EPS-HEP Conference 2021

European Physical Society conference on high energy physics 2021

Online conference, July 26-30, 2021

Measurements of collective behavior in pp, Xe+Xe, and Pb+Pb collisions with the ATLAS detector

Somadutta Bhatta
Stony Brook University
(on behalf of ATLAS)

Collectivity in Heavy Ion Collisions

Geometrically anisotropic initial collision region

Lumpy

Temperature and flow profile of an A + A collision from a hydrodynamic model.

Demonstration by an ultracold atom gas system

Anisotropic azimuthal distribution:

$$dN/d(\phi - \Psi_2) \sim 1 + 2v_2 \cos[2(\phi - \Psi_2)] \quad v_2: \text{elliptic flow}$$

Initial state fluctuations & lumpiness leads to final azimuthal anisotropy in p_T space

$$E \frac{d^3 N}{d^3 p} = \frac{1}{2\pi} \frac{d^2 N}{p_t dp_t dy} \left(1 + \sum_{n=1}^{\infty} 2v_n \cos(n(\phi - \Psi_r)) \right) \quad v_2 = \langle \cos 2(\phi - \Psi_r) \rangle, \quad \phi = \tan^{-1} \left(\frac{p_y}{p_x} \right)$$

- In HIC, Collective flow arises from interactions between particles in the formed medium.
- Correlations between particles and Geometrical effects give rise to anisotropic Azimuthal distribution.
- Several methods to measure collective flow: EP, SP, 2PC etc

Large vs Small systems (part 1)

Phys. Rev. C 96 (2017) 024908

$$C(\Delta\phi) = C_0 \left(1 + \sum_{n=1}^{\infty} v_{n,n}(p_T^a, p_T^b) \cos(n\Delta\phi) \right)$$

$$v_n(p_T^b) = \frac{v_{n,n}(p_T^a, p_T^b)}{v_n(p_T^a)} = \frac{v_{n,n}(p_T^a, p_T^b)}{\sqrt{v_{n,n}(p_T^a, p_T^a)}}$$

$$Y^{\text{templ}}(\Delta\phi) = Y^{\text{ridge}}(\Delta\phi) + F Y^{\text{periph}}(\Delta\phi)$$

$$Y^{\text{ridge}}(\Delta\phi) = G \left(1 + \sum_{n=2} 2v_{n,n} \cos(n\Delta\phi) \right)$$

- 2PC method uses correlation in η and ϕ space to measure magnitude of long-range correlations.
- Does QGP form in small systems? Do we see ridge in pp collisions?

Origin of Ridge(part 1)

VS

- Does QGP form in small systems? Do we see ridge in pp collisions?
- **Alternative argument:** The ridge can arise from hard/semi-hard processes in HIC

Sensitivity of flow to presence of Jets (part 1)

➤ Study effect of hard/semi-hard processes (Jets) in flow measurement using 2PC for pp@13 TeV.

- Classification of events into 4 groups:

- Inclusive:** Usual 2PC with all particles.
- AllEvents:** Remove tracks within $|\eta| < 1$ above jet $p_T \geq 10$ GeV.
- WithJet:** Events with at least 1 jet above chosen threshold.
- NoJet:** Events with No jet above chosen threshold.

➤ **Observation:**
 Ridge is present in All cases.

Sensitivity of flow to presence of Jets (part 1)

- v_2 with reduced jet contribution (AllEvents/NoJet) smaller than inclusive by 2-5%.
 - Partially from softening of spectra.
 - Affects p_T integrated v_2 over 0.5-5 GeV range

- v_3 with reduced jet contribution (AllEvents/NoJet) larger than inclusive by maximum of 14%.
 - Dijet contribution biases even and odd harmonic in opposite manner
 - Larger relative effect in v_3 owing to its smaller magnitude

Sensitivity of flow to presence of Jets (part 1)

- v_2 withJet consistent with inclusive measurement within errors.

- p_T differential v_2 measurement.
- Consistent between 3 samples for 0.5-3 GeV.
- No clear trend for WithJet sample due to large statistical error.

CONCLUSION: Long-range correlations slightly affected when particles associated with hard or semi-hard processes are removed.

Initial state Correlations (part 2)

$$\begin{array}{|c|} \hline S_A = S_B \\ R_A < R_B \\ \hline \end{array} \Rightarrow \begin{array}{|c|} \hline T_A > T_B \\ \hline \end{array} \Rightarrow \begin{array}{|c|} \hline \bar{p}_{t,A} > \bar{p}_{t,B} \\ \hline \end{array}$$

In Boltzmann statistics with massless ideal gas: $p \simeq E = 3T$

In Heavy Ion Collisions: $\langle p_T \rangle \simeq 3T$

In the limit of Small Fluctuations: $\frac{d\langle p_T \rangle}{\langle \langle p_t \rangle \rangle} = -3c_s^2 \frac{dR}{\langle R \rangle}$

$$1/R \longrightarrow [p_T]$$

- Similar total energy, smaller transverse size in the initial state creates stronger radial expansion or larger $[p_T]$.

$$\epsilon_n \longrightarrow v_n$$

- Initial state correlation between eccentricity and transverse size generates final state $v_n - [p_T]$ correlations.

flow-[pT] correlations(part 2)

PRC 102, 024901 (2020)

PRL 125, 192301 (2020)

TRENTTo model predictions

1. $\rho_2(\text{Pb+Pb}) > \rho_2(\text{Xe+Xe})$
2. $\rho_2(\text{Xe+Xe})$ and $\rho_2(\text{Pb+Pb})$ turns -ve towards peripheral centralities.
3. ρ_3 shows milder dependence on centrality (fluctuations driven)
4. $\rho_3(\text{Xe+Xe})$ turns -ve towards peripheral centralities.

IP-Glasma+MUSIC+URQMD predictions

1. Sign change observed in PbPb collisions at 5.02 TeV is not seen in AuAu collisions at 200 GeV.
2. Centrality dependence of ρ_2 arises from geometry dominance of v_2 in central and initial p_T anisotropy dominance in peripheral events.

Measurement of flow-[pT] correlations (part 2)

N_{ch}

Size

FCal E_T based centrality

Shape

ATLAS-CONF-2021-001

- Both Xe+Xe and Pb+Pb go -ve in very low N_{ch} for $n=2$.
- **Smaller** magnitude in Xe+Xe for $n=2$ & $n=4$.
- **Larger** magnitude in Xe+Xe for $n=3$ due to larger fluctuations in smaller system.
- As a function of centrality, ρ_2 is smaller in Xe+Xe but ρ_3 and ρ_4 are comparable.

Comparison with models (part 2)

[arXiv:2004.14463](https://arxiv.org/abs/2004.14463)

[arXiv:2004.00690](https://arxiv.org/abs/2004.00690)

[arXiv:2006.15721](https://arxiv.org/abs/2006.15721)

➤ Trento :

- Deformation strongly affects $n=2$ but not $n=3$
- Can explain some qualitative trends in data but not quantitatively
- Similar trend for $n=3$ seen both in data and model.
- Due to centrality fluctuation - any conclusion on deformation effect is not clear in Xe+Xe

➤ IP-Glasma+MUSIC+URQMD calculations:

- Predictions have large uncertainties.
- CGC+Hydro **cannot reproduce** the magnitude ordering between Xe+Xe and Pb+Pb
- **Cannot explain data qualitatively or quantitatively.**

Conclusion

PART 1: Sensitivity of flow measurement to hard/semi-hard processes in pp:

- a) Long-range correlations slightly affected when particles associated with hard or semi-hard processes are removed.
- b) Only hard or semi-hard processes can not describe the ridge observed in pp collisions.

PART 2: Measurement of flow- $[p_T]$ correlations.

- a) Both Xe+Xe and Pb+Pb has -ve $\rho(v_2^2, [p_T])$ for very low Nch.
- b) Models Can explain some qualitative trends in data but not quantitatively.
- c) Significant centrality fluctuation effect observed for $\rho(v_n^2, [p_T])$.
- d) Conclusion on effect of geometric deformations on ρ_2 from model comparisons remain unclear due to centrality fluctuation effects.