Measurements of long-range correlations in small systems with ATLAS

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Outline

1. Collectivity in $pp$ collisions tagged by $Z$-boson production
   arXiv:1906.08290

2. Recent results from exploration of ultra-peripheral collisions
   arXiv:1904.03536

3. Evidence of collectivity is photo-nuclear collisions

ATLAS-CONF-2019-022S:
What is the $pp \, v_2$ correlated with?

- In large systems, the impact parameter is strongly correlated with $v_2$
- Maybe impact parameter is important in $pp \, v_2$
- Multiplicity is not well correlated with impact parameter
- Large $Q^2$ (short distance scales) interactions
  - smaller impact parameter
  - More MPIs
- Require Z-boson: $Q^2 \sim (90 \, \text{GeV})^2$

Analysis method

Event with Z-boson identified by presence of two high-pT muons with invariant mass between 80-100 GeV

Correlate other particles in the event

Pileup vertices can be very close to Z-event vertex (indistinguishable).

Construct synthetic pileup contribution to Z-event correlations and subtract.
NEW: 13 TeV Z-tagged measurement and $p_T$ measurement
Z-tagged $v_2$ is consistent with inclusive $pp$.
Expansion of experimental techniques to perform correlation studies in high pileup conditions
Ultra-peripheral collisions with ATLAS

Two categories

- Pure EM processes
- Photo-nuclear interactions

All processes “may” also include one or both nuclei breaking up, due to additional soft photo exchange

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

Photon max energy
~ 80 GeV at LHC
Pure EM processes

Pure EM process: interactions of photons from each nucleus

lepton pair production
ATLAS-CONF-2016-025

photon pair production
Nature Physics 13 (2017) 852
Light-by-light scattering with ATLAS

- Updated measurement with 1.7 nb⁻¹ 2018 data
- 8.2σ observation
- Clean system
- Limits couplings for photons to axion-like particles
- Active goal of the LHC in Run 3 and 4.

arXiv:1904.03536
Photo-nuclear interactions

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

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

```
\begin{tikzpicture}
  \node (A) at (0,0) {Pb};
  \node (B) at (2,0) {Pb};
  \draw[thick,->] (A) -- ++(1,0);
  \draw[thick,->] (A) -- ++(2,0);
  \draw[thick,->] (A) -- ++(3,0);
  \draw[thick,->] (B) -- ++(1,0);
  \draw[thick,->] (B) -- ++(2,0);
  \draw[thick,->] (B) -- ++(3,0);
  \draw[thick,->] (A) -- (B);
  \draw[thick,->] (B) -- ++(1,0);
  \draw[thick,->] (B) -- ++(2,0);
  \draw[thick,->] (B) -- ++(3,0);
  \draw[red,thick,dashed] (A) -- ++(0,1);
  \draw[red,thick,dashed] (B) -- ++(0,1);
  \node at (1.5,1) {"On"};
  \node at (1.5,2) {Rapidity gap};
  \node at (1.5,3) {No rapidity gap};
\end{tikzpicture}
```
Photo-nuclear interactions

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

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

Dominant interaction
Select events based on primarily

- One-sided nuclear fragmentation (zero-degree calorimeter ZDC)
- Rapidity gaps

We have contributions from both diagrams
“High”-multiplicity photo-nuclear collisions

\[ Pb+Pb, \text{ 5.02 TeV} \]
\[ \text{Run: 355681} \]
\[ \text{Event: 1064766274} \]
\[ 2018-11-11 22:00:07 \text{ CEST} \]

\[ \not p_T^{\text{cal}} = 71 \text{ GeV (left), 0.9 GeV (right)} \]
\[ 71 \text{ tracks, } p_T > 0.4 \text{ GeV} \]
Gap definition (detector roll-out)

Event Selection: \( \Sigma_A \Delta \eta_{\text{gap}} < 3 \)
\( \Sigma_\gamma \Delta \eta_{\text{gap}} > 2.5 \)

\( \eta = -4.9 \)  \( \eta = +4.9 \)

\( \Sigma \Delta \eta_{\text{gap}} = a + b + c \)
Rapidity gaps $\Sigma_y \Delta \eta_{\text{gap}}$ and $N_{\text{ch}}$
Photo-nuclear events have large rapidity gaps in the photon going direction and steeply falling multiplicity distribution.
\( \frac{dN_{ch}}{d\eta} \) in \( \gamma A \) collisions

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

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

ATLAS Preliminary

Pb+Pb 2018, 1.73 nb\(^{-1}\)

\( \sqrt{s_{NN}} = 5.02 \text{ TeV}, 0pXn \)

\( \Sigma_{\gamma} \Delta\eta > 2.5, \Sigma_{A} \Delta\eta < 3 \)
ATLAS template fits to $\gamma A$ correlations

- High-multiplicity (HM) correlation data
- Low Multiplicity (LM) template for jet 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)

Clear $\cos(2\Delta \phi)$ modulation!
$v_2$ in photo-nuclear collisions

ATLAS Preliminary

$2.0 < |\Delta \eta| < 5.0$

$0.5 < p_T^{a,b} < 5.0$ GeV

Pb+Pb 2018, 1.73 nb$^{-1}$

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

$\Sigma \gamma \Delta \eta > 2.5$, $\Sigma A \Delta \eta < 3$

Significant $v_2$ in photo-nuclear collisions!

Photo-nuclear $v_2$ is smaller than $pp$ and $p$+Pb
$p_T$ dependence

Similar $p_T$ dependence to hadronic collisions systems

Photo-nuclear central values are lower than $pp$ and $p+Pb$ (with larger uncertainties)
Conclusions

Z-tagged and inclusive pp $v_2$ are consistent.

New: 13 TeV measurement and $p_T$ dependence

8.2$\sigma$ observation of light-by-light scattering

Photo-nuclear $v_2$ has a similar order of magnitude and trends as other previously measured hadronic systems

Intuitive property of hadronic-like photo-nuclear collisions (photo $\rightarrow$ vector meson).
Thank you
Consistency of $N_{ch}$ and $p_T$ in $\gamma A$

Now on same y-axis scale
Fit with: low-multiplicity data, pedestal, $\cos(2\Delta\phi)$

Low-multiplicity in a “template” for non-flow.