Initial state azimuthal anisotropies in small collision systems

T. Lappi

University of Jyväskylä, Finland

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Outline

This talk:

▶ Dilute probe scattering off CGC field:
  particle production and correlations
▶ Azimuthal correlations $v_n$ from MV/JIMWLK target
▶ Relating different approximations for the dipole-dipole correlator

Based on:

▶ T. L., “Azimuthal harmonics of color fields in a high energy nucleus,”
▶ T. L., B. Schenke, S. Schlichting and R. Venugopalan,
  “Tracing the origin of azimuthal gluon correlations in the color glass condensate,”
Long range in rapidity: early time

- Long range rapidity correlations: early time
  - Analogous to CMB
- $v_n =$ multiparticle correlation
  (usually long range in rapidity)
- Geometry is the ultimate infinite-range correlation
  - All rapidities sensitive to $\perp$ geometry
  - Hydro translates $x$-space correlations into $p$-space

Initial state QCD long range effects:
non-geometry correlations directly in momentum space

Seen as yield/trigger or as $v_n$:
[arXiv:1409.1792 [hep-ex]].
Domains in the target color field

Initial state CGC correlations: dilute-dense limit

Particle production

- $\sim$ collinear high-$x$ $q/g$
- $p_T$ transfer from target $E$-field

Correlations:

- Domains of size $\sim 1/Q_s$
- Several particles, same domain $\implies$ azimuthal correlations.

- $\sim Q_s^2 S_\perp$ domains ($S_\perp =$ size of interaction area, $\pi R_A^2$, $\pi R_B^2$)
- $\sim N_c^2$ colors

Correlation $\frac{1}{N_c^2 Q_s^2 S_\perp} \implies$ relatively stronger in small systems

Dense-dense: domain structure same (details more complicated)
Explicit setup for dilute-dense

- Passage of probe particle through target: eikonal Wilson line in color field

\[ V(x_T) = P \exp \left\{ ig \int dx^- A^+_{\text{cov}}(x_T, x^-) \right\} \]

- Localize quarks in Gaussian wave packet in probe:

\[ \frac{dN}{d^2p_T} \propto \int_{x_T, y_T} e^{-i p_T \cdot (x_T - y_T)} e^{-\frac{(x_T - b_T)^2}{2B}} e^{-\frac{(y_T - b_T)^2}{2B}} \frac{1}{N_c} \text{Tr} V_{x_T}^\dagger V_{y_T} \cdot \]

- Two particle correlation

\[ \frac{dN}{d^2p_T d^2q_T} = \int \cdots \left\langle \frac{1}{N_c} \text{Tr} V_{x_T}^\dagger V_{y_T} \frac{1}{N_c} \text{Tr} V_{u_T}^\dagger V_{v_T} \right\rangle \quad \Rightarrow \quad \nu_n \{2\} \]

- Need distribution of Wilson lines \( V \) for \( \langle \rangle \):

MV or JIMWLK (in Langevin method)
Anisotropy coefficients from JIMWLK and MV


- $p_T$-structure like data, but peak at lower $p_T$
- Depends on probe size $B$
- Stronger for larger $x$ (MV)

- Thick line: reference is all $p_T$'s
- Thin line: reference is same $p_T$ bin

Target homogenous & isotropic

$\Rightarrow v_n$ from fluctuations, not geometry
Anisotropy coefficients from JIMWLK and MV

▶ $p_T$-structure like data, but peak at lower $p_T$
▶ Depends on probe size $B$
▶ Stronger for larger $x$ (MV)
▶ $v_4$ at higher $p_T$

- Thick line: reference is all $p_T$’s
- Thin line: reference is same $p_T$ bin

Target homogenous & isotropic
⇒ $v_n$ from fluctuations, not geometry
Anisotropy coefficients from JIMWLK and MV


- $p_T$-structure like data, but peak at lower $p_T$
- Depends on probe size $B$
- Stronger for larger $x$ (MV)
- $v_4$ at higher $p_T$
- Also odd $v_n$ (only for quark probe)

Target homogenous & isotropic

$\Rightarrow v_n$ from fluctuations, not geometry
Azimuthal correlations analyzed in terms of the

- “Glasma graph” ridge correlation

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Dusling, Venugopalan, Phys. Rev. D 87 (2013) 9, 094034
[arXiv:1302.7018 [hep-ph]].
Calculations in the literature

Azimuthal correlations analyzed in terms of the
- “Glasma graph” ridge correlation
- E-field domain model

[arXiv:1406.5781 [hep-ph]].
Calculations in the literature

Azimuthal correlations analyzed in terms of the

- “Glasma graph” ridge correlation
- E-field domain model
- Dilute dense with full nonlinear JIMWLK

Azimuthal correlations analyzed in terms of the

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- Dense-dense with Classical Yang-Mills

Calculations in the literature

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Physics of color field domains same; approximations different
Difference between approximations

Need \( \langle \text{Tr } V(x_T) V(y_T) \text{Tr } V(u_T) V(v_T) \rangle \)

Often parametrized as \( V(x_T) = P \exp \left\{ ig \int dx^- \rho(x_T, x^-) \nabla_T^2 \right\} \),

Approximations in dilute-dense

- JIMWLK: Langevin equation for \( V(x_T) \).
  Close to Gaussian in \( \rho \), but nonlinear ("nonlinear Gaussian")
- "Glasma graph": linearize in \( \rho \), Gaussian \( \rho \)
- "E-field domain model", small dipole limit

\[
\frac{1}{N_c} V^\dagger(b_T + r_T/2) V(b_T - r_T/2) \approx 1 - \frac{r_i r_j}{4N_c} E_i^a(b_T) E_j^a(b_T)
\]

+ non-Gaussian 4-point correlation with extra parameter \( \Lambda \)

CYM: nonlinear with Gaussian \( \rho \) for both nuclei

+ final state evolution
Numerical comparison of approximations


Compare full MV or JIMWLK $v_n \{2\}$ to

- Nonlinear Gaussian (Gaussian $\rho$, do not linearize):
  accurate within 10%

- "Glasma graph" (Gaussian + linearized)
  differs by factor 2 at most

Remarkable consistency between approximations
Effect of reference $p_T$

- Correlation more localized in $p_T$ than experimental data
  (Hadronization will change this, but how much?)
- MV
  - GG decorrelates particularly fast
- JIMWLK:
  - Little difference between approximations
\[ \langle E^i E^j \rangle \sim \left[ \delta^{ij} (1 - A) + 2 A \hat{a}^i \hat{a}^j \right] \]

Then average over color field direction \( \hat{a} \).
Result: non-Gaussianity with unknown parameter \( A \):

\[ \langle E E E E \rangle = \left( 3 \text{ Gaussian} + \hat{a}^2 \text{ from } \hat{a} \right) \langle E E \rangle \langle E E \rangle \]

What does \( A \) represent?

1. Effect of nonlinearities? (Gaussian \( \rho \), but nongaussian \( V \))
   “Glasma graph” linearization is factor \( \sim 2 \) effect.

2. Nongaussianities from JIMWLK?
   \( \sim 10\% \) effect, but interesting for theorist.

3. New structure beyond conventional CGC (MV+JIMWLK)?
   Origin? Timescales? \( N_c \)-counting?
Conclusions

Initial gluon field contribution to $v_n$'s

- Can be significant contribution to observed flow signal, especially for small systems
- Hadronization, $p_T$-dependence?
- Calculated in different approximations of CGC
  Differences in terminology, but same physical picture

For the future: rapidity structure

- All of these neglect decorrelation in rapidity due to gluon emissions, parametrically important for $\Delta y \gtrsim 1/\alpha_s$
- Rapidity decorrelation formulated
  but not implemented
MV/JIMWLK: correlation is $N_c$-suppressed

\[ \sqrt{N_c^2 - 1} v_n \text{ independent of } N_c \implies v_n \sim 1/N_c \]