons

\[
\frac{y}{A} \quad \frac{x}{A} \quad \gamma
\]