Measurements of multi-jet production in ultra-peripheral lead-lead 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 photo-production in ultra-peripheral nuclear collisions
    ⇒ Until recently, not realized by any experiment
Photo-nuclear processes

- **Two processes:**
  - Left: “direct” - photon enters hard scattering
  - Right: “resolved” - photon virtually splits into partons/hadron, which scatters

- Use Zero Degree Calorimeters (ZDCs) to select Pb+Pb 0nXn events
- +gap requirements to select photo-production
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.

⇒ 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 &\equiv \frac{m_{\text{jets}}}{\sqrt{s}} e^{-y_{\text{jets}}} \\
  z_\gamma &\equiv \frac{m_{\text{jets}}}{\sqrt{s}} e^{+y_{\text{jets}}}
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- \(p_z\), \(z_\gamma\), \(y\) defined to be positive in photon direction
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H_T \equiv \sum p_{T_i}
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– \(p_z, z_\gamma, y\) defined to be positive in photon direction

• 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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- Fiducial acceptance:
  - $p_T^{\text{lead}} > 20$ GeV, $p_T^{\text{sub-lead}} > 15$ GeV
  - $|\eta_{\text{jet}}| < 4.4$, $H_T > 40$ GeV
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  \[\Rightarrow p_{T_{\text{lead}}} > 20 \text{ GeV}, p_{T_{\text{sub-lead}}} > 15 \text{ GeV}\]
  \[\Rightarrow |\eta_{\text{jet}}| < 4.4, H_T > 40 \text{ GeV}\]

• No unfolding for jet response
Monte Carlo

Pythia 6 photo-production (gamma/mu+p)
  - re-weighted to match STARlight photon spectrum
  ⇒ Re-weighted MC agrees well (not perfectly) with data for all topology, kinematic distributions
  ⇒ Although ∃ conceptual issues w/ re-weighting
Acceptance in \((z_{\gamma}, x_A)\) strongly dependent on minimum jet system mass

- Determined by minimum \(p_T\) in analysis

\(\Rightarrow\) Easiest way to get to low \(x_A\) is large \(z_{\gamma}\)
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

**ATLAS Preliminary**

2015 Pb+Pb data, 0.38 nb$^{-1}$

$\sqrt{s_{NN}} = 5.02$ TeV, 0nXn

anti-$k_t$, $R=0.4$ jets

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

$H_T$ [GeV]
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

$\Rightarrow$ But limitations in MC sample (e.g. no $\gamma+n$, no nPDF)
• Presented a measurement of photo-nuclear jet production: ATLAS-CONF-2017-011
  – Qualitatively different than normal jet production in hadronic collisions
  – 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
• Proof of principle that photo-nuclear dijet/multi-jet measurements possible in Pb+Pb collisions
  – Can access $x_A$, $Q^2$ ($H_T$) range not covered by existing fixed-target data.
    ⇒ kinematic coverage primarily constrained by minimum jet $p_T$, but also $\Sigma\gamma\Delta\eta > 2$ requirement
Measurement Coverage

1612.05741 [hep-ph]

Figure adapted from EPPS16

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
\( p_T^{\text{lead}} > 20 \text{ GeV, } m_{\text{jets}} > 35 \text{ GeV} \)
\( 0.0001 < z_j < 0.05 \)

Not unfolded for detector response

\[ \frac{d^2\tilde{\sigma}}{dH_T \, dx_A} \, [ \mu \text{b GeV}^{-1}] \]

ATLAS-CONF-2017-011
Backup
Corrections and systematics

• Correct for inefficiency introduced by event selection requirements
  – ZDC inefficiency: can lose 0n1n contribution
    ⇒ On average: 0.98 ± 0.01
  – “EM pileup”: extra neutrons from EM dissociation
    ⇒ 5 ± 0.5% on overall normalization
  – Signal events removed by gap requirement
    ⇒ resulting inefficiency evaluated in MC sample
    ⇒ ~1% correction except at very large $z_\gamma$

• Luminosity: 6.1% uncertainty

• Jet response:
  – energy scale and resolution uncertainties
    ⇒ vary with $H_T$, $x_A$, $z_\gamma$
• Provides valuable estimate/constraint on potential $\gamma\gamma \rightarrow qq\bar{q}b$ backgrounds

– $qq\bar{q}b$ rate @ given, $M, y \sim$ dimuon

$\Rightarrow$ After gap cuts, negligible background
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
Triggers & Event selection

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

• Two additional triggers were used that required jets with \( p_T > 25 \text{ GeV} \) (nominally).
  – Jet triggers sampled total luminosity of 0.38 \( \text{nb}^{-1} \)
    ⇒ Note: Pb+Pb hadronic cross-section is 7.7 \( \text{b} \).

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

• Additional gap requirements to suppress hadronic, diffractive, \( \gamma\gamma \rightarrow q\bar{q} \text{bar} \) backgrounds
Ultra-peripheral Pb+Pb collisions

- Ultra-relativistic nuclei source strong EM fields
- Photons coherently emitted by entire nucleus are enhanced by Z2
  \[ k_\gamma \perp \sim \frac{\hbar c}{2RA} \sim 15 \text{ MeV}, \]
  \[ k_\gamma z = \gamma \text{boost} \times k_\gamma \perp \sim 40 \text{ GeV} \]
  \[ \Rightarrow \text{In AA collisions, energetic enough to stimulate hard scattering processes at low x in the target} \]
  \[ \Rightarrow \text{Cross-section enhanced by Z2A} \sim 1.5 \times 10^6 \]
  compared to pp collisions at the same \( \sqrt{s} \)

- This measurement:
  \[ \text{Photoproduction of di/multi-jets using 0.38 nb}^{-1} \text{ of} \]
  \[ \sqrt{s_{NN}} = 5.02 \text{ TeV Pb+Pb data from 2015}. \]
Zero degree calorimeters (ZDCs)

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

⇒ However, additional soft photon exchanges cause neutron emission ~ 30% of the time.
ZDC selection

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

• ZDC used to select 0nXn events (fiducial)
  ⇒ Observe some inefficiency in ZDC trigger rejection due to out-of-time pile-up

• + gap requirements to reject hadronic, photodiffractive, $\gamma\gamma \rightarrow qq\bar{q}$ backgrounds
Measurement Coverage

Figure adapted from EPPS16
1612.05741 [hep-ph]
Gap Distributions

• Left: comparison of traditional (edge) gap and photon-side sum ($\Sigma\gamma \Delta\eta$) gaps
  ⇒ off-diagonal events are mostly resolved photons

• Right: distribution of nucleus ($\Sigma_A \Delta\eta$) vs photon ($\Sigma\gamma \Delta\eta$) gap sums
Gap Distributions

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  - with selection cuts indicated.
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
    ⇒ Does not have right 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:
Data-MC comparisons

- Good agreement for $\Sigma \gamma$ $\Delta \eta$ after re-weighting
  $\Rightarrow$ Can trust MC-based corrections for event selection efficiency

- Also good agreement for $y_{jets}$
  $\Rightarrow$ See backward shift because $z_{\gamma} < x_{A}$