The role of the glasma and hydrodynamics for azimuthal anisotropies in nuclear collisions

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Brief outline

- Gluon saturation and initial glasma state (IP-Glasma model)
- Flow and fluctuations in heavy-ion collisions
- Multiplicity in pp and pA collisions
- Azimuthal anisotropy in pA and dA collisions
Introduction: Gluon saturation

Towards higher energy / smaller $x$: gluons split, number increases:

BFKL (Balitsky, Fadin, Kuraev, Lipatov) equation describes $x$-evolution but violates unitarity: cross-sections grow without bound

JIMWLK (Jalilian-Marian, Iancu, McLerran, Weigert, Leonidov, Kovner) and BK (Balitsky, Kovchegov) equations include non-linear evolution $\rightarrow$ saturation

$p_T \lesssim$ saturation scale $Q_s(x)$:

- strong saturated fields $A_\mu \sim 1/g$
- occupation numbers $\sim 1/\alpha_s$
- $\Rightarrow$ classical field approximation

Evolution equations determine $Q_s(x)$

$x = \text{longitudinal momentum fraction of partons in a hadron or nucleus}$

McLerran and Venugopalan, Phys.Rev. D49 (1994) 2233-2241
Saturation model for the color charge density

Energy and impact parameter $b$ dependence of $Q_s(x, b)$ can be modeled in the **IP-Sat model** Kowalski, Teaney, Phys.Rev. D68 (2003) 114005

Parametrize cross sections for DIS on protons and fit to HERA diffractive data $\rightarrow Q_s(x, b)$

For a nucleus sample nucleon positions and add all $T_p$

$$\frac{d\sigma_{\text{dip}}^p}{d^2x_\perp} (r_\perp, x, x_\perp) = 2 \mathcal{N}(r_\perp, x, x_\perp) = 2 \left[ 1 - \exp \left( -\frac{\pi^2}{2N_c} r_\perp^2 \alpha_s(Q^2) x g(x, Q^2) \sum_{i=1}^A T_p(x_\perp - x_{T,i}) \right) \right]$$

then determine $Q_s(x, x_\perp)$ ($\mathcal{N}(1/Q_s(x, x_\perp), x, x_\perp) = 1 - e^{-1/2}$)

Color charge density $g\mu(x, x_\perp)$ is proportional to $Q_s(x, x_\perp)$
Sample color charges $\rho^a$ from local Gaussian for each nucleus

$$\langle \rho^a(x_\perp) \rho^b(y_\perp) \rangle = \delta^{ab} \delta^2(x_\perp - y_\perp) g^2 \mu^2(x_\perp)$$

Color charges determine incoming color currents:

$$J_1^\nu = \delta^{\mu+} \rho_1(x^-, x_\perp)$$

$$[D_\mu, F^{\mu\nu}] = J_1^\nu$$

$$J_2^\nu = \delta^{\mu-} \rho_2(x^+, x_\perp)$$

$$[D_\mu, F^{\mu\nu}] = J_2^\nu$$

Solve Yang-Mills equations for the gauge fields $A^+(x^-, x_\perp) = -\frac{g \rho(x^-, x_\perp)}{\nabla_\perp^2 + m^2}$

Wilson line correlator shows degree of fluctuations in the gluon fields:
Fluctuation scale: $1/Q_s$
IP-Glasma: Gauge fields after the collision

Initial condition on the lightcone:

\[ A_\mu^{(1)} A_\mu^{(2)} A_\mu^{(3)} = 0 \]

Configuration in Schwinger gauge \( A^\tau = 0 \)

Solution:


\[
A^i_{(3)} |_{\tau=0} = A^i_{(1)} + A^i_{(2)} \\
A^\eta_{(3)} |_{\tau=0} = \frac{ig}{2} [A^i_{(1)}, A^i_{(2)}]
\]

We solve for the gauge fields numerically


Time evolution follows Yang-Mills equations
Compute energy density in the fields at $\tau = 0$
and later times with CYM evolution

for comparison:

arbitrary units
same nucleon positions in both events, impact parameter $b=4$ fm

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\( \frac{dN_g}{dy} \) in transverse Coulomb gauge \( \partial_i A^i = 0 \)

\( N_{\text{part}} \) from MC-Glauber with \( \sigma_{NN} = 42 \text{ mb} \) and \( 64 \text{ mb} \) respectively

Running coupling \( \alpha_s \left( \langle Q_s^{\text{max}} \rangle \right) \)


Normalized to RHIC data
IP-Glasma model gives a convolution of negative binomial distributions
No need to put them in by hand
Yang-Mills + viscous fluid-dynamic evolution

Energy density and initial flow velocity from $u_{\mu}T_{YM}^{\mu\nu} = \varepsilon u^\nu$
as input for fluid-dynamic simulation

Yang-Mills evolution
Yang-Mills + viscous fluid-dynamic evolution

Energy density and initial flow velocity from $u_\mu T_{YM}^{\mu\nu} = \varepsilon u^\nu$ as input for fluid-dynamic simulation
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Viscous flow at RHIC and LHC

RHIC $\eta/s = 0.12$

LHC $\eta/s = 0.2$

Lower effective $\eta/s$ at RHIC than at LHC needed to describe data
Hints at increasing $\eta/s$ with increasing temperature
Analysis at more energies can be used to gain information on $(\eta/s)(T)$

Experimental data:
Learning about QCD

Example: extraction of $(\eta/s)(T)$

Graph showing the approximate range of maximal initial temperatures probed by RHIC and the AdS/CFT limit. The graph also indicates possible temperature dependence and the approximate range of maximal initial temperatures probed by LHC.
Temperature dependent $\eta/s$

Use $\eta/s(T)$ as in Niemi et al., Phys.Rev.Lett. 106 (2011) 212302

Experimental data:  

One $(\eta/s)(T)$ will be able to describe both RHIC and LHC data

Used parametrization not yet perfect: no surprise

More detailed study needed - include different RHIC energies and LHC
Event-by-event distributions of $v_n$

Experimenatal data:
ATLAS collaboration, arXiv:1305.2942

0-5%

20-25%

Event-by-event distributions of $v_n$ - other models

Showing eccentricity distributions (yellow on the right)

Event-by-event distributions can distinguish between different initial state models → see Harri Niemi’s talk

Experimental data: ATLAS collaboration, arXiv:1305.2942
Establish a baseline for pp and pA/dA collisions

Note: Normalization depends on scale used in the running coupling. Using the produced gluon $k_T$, energy dependence is too weak. Need to include normalization $\propto \ln \sqrt{s}$ to account for this

$\eta$-dependence then comes from IP-Sat

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Multiplicity distributions in pp

Fluctuation of $Q_s$ needed to describe the multiplicity distribution in p+p

Result in red includes a smearing of $Q_s$ by 9% around its mean
Multiplicity distributions in pPb

\[ P( N_{\text{ch}} / \langle N_{\text{ch}} \rangle) \]

- IP-Glasma
- CMS preliminary \( N_{\text{track}} \)

note: comparing to uncorrected data

Schenke, Tribedy, Venugopalan, in preparation
d+Au collisions

IP-Glasma results differ significantly from a typical MC-Glauber model:

Energy density for the same nucleon positions:

In MC-Glauber all nucleons that are barely ’touched’ contribute fully to the energy density

an MC-Glauber implementation is used in e.g. P. Bozek, Phys.Rev. C85 (2012) 014911
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System size in p+p and p+Pb in the IP-Glasma model

Radius defined by where energy density reaches $\Lambda_{QCD}^4$ or $10\Lambda_{QCD}^4$
Radius scales with $(dN_g/dy)^{1/3}$ for low $dN_g/dy$
Eccentricities from different models can differ significantly

MC-Glauber 1: smeared energy density deposited around center of wounded nucleons

MC-Glauber 2: smeared energy density deposited around binary collision position
Hydro-evolution in d+Au

$t = 0.2 \text{ fm}$
Hydro-evolution in d+Au

t = 0.2 fm

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Flow generated by hydrodynamics alone is much smaller than experimental results when using IP-Glasma initial conditions and $\eta/s = 0.08$

How much $v_2(2\text{PC})$ comes from the initial state?

Compute two-particle correlations from the initial glasma state:
- compute $dN_g/dy d^2k_T$ from the Fourier transformed glasma fields
- compute the correlation

$$\frac{S(k_1, k_2, \Delta \phi)}{B(k_1, k_2, \Delta \phi)} = \frac{\left\langle \left\langle \frac{d^2N}{d^2k_T}(k_1, \phi_1) \frac{d^2N}{d^2k_T}(k_2, \phi_1 + \Delta \phi) \right\rangle \right\rangle_{\phi_1}}{\left\langle \left\langle \frac{d^2N}{d^2k_T}(k_1, \phi_1) \right\rangle \left\langle \frac{d^2N}{d^2k_T}(k_2, \phi_1 + \Delta \phi) \right\rangle \right\rangle_{\phi_1}}$$

which is $\propto \frac{1}{N_{\text{trig}}} \frac{dN_{\text{pair}}}{k_1 k_2 dk_1 dk_2 d\Delta \phi}$
- Fourier expand

$$\frac{1}{N_{\text{trig}}} \frac{dN}{d\Delta \phi} = \frac{N_{\text{assoc}}}{2\pi} \left[ 1 + \sum_n 2V_{n\Delta} \cos(n\Delta \phi) \right]$$

- Finally define

$$v_n(2\text{PC})(p_T) = \frac{V_{n\Delta}(p_T, p_T^{\text{ref}})}{\sqrt{V_{n\Delta}(p_T^{\text{ref}}, p_T^{\text{ref}})}}$$
Correlation functions with Fourier-fits

Near-side and away-side peaks are the same initially (no $v_3$) ... differ after rescattering in the evolution (introduces $v_3$)

todo: include additional correlations through JIMWLK evolution

Schenke, Venugopalan, preliminary
How much $v_2(2\text{PC})$ comes from the initial state?

$0.5 \text{ GeV} < p_T^{\text{ref}} < 4 \text{ GeV}$

Schenke, Venugopalan, preliminary

$v_2\{4\}$ in progress. Need lots of statistics.

no hydro
Is there an initial $v_3(2PC)$?

$0.3 \text{ GeV} < \frac{p_T^{\text{ref}}}{p_T} < 3 \text{ GeV}$

Schenke, Venugopalan, preliminary

No initial $v_3$! But significant build-up in Yang-Mills evolution.
Summary and conclusions

- IP-Glasma model + hydrodynamics very successful in describing higher flow harmonics in heavy-ion collisions
- Effective shear viscosity at RHIC smaller than at LHC
- Can reasonably reproduce multiplicity distributions in pp, pA, AA
- In small systems like p+Pb, initial shape and system size is very sensitive to model assumptions
- Hydro needs very small $\eta/s$ in p+Pb to get close to the observed $v_n$ - with IP-Glasma initial conditions it will not get there
- Significant initial $v_2$ from 2-particle correlations in the glasma
- No initial $v_3$, but built-up during Yang-Mills evolution
Flow in \( p+p \), \( p+Pb \) and \( d+Au \) collisions

Only qualitative scaling between flow and eccentricities

\( p+p \) (at \( b = 0 \) fm) and \( p+Pb \)

\[ \langle \nu_n^2 \rangle^{1/2} \text{ vs } N_{\text{part}} \]

\( p+Pb \): Elliptic flow decreases with \( N_{\text{part}} \)

\( d+Au \): Elliptic flow increases with \( N_{\text{part}} \)

\( p+p \): Elliptic flow small, but not as small as expected from eccentricity

Need sophisticated centrality selection to compare with experiments

**p+A collisions - is viscous hydro valid?**

Initial $\pi_0^{\mu\nu} = 0$, $b = 0$ fm, IP-Glasma. Cells within f.o. surface that have $> 25\%$ viscous correction in p+Pb and Pb+Pb:

![Graph](image)

Important: Lifetime in Pb+Pb is about 6 times longer than in p+Pb

Also see Dumitru, Molnar, Nara, Phys.Rev. C76 (2007) 024910
p+A collisions - is viscous hydro valid?

same with Navier-Stokes $\pi_0^{\mu\nu}$, count cells within f.o. surface that have more than a 25% viscous correction in p+Pb and Pb+Pb:

Important: Lifetime in Pb+Pb is about 6 times longer than in p+Pb
p+A collisions - is viscous hydro valid?

Initial Navier-Stokes $\pi_0^{\mu\nu}$, count cells within f.o. surface that have more than a 50% viscous correction in p+Pb and Pb+Pb:

Important: Lifetime in Pb+Pb is about 6 times longer than in p+Pb
$p_T$ distribution in pp

![Graph showing $p_T$ distribution in pp](image)

Charged hadrons from KKP fragmentation

Kniehl, Kramer, Potter, NPB582 (2000) 514

As expected, spectra are too hard as in the MV model

We do not include an anomalous dimension $\gamma$

Schenke, Tribedy, Venugopalan, in preparation

$p_T$ distribution in pPb

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Existing initial state models

There are several models of fluctuating initial conditions in HICs. Most commonly used with fluid-dynamic simulations:
Both include geometric fluctuations of nucleons in nucleus

- **MC-Glauber model**
  Participants determined from nucleon-nucleon cross-section
  Gaussian energy density assigned to each wounded nucleon

- **MC-KLN model**
  Saturation based model (we’ll get to that)
  Initial energy density from convolution of the two gluon distribution functions

Testing initial state models with higher harmonics

MC-KLN $\eta/s = 0.2$

MC-Glauber $\eta/s = 0.08$

Negative binomial fluctuations


Fluctuations in the total energy per unit rapidity produce negative binomial distribution (NBD).

\[ P(n) = \frac{\Gamma(k + n)}{\Gamma(k)\Gamma(n + 1)} \frac{\bar{n}^n k^k}{(\bar{n} + k)^{n+k}} \]

Good, since multiplicity in pp collisions can be described well with NBD.

In AA, convolution of NBDs at all impact parameters describes data well too.

P. Tribedy and R. Venugopalan

MC-KLN does not do that - these fluctuations need to be put in by hand.

see Dumitru and Nara arXiv:1201.6382
Eccentricities


Characterize the initial distribution by its ellipticity, triangularity, etc...

\[ \varepsilon_n = \sqrt{\langle r^n \cos(n\phi) \rangle^2 + \langle r^n \sin(n\phi) \rangle^2 / \langle r^n \rangle} \]

- \( \varepsilon_n \) larger in Glasma model for odd \( n \)
- \( \varepsilon_n \) smaller in Glasma model for \( n = 2 \) (for \( b > 3 \text{ fm} \))
  - about equal for \( n = 4 \), larger for \( n = 6 \)