Measurements of photo-nuclear jet production in Pb+Pb collisions with ATLAS

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Parallel Session 1.1: Initial State Physics and Approach to Equilibrium
Nuclear Parton Distributions

- 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
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 $Z^2$
    ▶ $k_{\perp} \gamma \sim \frac{\hbar c}{2R_N} \sim 15 \text{ MeV}, k_z \gamma = \gamma_{\text{boost}} \times k_{\perp} \gamma \sim 40 \text{ GeV}$
  – In AA collisions, energetic enough to stimulate hard scattering processes at low $x$ in the target
    ▶ Enhanced by $Z^2A \sim 10^6$ compared to $pp$

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

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

Figure adapted from EPPS16
1612.05741 [hep-ph]
Preliminary ATLAS -1 2015 Pb+Pb data, 0.38 nb⁻¹  
\( \sqrt{s_{\text{NN}}} = 5.02 \text{ TeV}, 0nXn \)

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

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

\( 0.0001 < z < 0.05 \)

Not unfolded for detector response

Figure adapted from EPPS16
1612.05741 [hep-ph]
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

Gap partially filled

Nucleus breaks up
Multiple neutrons
“Xn”

Rapidity

Depending on hadronic/partonic structure of photon

“0n”
The Measurement: Event Selection

- Using 2015 Pb+Pb data; $\sqrt{s_{NN}}=5.02$ 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 $\gamma$ 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: 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 $z_\gamma$:

$$m_{jets} = \left( \sum E_i - \left| \sum \vec{p}_i \right| \right)^{1/2} \quad \quad y_{jets} = \pm \frac{1}{2} \ln \left| \frac{\sum E_i + \sum p_{z_i}}{\sum E_i - \sum p_{z_i}} \right|$$

$$H_T = \sum p_{T_i} \quad \quad x_A = \frac{m_{jets}}{\sqrt{s}} e^{-y_{jets}} \quad \quad z_\gamma = \frac{m_{jets}}{\sqrt{s}} e^{+y_{jets}}$$

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

- $p_T$ lead > 20 GeV
- $p_T$ sublead > 15 GeV
- $|\eta| < 4.4$
- $m_{jets} > 35$ 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 $\tilde{\sigma}$
Theoretical Model (I)

• 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 hadron 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

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

Data/MC ratio

Not unfolded for detector response

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
Data-MC Comparisons

- Good description of gap quantity
  - Comfortable w/ MC-based corrections

- Positive rapidity in photon direction
  - 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
    ▷ 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

- 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

- 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

\[
\frac{d^2\sigma}{dH_T \, dx_A} \quad [\mu b / GeV]
\]

- Data
- Pythia+STARlight scaled to data
- Not unfolded for detector response

\[
\frac{d^2\sigma}{dz_\gamma \, dx_A} \quad [\mu b]
\]

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

- anti-$k_T$, $R=0.4$ jets
- $p_{T}^{\text{lead}} > 20$ GeV
- $m_{\text{jets}} > 35$ GeV

\[
0.0002 < z_\gamma < 0.0003
\]
\[
0.0003 < z_\gamma < 0.0006 \times 10^{-3}
\]
\[
0.0006 < z_\gamma < 0.0012 \times 10^{-3}
\]
\[
0.0012 < z_\gamma < 0.0022 \times 10^{-3}
\]
\[
0.0022 < z_\gamma < 0.0042 \times 10^{-3}
\]
\[
0.0042 < z_\gamma < 0.0077 \times 10^{-3}
\]
\[
0.0077 < z_\gamma < 0.0144 \times 10^{-3}
\]
\[
0.0144 < z_\gamma < 0.0269 \times 10^{-3}
\]

\[
0.0002 < x_A < 0.0003
\]
\[
0.0003 < x_A < 0.0006
\]
\[
0.0006 < x_A < 0.0012
\]
\[
0.0012 < x_A < 0.0022
\]
\[
0.0022 < x_A < 0.0042
\]
\[
0.0042 < x_A < 0.0077
\]
\[
0.0077 < x_A < 0.0144
\]
\[
0.0144 < x_A < 0.0269
\]

Slices of $H_T$
Slices of $z_\gamma$
Summary and Conclusions

• 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

• 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
Extras
Event topology: 0nXn

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

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

- \( \eta \) neutrons in ZDC\(_A\)
- \( \phi \) neutrons in ZDC\(_\gamma\)

Traditional "edge gap"

Photon-going direction

\( N\) neutrons in ZDC\(_A\)

0 neutrons in ZDC\(_\gamma\)
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: \( \Sigma_A \Delta \eta < 3 \)
Jet kinematic distributions

- **Left**: jet $p_T$ spectra
- **Right**: leading - sub-leading $\Delta \phi$ distributions for different numbers of jets
Event topology: gaps

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

- Right: $\Sigma \gamma \Delta \eta$ vs $\Sigma A \Delta \eta$
  $\Rightarrow$ backgrounds (e.g. $\gamma \gamma \to e^+e^-$) for large $\Sigma \gamma \Delta \eta$
The total cross section is obtained by multiplying by $d\sigma_{\text{Pb+Pb}}^{\text{UPC}} / dE = 2 \int d^2 b P_{\text{UPC}}(b) \int d^2 s_B \frac{d^2 N_{\gamma}^{\text{Pb}}}{dE d^2 s_A} \bigg|_{s_A = \vec{b} - \vec{s}_B}$.

From STARlight

$w(E) \equiv \frac{dN_{\gamma}^{\text{eff}}}{dE} / \frac{dN_{\gamma}}{dE}$

Apply per-event weight to Pythia sample

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

Resolved

Rapidity

Nucleus intact
No neutrons

Nucleus intact
No neutrons

Nucleus breaks up
Multiple neutrons

Gap partially filled

Nucleus breaks up
Multiple neutrons

Rapidity gap

No rapidity gap

No rapidity gap

$y_\gamma$

$X_A$

$y_\gamma$

$X_A$

$X_\gamma$