Attributions of fluctuations in azimuthal anisotropies

by

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IN THIS TALK:

- Anisotropy is a collective long-range phenomenon.

- Fluctuations are dynamical (driven by initial-state physics).

- Focus on questions driven by new data/developments.
THE EXOTIC QUESTION
is there anisotropy without fluctuations?

Yes.

[Ollitrault, 1992]
Eccentricity of the average energy density, $<T^{00}>$. 

$$\varepsilon = \frac{\int dxdy(x^2 - y^2) \left< T^{00}(x, y) \right>}{\int dxdy(x^2 + y^2) \left< T^{00}(x, y) \right>}. $$

Central to mid-central collisions, one has:

$$v_2\{4\} \approx \kappa \varepsilon$$

I dub $T_A$ and $T_B$ the optical participant densities.

$\langle T^{00}(x) \rangle \propto \left( \frac{T_A^p(x) + T_B^p(x)}{2} \right)^{1/p}$

$\langle T^{00}(x) \rangle \propto \left( T_A(x) T_B(x) \right)^q$

[ALICE Collaboration, 1804.02944]
Experimental data suggests:

\[
\langle T^{00}(x, \tau = 0^+) \rangle \propto \left( T_A(x)T_B(x) \right)^q
\]

q=1  \quad \rightarrow \quad \text{prediction of the color glass condensate (CGC).}

[Lappi hep-ph/0606207]

q=\frac{1}{2}  \quad \rightarrow \quad \text{Only TRENTo parametrization of the form } T_A^*T_B. \text{ Strongly favored by Bayesian analyses.}


Time evolution of q is known fairly well.

[Lappi, Venugopalan nucl-th/0609021]

[Giacalone, Mazeliauskas, Schlichting, 1908.02866]

Average anistropy in data is consistent with a CGC-like model.
2005: Breakthrough discovery by the PHOBOS collaboration. 

At a given impact parameter:

$$\left\langle T^{00}(x)T^{00}(y) \right\rangle - \left\langle T^{00}(x) \right\rangle \left\langle T^{00}(y) \right\rangle \neq 0$$

The initial condition fluctuates event-by-event!

Anisotropy is broken to all orders in the interaction region. The energy density has **non-vanishing multipole moments**.

$$\mathcal{E} \propto \int r dr d\phi \ r^m e^{im\phi} T^{00}(r, \phi) \neq 0$$

\[ [\text{Alver, Roland 1003.0194} ] \]

\[ [\text{Teaney, Yan 1010.1876} ] \]
Connected 2-point function in the CGC derived in:

\[
\frac{\langle T^{00}(x)T^{00}(y) \rangle}{\langle T^{00}(x) \rangle \langle T^{00}(y) \rangle} - 1
\]

[Albacete, Guerrero-Rodriguez, Marquet 1808.00795]

[Giacalone et al. 1902.07168]

"new paradigm" approximation

- full MV model, analytical
- full MV model, numerical

[courtesy: Pablo Guerrero-Rodríguez, Sanghoon Lim, Jamie Nagle]

Color-charge fluctuations are small, scale is \(\sim 1/Q_s\).

We need additional fluctuations on nuclear/hadronic scales.
ANISOTROPY #1 – nuclear structure: collective phenomena

Deformation: emergent property of nuclei. Collective ‘organization’ of nucleons. [Bohr, Mottelson 1957]

Rotational model: nuclei as ellipsoids with a random orientation.

\[Q_2 \propto \left\langle Y^0_2(\Theta, \Phi) r^2 \right\rangle \neq 0\]

Dimensionless deformation parameter:

\[\beta \propto \frac{Q_2}{\left\langle r^2 \right\rangle}\]

\[\begin{array}{ccc}
\beta \approx -0.3 & \beta \approx 0 & \beta \approx +0.3 \\
\end{array}\]
New source of fluctuations: the shape of the overlap area.

Manifestations observed in elliptic flow data.

New spectacular signatures discovered at STAR this year.

[ Talk by J. Jia, Thursday Jan 14th, contribution #55 ]
Soumya Mohapatra, IS2019:

“Can Xe-Xe @ LHC have the same impact as Cu-Cu @ RHIC?”

129Xe is not 238U.

Shape is not sharply defined.

Co-existence of prolate and oblate configurations.

Average geometry is triaxial.

Precision data on elliptic flow requires state-of-the-art nuclear theory.
NUCLEAR DEFORMATION

length scale $\sim R_A$
ANISOTROPY #2 – nuclear structure: individual nucleons

Nuclear structure on shorter scales: Quantum noise due to nucleons. A mean-field approach: **Glauber Monte Carlo.**

\[
\rho(r) = \frac{\rho_0}{1 + \exp\left(\frac{r-R}{a}\right)}
\]

Energy density obtained from nucleon-nucleon interactions.

\[
T_A(x)T_B(x) \rightarrow \sum_{i,j} T_{A,i}(x)T_{B,j}(x)
\]

[Miller, Reygers, Sanders, Steinberg nucl-ex/0701025]
Explains elliptic flow fluctuations and triangular flow.

- [ALICE Collaboration, 1804.02944]
- IP-Glasma+MUSIC+urQMD [Schenke, Shen, Tribedy 2005.14682]
- TRENTo+hydro [Bass, Bernhard, Moreland Nature Phys. 15 (2019)]

But wait a minute...
... those models “look” fairly different.
Picture of the QGP over the years. (b=0, initial energy density)

- QGP has been rather spiky until 2019-2020.
- Latest Bayesian analyses return smoother medium.
  [Bass, Bernhard, Moreland 1808.02106, Nature Phys. 15 (2019)]
- Anisotropies $v_n\{2\}$ are roughly the same.
Can anisotropy discern spiky and smooth profiles?
Golden probes: do not involve the 1-point function! (i.e. v2)

Primordial non-Gaussianity (is negative!)
[Abbasi, Allahbakhshi, Davody, Taghavi 1704.06295]

Ultra-sensitive to fluctuations

Simple IP-Glasma-like TRENTo calculation captures the data.
QUESTION ADDRESSED BY THESE COMPARISONS:

1 – Role of short-scale structures.

2 – The fate of the bulk viscosity. Tension in the literature?
NUCLEAR DEFORMATION length scale \( \sim R_A \)

INDIVIDUAL NUCLEONS length scale \( \sim [1 \text{ fm}, R_A] \)
ANISOTROPY #3 – nucleon structure

Anisotropy observed in pA (and pp).
The crucial question: can we use the same 1-point function?

\[ \left\langle T^{00}(x, \tau = 0^+) \right\rangle \propto \left( T_A(x)T_B(x) \right)^q \]

Yes, but you’ll need more structures. [Schenke, Venugopalan 1405.3605]

**IP-Glasma**: Shape fluctuations in protons. [Mäntysaari, Schenke 1603.04349, 1607.01711]
[Mäntysaari, Schenke, Shen, Tribedy 1705.03177]

**TRENTo**: Combined analysis of p-Pb and Pb-Pb collisions
[Bass, Bernhard, Moreland 1808.02106]

\[\text{p+Pb, 5.02 TeV} \quad \text{TRENTo p=0}\]
Is there experimental evidence of this behavior in small systems?

$$\langle T^{00}(x, \tau = 0^+) \rangle \propto \left( T_A(x) T_B(x) \right)^q$$

Nontrivial information from $v_n<$p_T$>$ correlation.

- Experimental ATLAS data is **negative** in high-multiplicity pA.
- Supports IP-Glasma or TRENTo $p=0$-like scaling.
DO WE HAVE THE RIGHT MODEL: OPEN QUESTIONS #1

Beautiful observation by CMS in p-Pb collisions:

\[ \frac{v_2\{4\}}{v_2\{2\}} = \frac{v_3\{4\}}{v_3\{2\}} \]

Calculation with TRENTo p=1 (wounded nucleons) points to geometric origin of observables.

[CMC Collaboration, 1904.11519]

- Calculation with TRENTo p=1 (wounded nucleons) points to geometric origin of observables. [Giacalone, Noronha-Hostler, Ollitrault, 1702.01730]

- TRENTo p=1 is ruled out... results from sub-structure models?
DO WE HAVE THE RIGHT MODEL: OPEN QUESTIONS #2

Mixed correlations measured with great accuracy.

There are no results from recent sub-structure models. I tried with the eccentricities and get the wrong sign. [NSC(3,2)>0]

[also observed in p-p: Zhao, Zhou, Murase, Song 2001.06742]

Results for p-p (or Ntrk~100) sensitive to details of hot-spot deposition.

[Albacete, Elfner, Soto-Ontoso 1707.05592]
NUCLEAR DEFORMATION  
length scale  $\sim R_A$

INDIVIDUAL NUCLEONS  
length scale  $\sim [1 \text{ fm}, R_A]$

SUB-NUCLEONIC STRUCTURES  
length scale  $\sim [1/Qs, 1 \text{ fm}]$
ANISOTROPY #4 – momentum space deformation

Vast literature describing long-range anisotropy in pp, pA collisions from initial-state effects in the CGC. [Altinoluk, Armesto 2004.08185]

Address the question with IP-Glasma initial conditions. Ellipticity of the tensor modes:

\[ \mathcal{E}_p \equiv \varepsilon_p e^{i2\psi_2} \equiv \frac{\langle T^{xx} - T^{yy} \rangle + i \langle 2T^{xy} \rangle}{\langle T^{xx} + T^{yy} \rangle} \]

Primordial momentum anisotropy
For small multiplicities, $\varepsilon_p$ is the dominant source of elliptic flow.

[Schenke, Shen, Triedy, 1908.06212]

**OUR FINDING: QUALITATIVE SIGNATURES IN SMALL SYSTEMS**

[Giacalone, Schenke, Shen, 2006.15721]

Correlator goes from negative to positive as we decrease $dN/d\eta$. 
QUALITATIVE SIGNATURES IN PERIPHERAL A-A

- Double sign change @ LHC
- No sign change @ RHIC

[consistent with preliminary STAR data]
Normalized symmetric cumulant shows similar signatures.

With initial momentum anisotropy the cumulant stays negative!
NUCLEAR DEFORMATION  \( \text{length scale } \sim R_A \)

INDIVIDUAL NUCLEONS  \( \text{length scale } \sim [1 \text{ fm}, R_A] \)

SUB-NUCLEONIC STRUCTURES  \( \text{length scale } \sim \left[ \frac{1}{Q_s}, 1 \text{ fm} \right] \)

MOMENTUM SPACE ANISOTROPY

[Not covered: anisotropy from EM fields, longitudinal fluct, principal components]
ALL TOGETHER: “HEAVY-ION COLLISIONS 2.0”

PERIPHERAL COLLISIONS
PRIMORDIAL
MOMENTUM
ANISOTROPY

\[ \langle T^{xx} - T^{yy} \rangle + i \langle 2T^{xy} \rangle \]
\[ \langle T^{xx} + T^{yy} \rangle \]

MULTIPLICITY DEPENDENCE
1-POINT AND 2-POINT FUNCTIONS OF \(T^{00}\)

\[ \langle T^{00}(x) \rangle \propto (T_A T_B)^q \]

\[ \langle T^{00}(x)T^{00}(y) \rangle - \langle T^{00}(x) \rangle \langle T^{00}(y) \rangle \]

CENTRAL COLLISIONS
NUCLEAR DEFORMATION

\( \beta \approx 0.3 \)