Initial conditions in AA and pA collisions

T. Lappi

University of Jyväskylä, Finland

Confinement XII, Thessaloniki
Outline

- From nuclear wavefunction to collision
  - Small $x$ and saturation
  - Classical Yang-Mills
- Control experiments: probing small $x$
- Long range correlations: direct signs of initial state in data?
Initial state is small $x$

- Gluons ending in central rapidity region: multiple splittings from valence quarks
- Emission probability $\alpha_s \frac{dx}{x}$
  \[ \Rightarrow \] rapidity plateau for $\Delta y \ll /\alpha_s$
- Many gluons, in fact
  \[
  N \sim \sum_n \frac{1}{n!} (\alpha_s \ln \sqrt{s})^n \sim \sqrt{s}^{\alpha_s}
  \]
Small $x$ and saturation

- Eventually gluons in cascade overlap
- YM covariant derivative
  
  $$-iD_\mu = -i\partial_\mu + gA_\mu = p_\mu + gA_\mu$$

- Nonlinearities when $p_T \sim gA_\perp \sim Q_s$
  
  $$\implies A_\perp \sim Q_s/g$$

  (LC gauge gluons have $\mu \rightarrow \perp$)

Weak coupling, but nonperturbative

- $\alpha_s$ small
- $f(k) \sim A_\mu A_\mu \sim 1/\alpha_s$ large

True when $Q_s \gg \Lambda_{\text{QCD}}$

$$\implies$$ gets better at large $\sqrt{s}$
Wilson line

Classical color field described as Wilson line

\[ V(x_T) = P \exp \left\{ ig \int dx^- A_{\text{cov}}^\dagger(x_T, x^-) \right\} \in SU(3) \]

Physical interpretation:
Eikonal propagation of parton through target color field

\( Q_s \) is characteristic momentum/distance scale

Precise definition used here:

\[ \frac{1}{N_C} \left\langle \text{Tr} \ V^\dagger(0_T) V(x_T) \right\rangle = e^{-\frac{1}{2}} \]

\[ \leftrightarrow \quad x_T^2 = \frac{2}{Q_s^2} \]
Classical Yang-Mills initial state

Classical Yang-Mills

Change to LC gauge:

\[ A^i_{(1,2)} = \frac{i}{g} g_{(1,2)}(x_T) \partial_i U^\dagger_{(1,2)}(x_T) \]

Same Wilson line \( U(x_T) \)

\( \eta = \text{cst.} \)

\( \tau = \text{cst.} \)

\( A^\mu = \text{pure gauge 1} \)

\( A^\mu = \text{pure gauge 2} \)

\( A^\mu = 0 \)
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At \( \tau = 0 \):

\[ A^i|_{\tau=0} = A^i_{(1)} + A^i_{(2)} \]

\[ A^\eta|_{\tau=0} = \frac{ig}{2} [A^i_{(1)}, A^i_{(2)}] \]
Classical Yang-Mills initial state

Classical Yang-Mills

$A_\mu = \text{pure gauge 1}$

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$A_\mu = \text{pure gauge 2}$

$\eta = \text{cst.}$

$\tau = \text{cst.}$

$\tau > 0$ Solve Classical Yang-Mills CYM equations.

This is the glasma field $\implies$ Then average over $U(x_T)$.

In dilute limit reduces to $k_T$-factorization.

Change to LC gauge:

$A^i_{(1,2)} = \frac{i}{g} U_{(1,2)}(x_T) \partial_i U^\dagger_{(1,2)}(x_T)$

Same Wilson line $U(x_T)$

At $\tau = 0$:

$A^i|_{\tau=0} = A^i_{(1)} + A^i_{(2)}$

$A^\eta|_{\tau=0} = \frac{ig}{2} [A^i_{(1)}, A^i_{(2)}]$
Properties of the glasma initial state

- $\tau = 0$: longitudinal $E$ and $B$ field,
- At $\tau \gtrsim 1/Q_s$: gluons with $p_T \sim Q_s$ — strings of size $R \sim 1/Q_s$
- Correlation length $1/Q_s$

Pressure components:

\[
P_\perp = \frac{1}{2} \left( E_L^2 + B_L^2 \right) \sim \frac{1}{\tau}
\]

\[
P_L = \frac{1}{2} \left( E_\perp^2 + B_\perp^2 - E_L^2 - B_L^2 \right)
\ll P_\perp \implies \text{anisotropy}
\]

Talks Zhu (Mon), Kurkela (Fri)
Universality in the IR

Dumitru, T.L., Nara 2014

Gluon spectrum:
- UV depends on initial condition
- IR scales, close to

\[ \frac{dN}{d^2p_T} \sim \frac{1}{\rho_T} \]
Universality in the IR

Dumitru, T.L., Nara 2014

Gluon spectrum:
- UV depends on initial condition
- IR scales, close to
\[
\frac{dN}{d^2 p_T} \sim \frac{1}{p_T}
\]

Spatial Wilson loop:
\[
W = \exp \{-(\sigma A)\gamma\}
\]
- UV (small loop): initial slope \(\gamma\) stays
- IR (big loop): universal area law
Dilute-dense control measurements
DIS at small $x$: dipole picture

- CGC: dipole cross section is Wilson line correlator

\[
\sigma_{q\bar{q}}(r_T) = \int d^2 b_T \frac{1}{N_c} \text{Tr} \left\langle 1 - U^\dagger \left( b_T + \frac{r_T}{2} \right) U \left( b_T - \frac{r_T}{2} \right) \right\rangle
\]

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

- High energy: energy dependence from JIMWLK (for $U$) or BK (for $\sigma_{q\bar{q}}$) equations

Total DIS cross section

\[
\sigma^{\gamma^* H}_{\text{tot}} = |\Psi(\gamma^* \rightarrow q\bar{q})|^2 \otimes \sigma_{q\bar{q}}
\]

Same Wilson line $U(x_T)$ as in initial glasma color field.
Control measurement 1: DIS

Initial state description should:

- Be consistent with DIS measurements from HERA, e.g.

Proton $F_2$ rcBK
T.L., Mäntysaari

Proton $F_2^C$ IPsat
Rezaeian et al

- Give testable predictions for EIC.
Control measurement 2: $R_{pA}$

$R_{pA}$ = Cross section ratio between $pp$ and $pA$ collisions

- Need **unintegrated** gluon distribution
  - Fourier transform of dipole cross section
- Normalization corrected with “$K$-factor” (Cancels in $R_{pA}$)
- Nuclear geometry

Compare with state of the art BK evolution in 2010:

![Graphs showing $R_{pA}$ vs. $p_T$ (GeV) for different energies and N_{coll}](image)

Albacete, Marquet arXiv:1001:1378

Similar $r_{cBK}$ — main difference is nuclear geometry

Similarly: $J/\psi$ $R_{pA}$: Ducloué., T.L., Mäntysaari 2015

T.L., Mäntysaari, arXiv:1309.6963
Moving to NLO: BK evolution

- Balitsky-Kovchegov equation: energy dependence of dipole cross section.
- LO (≈1995): used routinely
- NLO equation: Balitsky, Chirilli 2008

Equation unstable: Plot here: T.L., Mäntysaari 2015
Resummation of double logs: Iancu et al
Resummation & finite NLO: T.L., Mäntysaari 2016
With suitable scale choice: finite NLO part small

See also previous talk: Triantafyllopoulos: first actual fit to HERA DIS data
Single inclusive particle production at NLO

- NLO calculation: Chirilli, Xiao, Yuan 2012
- Cross section negative: Stasto, Xiao, Zaslavsky 2013

Ducloué, T.L., Zhu arXiv:1604.00225:
Problem is subtraction in BK-factorization:
  - Identify from color factor ($N_c < \infty$!)
  - Solution: probe $\rightarrow$ target momentum ordering

Iancu, Mueller, Triantafyllopoulos arXiv:1608.05293:
new manifestly positive formulation
Correlations: direct signals of initial state?
Long range in rapidity: early time

See also talk by S. Schlichting

- 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

ATLAS arXiv:1409.1792
Domains in the target color field

Initial state CGC correlations in dilute-dense limit

- \( \sim \) collinear high-\( x \) \( q/g \)
- Momentum transfer from target \( E \)-field
- Domains of size \( \sim \frac{1}{Q_s} \)
- Several particle see same domain: multiparticle azimuthal correlations.

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

Correlation \( \frac{1}{N_c^2 Q_s^2 S_\perp} \implies \) relatively stronger in small systems
Initial state angular correlation calculations

Analyzed in terms of the

- Ridge correlation

Dusling, Venugopalan, arXiv:1302.7018
Initial state angular correlation calculations

Analyzed in terms of the

- Ridge correlation
- E-field domain model

Dumitru, Giannini arXiv:1406.5781
Initial state angular correlation calculations

Analyzed in terms of the

- Ridge correlation
- E-field domain model
- Dilute dense with full nonlinear JIMWLK

T.L., arXiv:1501.05505
Initial state angular correlation calculations

Analyzed in terms of the

- Ridge correlation
- E-field domain model
- Dilute dense with full nonlinear JIMWLK
- Dense-dense with CYM

Schenke, Schlichting, Venugopalan

arXiv:1502:01331
Initial state angular correlation calculations

Analyzed in terms of the

- Ridge correlation
- E-field domain model
- Dilute dense with full nonlinear JIMWLK
- Dense-dense with CYM

Main physics idea in these is the same; approximations in the calculations different.
Difference between approximations

For $V(x_T) = P \exp \left\{ ig \int d\rho(x_T, x^-) \frac{\rho(x_T, x^-)}{\nabla T^2} \right\}$,

need $\left\langle \text{Tr} \ V^\dagger(x_T) V(y_T) \text{Tr} \ V^\dagger(u_T) V(v_T) \right\rangle$

Different approximations used

- “Nonlinear Gaussian”: Gaussian in $\rho$ + nonlinear $\rho \rightarrow V$
- “Glasma graph”: linearize in $\rho$, Gaussian $\rho$
- “E-field domain model”, small dipole limit + intrinsic non-Gaussianity
- CYM: nonlinear with Gaussian $\rho$ for both nuclei + final state evolution

More recent focus: decorrelations for parametrically large rapidity separations. See talk by S. Schlichting
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
Conclusions

- CGC picture of initial stage of an AA collision: nonperturbatively strong, classical gauge fields \( \Rightarrow \) anisotropic system of gluons
- Dilute-dense control processes: moving to NLO accuracy
- Correlations \((v_n)\) in small systems: interplay between initial and final state collective effects
Initial state extraction from hydro?

Hydro, Bayesian global fit Bernhard et al arXiv:1605.03954

Initial entropy density parametrized as

\[
s(x_T) \sim \left( \frac{(T_A(x_T))^p + (T_B(x_T))^p}{2} \right)^{\frac{1}{p}}
\]

Heavy ion data favors particle production from gluon saturation \((p \approx 0)\):

![Graph showing KLN, EKRT, and WN models with p on the x-axis and other parameters on the y-axis.](image)
Effect of reference $p_T$

**MV**

$\rho_{T_{\text{ref}} = \text{all}}$

$\rho_{T_{\text{ref}} = p_T}$

**JIMWLK**

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