AZIMUTHAL MOMENTUM ANISOTROPIES
IN PROTON-PROTON COLLISIONS
AND OTHER SMALL SYSTEMS:
A MINI-REVIEW

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XIIIth Quark Confinement and the Hadron Spectrum
Maynooth University, Maynooth, Ireland
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/$c$

$1 \frac{d^2N_{\text{pair}}}{N_{\text{trig}} d\Delta \eta d\Delta \phi}$

35-40%
RIDGE IN HEAVY ION COLLISIONS

First seen in heavy ion collisions at RHIC

STAR COLLABORATION, PHYS. REV. C80 (2009) 064912
PHOBOS COLLABORATION, PHYS. REV. LETT. 104 (2010) 062301

Interpretation in heavy ion collision:

• 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
RIDGE IN HEAVY ION COLLISIONS

Azimuthal structure quantified using Fourier expansion

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

\[ v_n = \sqrt{V_{n\Delta}} \]
RIDGE IN HEAVY ION COLLISIONS

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 COLLABORATION, JHEP 02 (2014) 088

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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 $p_T \lesssim Q_S$ )


Pressure gradients drive the evolution
Described by hydrodynamics

Quantitative description of the experimental data!

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

minimum bias p+p

high multiplicity p+p

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

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

CMS COLLABORATION, JHEP09 (2010) 091

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\( V_{2\Delta} \) 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
\( V_{2\Delta} \) 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

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RIDGE IN p+Pb COLLISIONS

high multiplicity p+Pb

(a) ALICE

(b) ATLAS

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

(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
PHYS. LETT. B719 (2013) 29-41;
PHYS. REV. C 90, 054901

ATLAS COLLABORATION
PHYS. REV. LETT. 110, 182302 (2013); PHYS. REV. C 90.044906 (2014)

CMS COLLABORATION
PHYS.REV.LETT. 115, 012301 (2015)

CMS PAS HIN-15-009

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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; ...
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.


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NEED PROTON SHAPE FLUCTUATIONS!

e+p (HERA) Exclusive diffractive J/Ψ production:
Incoherent x-sec sensitive to fluctuations


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IP-Glasma + hydro + fluctuating proton geometry

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
NEGATIVE PRESSURE WITH BULK VISCOSITY

$1 + \Pi/P$
in a p+Pb collision
KINETIC THEORY “ANISOTROPIC ESCAPE”


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.
**INITIAL 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
**INITIAL STATE PICTURE**

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 NPA 810, 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

System dependence of anisotropies

Recent results from initial state momentum correlations:

System dependence present when selecting 0-5% central events (which have different multiplicities in different systems)

Mark Mace, Vladimir V. Skokov, Prithwish Tribedy, Raju Venugopalan, arXiv:1805.09342
Rescaling proton color charge density $\rho_p \rightarrow c \rho_p$

$$\frac{dN}{dy} [\rho_p, \rho_t] \rightarrow c^2 \frac{dN}{dy} [\rho_p, \rho_t] + \mathcal{O}(c^3)$$

$Q_{2n} \rightarrow Q_{2n}$ and $Q_{2n+1} \rightarrow cQ_{2n+1} \sim \sqrt{dN/dy}$

BECAUSE HIGHER ORDER EFFECT
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
Calculate the relative contribution of “glasma graphs” and final state effects.
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)

\[ \frac{dN_g}{dyd^2 x_T d^2 p_T} \]
Wigner Distribution

sample gluons

run BAMPS (pQCD)

smear \rightarrow Husimi Distribution

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


High multiplicity 

$\langle dN_s/dy \rangle = 26$

$t=0.2$ fm/c, rand. azimuth

$t=2.0$ fm/c, rand. azimuth

Low multiplicity

$\langle dN_s/dy \rangle = 6$

IP-Glasma

+BAMPS

$p_T$ [GeV]

0 1 2 3 4 5 6 7 8

with initial corr.

without initial corr.

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Effect of initial correlations on final $v_2$


- **High multiplicity**
  - 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?
IP-Glasma + hydrodynamics

\( p + Pb \) events in 80-90% Pb+Pb class

\[ \epsilon_p = \sqrt{\frac{\langle T^{xx} - T^{yy} \rangle^2 + 2\langle T^{xy} \rangle^2}{\langle T^{xx} + T^{yy} \rangle^2}} \]

**IP-Glasma**

- IP-Glasma evolution close to free streaming
- \( \epsilon_p \) \( \sim \) constant when using full \( T^{\mu\nu} \)
- \( \epsilon_p \) grows when using ideal part of \( T^{\mu\nu} \)

\( \rightarrow \) anisotropic flow and \( T^{\mu\nu} \) both grow

B. Schenke, C. Shen, P. Tribedy, in preparation
$\epsilon_p = \sqrt{\frac{\langle T^{xx} - T^{yy} \rangle^2 + 2\langle T^{xy} \rangle^2}{\langle T^{xx} + T^{yy} \rangle^2}}$

Switching at $\tau=0.6$ fm:
$\epsilon_p$ with full $T^{\mu\nu}$ ~45% from initial flow

Switching at $\tau=0.2$ fm:
$\epsilon_p$ with full $T^{\mu\nu}$ ~35% from initial flow

5.02 TeV $p+Pb$ in Pb+Pb 80-90% bin
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

DIFFRACTIVE J/Ψ PRODUCTION

H. MÄNTYSAAARI, B. SCHENKE, ARXIV:1603.04349, ARXIV:1607.01711

No exchange of color charge
Large rapidity gap

Coherent diffraction:
Proton remains intact
Sensitive to average gluon distribution in the proton

Incoherent diffraction:
Proton breaks up
Sensitive to shape fluctuations
Diffractive eigenstates are color dipoles at fixed $r_T$ and $b_T$.

Scattering amplitude

\[ A \sim \int d^2b dz d^2r \, \psi^* \psi^V(r, z, Q^2) e^{-i b \cdot \Delta} N(r, x, b) \]

\[ \sigma_{\text{dip}}(x, r, \Delta) = 2 \int d^2b e^{i b \cdot \Delta} N(r, x, b) \]

AVERAGING OVER THE TARGET

H. MÄNTYSAARI, B. SCHENKE, ARXIV:1603.04349; ARXIV:1607.01711

COHERENT DIFFRACTION:
TARGET STAYS INTACT

\[
\frac{d\sigma^{\gamma^* p \to Vp}}{dt} = \frac{1}{16\pi} \left| \langle A^{\gamma^* p \to Vp}(x_p, Q^2, \Delta) \rangle \right|^2
\]

INCOHERENT DIFFRACTION:
TARGET BREAKS UP

\[
\frac{d\sigma^{\gamma^* p \to Vp^*}}{dt} = \frac{1}{16\pi} \left( \left\langle \left| A^{\gamma^* p \to Vp}(x_p, Q^2, \Delta) \right|^2 \right\rangle \\
- \left| \langle A^{\gamma^* p \to Vp}(x_p, Q^2, \Delta) \rangle \right|^2 \right)
\]

SENSITIVE TO FLUCTUATIONS!

SEE
H. I. MIETTINEN
AND J. PUMPLIN
PHYS. REV. D18 (1978) 1696

Y. V. KOVCHEGOV
AND L. D. MCLERRAN
PHYS. REV. D60 (1999) 054025

A. KOVNER AND
U. A. WIEDEMANN
PHYS. REV. D64 (2001) 114002
\( \tau = 0.0 \text{ fm/c} \)

Significant \( v_2 \) at time 0

No odd harmonics for gluons without final state interactions
Correlations from the Initial State

\[ \tau = 0.2 \text{ fm/c} \]

Gluons

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Fourier harmonics (event average)

\[ v_2, v_3 \]

\[ p+Pb \]

\[ \text{Gluons } \tau = 0.2 \text{ fm/c} \]

\[ \text{v}_2(2PC) \]

\[ \text{CMS v}_3(4) \]

\[ \text{ATLAS v}_3(2PC) \]

\[ \text{CMS v}_3(2) \]

\[ \text{p}_T \text{ [GeV]} \]

\[ \text{p}_T \text{ [GeV]} \]

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**CORRELATIONS FROM THE INITIAL STATE**

SCHENKE, SCHLICHTING, VENUGOPALAN, PHYS. LETT. B747, 76-82 (2015)

\[ \tau = 0.4 \text{ fm/c} \]

**Fourier harmonics (event average)**

- **Gluons**
  - ATLAS \(v_2\)(2PC) 55 GeV \(< E_{\text{T}}^\text{Pb} < 80 \text{ GeV}\)
  - CMS \(v_2\){4} 120 \(< N_{\text{trk}} < 150 \)
  - ATLAS \(v_3\)(2PC) 55 GeV \(< E_{\text{T}}^\text{Pb} < 80 \text{ GeV}\)
  - CMS \(v_3\){2} 120 \(< N_{\text{trk}} < 150 \)

**Odd harmonics generated by pre-equilibrium dynamics**

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