EIC at small-$x$ : connections to $p+p/A$ & $A+A$ physics at RHIC & LHC

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Outline

- HERA e+p data & modeling p+p/A & A+A collisions at small-x
- Correlation measurements & phenomenology at RHIC/LHC
- Towards phenomenology of EIC: can lessons from RHIC/LHC help?
The reactions/collisions at relativistic energies ($E >> m$)

A standard model of heavy ion collisions:

- **A+A**
  - Initial Singularity
  - CGC
  - Glasma
  - sQGP
  - Hadron Gas

- **p+A**

- **p+p**

Relativistic collisions

- **e+A**

**Future (>2025): The Electron Ion collider**

Future (EIC) vs Past (HERA)

At small-$x$ → universal framework for $e+p$, $e+A$ to $p+p$, $p+A$ & $A+A$

The landscape of QCD

Aschenauer *et al.*, arXiv:1708.01527

- **RHIC and LHC** (present days)

Elastic proton-proton collisions ($p+p$)

Parton Density vs Energy ($\sqrt{s}$)

- **Strongly Correlated Quark-Gluon Dynamics**
- **Linear evolution**
- **Non-linear evolution**
- **High-Density Gluon Matter**

Hardness of the probe vs Resolution

- **Q^2 (GeV^2)**
- **Quarks and Gluons**
- **Confinement, Chiral Symmetry Breaking**
- **Pomerons Regge trajectories**
- **Energy ($\sqrt{s}$)**

Future (EIC) vs Past (HERA)
Universal approach at small-x
Where are the connections?

Flow chart of phenomenology in p+p/A & A+A at high energy, small-x

Input (Requirements)
- DIS $e+p$ cross section
- $Q_s(x,b)$
- dipole-nuclei S-Matrices

Framework
- Color Glass Condensate
- LC gauge-fields
- $U(x,b)$
- Stress-Energy Tensor
- $n$-gluon distributions
- DP, WW TMDs $(G,h)$

Output
- Pythia
- $p+p/A$
- Hydro
- $p/d/A+A$
- Pythia
- $e+p/A$

State-of-the art phenomenology at RHIC/LHC

P.Tribedy, CIPANP, Palm Spring, 2018
Where are the connections?

HERA (diffractive DIS)

- DIS e+p cross section
- dipole-nuclei S-Matrices
  - $Q_s(x,b)$

Color Glass Condensate (LC gauge-fields)

- $U(x,b)$
- DP, WW TMDs (G,h)

RhIC/LHC (di-hadron correlations)

- $n$-gluon distributions
- Stress-Energy Tensor
- Pythia
  - $p+p/A$
  - $p/d/A+A$
  - $e+p/A$

Phenomenology at RHIC/LHC is constrained by e+p HERA data

EIC (new observables)
Biggest uncertainty: initial stages of the colliding nuclei

Transverse geometry: our understanding has improved over the years
Longitudinal structure: we have only started to explore

EIC→ ultimate machine, how can we use the lessons from RHIC/LHC
Experimental observables in p+p/A,A+A
Long range azimuthal correlations: Ridge

Ridge phenomenon (most striking and widely studied):
Di-hadron correlations in relative pseudorapidity ($\Delta \eta$) & azimuth ($\Delta \phi$)
High multiplicity $p+p/A$ $\rightarrow$ strikingly similar to $A+A$
Ridge across different collision systems

No ridge appears in e+e, e+p, and low multiplicity p+p/A collisions

Interesting systematics with collisions system
The qualitative picture: what drives ridge?

Dynamics of early time spread over wide range of rapidity

Causality limits signals from different $\tau$ to spread at different $\Delta \eta$

Long-range rapidity correlations $\rightarrow$ generated at early times

Dumitru et al 0804.3858

$C'(\Delta \eta)$

Short-range
Intermediate
Long-range
The qualitative picture: what drives ridge?

Initial state correlations (colliding hadrons/nuclei)

Momentum space correlations

(Mini-) jets, n-parton correlations

Fragmentation

Position space correlations

Initial spatial anisotropy

Transport, Hydrodynamic

Experimentally observed correlations (both should contribute)
Phenomenology at small-x

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Output

- Pythia
  - n-gluon distributions
  - Stress-Energy Tensor
  - DP, WW TMDs (G,h)
- Hydro
  - p/d/A+A
- Pythia
  - e+p/A

State-of-the art phenomenology at RHIC/LHC
Colliding protons at small-x

Ridge → long-range correlations → driven by initial state effects

Ridge probes the wave function of colliding hadrons/nuclei

Momentum Space

Most gluons are here (∼ Q_s)

transverse momentum of gluon (GeV)

Kowalski, Teaney hep-ph/0304189v3

Coordinate Space

Input : HERA DIS e+p coherent diffractive cross section :

\[ \frac{d \sigma}{d t} \]
Colliding nuclei at small-\(x\) : IP-Sat/Glasma

Nucleus → multiple scattering centers (from Glauber) + IP-Sat :

\[
S_A^\text{dip}(r_\perp, x, b_\perp) = \prod_{i=0}^{A} S_i^\text{dip}(r_\perp, x, b_\perp)
\]

\(Q^2_{s,A}(\sqrt{s}) \sim A^{1/3} Q^2_{s,\text{proton}}(\sqrt{s}) \rightarrow \) less boost is needed to saturate nuclei

One obtains saturation scales for different configurations of a nucleus
Phenomenology at small-\(x\)

Flow chart of phenomenology in p+p/A & A+A at high energy, small-\(x\)

Input (Requirements)

- DIS \(e+p\) cross section
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Framework

- Color Glass Condensate
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- Pythia
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- \(e+p/A\)

State-of-the-art phenomenology at RHIC/LHC
Color Glass Condensate, MV model, Glasma

- Fundamental objects are Color Charge density matrices $\rho^a(x_\perp, y)$, local Gaussian distribution $W[\rho]$ (MV-Model)

$$\langle \rho^a(x_\perp) \rho^b(y_\perp) \rangle \propto \delta^{ab} \delta^2(x_\perp - y_\perp) Q_s^2(x_\perp)$$

- Color field before collisions: solving Yang Mills equations for each configuration of source $\rho(x_\perp)$ & current $J^\nu = \delta^\nu \rho(x_\perp)$

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

- Compute & evolve the color fields after collisions:

$$A^i = A^i(A) + A^i(B) \quad A^\eta = \frac{ig}{2} \left[ A^i(A), A^i(B) \right]$$

Light-cone gauge fields $A^i(x_\perp)$

→ Building blocks for any calculation

Phenomenology at small-\(x\)

Flow chart of phenomenology in p+p/A & A+A at high energy, small-\(x\)

Input (Requirements)

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Output

- Pythia
- Hydro
- Pythia

- n-gluon distributions
- Stress-Energy Tensor
- DP, WW TMDs (\(G,h\))

State-of-the-art phenomenology at RHIC/LHC
**Initial state correlations**

Momentum space correlations: n-gluon distribution

\[
\frac{dN_g}{dy} = 2 \frac{g^2}{N^2} \int \frac{d^2k_T}{k_T} \left[ \frac{g^2}{\tau} \text{tr} \left( E_i(k_\perp)E_i(-k_\perp) \right) + \tau \text{tr} \left( \pi(k_\perp)\pi(-k_\perp) \right) \right]
\]

Input to PYTHIA, p+p/A collisions

Position space correlations: Stress-Energy Tensor

\[
T^{\mu\nu} = -g^{\gamma\delta} F^\mu_{\gamma} F^\nu_{\delta} + \frac{1}{4} g^{\mu\nu} F^\gamma_{\delta} F^\delta_{\gamma}
\]

Input to hydro, transport, p+A, A+A collisions

Light-cone gauge-fields

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

Wave functions: Dipole-gluon & WWs TMDs

\[
x G^{ij}_{WW}(x, k) = \frac{8\pi}{L^2} \int \frac{d^2x_T}{(2\pi)^2} \frac{d^2y_T}{(2\pi)^2} e^{-i k_T \cdot (x_T - y_T)} \times \left\langle A^i_a(x_T)A^j_a(y_T) \right\rangle
\]

Input for EIC observables e+p/A collisions
Momentum space correlations

Momentum space correlations: n-gluon distribution

\[ \frac{dN_g}{dy} = \frac{2}{N^2} \int \frac{d^2k_T}{k_T} \left[ \frac{g^2}{\tau} \text{tr} (E_i(k_\perp)E_i(-k_\perp)) + \tau \text{tr} (\pi(k_\perp)\pi(-k_\perp)) \right] \]

Input to PYTHIA, p+p/A collisions

Light-cone gauge-fields

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Position space correlations: Stress-Energy Tensor

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Input to hydro, transport, p+A, A+A collisions

Wave functions: Dipole-gluon & WWs TMDs

\[ xG_{WW}^{ij}(x, k) = \frac{8\pi}{L^2} \int \frac{d^2x_T}{(2\pi)^2} \frac{d^2y_T}{(2\pi)^2} e^{-ik_T \cdot (x_T - y_T)} \times \langle A^+_i(x_T) A^+_a(y_T) \rangle \]

Input for EIC observables e+p/A collisions

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Success of small-x phenomenology in p+p/A

Momentum space correlations: n-gluon distribution

\[
\frac{dN_g}{dy} = \frac{2}{N^2} \int \frac{d^2k_T}{k_T} \left[ g^2 \frac{\text{tr} \left( E_i(k_{\perp})E_i(-k_{\perp}) \right)}{\tau} + \tau \left( \pi(k_{\perp})\pi(-k_{\perp}) \right) \right]
\]

Input to PYTHIA, p+p/A collisions

\[ T_{\mu\nu} = g F_{\mu\nu} + \frac{1}{4} g_{\mu\nu} F_{\lambda\sigma} F^{\lambda\sigma} \]

Schenke, Schlichting, PT, Venugopalan 1607.02496

\[ C(\Delta\phi, \Delta\eta) \]

Mace, Skokov, PT, Venugopalan 1805.09342

\[ v_2(\{2\}) \]

\[ p+Au \sqrt{s_{NN}}=200 \text{ GeV } 0.5\% \]

P.Tribehy,CIPANP, Palm Spring, 2018
Position space correlations

n-gluon distribution

\[ \frac{dN_g}{dy} = \frac{2}{N^2} \int \frac{d^2k_T}{k_T} \left[ \frac{g^2}{\tau} \text{tr} \left( E_i(k_{\perp}) E_i(-k_{\perp}) \right) + \tau \text{tr} \left( \pi(k_{\perp}) \pi(-k_{\perp}) \right) \right] \]

Input to PYTHIA, p+p collisions

Light-cone gauge-fields

Position space correlations : Stress-Energy Tensor

\[ T^{\mu\nu} = -g^{\gamma\delta} F^{\mu\gamma}_{\nu \delta} + \frac{1}{4} g^{\mu\nu} F^{\gamma}_{\delta \gamma} F^{\delta}_{\gamma} \]

Input to hydro, transport, p+\(A\), A+A collisions

Dipole-gluon & WWs TMDs

\[ xG^{ij}_{WW}(x, k) = \frac{8\pi}{L^2} \int \frac{d^2x_T}{(2\pi)^2} \frac{d^2y_T}{(2\pi)^2} e^{-ik\cdot(x_T-y_T)} \times \langle A^i_a(x_T)A^j_a(y_T) \rangle \]

Input for EIC observables e+p/A collisions
Success of small-$x$ phenomenology in $p/A+A$

Position space correlations: Stress-Energy Tensor

$$T^{\mu\nu} = -g^{\gamma\delta} F_{\mu\nu} F_{\gamma\delta} + \frac{1}{4} g^{\mu\nu} F_{\gamma\delta} F_{\gamma\delta}$$

Input to hydro, transport, $p+A$, $A+A$ collisions

Gale, Jeon, Schenke, PT, Venugopalan 1209.6330
Mantysaari, Schenke, Shen, PT 1705.03177
How about EIC observables?

n-gluon distribution

\[
\frac{dN_g}{dy} = \frac{2}{N^2} \int \frac{d^2k_T}{k_T} \left[ \frac{g^2}{\tau} \text{tr}(E_i(k_\perp)E_i(-k_\perp)) + \tau \text{tr}(\pi(k_\perp)\pi(-k_\perp)) \right]
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Input to PYTHIA, p+p collisions

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\]

Input for EIC observables e+p/A collisions

P.Tribeedy, CIPANP, Palm Spring, 2018
Towards phenomenology of EIC

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Steps towards EIC observables

General ingredients: TMDs that appear in different processes

Dipole gluon distribution (DP): \((G^{(2)}) + \) linearly polarized partner \((h^{(2)})\).

Weizsacker-Williams (WW): gluon distribution \((G^{(1)}) + \) linearly polarized partner \((h^{(1)})\).

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<th>(pA \rightarrow \gamma \text{jet} X)</th>
<th>(e p \rightarrow e' Q \overline{Q} X)</th>
<th>(e p \rightarrow e' j_1 j_2 X)</th>
<th>(p p \rightarrow \eta_{c,b} X)</th>
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Table: D. Boer 1611.06089, V. Skokov

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Inclusive dijets at the EIC


Azimuthal anisotropy in DIS dijet production are long range & probe WW TMDs in nuclei

Weizsacker-Williams (WW) : gluon distribution \(G^{(1)}\) + linearly polarized partner \(h^{(1)}\)

Rapidity imbalance \(\xi = \log \frac{1 - z}{z}\)

Relative azimuth \(\phi = (\vec{P}_\perp \cdot \vec{q}_\perp) / (|\vec{P}_\perp| |\vec{q}_\perp|)\)

Analogy to \(\Delta \eta - \Delta \phi\) ridge
Step 1: TMDs from the IP-Sat model for nuclei

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

\[ A^i(x_T) = \frac{1}{ig} U^\dagger(x_T) \partial_i U(x_T) \]

We apply the approach similar to small-x phenomenology in p+A, A+A.

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Weizsacker-Williams gluon distributions

\[ xG^{ij}_{\text{WW}}(x, \vec{k}) = \frac{8\pi}{L^2} \int \frac{d^2x_T}{(2\pi)^2} \frac{d^2y_T}{(2\pi)^2} e^{-i\vec{k} \cdot (\vec{x}_T - \vec{y}_T)} \langle A^i_a(x_T) A^j_a(y_T) \rangle \]

\[ Q_s^2(x_\perp, y_\perp) \]

\[ xG^{(1)}(q_x, q_y) \]

\[ xG^{ij}_{\text{WW}} = \frac{1}{2} \delta^{ij} xG^{(1)} - \frac{1}{2} \left( \delta^{ij} - 2 \frac{k^i k^j}{k^2} \right) xh^{(1)}_{\perp} \]
Weizsacker-Williams gluon distributions

\[ xG_{WW}^{ij} = \frac{1}{2} \delta^{ij} x \langle G(1) \rangle - \frac{1}{2} \left( \delta^{ij} - 2 \frac{k^i k^j}{k^2} \right) x h_{\perp}^{(1)} \]

TMDs for different nuclei at fixed rapidity, JIMWLK evolution left for future work
Step 2: WW gluon distributions & q-qbar jets in DIS

\[ xG_{WW}^{ij} = \frac{1}{2} \delta^{ij} xG^{(1)} - \frac{1}{2} \left( \delta^{ij} - 2 \frac{k^i k^j}{k^2} \right) xh_\perp^{(1)} \]

\[ E_1 E_2 \frac{d\sigma^{* \gamma_L} A \rightarrow q\bar{q} X}{d^3k_1d^3k_2d^2b} = \alpha_em^2 \alpha_s \delta(x_\gamma^* - 1) z^2 (1 - z)^2 \frac{8\epsilon_f^2 P_\perp^2}{(P_\perp^2 + \epsilon_f^2)^4} \times \left[ xG^{(1)}(x, q_\perp) + \cos(2\phi) xh_\perp^{(1)}(x, q_\perp) \right] \]

Quark-antiquark jet correlation azimuthal anisotropy in DIS

Large long-range azimuthal correlations in DIS dijet production predicted which probes WW TMDs in nuclei
Another connection: chiral magnetic effect

QCD anomaly driven chirality imbalance leads to electric current along B-field

RHIC is doing isobar collisions to search for the Chiral Magnetic Effect

Images of RHIC experiments showing neutrons and protons with arrows indicating the direction of the magnetic field.

Signals of CME → Axial charge density correlator:

$$\propto (G_{A1}^{(1)}(x, y))^2 (G_{A2}^{(1)}(x, y))^2 - (h_{A1}^{(1)}(x, y))^2 (h_{A2}^{(1)}(x, y))^2$$

Experimental observable: charged dependent azimuthal correlations

This also probes TMDs (will enable us to make better predictions for EIC)
Summary

Constraints from DIS + CGC framework have revolutionized p+p, p+A, A+A phenomenology over past years at RHIC & LHC energies.

Long range azimuthal anisotropy is the key observable across different systems.

We can follow the same path of EIC:

- The fundamental ingredients are TMDs for EIC observables.
- TMDs can be estimated consistently in the small-x approach.
- Large long-range $\cos(2\phi)$ anisotropy in DIS dijets is predicated to probe TMDs.

Lessons from RHIC/LHC will be helpful to build Monte-Carlo generators for EIC.
Thank you