Measurements of dijet production in ultra-peripheral Pb+Pb collisions with the ATLAS detector

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Nuclear parton distributions

• Recent CTEQ analysis of nuclear PDFs with comparisons to other fits

⇒ Large uncertainties, especially at low x

• New data needed to reduce uncertainties

– Theoretical proposal by Strikman et al in 2005:

⇒ measure dijet photoproduction in ultra-peripheral nuclear collisions

⇒ Until now, not realized by any experiment
Measurement Coverage

Figure adapted from EPPS16
1612.05741 [hep-ph]
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Photo-nuclear processes

- **Left: direct processes**
  - photon couples directly to nuclear parton
- **Right: resolved processes**
  - photon virtually resolved into “hadronic” state which subsequently scatters
- **For both, struck nucleus breaks up**
  - (nominally) photon-emitting nucleus does not
Zero degree calorimeters (ZDCs)

- ATLAS ZDCs measure beam-rapidity neutrons emitted in Pb+Pb collisions
  - hadronic collisions in nucleus produce $\geq 1$ neutron in target direction with probability $\approx 1$
  - photon-emitting nucleus nominally emits 0 neutrons

$\Rightarrow$ However, additional soft photon exchanges cause neutron emission $\sim 30\%$ of the time.
Triggers & Event selection

• The base trigger required:
  – $\geq 1$ neutron in one ZDC, zero neutrons in the other
  ⇒ exclusive OR
  – Minimum total transverse energy, $\Sigma E_T > 5$ GeV
  – Maximum total transverse energy, $\Sigma E_T < 200$ GeV

• Two additional triggers were used that required jets with $p_T > 25$ GeV (nominally).
  – Jet triggers sampled total luminosity of 0.38 nb$^{-1}$

• ZDC used to select 0nXn events (fiducial)
  ⇒ no correction for photon emitter breakup

• Additional gap requirements to suppress hadronic, diffractive, $\gamma\gamma\rightarrow q\bar{q}bar$ backgrounds
ZDC selection

Beware suppressed contribution @ $E_{\gamma}^{ZDC} = 0$

- Events selected with ZDC “XOR” trigger
  - Red: photon-going direction, 0n
  - Black: nuclear direction, Xn

$\sqrt{s_{NN}} = 5.02$ TeV, UPC trigger

\[ \frac{1}{N_{\text{evt}}} dN/d(E_{ZDC} / 2.51 \text{ TeV}) \]

- Some inefficiency in ZDC trigger rejection due to out-of-time pile-up (preceding collisions)
Gap analysis

- Require gap on photon side: \( \Sigma_\gamma \Delta \eta > 2 \)
- Reject large gaps on nuclear side: \( \Sigma_A \Delta \eta < 3 \)
Event Topology: Gaps vs Multiplicity

- **Left:** $\Sigma \gamma \Delta \eta$ vs $N_{\text{trk}}$ for 0nXn
- **Right:** $N_{\text{trk}}$ distributions for events with $(\Sigma \gamma \Delta \eta > 2)$ and without $(\Sigma \gamma \Delta \eta < 1)$ gaps.

$\Rightarrow$ clear difference between photo-nuclear and hadronic collision events
The measurement: jets and kinematics

- Jets reconstructed using anti-\( k_t \) algorithm w/ \( R = 0.4 \)
  - EM+JES calibration + flavor correction
- Measure differential cross-sections vs \( H_T, x_A, z_\gamma \)

\[
\begin{align*}
 m_{\text{jets}} & \equiv \left( \sum E_i - \left| \sum \vec{p}_i \right| \right)^{1/2} \\
 y_{\text{jets}} & \equiv \pm \frac{1}{2} \ln \left| \frac{\sum E_i + \sum p_{z_i}}{\sum E_i - \sum p_{z_i}} \right| \\
 H_T & \equiv \sum p_{T_i} \\
 x_A & = \frac{m_{\text{jets}}}{\sqrt{s}} e^{-y_{\text{jets}}} \\
 z_\gamma & = \frac{m_{\text{jets}}}{\sqrt{s}} e^{+y_{\text{jets}}} \\
 \end{align*}
\]

- \( p_z, z_\gamma, y \) defined to be positive in photon direction
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H_T \equiv \sum p_{T_i} \quad x_A \equiv \frac{m_{\text{jets}}}{\sqrt{s}} e^{-y_{\text{jets}}} \quad z_\gamma \equiv \frac{m_{\text{jets}}}{\sqrt{s}} e^{+y_{\text{jets}}}
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- For 2\(\rightarrow\)2 processes:
  - \(x_A \rightarrow x\) of struck parton in nucleus, \(z_\gamma \rightarrow x_\gamma y_\gamma\), \(H_T \rightarrow 2Q\)
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- For \(2 \rightarrow 2\) processes:
  - \(x_A \rightarrow x\) of struck parton in nucleus, \(z_\gamma \rightarrow x_\gamma y_\gamma, H_T \rightarrow 2Q\)
- Fiducial acceptance:
  \[ \Rightarrow p_{T,\text{lead}} > 20\ \text{GeV}, \ p_{T,\text{sub-lead}} > 15\ \text{GeV} \]
  \[ \Rightarrow |\eta_{\text{jet}}| < 4.4, \ H_T > 40\ \text{GeV} \]
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• No unfolding for jet response (in progress)
Jet kinematics

• **Left:**
  – Single jet $p_T$ for leading, sub-leading, all other jets

• **Right:**
  – Dijet $\Delta\phi$ distributions for 2, 3, >3 jet events
Photo-nuclear Monte Carlo

- Pythia 6 used in “mu/gamma + p” mode to simulate photo-production @ 5.02 TeV
  - Contains mixture of direct and resolved processes
  - But does not have appropriate photon flux
- “STARlight” model describes photon flux in ultra-peripheral nucleus-nucleus collisions
  - Used modified STARlight to calculate weights applied on per-event basis to Pythia sample:

\[
\frac{d\sigma_{UPC}}{dE} = 2 \int \int d^2b \ P_{UPC}(b) \int d^2s_B \ \frac{d^2N_{Pb}}{dE \ d^2s_A} \bigg|_{s_A = \vec{b} - \vec{s}_B} \\
T_{Pb(s_B)} \sigma_{\gamma N} \equiv \frac{dN_{eff}}{dE} \sigma_{\gamma N}
\]

\[
w(E) \equiv \frac{dN_{eff}}{dE} \bigg/ \frac{dN_{PYTHIA}}{dE}
\]
Monte Carlo re-weighting

**Data and MC** $\gamma$ distributions and ratio
– with and w/o re-weighting

**ATLAS** Preliminary
Pb+Pb 2015, 0.38 nb$^{-1}$
$\sqrt{s_{NN}} = 5.02$ TeV, 0nXn
anti-$k_t$, $R = 0.4$ jets
$p_T^{\text{lead}} > 20$ GeV, $m_{\text{jets}} > 35$ GeV

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

- **Data and MC** $z_\gamma$ distributions and ratio
  - with and w/o re-weighting
• Good agreement for $\Sigma_\gamma \Delta \eta$ after re-weighting
  ⇒ Can trust MC-based corrections for event selection efficiency

• Also good agreement for $y_{jets}$
  ⇒ See backward shift because $z_\gamma < x_A$
• 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 0n1n contribution
    \[ \Rightarrow \text{On average: } 0.98 \pm 0.01 \]
  - “EM pileup”: extra neutrons from EM dissociation
    \[ \Rightarrow 5 \pm 0.5\% \text{ on overall normalization} \]
  - Signal events removed by gap requirement
    \[ \Rightarrow \text{resulting inefficiency evaluated in MC sample} \]
    \[ \Rightarrow \sim 1\% \text{ correction except at very large } z_\gamma \]

- Luminosity: 6.1\% uncertainty

- Jet response:
  - Energy scale and resolution uncertainties
    \[ \Rightarrow \text{vary with } H_T, x_A, z_\gamma \]
Results: $H_T$ Dependence

**Differential cross-section in 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
Results: $z_\gamma$ dependence

Differential cross-section in slices of $H_T$

Largest disagreement with model at small $z_\gamma$
where re-weighted distribution most disagrees with data

Can extend to lower $x_A$ by going to higher $z_\gamma$
Results: $x_A$ Dependence

- Data agrees w/ MC over most of acceptance
  ⇒ But limitations in MC sample (e.g. no $\gamma+n$, no nPDF)
Summary, conclusions

• Presented a preliminary ATLAS measurement of photo-nuclear jet production:
  – Demonstration that original proposal by Strikman can be realized
    ⇒ access a kinematic range not otherwise covered
  – Expected features—rapidity gaps and neutron distributions—observed in the data
  – Good but not perfect MC-data agreement
    ⇒ Need MC with Pb+Pb EPA photon flux to avoid re-weighting which has conceptual difficulties
    ⇒ Which we now have (Pythia8 — big advance)
  – Now working on unfolding and controlling the resolved photon contribution.
    ⇒ 3-d unfolding in HT, $x_A$, $z_Y$ is challenging
Jet kinematics

- **Left:**
  - single jet $p_T$ for leading, sub-leading, all other jets

- **Right:**
  - dijet $\Delta \phi$ distributions for 2, 3, >3 jet events
Direct processes

Nucleus intact
No neutrons
“0n”

Rapidity gap

No rapidity gap

Nucleus breaks up
Multiple neutrons
“Xn”
Resolved processes

Nucleus intact
No neutrons

Gap partially filled

No rapidity gap

Nucleus breaks up
Multiple neutrons

"Xn"

Rapidity

"0n"
• Provides valuable estimate/constraint on potential $\gamma \gamma \rightarrow q\bar{q}q\bar{q}$ backgrounds
  – $q\bar{q}$ rate @ given, $M$, $y$ ~ dimuon
  ⇒ After gap cuts, negligible background