Recent experimental results on collectivity in small-systems

Soumya Mohapatra
(Columbia University)
On behalf of the ATLAS and CMS Collaborations

This work is supported by the United States Department of Energy Grant
DOE-FG02-86ER-40281
QGP in small systems?

Ion-ion QGP

Proton-ion QGP?
QGP in small systems?

- **ion-ion**
  - QGP
  - ✔️

- **proton-ion**
  - QGP
  - ✔️
QGP in small systems?

- ion-ion QGP ✓
- proton-ion QGP ✓
- proton-proton QGP ?
QGP in small systems?

Many new measurements performed in last few years some of which will be discussed today.
QGP in small systems?

- ion-ion: QGP
- proton-ion: QGP
- proton-proton: ?
- photon-ion: QGP
- photon-proton: What about even smaller systems?
First indication of “collective behavior” in pp collisions was the observation of the ridge in two-particle correlation measurements.

Try to further our understanding of the origin of the pp ridge.
- Does it arise from collective (hydro) behavior?
- Or is it driven by semi-hard processes? Perhaps related to gluon saturation.

If latter, then actively selecting/rejecting events with semi-hard processes (low-$p_T$ jets) should enhance/weaken the ridge.
Define multiple correlation classes

- $h$: inclusive hadrons (tracks) in the event
- $h^{UE}$: tracks from the underlying event (UE):
  - require that the track is at least one unit in $|\eta|$ from all jets with $p_T > 15$ GeV
Define multiple correlation classes

- $h$: inclusive hadrons (tracks) in the event
- $h_{\text{UE}}$: tracks from the underlying event (UE):
  - require that the track is at least one unit in \(|\eta|\) from all jets with $p_T > 15$ GeV

![Diagram showing $h_{\text{UE}}$ and $h$ in $\phi$ and $\eta$ planes with regions for rejected and accepted particles.](image)
Define multiple correlation classes

- $h$: inclusive hadrons (tracks) in the event
- $h^{UE}$: tracks from the underlying event (UE):
  - require that the track is at least one unit in $|\eta|$ from all jets with $p_T > 15$ GeV
- $h^J$: track associated with a jet
  - require that the track is within a 0.4 cone of a $p_T > 40$ GeV Jet
The $v_2$ values are observed to vary weakly with multiplicity,

- $v_2$ values for the $h^{UE}$-$h^{UE}$ correlations: NoJets, WithJets and All Events are identical
- Removing particles associated with jet has negligible impact on $v_2$
- Presence/absence of Jets in events does not impact the $v_2$

- $h^{UE}$-$h^{J}$ $v_2$ consistent with zero within uncertainties
- Ridge is not related to jets!
\( v_2 \) : comparison between cases

- The \( v_2 \) values are observed to vary weakly with multiplicity,
  - \( v_2 \) values for the \( h^{UE-h^{UE}} \) correlations: NoJets, WithJets and All Events are identical
  - Removing particles associated with jet has negligible impact on \( v_2 \)
  - Presence/absence of Jets in events does not impact the \( v_2 \)
- \( h^{UE-h^{J}} \) \( v_2 \) consistent with zero within uncertainties
  - Ridge is not related to jets!
  - Behavior is true as function of pT as well.

**ATLAS: PRL 131 (2023) 162301**
• CMS measurements to explore if there is “collective” behavior within constituents of high-multiplicity-jet.
  • Align coordinate system with jet-axis (\(\eta^*\))
  • Measure two-particle correlations in \((\Delta\eta^*, \Delta\phi^*)\) between constituents
• CMS measurements to explore if there is “collective” behavior within constituents of high-multiplicity-jet.
  • Align coordinate system with jet-axis ($\eta^*, \Delta\phi^* \rightarrow$)
  • Measure two-particle correlations in ($\Delta\eta^*, \Delta\phi^*$) between constituents
• Shown here are 2PCs for low-multiplicity and high-multiplicity jets

CMS: arXiv:2312.17103
Intra-jet Collectivity

- 1D correlation functions with Fourier components (Data and MC)
- See small near-side peak for high multiplicity jets the data
- Such a peak is absent in the MC (Pythia/Sherpa)
Intra-jet Collectivity

- The $v_2$ values vs jet multiplicity in Data and MC
  - MC & Data $v_2$ decreases with multiplicity
    - Consistent for jet multiplicity < 80
  - For multiplicity > 80: $v_2$ in data increase,
    - Inconsistent with MC

- Indicating of some collective behavior?
  - Need more guidance from theory

CMS: arXiv:2312.17103
Photon-ion and photon-proton collisions

**Ultra Peripheral Pb+Pb**

EM fields of Lorentz contracted nuclei can be treated as flux of quasi-real photons.

In UPC Pb+Pb collisions, Photons coherently emitted from one Pb nuclei can interact with another: $\gamma$+Pb collisions

**Ultra Peripheral Pb+p**

Similar process in UPC Pb+p : $\gamma$+p collisions

Also see talk by Joakim Nystrand yesterday
- The $v_2$ in $\gamma$+Pb are extracted using a non-flow subtraction procedure.
- Correlation in low multiplicity (LM) events subtracted from correlation measured in higher multiplicity (HM) events.
- Subsequently Fourier harmonics $v_n$, extracted from the “Non-flow” corrected correlation.
Collectivity in $\gamma$+Pb collisions

- $p_T$-differential $v_2$ comparable with $pp$ over the 0.4-2 GeV $p_T$ range.
- Can be reproduced by tuning CGC calculations (initial-state effects only).
  - Shu et al., PRD 103, 054017
  - Considerable leeway available in tuning.

ATLAS: Phys. Rev. C. 104 104903
Collectivity in $\gamma$+Pb collisions

- Comparison of $v_2$, $v_3$ of multiplicity dependence to 3+1D hydro calculations
  - Zhao, Shen, Schenke, PRL 129, 252302
  - Treating the $\gamma$ as meson
  - Good agreement for $v_2$.

ATLAS: Phys. Rev. C. 104 104903
First look at $\gamma+p$ collisions

- Select enriched sample of $\gamma+p$ events in UPC $p+Pb$ collisions.
- Require no neutron on Pb-going size ZDC, as well as a large region with no detector activity on Pb going side.
- Plots show 2D and 1D 2PCs in $\gamma+p$ events and min-bias $p+Pb$ events.
- Stronger away-side correlation observed in $\gamma+p$ events compared to min-bias $p+Pb$.

First look at $\gamma+p$ collisions

- Larger $v_2$ observed in $\gamma+p$ events compared to min-bias events
  - Need to be careful as no "non-flow" subtraction is performed
  - i.e. jet-like correlations dominate the measurement.
- Measurements can extend search for collectivity to $\gamma+p$ events
Multiple recent measurements from ATLAS and CMS investigate collectivity in small collision systems.

ATLAS: ridge in $pp$ collisions with/without jets, “jet-constituent”-UE correlations
- low-$p_T$ $v_2$ not affected by presence/absence of jets. (See also ALICE: arXiv:2308.16591)
- Jet-fragments do not exhibit correlations with UE particles.
- Hard-scattering & UE-collectivity are uncorrelated!

CMS: Measured correlations within jet-fragments
- Correlation in low multiplicity jets consistent with MC generators.
- Constituents in highest multiplicity jets show hints of collectivity.

CMS & ATLAS: 2PC measurements in $\gamma+p$ and $\gamma+Pb$ events.
- Smallest collision systems at the LHC.

Not covered in this talk: ATLAS and CMS: also measured HF $v_2$ in $pp$ events.
- charm $v_2$ consistent with inclusive hadrons, bottom $v_2$ consistent with zero.
• Measured $v_2$ of muons produced in the semi-leptonic decays of $b$ and $c$ hadrons.

• Significant anisotropy observed for muons from charm decay: consistent with inclusive hadrons.

• $v_2$ for muons from $b$ decays consistent with zero.

• These HF anisotropy measurements can lead to further understanding of origin of the $pp$ ridge.
Extra-2: HF collectivity in \( pp \) collisions

HF collectivity can potentially separate initial vs final-state effects

\( v_2 \) of prompt \( D^0 \) mesons in \( pp \) collisions.

Significant anisotropy observed: Comparable to inclusive hadrons.

Comparable to \( v_2 \) in \( p+\text{Pb} \) collisions at similar multiplicity.

CMS: PLB 813,136036
Comparison of ridge-yield in $e^+e^-$ (ALEPH) vs similar multiplicity $pp$ collisions (ALICE).

pp Yields significantly larger over 8-18 multiplicity range
Data from ALEPH (91 TeV)
- Similar measurements shown by BELLE
- Correlations well reproduced by PYTHIA6
- No indications of ridge in high-multiplicity events.

Possibilities
- Not high-enough energy density (P. Castorina et al, arXiv:2011.06966)
- Not expected in a single color-string (J. Nagle et al, PRC 97, 024909 (2018))
Extra-5: And in \(ep\) collisions

- \(ep\) measurements at HERA
- Measured using 4-particle cumulants
  - Consistent with no collectivity