Measurements of long-range correlations in photonuclear collisions with ATLAS

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Which small systems do we know flow?

*pp*

Near-side ridge
Which small systems do we know flow?

- **pp**
- **e+p**
- **e^+e^-**
- **γ+p**

**Near-side ridge**

- Cumulants say $v_2 < 5%$
  - arXiv:1912.07431
- No near-side ridge
  - arXiv:1906.00489
  - CMS-PAS-HIN-18-008
Which small systems do we know flow?

- **pp**
- **e+p**
- **e^+e^-**
- **γ+p**
- **γ+A**

Near-side ridge

- Cumulants say $\nu_2 < 5\%$
  - arXiv:1912.07431
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When $b > 2R_A$ two categories of interactions

- Pure EM processes
  - $\gamma\gamma \rightarrow \mu\mu$ [arXiv:2011.12211](https://arxiv.org/abs/2011.12211)
- Photonuclear interactions
  - $\gamma + A \rightarrow A^* + V$
  - $\gamma + A \rightarrow X$

Coulomb fields of moving charges can be treated as an equivalent flux of photons which are boosted to high energies.

Photons reach energies of 10s of GeV with 5.02 TeV Pb+Pb at the LHC.
Photonuclear interactions

Direct $\gamma A$ collisions
Photon couples directly to nuclear parton

\[ Pb \rightarrow Pb \]
Photonuclear interactions

Direct $\gamma A$ collisions
Photon couples directly to nuclear parton

Diagram:
- Photon interacts with nuclear parton
- Rapidity gap indicated
- No rapidity gap indicated
- Pb and Xn shown in diagram
Photonuclear interactions

Direct $\gamma A$ collisions
Photon couples directly to nuclear parton

Resolved $\gamma A$ collisions
Photon virtually resolved into hadronic state

Vector meson

Pb Xn

Pb 0n

Rapidity gap

Rapidity

+y

-y
Photonuclear interactions

Direct $\gamma A$ collisions
Photon couples directly to nuclear parton

Resolved $\gamma A$ collisions
Photon virtually resolved into hadronic state

Select events based on primarily
- Single-sided nuclear breakup “$0^\text{on}Xn$” (zero-degree calorimeter ZDC)
- Rapidity gaps

Minimum bias selection includes both but is dominated by resolved events.
“High”-multiplicity photonuclear collisions

\[ \text{Pb} + \text{Pb}, 5.02 \text{ TeV} \]

Run: 365681
Event: 1064766274
2018-11-11 22:00:07 CEST

\[ \Delta E_{\text{cal}} = 71 \text{ GeV (left)}, 0.9 \text{ GeV (right)} \]
71 tracks, \( p_T > 0.4 \text{ GeV} \)
“High”-multiplicity photonuclear collisions

Pb+Pb, 5.02 TeV
Run: 365681
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Pb going direction
Xn

Pb going direction

Rapidity gap
Sparse particle production

$$\Delta E^{\text{cal}} = 71 \text{ GeV (left)}, 0.9 \text{ GeV (right)}$$
71 tracks, $$p_T > 0.4 \text{ GeV}$$
Photonuclear rapidity gaps $\Sigma \Delta \eta$ and $N_{ch}$

**ATLAS Preliminary**

Pb+Pb 2018, 1.73 nb$^{-1}$
$\sqrt{s_{NN}} = 5.02$ TeV, 0nXn
MB trigger

Sum of rapidity gaps between particles greater than 0.5

$\Sigma_{\gamma\Delta\eta_{gap}}$
Photonuclear events have large rapidity gaps in the photon-going direction and a steeply falling multiplicity distribution.

Photonuclear rapidity gaps $\Sigma \gamma \Delta \eta$ and $N_{ch}$

**ATLAS** Preliminary
Pb+Pb 2018, 1.73 nb$^{-1}$
$\sqrt{s_{NN}} = 5.02$ TeV, 0nXn
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**ATLAS** Preliminary
Pb+Pb 2018, 1.73 nb$^{-1}$
$\sqrt{s_{NN}} = 5.02$ TeV, 0nXn

$|\eta|<2.5, p_T>400$ MeV
Photonuclear event properties

Several data-MC comparisons included in our new results!

\[ N_{ch} \quad \text{d}N_{ch}/\text{d}\eta \quad \Sigma_{\gamma} \Delta\eta \]
Photonuclear event properties

Several data-MC comparisons included in our new results!

Photonuclear > 97% purity across $N_{\text{ch}}$ range of analysis

CERN-EP-2020-246
ATLAS template fit to γA correlation

High-multiplicity (HM) correlation data

Low multiplicity (LM) template for jet/nonflow correlation

\[ Y^{HM}(\Delta\phi) = F Y^{LM}(\Delta\phi) + G \left\{ 1 + 2 \sum_{n=2}^{3} v_{n,n} \cos(n\Delta\phi) \right\} \]

HM – (scaled LM) removes nonflow

Clear \( \cos(2\Delta\phi) \) modulation

Same technique used in \( pp \) and \( p+Pb \) flow measurements
$\nu_n$ in photonuclear collisions

Significant nonzero $\nu_2$ and $\nu_3$ in photonuclear collisions

Flat $\nu_2(N_{ch})$ within statistical precision
**ν_n in photonuclear collisions**

Significant nonzero ν₂ and ν₃ in photonuclear collisions

Flat ν₂(N_ch) within statistical precision

Changing pp to 0.4 < p_T < 2.0 is predicted to lower pp ν₂ by ~10% which does not lead to agreement between pp and γA

Consistent ν₃ between γA and pp given large uncertainties on both
Similar trend in $v_2(p_T)$ as other hadronic systems.

Similar low-$p_T$ behavior as $pp$ and $p+Pb$ but systematically lower.

High-$p_T$ $v_2$ is falling to large negative values (see backup) which is from the over-subtraction of nonflow.

This effect is present in $pp$ but is larger and sets in at lower $p_T$ in $\gamma A$ (ATLAS-CONF-2020-018)
\( v_2(p_T) \) comparison with CGC calc.

Compared to Color Glass Condensate (CGC) framework calculation of \( v_2(p_T) \) with \( Q_s^2 = 5 \text{ GeV}^2 \) and \( B_p^2 = 25 \text{ GeV}^{-2} \)

Model is consistent with data at low-\( p_T \)

Theory uncertainty from hadron fragmentation

Color Glass Condensate model calculation containing **initial-state correlations** which gives rise to nonzero $v_2$

- Larger number of domains struck $\rightarrow$ lower $v_2$
- Quasi-real photon is predicted to have large $B_P$
Color Glass Condensate model calculation containing initial-state correlations which gives rise to nonzero $v_2$

\[ v^2 \]

Similar calculations describing $p+Pb$ (arXiv:1808.09851)

Difference in $v_2$ is a result of a smaller $B_p^2$ for a proton where $B_p^2 \sim 1/\Lambda_{QCD}$

Correlated color domain size is $\sim 1/Q_s$
Conclusions

Photonuclear $\nu_n$ has a similar order of magnitude and trends as other previously measured hadronic systems

Intuitive property of hadronic-like photonuclear collisions (photon $\rightarrow$ vector meson).

Difference with $pp$ might be a consequence of (and further studied by) CM energy, CM-frame rapidity acceptance, and decorrelations effects.

Compared to CGC model and are interested in models which include final-state effects.

This observation is guiding new theoretical calculations which are relevant for future Electron-Ion Collider data.
Thank you
**Gap definition**  
(detector roll-out)

**Event Selection:**

\[ \Sigma_A \Delta \eta_{gap} < 3 \]

\[ \Sigma_\gamma \Delta \eta_{gap} > 2.5 \]
• DPMJET-III predicts the photon energy changes by about 1-2 standard deviations over the multiplicity range of the measurement and a doubling of the mean $W_{\gamma N}$ for 10 to 60 $N_{\text{ch}}^{\text{rec}}$.

• Large difference between measured $v_{n,n}$ before and after template nonflow subtraction for data and DPMJET-III.

• Small negative $v_{2,2}$ after template fit
More jet-like away side in DPMJET-III than in data. This produces the larger unsubtracted $v_{2,2}$ seen on the previous slide. Small remaining modulation after nonflow subtraction seen in the lower panel. DPMJET-III is of limited use in modeling the soft correlations in photonuclear events.
\( \frac{dN_{\text{ch}}}{d\eta} \) in \( \gamma A \) collisions

- \( \frac{dN_{\text{ch}}}{d\eta} \) of events passing the photonuclear event selection.

- Very similar shape \( \frac{dN_{\text{ch}}}{d\eta} \) for events with \( N_{\text{ch\ rec}} \geq 10 \).

ATLAS Preliminary

Pb+Pb 2018, 1.73 nb\(^{-1}\)
\( \sqrt{s_{NN}} = 5.02 \) TeV, 0nXn
\( \Sigma \eta > 2.5, \Sigma A\eta < 3 \)
ATLAS template fitting method
Factorization $v_2(N_{\text{ch}})$

$v_2(N_{\text{ch}})$ shows insensitivity to associated particle $p_T$ range. This is consistent with a hydrodynamic paradigm where particle anisotropies are generated from a single-particle flow vector for all $p_T$. 

$$v_n(p_T^a) = v_{n,n}(p_T^a, p_T^b)/v_n(p_T^b) = v_{n,n}(p_T^a, p_T^b)/\sqrt{v_{n,n}(p_T^b, p_T^b)}$$
Photonuclear event properties

Left: $N_{\text{ch}}^{\text{rec}}$ distribution in data, corrected for trigger and reconstruction efficiency and normalized per event (black points), compared with that in DPMJET-III $\gamma$+Pb (dot-dashed green histogram), DPMJET-III $\gamma$+p (dotted red histogram), and PYTHIA $\gamma$+p (dashed blue histogram). The bottom panel shows the ratios of the MC distributions to the data distributions. Right: $\Sigma_\Delta\eta$ distribution in data for $N_{\text{ch}}^{\text{rec}} \geq 10$ (black points), normalized per event, and compared with that in DPMJET-III $\gamma$+Pb (dot-dashed green histogram), PYTHIA $\gamma$+p (dashed blue histogram), peripheral Hijing Pb+Pb (solid magenta histogram), and DPMJET-III $\gamma$+p (dotted red histogram).

Charged-particle pseudorapidity distribution, $dN_{\text{ch}}/d\eta$, in selected $N_{\text{ch}}^{\text{rec}}$ ranges. The distributions are normalized to the same integral and are shown in arbitrary units. Here, positive and negative $\eta$ denote the photon-going and nucleus-going directions, respectively. Right: $dN_{\text{ch}}/d\eta$ distribution in data for $N_{\text{ch}}^{\text{rec}} > 10$ (black points), normalized per event, and compared with that in DPMJET-III $\gamma$+Pb (dot-dashed green histogram), PYTHIA $\gamma$+p (dashed blue histogram), peripheral Hijing Pb+Pb (solid magenta histogram), and DPMJET-III $\gamma$+p (dotted red histogram) with the same reconstruction-level selection as the data. All distributions have been normalized to have the same value as DPMJET-III $\gamma$+Pb at $\eta = 0$. 
Triggering on photonuclear events

• Due to trigger strategy, the high-statistics portion of the $N_{\text{ch}}$ range is for $N_{\text{ch}} > 15$

Triggering included

• Level-1 requirements on
  • Minimum event activity to collect high-multiplicity $\gamma A$ events
  • Maximum event activity to reject Pb+Pb collisions
  • Single-sided nuclear breakup (zero-degree calorimeter).

• High-level trigger requirements on
  • Minimum number of tracks to collect high-multiplicity events
  • Maximum energy in photon-going FCAL ($3.2 < \eta < 4.9$)