Collectivity signals in ultra-small collision systems at RHIC and the LHC

Blair Daniel Seidlitz
University of Colorado Boulder
Azimuthal anisotropy

Clear collectivity signatures in many system sizes
• Nearside ridge present in 2-particle correlation
• Precise measurements of \( v_n \)
• Multi-particle correlations \( \rightarrow \) global correlation

Which small systems do we know flow?

Collectivity in $pp$
- Near-side ridge
- Multi-particle correlation
- Initial state geometry?

$\text{arXiv:1606.06198}$
Which small systems do we know flow?

- **pp**
  - Near-side ridge

- **e+p**
  - Cumulants say $v_2 < 4$
    - $e^+p$
    - $u, d, s$
    - $27.6$ GeV

- **e^+e^-**
  - No near-side ridge

- **γ+p**
  - No near-side ridge

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arXiv:1912.07431  
arXiv:1906.00489  
CMS-PAS-HIN-18-008
Which small systems do we know flow?

- **pp**
  - Near-side ridge
  - Cumulants say $\nu_2 < 5\%$

- **e+p**
  - No near-side ridge

- **e$^+$+e$^-$**
  - No near-side ridge

- **$\gamma$+p**
  - No near-side ridge

- **$\gamma$+A**
  - ?
Lorentz contracted electromagnetic fields of moving charges can be treated as a flux of photons.

Equivalent photon approximation (EPA)
- EM field are a flux of quasi-real photons
- Developed by Fermi, Weizäcker, and Williams
- Implemented in STARLIGHT
- Differences with QED calculations

\[ E\gamma_{\text{proj. frame}} = \frac{1}{2 \times (1.2 A^{1/3} \text{ fm})} \]
\[ E\gamma_{\text{lab frame}} = \gamma/(1.2 A^{1/3} \text{ fm}) \]
\[ W_{\gamma N} = \sqrt{(4E\gamma E_N)} \]

<table>
<thead>
<tr>
<th></th>
<th>(E\gamma_{\text{proj. frame}})</th>
<th>(E\gamma_{\text{lab frame}})</th>
<th>(W_{\gamma N})</th>
</tr>
</thead>
<tbody>
<tr>
<td>LHC</td>
<td>30 MeV</td>
<td>160 GeV</td>
<td>1.7 TeV</td>
</tr>
<tr>
<td>RHIC</td>
<td>30 MeV</td>
<td>6 GeV</td>
<td>50 GeV</td>
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</tbody>
</table>

Brandenburg, GHP 2021 - good up-to-date review as well: arXiv:2103.16623
Ultra-peripheral collisions at the LHC

Steinberg, Initial Stages 2019


Pure EM interactions
- For example, $\gamma\gamma \rightarrow l^+l^-$
- Precision tests of EPA and QED calculations of photon flux
- Active area of research
  - $b$ dependence of photon $p_T$
  - Photon polarization

arXiv:2103.16623

Vector meson quantum fluctuation

$$\Delta t \approx \frac{\hbar}{M_V c^2}$$

collision time

$$\Delta t \approx b/(\gamma v)$$

Photo-nucleus interactions
- Bare photon + vector meson wave function
- QCD diffractive vector meson production $\gamma + A \rightarrow A^* + V$
- Non-diffractive $\gamma + A \rightarrow X$
Photonuclear interactions

Direct γA collisions
Photon couples directly to nuclear parton

[Diagram showing direct γA collisions with arrows indicating the collision process]
Photonuclear interactions

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

Diagram:
- $Pb$ to $0n$
- $Pb$ to $Xn$
- Rapidity gap
- No rapidity gap

Rapidity scale:
- $+y$
- $-y$
Photonuclear interactions

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

\[ \text{Pb} \to \text{Xn} \]

Rapidity gap

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

\[ \text{Pb} \to \text{vector meson} \]

Rapidity gap

\[ +y \quad -y \]
Photonuclear interactions

Direct γA collisions
Photon couples directly to nuclear parton

Resolved γA collisions
Photon virtually resolved into hadronic state

Select events based on primarily
- Single-sided nuclear breakup “0nXn” (zero-degree calorimeter ZDC)
- Rapidity gaps

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

Pb+Pb, 5.02 TeV
Run: 365681
Event: 1064766274
2018-11-11 22:00:07 CEST

\[ \Delta E_{\text{cal}} = 71 \text{ GeV (left), 0.9 GeV (right)} \]

71 tracks, \( p_T > 0.4 \text{ GeV} \)
“High”-multiplicity photonuclear collisions

\[ \text{Pb} \rightarrow \text{Pb}, \ 5.02 \ \text{TeV} \]
\[ \text{Run:} \ 365681 \]
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\[ \Delta E_{\text{Cal}} = 71 \ \text{GeV (left)}, \ 0.9 \ \text{GeV (right)} \]
\[ 71 \ \text{tracks, } p_T > 0.4 \ \text{GeV} \]
Photonuclear rapidity gaps $\Sigma \gamma \Delta \eta$ and $N_{ch}$

Sum of rapidity gaps between particles greater than 0.5

$\Sigma \gamma \Delta \eta_{\text{gap}}$
Photonuclear events have large rapidity gaps in the photon-going direction and a steeply falling multiplicity distribution.
Rapidity gap comparison to MC

- DPMJET-III $\gamma+A$
  - Photon flux generated by STARLIGHT
  - DPMJET simulates $\gamma A$ collision
- DPMJET-III $\gamma+\rho$
  - Utilizes a Pb+Pb photon flux from STARLIGHT
  - Serves as a comparison to PYTHIA8
- PYTHIA8 $\gamma+\rho$
  - Reweighted to STARLIGHT flux
- HIJING Pb+Pb background MC

MC normalized to data in control regions

Qualitative agreement with MCs, PYTHIA being the most compatible

Indicates high purity $\gamma+A$ sample for $\Sigma_\gamma \Delta\eta > 2.5$

arXiv:2101.10771
Rough $N_{\text{ch}}$ comparison $\gamma+A/p$

- Future minimum-bias measurements would add fundamental understanding.
- Such measurements would also add to interesting hadron physics in color fluctuations and more.

Very rough $N_{\text{ch}}$ comparison: different proton energy, acceptance and selection

arXiv:2101.10771
$dN_{\text{ch}}/d\eta$ in $\gamma A$ collisions

$\frac{dN_{\text{ch}}}{d\eta}$ of photonuclear events - very similar shape with $N_{\text{ch}} \geq 10$

MC comparison show 200 GeV to 1 TeV CM energy ($W_{\gamma N}$)

$W_{\gamma N}(N_{\text{ch}})$ trend comports with $N_{\text{ch}}$ trend in data $dN_{\text{ch}}/d\eta$

arXiv:2101.10771
2-particle correlation of charged tracks

No clear nearside ridge

Away-side correlation
Momentum conservation
Jets
Termed “nonflow”
Not collective phenomenon

Need to remove nonflow

arXiv:2101.10771
Non-flow removal in γA correlations

- High-multiplicity (HM) correlation data
- Low multiplicity (LM) template for jet/non-flow correlation
Non-flow removal in γA correlations

High-multiplicity (HM) correlation data

Low multiplicity (LM) template for jet/non-flow correlation

Nonflow subtraction
- HM fit with LM data and flow coef.
- HM and LM assumed to have same flow shape
- Different LM selection leads to similar results

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

After nonflow subtraction clear \( \cos(2\Delta \phi) \) modulation
$\nu_n$ in photonuclear collisions

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

Flat $\nu_2(N_{\text{ch}})$ within statistical precision

arXiv:2101.10771
**$v_n$ in photonuclear collisions**

Significant nonzero $v_2$ and $v_3$ in photonuclear collisions

Flat $v_2(N_{ch})$ within statistical precision

Changing $pp$ to $0.4 < p_T < 2.0$ is predicted to lower $pp$ $v_2$ by ~10% which does not lead to agreement between $pp$ and $\gamma A$

Consistent $v_3$ between $\gamma A$ and $pp$ given large uncertainties on both

arXiv:2101.10771
\( v_2(p_T) \) comparison with \( pp \) and \( p+Pb \)

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)

arXiv:2101.10771
$v_2(p_T)$ 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.

Final state effects

Initial-state geometry $\rightarrow$ hydro $\rightarrow$ final-state anisotropy has described simultaneously many systems

- In small systems the initial geometry is largely determined by fluctuation.
- We ran a constituent quark model, 2 vs 3 quarks on Pb and found almost no difference in $\varepsilon_2$ and $\varepsilon_3$.
- In that sense, one might expect similar results for $p+$Pb and rho+Pb at fixed multiplicity.
- A more complete calculation is needed also considering the bare photon portion of the wave function, color fluctuations, possible correlations between the impact parameter and photon energy etc.

Initial state correlation

Less success in the description of a diverse set of observables.

- A schematic CGC calculation is discussed in the next slide.
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 $B_p$

Correlated color domain size is $\sim 1/Q_s$
Color Glass Condensate model calculation containing initial-state correlations which gives rise to nonzero $v_2$

- Similar calculations describing $p+\text{Pb}$ (arXiv:1808.09851)
- Difference in $v_2$ is a result of a smaller $B_p^2$ for a proton where $B_p^2 \sim 1/\Lambda_{QCD}^2$

Correlated color domain size is $\sim 1/Q_s$
CGC prediction at the EIC

Deferring probe size would affect $v_2$ in a CGC or hydro picture.

Prediction only in low $Q/Q_s$ regime
Constraints from DIS: ep at HERA

H1 detector at HERA ep collisions

- Dataset: 2006-2007
- Beam energy: $E_e = 27.6 \, \text{GeV}$, $E_p = 920 \, \text{GeV}$
- Much higher beam energy than CGC EIC predictions
- Lower multiplicities than LHC $\gamma A \rightarrow$

No near-side ridge
H1 searches in DIS and photoproduction

2-particle correlation →
- No nonflow removal
- Results consistent with MC with no collectivity (RAPGAP)

Multi-particle correlations →
- Suppresses nonflow
- Negative $C_2\{4\}$ is associated with flow-like signal
  $$v_n\{4\} = \sqrt{-c_n\{4\}}.$$ 
- Consistent with MC w/o collectivity

Extended geometry in DIS?

Chuan Sun, DIS 2021  H1prelim-20-033
H1 photoproduction results

- 2-particle and multi-particle correlations indicate similar results as DIS (no obvious ridge yield)
- \( Q/Q_s \) is larger in \( ep \) photoproduction compared to \( \gamma A \) at the LHC
- If applicable, the CGC calculation shown earlier would naively predict a larger \( v_2 \)?
- Further studies could be more directly comparable such as similar treatment of nonflow in \( ep \) and multi-particle correlations in \( \gamma A \)
γ +Au with STAR

If a high statistics Au+Au 200 GeV dataset if accumulated by STAR from the anticipated 2023 run of RHIC it will provide a golden opportunity to study photonuclear events with the forward upgrades. The same can be done in the photo production limit of e+A at EIC. Key measurements: 1. ridge 2. chemistry (π/k/p yield) and how they change when compared to hadronic events at the same multiplicity.

Collectivity searches in $e^+e^-$

2-particle correlation in $e^+e^-$

- Utilizes both detector coordinates and thrust coordinates (below)
- Large amount of nonflow – could it be removed?

No obvious extended (in $\eta$) geometry in $e^+e^-$

Would not necessarily expect ridge even if collective effects exist
Conclusions

Results
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 → vector meson).

Theory
Compared to CGC model and are interested in models which include final-state effects.
Quantitative comparison between $ep$ photoproduction and $\gamma A$

Future study in $\gamma A$
Difference with $pp$ might be a consequence of (and further studied by) CM energy, CM-frame rapidity acceptance, decorrelations effects, and multi-particle correlations.
Thank you
Gap definition (detector roll-out)

Event Selection: $\sum \sum \gamma \Delta \eta_{\text{gap}} > 2.5$
• 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.
Purity of the photonuclear selection

- A two-component fit was performed (signal MC) + (background MC) to data distributions to determine the purity.

- The $N_{\text{ch}}$ and $\Sigma_{\gamma}\Delta\eta$ distributions were used.

- A conservative approach was taken and the worst purities were used to assess possible effects.

- A $pp$ $\Delta\phi$ correlation with the same selections was subtracted (according to the bins purity) from the photonuclear data as a systematic variation and the sensitivity is included in the final result.
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 $p_T$. 

\[
v_n(p_T^a) = v_{n,n}(p_T^a, p_T^b)/v_n(p_T^b) = v_{n,n}(p_T^a, p_T^b)/\sqrt{v_{n,n}(p_T^b, p_T^b)}
\]
Triggering on photonuclear events

Triggering included

- Level-1 requirements on
  - Minimum event activity to collect high-multiplicity $\gamma A$ events
  - Maximum event activity to reject hadronic 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 ($3.2 < \eta < 4.9$)

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

It has been largely established that hydrodynamic properties of the QGP governs many of the emergent phenomenon in HI

Initial geometry → Hydro → azimuthal anisotropy

Average HI collision has elliptic initial energy deposition
Long-range azimuthal anisotropy

Extended in transverse direction

Long range in $\Delta \eta$
Raw moments of 2PC (no non-flow removal)

CMS-PAS-HIN-18-008

\[ \gamma + p \] final results

- \( v_{2,2} \) grows with \( N_{\text{ch}} \) – evidence of a dominant and \( N_{\text{ch}} \)-dependent-hardening jet shape
- Similar conclusion for \( v_{3,3} \)
- Although very different multiplicities, \( \gamma + p \) has a much stronger correlation than \( \gamma + A \).

No trivial way of removing non-flow and require further study!

arXiv:2101.10771
Consistency of $N_{\text{ch}}$ and $p_T$ in $\gamma A$

Now on same $y$-axis scale
$dN_{ch}/d\eta$ in $\gamma A$ collisions