TWO-PARTICLE CORRELATIONS

2-particle correlation as a function of $\Delta \eta$ and $\Delta \phi$

$\Delta \eta$: DIFFERENCE IN PSEUDO-RAPIDITY

$\Delta \phi$: DIFFERENCE IN AZIMUTHAL ANGLE

Ridge:
Structure that is long range in $\Delta \eta$
and generally shows two bumps in $\Delta \phi$
"double-ridge"

CMS PbPb 2.76 TeV
$1 < p_T < 3$ GeV/c

CMS COLLABORATION, EUR. PHYS. J. C72 (2012)

Björn Schenke, BNL
RIDGE IN HEAVY ION COLLISIONS

First seen in heavy ion collisions at RHIC

- Long range correlations emerging from early times (causality)
- Azimuthal structure formed by the medium response to the initial transverse geometry (well described by hydrodynamics)

2 ridges come from dominant cos(2\Delta\Phi) contribution due to the mostly elliptic shape

Björn Schenke, BNL
Azimuthal structure quantified using Fourier expansion

\[
\frac{1}{N_{\text{trig}}} \frac{dN_{\text{pair}}}{d\Delta \phi} \sim 1 + 2 \sum_{n=1}^{n=\infty} V_{n\Delta}(p_T^{\text{trig}}, p_T^{\text{assoc}}) \cos(n\Delta \phi)
\]

\[ v_n = \sqrt{V_{n\Delta}} \]
Azimuthal structure quantified using Fourier expansion

$$\frac{1}{N_{\text{trig}}} \frac{dN_{\text{pair}}}{d\Delta \phi} \sim 1 + 2 \sum_{n=1}^{n=\infty} V_{n\Delta}(p_T^{\text{trig}}, p_T^{\text{assoc}}) \cos(n\Delta \phi)$$

$$v_n = \sqrt{V_{n\Delta}}$$

**CMS Preliminary**

PbPb $\sqrt{s_{\text{NN}}} = 2.76$ TeV

0-0.2% centrality

**CMS COLLABORATION, JHEP 02 (2014) 088**
THEORETICAL DESCRIPTION IN HEAVY IONS

Fluctuating nucleon positions and color charges → Fluctuating deposited energy

High energy: Initial energy density can be computed in the color glass condensate framework (effective theory of QCD)

One realization is the IP-Glasma model

Includes gluon saturation at high densities (small $x$ and small transverse momentum $p_T \ll Q_S$)


Pressure gradients drive the evolution

Described by hydrodynamics

Quantitative description of the experimental data!

ALICE COLLABORATION, PHYS. REV. LETT. 107, 032301 (2011)
RIDGGE IN SMALL COLLISION SYSTEMS

minimum bias p+p

high multiplicity p+p

CMS MinBias, 1.0 GeV/c < p_T < 3.0 GeV/c

CMS pp 7 TeV, N_{trk} > 110
1 < p_T < 3 GeV/c

CMS COLLABORATION, JHEP09 (2010) 091

Björn Schenke, BNL
$V_{2\Delta}$ IN $p+p$ COLLISIONS

Result after correcting for back-to-back jet correlations estimated from low multiplicity events

No ridge in PYTHIA

CMS PAS HIN-15-009

But progress including final state effects via ‘string shoving’

In Pythia8 v.8.235; Bierlich, Gustafson, Lönnblad: PLB779 (2018) 58-63
Bierlich, Gustafson, Lönnblad, Tarasov
JHEP 1503 (2015) 148

Björn Schenke, BNL
V$_2^{\Delta}$ IN p + p COLLISIONS

Result after correcting for back-to-back jet correlations estimated from low multiplicity events

We are apparently missing important physics in our standard p+p event generators!

No ridge in PYTHIA

In Pythia8 v.8.235; Bierlich, Gustafson, Lönnblad: PLB779 (2018) 58-63
Bierlich, Gustafson, Lönnblad, Tarasov JHEP 1503 (2015) 148
RIDGE IN p+Pb COLLISIONS

high multiplicity p+Pb

pPb $\sqrt{s_{NN}} = 5.02$ TeV at the LHC

(a) ALICE
(b) ATLAS
(c) CMS

ALICE COLLABORATION, PHYS. LETT. B 719 (2013) 29
ATLAS COLLABORATION, PHYS. REV. LETT. 110 (2013) 182302
CMS COLLABORATION, PHYS. LETT. B 718 (2013) 795
$v_2$ IN $p+p$, $p+Pb$, $Pb+Pb$ Collisions

SEE ALSO:

**ALICE Collaboration**


**ATLAS Collaboration**


**CMS Collaboration**


**CMS PAS HIN-15-009**

Björn Schenke, BNL
HYDRO IN SMALL SYSTEMS

MC-Glauber initial state + viscous hydrodynamics works

ATLAS Coll. PLB725 (2013) 60-78


Bozek, Broniowski, PRC88 (2013) 014903

Shen, Paquet, Denicol, Jeon, Gale, PRC95 (2017) 014906

Also see: Kozlov, Luzum, Denicol, Jeon, Gale; Werner, Beicher, Guiot, Karpenko, Pierog; Romatschke; Kalaydzhyan, Shuryak, Zahed; Ghosh, Muhuri, Nayak, Varma; Qin, Mueller; Bozek, Broniowski, Torrieri; Habich, Miller, Romatschke, Xiang; T. Hirano, K. Kawaguchi, K. Murase; ...
IP-Glasma + hydro + fluctuating proton geometry


Constrain that fluctuating geometry by HERA diffractive $J/\Psi$ prod.


Round proton would produce much smaller $v_n$

Would not describe the data
CAN WE TRUST HYDRODYNAMICS?

Knudsen number: ratio of a microscopic over macroscopic scale
Small Knudsen number means hydrodynamics is valid

H. NIEMI, G.S. DENICOL, E-PRINT: ARXIV:1404.7327
see review W. Florkowski, M. P. Heller, M. Spalinski, Rept.Prog.Phys. 81 (2018) 046001 on recent progress in understanding the validity of relativistic hydrodynamics in systems with large gradients

SEE TALK BY S. FLOERCHINGER ON TUESDAY
Kinetic Theory “Anisotropic Escape”

A. Bzdak, G.-L. Ma, PRL 113 (2014) 252301; G.-L. Ma, A. Bzdak, PLB 739 (2014) 209-213;

Final state effect, but weakly interacting (3 mb x-sect.)

Described in AMPT

Partons are more likely to escape in the short direction $\rightarrow v_n$

also see Kurkela, Wiedemann, Wu, arXiv:1803.02072
INITIAL STATE MOMENTUM CORRELATIONS

LOOKS LIKE A DUCK.

QUACKS LIKE A DUCK.

QUACK!

IT MUST BE A DUCK.
INTIAL STATE PICTURE

**Intuitive picture:**
Quarks or gluons are produced from color field domains in the Pb or p target.

Particles that come from the same domain are correlated.

Effect is suppressed by the number of colors and the number of domains (it is small for heavy ions).

**FIGURE:** T. LAPPI, B. SCHENKE, S. SCHLICHTING, R. VENUGOPALAN
L. MCLERRAN, V. SKOKOV, PHYS.LETT.B743 (2015), 134; V. SKOKOV. PHYS.REV.D91 (2015) 054014
High-multiplicity events are rare configurations of nuclear wave-function with large number of small-x gluons

Situation described by the Color Glass Condensate, an effective theory of QCD at high energy. Particle production is governed by the Yang Mills equations

\[ [D_\mu, F^{\mu\nu}] = J^\nu \]

\( J^\nu \): Combination of incoming target and projectile color currents

This is it.

Different approximations and assumptions on the market
APPROXIMATIONS

- **Glasma graph approximation:** two gluon exchange (not more) and Gaussian statistics of color charges (MV model)
  Gelis, Lappi, Venugopalan PRD 78 054020 (2008), PRD 79 094017 (2009); Dumitru, Gelis, McLerran, Venugopalan NPA 810, 91 (2008); Dumitru, Jalilian-Marian PRD 81 094015 (2010); Dusling, Venugopalan PRD 87 (2013), ...

- **Non-linear Gaussian approximation:**
  Resums multi-gluon exchanges - still Gaussian statistics
  McLerran, Venugopalan, PRD 59 (1999) 094002; Dominguez, Marquet, Wu, NPA 823 (2009) 99; Lappi, Schenke, Schlichting, Venugopalan, JHEP 1601 (2016) 061; ...

- **Numerical solution:** Solves the Yang-Mills equations exactly for any initial color source statistics and spatial configuration, includes multiple-gluon exchange, “rescattering”

- One can add **JIMWLK** evolution which will introduce leading quantum correction and (some) non-Gaussian correlations
  Lappi, PLB 744 (2015) 315-319, ...
INITIAL STATE PICTURE GENERATES ANISOTROPY

Dumitru, Gelis, McLerran, Venugopalan NPA810, 91 (2008); Dumitru, Jalilian-Marian PRD 81 094015 (2010);
Dusling, Venugopalan PRD 87 (2013) 5, 051502; PRD 87 (2013) 5, 054014; PRD 87 (2013) 9, 094034

CAN WE DISTINGUISH INITIAL FROM FINAL STATE EFFECTS?

Many possibilities. Different observables.
I will focus on studying
Different collision systems: Allow to control initial geometry
They are (were?) the most promising tool
SYSTEM DEPENDENCE OF ANISOTROPIES

Hydrodynamics converts initial shape to momentum anisotropy. At RHIC different systems with different average shapes were studied.

Hydrodynamics correctly describes anisotropies in different systems

Recent results from initial state momentum correlations:

System dependence present when selecting 0-5% central events (which have different multiplicities in different systems)
First step towards an event generator with dense initial gluon fields and Lund fragmentation

Sample gluons and connect with Lund strings
Arrange similar to what color reconnection would do

Emission from common boosted source: mass splitting
STUDY RELATIVE STRENGTH OF INITIAL AND FINAL STATE CORRELATIONS IN THEORY

Calculate the relative contribution of "glasma graphs" and final state effects

S. Schlichting, Quark Matter 2015
IP-Glasma + parton cascade

To study how final state interactions affect the initial state correlations, we use a microscopic final state model, the parton cascade BAMPS

Z.Xu, C. Greiner, PRC71, 064901 (2005)

IP-Glasma

\[ \frac{dN_g}{dyd^2x_Td^2p_T} \]

Wigner Distribution

sample gluons

run BAMPS (pQCD)

smear → Husimi Distribution

study momentum anisotropy as function of time
Effect of initial correlations on final $v_2$

Effect of initial correlations on final $v_2$


negligible effect at small $p_T$ and high multiplicity

significant effect at $p_T > 2$ GeV and low multiplicity

visible effect at $p_T > 3$ GeV and high multiplicity
CONCLUSIONS & OUTLOOK

• Multi-particle correlation measurements in small systems (p+p, p/d/He+A) have revealed interesting structures

• There are contributions from initial momentum anisotropies in the QCD particle production

• With increasing multiplicity, final state effects become important: similar to A+A collisions - QGP in p+p?

• Our standard event generators apparently miss this important physics. Work in progress for PYTHIA final state effects. What about the production process in high multiplicity events?
\( p + Pb \ v_2 \) from IP-GLASMA + Hydro

Model worked well in A+A. In \( p + A \) it did not. Not because hydro does not work. But because initial state was missing physics.


NEED PROTON SHAPE FLUCTUATIONS!

\textbf{e+p (HERA) Exclusive diffractive }J/\Psi\textbf{ production:}

\textbf{Incoherent }x\text{-sec sensitive to fluctuations}

\begin{figure}
\centering
\includegraphics[width=\textwidth]{graph.png}
\end{figure}


Björn Schenke, BNL
MULTI-PARTICLE CUMULANTS

Hydrodynamics produces \( \sim \) equal \( v_2\{2m\} \) for all \( m \geq 4 \)

All particles correlated with a common event plane

see e.g. L. Yan, J.-Y. Ollitrault, Phys. Rev. Lett. 112, 082301 (2014)

\( v_2\{4\} \) imaginary in 2-gluon exchange approximation

V. Skokov, Phys.Rev. D91 (2015) 054014

Including multiple interactions will make it real

\[
\begin{align*}
\text{Abelian version} \\
\end{align*}
\]
How to distinguish "flow" from an "initial state" scenario

- $^3$He+Au, d+Au: Systematics of flow in different systems Explained by hydrodynamics. Initial state: no calculation

- Higher order cumulants: Data shows that $v_2\{4\} \approx v_2\{6\} \approx v_2\{8\} \ldots$
  Natural in hydrodynamics but not a unique feature
HOW TO DISTINGUISH “FLOW” FROM AN “INITIAL STATE” SCENARIO

- **Mass splitting of mean $p_T$ and $v_n$:**
  Natural in any situation where particles are produced from a common boosted source: e.g. fluid cell, strings

- **$c_2\{4\}$ turning positive** as multiplicity increases could mean collectivity sets in but also alternative explanations

- **HBT**: Relative radii in $p+p$, $p+Pb$ and $Pb+Pb$: Data favors description that yields similar radii in $p+p$ and $p+Pb

DUMITRU, MCLERRAN, SKOKOV, PHYS.LETT. B743 (2015) 134-137

ALICE COLLABORATION, PHYS. LETT. B 739 (2014) 139-151
Approximations

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