“Understanding the Heavy Ion Initial State with Diffraction at the EIC”
QEIC, IIT Bombay

January 5, 2020
Tobias Toll
IIT Delhi
Our Understanding of Gluons

\[ x \sim \frac{1}{3} \]
Our Understanding of Gluons

\[ x \sim 1/6 \]

\[ \Delta t \propto \frac{1}{V} \]
Our Understanding of Gluons

\[ x \sim \frac{1}{9} \]

\[ \Delta t \propto \frac{1}{V} \]
Our Understanding of Gluons

\[ x \sim 1/12 \]

\[ \Delta t \propto \frac{1}{V} \]
Our Understanding of Gluons

\[ \Delta t \propto \frac{1}{V} \]
Our Understanding of Gluons

$Q^2$

Probing Photon

$V_1 < V_2 < V_3$

Valence quark

Dokshitzer Gribov Lipatov Altarelli Parisi DGLAP
Our Understanding of Gluons

\[ Q^2 \]

Probing Photon

\[ V_1 < V_2 < V_3 \]

Valence quark

Dokshitzer Gribov Lipatov Altarelli Parisi DGLAP
DGLAP in e+p collisions at HERA?

\[ \sigma_r(x, Q^2) = F_2^A(x, Q^2) - \frac{y^2}{Y} F_L^A(x, Q^2) \]

**quark+anti-quark momentum distributions**

**gluon momentum distribution**

**HERA Structure Functions Working Group**

DGLAP in e+p collisions at HERA?

\[ \sigma_r(x, Q^2) = F^A_2(x, Q^2) - \frac{y^2}{Y + F_L^A(x, Q^2)} \]

**HERA F**

- ZEUS NLO QCD fit
- H1 PDF 2000 fit
- H1 94-00
- H1 (prel.) 99/00
- ZEUS 96/97
- BCDMS
- E665
- NMC

**quark-anti-quark momentum distributions**

**gluon momentum distribution**

**HERA-I PDF (prel.)**

- experimental uncertainty
- model uncertainty

HERA Structure Functions Working Group

**Q^2 = 10 GeV^2**

\[ x_U, x_d, x_g (\times 1/20) \]

\[ x_S (\times 1/20) \]
DGLAP in e+p collisions at HERA?

\[ \sigma_r(x, Q^2) = F_2^A(x, Q^2) - \frac{y^2}{Y + F_L^A(x, Q^2)} \]

**HERA F₂**

- ZEUS NLO QCD fit
- H₁ PDF 2000 fit

**HERA-I PDF (prel.)**

- experimental uncertainty
- model uncertainty

\( Q^2 = 10 \text{ GeV}^2 \)

quark + anti-quark momentum distributions

**gluon momentum distribution**

\( r(x, Q^2) = F_A^2(x, Q^2) + F_A^L(x, Q^2) \)

\( Y^2 = x \)
Our understanding of some fundamental properties of the Glasma, sQGP and Hadron Gas depend strongly on our knowledge of the initial state!
Our understanding of some fundamental properties of the Glasma, sQGP and Hadron Gas depend strongly on our knowledge of the initial state!

3 Questions best answered by (Exclusive) Diffraction

How do gluons Saturate?
How are gluons distributed?
How are gluons fluctuating?

In Protons and Nuclei
Elliptic Flow – Indicator for Early Thermalization

Sensitive to early interactions and pressure gradients

In ideal hydrodynamics $v_2 \propto$ spatial eccentricity $\epsilon_2$: 
$$\epsilon_2 = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle}$$

$v_2/\epsilon$ versus particle density is sensitive test of ideal hydrodynamic:

$$\frac{v_2}{\epsilon_2} = \frac{h}{1 + B / \left( \frac{1}{S} \frac{dN}{dy} \right)}$$

$S$= transverse area, 
$h$ = hydro limit of $v_2/\epsilon$ and $B \propto \eta/s$
Different initial distributions gives different flows!

\[ \epsilon_2 = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle} \]

Two methods for \( \epsilon \):
- Glauber (non-saturated)?
- CGC (saturated)?

**KLN(CGC)**

**Glauber (Woods-Saxon)**

The question is what is \( \epsilon \)?
RHIC & LHC: low-\( p_T \) realm
- driven almost entirely by glue
\[ \Rightarrow \text{spatial distribution of glue in nuclei?} \]

\[ Au+Au \quad \epsilon_{CGC} > \epsilon_{Glauber} \]

Kuhlman, Heinz, and Kovchegov, PLB838, 171
What is $\eta/s$?

IP-Glasma

KLN(CGC)

Glauber (Woods-Saxon)

$1/(4\pi) \sim 0.08$

Schenke, Tribedy, Venugopalan arXiv:1202.6646

Different initial states =

different fluctuation scales
What is $\eta/s$?

### IP-Glima

![IP-Glima](image)

$1/(4\pi) \approx 0.08$

### KLN(CGC)

![KLN(CGC)](image)

### Glauber (Woods-Saxon)

![Glauber (Woods-Saxon)](image)

### Different initial states = different fluctuation scales
What is $\eta/s$?

IP-Glasma

KLN(CGC)

Glauber (Woods-Saxon)

$1/(4\pi) \sim 0.08$

Different initial states = different fluctuation scales
$h-h$ Forward Correlation in $p(d)A$ at RHIC

Low gluon density (pp):

- pQCD predicts $2 \rightarrow 2$ process $\Rightarrow$
- back-to-back di-jet
**h-h Forward Correlation in p(d)A at RHIC**

**Side-view**
- p
- A

**Beam-view**
- $\pi$

**Low gluon density (pp):**
- pQCD predicts $2\rightarrow 2$ process ⇒
- back-to-back di-jet

**Legend:**
- $x_1$: Large-x (q dominated)
- $x_2$: Low-x (g dominated)
**h-h** Forward Correlation in p(d)A at RHIC

- Small-x evolution ↔ multiple emissions
- Multiple emissions → broadening
- Back-to-back jets (here leading hadrons) may get broadening in $p_T$ with a spread of the order of $Q_S$

**Low gluon density (pp):**
pQCD predicts $2 \rightarrow 2$ process ⇒ back-to-back di-jet

**High gluon density (pA):**
$2 \rightarrow $many process ⇒ expect broadening of away-side

First prediction by: C. Marquet ('07)  
Striking broadening of away side peak in central dA compared to pp and peripheral dA!
π⁰-π⁰ forward correlation in pp and dA at RHIC

\[ p+p \rightarrow \pi^0 \pi^0 + X, \quad \sqrt{s} = 200 \text{ GeV} \]
\[ p_{TL} > 2 \text{ GeV/c}, \ 1 \text{ GeV/c} < p_{T,S} < p_{T,L} \]
\[ \langle \eta_L \rangle = 3.2, \langle \eta_S \rangle = 3.2 \]

\[ \Delta \phi \]
\[ \sigma \]
\[ 0.41 \pm 0.01 \]
\[ 0.68 \pm 0.01 \]

**STAR Preliminary**

\[ d+Au \rightarrow \pi^0 \pi^0 + X, \quad \sqrt{s} = 200 \text{ GeV} \]
\[ p_{TL} > 2 \text{ GeV/c}, \ 1 \text{ GeV/c} < p_{T,S} < p_{T,L} \]
\[ \langle \eta_L \rangle = 3.2, \langle \eta_S \rangle = 3.2 \]

**Peaks**
\[ \Delta \phi \]
\[ \sigma \]
\[ 0.46 \pm 0.02 \]
\[ 0.99 \pm 0.06 \]

**STAR Preliminary**

\[ d+Au \rightarrow \pi^0 \pi^0 + X, \quad \sqrt{s} = 200 \text{ GeV} \]
\[ p_{TL} > 2 \text{ GeV/c}, \ 1 \text{ GeV/c} < p_{T,S} < p_{T,L} \]
\[ \langle \eta_L \rangle = 3.1, \langle \eta_S \rangle = 3.2 \]

**Peaks**
\[ \Delta \phi \]
\[ \sigma \]
\[ 0.44 \pm 0.02 \]
\[ 1.63 \pm 0.29 \]

**STAR Preliminary**

**arXiv:1008.3989v1**

Striking broadening of away side peak in central dA compared to pp and peripheral dA!
1 question, 2 answers

Initial and final state multiple scattering

Initial state saturation model

Albacete, Marquet

Away side parton randomized by strong color field

d+Au → π0π0+X, √s = 200 GeV, 2000 < ΣQ_{BEC} < 4000

p_T > 2 GeV/c, 1 GeV/c < p_T < p_T

⟨η⟩ = 3.1, ⟨η_s⟩ = 3.2

- CGC+offset

Peaks
Δφ σ
0 0.48±0.02
π 1.75±0.21

Preliminary

Hadjir2.20091004.2

20091120

Kang, Vitev, Xing arXiv:1112.6021v1

⟨q^2⟩_{dAu} = ⟨q^2⟩_{pp} + Δ ⟨q^2⟩

How saturated is the initial state?
Saturation at EIC

\[ Q_s^2(x) \sim \left( \frac{1}{x} \right)^\lambda \]
Saturation at EIC

\[ Q_s^2(x) \sim A^{1/3} \left( \frac{1}{x} \right)^\lambda \]
Saturation at eRHIC

Pocket formula: \( Q_s^2(x) \sim A^{1/3} \left( \frac{1}{x} \right)^{\lambda} \sim \left( \frac{A}{x} \right)^{1/3} \)

Gold: A=197, \( x \) 197 times smaller!

Model-I: bSat, Model-II: rcBK

\[ Q_s^2, \text{quark} \]

\[ Q_s^2(x) \sim A^{1/3} \left( \frac{1}{x} \right)^{\lambda} \sim \left( \frac{A}{x} \right)^{1/3} \]

\[ x_{\text{BJ}} \times 300 \]

\[ \sim A^{1/3} \]

\[ Q_s^2, \text{quark}, \text{all } b=0 \]
Saturation at eRHIC

Pocket formula: \[ Q_s^2(x) \sim A^{1/3} \left( \frac{1}{x} \right)^\lambda \sim \left( \frac{A}{x} \right)^{1/3} \]

Gold: \( A = 197 \), \( x \) 197 times smaller!
**eRHIC predictions:**

Dihadron correlations, away peak

Can constrain models a lot with a few months of running!
DIS $ep$ and $eA$
DIS $ep$ and $eA$
diffraction $ep$ and $eA$
Diffraction $ep$ and $eA$

**HERA:**
Proton collides with electron at CMS energy $\sim 300m_p$.
In $\sim 15\%$ of measured collisions proton stays intact!

**eRHIC $e+A$:**
Ion predicted to stay intact in $25\%-40\%$ of events!
HERA: Proton collides with electron at CMS energy $\sim 300 m_p$. In $\sim 15\%$ of measured collisions proton stays intact!

eRHIC $e^+A$: Ion predicted to stay intact in $25\%-40\%$ of events!
Why is diffraction so great? Pt. 1

Diffraction sensitive to gluon momentum distributions\(^2\):

\[ \sigma \propto g(x, Q^2)^2 \]

How does the gluon distribution saturate at small \(x\)?

![Image of proton parton distribution functions](image-url)
Diffraction $ep$ and $eA$

Depend on $t$, momentum transfer to proton/ion.

Fourier transform of $t$-distribution

$\equiv$

transverse spatial distribution

Spatial imaging!
Why is diffraction so great? Pt. 2

Sensitive to spatial gluon distributions

Light scattering off a circular screen of radius $R$

A projectile scattering off a nucleus of radius $R$ -not a ‘black disk’, edge effects -target may break up

\[ \theta_i \sim \frac{1}{kR} \]

\[ |t|_i \sim \frac{1}{R^2} \]
Incoherent Scattering

Good, Walker:

Nucleus dissociates ($f \neq i$):

$$\sigma_{\text{incoherent}} \propto \sum_{f \neq i} \langle i | A | f \rangle^\dagger \langle f | A | i \rangle$$

The complete set

$$= \sum_f \langle i | A | f \rangle^\dagger \langle f | A | i \rangle - \langle i | A | i \rangle^\dagger \langle i | A | i \rangle$$

$$= \langle i | |A|^2 | i \rangle - |\langle i | A | i \rangle|^2 = \langle |A|^2 \rangle - |\langle A \rangle|^2$$

The incoherent CS is the variance of the amplitude!!

$$\frac{d\sigma_{\text{total}}}{dt} = \frac{1}{16\pi} \left\langle |A|^2 \right\rangle$$

$$\frac{d\sigma_{\text{coherent}}}{dt} = \frac{1}{16\pi} |\langle A \rangle|^2$$
How to measure $t = (P_A - P_A')^2$

Need to measure $P_A$.

Coherent case: $A'$ disappears down beampipe
Incoherent case: Cannot measure all beam remnants

Only possibility: Exclusive diffraction

$e + A \rightarrow e' + VM + A'$

$t = (P_{VM} + P_{e'} - P_e)^2$
eRHIc predictions: Exclusive diffraction

Glauber (Woods-Saxon)

T. Ullrich & T.T.
Exclusive diffraction Sartre

Dipole model with Glauber bSat and bNonSat

\[
\frac{d\sigma_{q\bar{q}}}{db} = 2 \left[ 1 - \exp \left( -\frac{\pi^2}{2N_c} r^2 \alpha_s(\mu^2) x g(x, \mu^2) T(b) \right) \right]
\]

\[
\frac{d\sigma_{q\bar{q}}^{\text{nosat}}}{db} = \frac{\pi^2}{N_c} r^2 \alpha_s(\mu^2) x g(x, \mu^2) T(b)
\]

Glauber (Woods-Saxon)
Exclusive diffraction Sartre


(a) proton

\( x = 10^{-3}, \ z = 0.5, \ b = 0 \)

(b) Pb

<table>
<thead>
<tr>
<th>Model</th>
<th>( \chi^2/Ndf )</th>
<th>N</th>
<th>( m_l ) (GeV)</th>
<th>( m_c ) (GeV)</th>
<th>( C )</th>
<th>( A_g )</th>
<th>( \lambda_g )</th>
<th>( R_{\text{shrink}} ) (fm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>bNonSat (damped)</td>
<td>1.108</td>
<td>409+34</td>
<td>0.05116</td>
<td>1.3446</td>
<td>1.7076</td>
<td>2.3938</td>
<td>0.06581</td>
<td>0.9025</td>
</tr>
<tr>
<td>bSat (damped)</td>
<td>1.270</td>
<td>409+34</td>
<td>0.004</td>
<td>1.4280</td>
<td>1.9724</td>
<td>2.1945</td>
<td>0.09593</td>
<td>1.1889</td>
</tr>
<tr>
<td>bNonSat [6]</td>
<td>1.317</td>
<td>410+33</td>
<td>0.1497</td>
<td>1.3180</td>
<td>3.5445</td>
<td>2.8460</td>
<td>0.008336</td>
<td></td>
</tr>
<tr>
<td>bSat [6]</td>
<td>1.290</td>
<td>410+33</td>
<td>0.03</td>
<td>1.3210</td>
<td>1.8178</td>
<td>2.0670</td>
<td>0.09575</td>
<td></td>
</tr>
</tbody>
</table>

Comparing to Ultra-Peripheral Collisions

\[ p + Pb \rightarrow p + Pb + J/\psi \]

Sartre:
- bSat
- bNonSat

ALICE p-Pb \( \sqrt{s} = 5.02 \) GeV

CMS coherent

J/\psi, PbPb \( \sqrt{s} = 5.02 \) GeV

Est. effect from gluon fluct. PLB772, 832
Can constrain models a lot with a few months of running!
First 4 dips obtainable.
Probing the spatial gluon distribution at EIC

\[
\frac{d\sigma}{dt} = \frac{1}{16\pi} |A(\Delta)|^2 \\
\Delta \approx \sqrt{-t}
\]

\[A(\Delta) \sim \mathcal{F}ourier(\text{Wave Overlap} \cdot \text{Dipole Model}(b))\]

Fourier transform again to retain spatial distribution:

\[F(b) = \frac{1}{2\pi} \int_0^\infty d\Delta \Delta J_0(\Delta b) \sqrt{\frac{d\sigma_{\text{coherent}}}{dt}(\Delta)} \bigg|_{\text{mod}}\]
Probing the spatial gluon distribution at EIC

\[ F(b) = \frac{1}{2\pi} \int_0^\infty d\Delta \Delta J_0(\Delta b) \sqrt{\frac{d\sigma_{\text{coherent}}}{dt}(\Delta)} \mod \]

\[ b (fm) \]

Woods-Saxon

Probing the spatial gluon distribution at EIC

\[ F(b) = \frac{1}{2\pi} \int_0^\infty d\Delta \Delta J_0(\Delta b) \sqrt{\frac{d\sigma_{\text{coherent}}}{dt}(\Delta)} \bigg|_{\text{mod}} \]

\[ F(b)/\int F(b) \, db \]

\[ b \text{ (fm)} \]

\[ \text{tt (GeV}^2) \]

Probing the spatial gluon distribution at EIC

\[ F(b) = \frac{1}{2\pi} \int_0^\infty d\Delta \Delta J_0(\Delta b) \sqrt{\frac{d\sigma_{\text{coherent}}}{dt}(\Delta)_{\text{mod}}} \]
Probing the spatial gluon distribution at EIC

\[
F(b) = \frac{1}{2\pi} \int_0^\infty d\Delta \Delta J_0(\Delta b) \sqrt{\frac{d\sigma_{\text{coherent}}}{dt}(\Delta)} \Bigg|_{\text{mod}}
\]

Probing the spatial gluon distribution at EIC

\[ F(b) = \frac{1}{2\pi} \int_{0}^{\infty} \Delta \Delta J_0(\Delta b) \sqrt{\frac{d\sigma_{\text{coherent}}}{dt}(\Delta)} \left|_{\text{mod}} \right. \]

arXiv:1211.3048
Probing the spatial gluon distribution at EIC

\[ F(b) = \frac{1}{2\pi} \int_0^\infty d\Delta \Delta J_0(\Delta b) \left[ \frac{d\sigma_{\text{coherent}}}{dt}(\Delta) \right]_{\text{mod}} \]

Probing the spatial gluon distribution at EIC

\[ F(b) = \frac{1}{2\pi} \int_0^\infty d\Delta \Delta J_0(\Delta b) \sqrt{\frac{d\sigma_{\text{coherent}}}{dt}(\Delta)} \mod(\Delta) \]

Probing the spatial gluon distribution at EIC

\[ F(b) = \frac{1}{2\pi} \int_0^\infty d\Delta \Delta J_0(\Delta b) \sqrt{\frac{d\sigma_{\text{coherent}}}{dt}(\Delta)} \mod \]

\[ b \text{ (fm)} \]

ZDC veto

\( E_\gamma > 40 \text{ MeV}, \pi^\pm, K^\pm, \bar{p}, n, \bar{n} \)

Central + ZDC veto
+ nucleon/charged meson after first dipole

Central + ZDC veto
+ photon

V. Morozov et al., PoS DIS2018 (2018) 175
Probing the spatial gluon distribution at EIC

\[ F(b) = \frac{1}{2\pi} \int_0^\infty d\Delta \Delta J_0(\Delta b) \sqrt{\frac{d\sigma_{\text{coherent}}}{dt}(\Delta)} \mid_{\text{mod}} \]

(a) \hspace{2cm} (b)

(c) \hspace{2cm} (d)

Fluctuations inside Nucleons

Two different fluctuations:
Around low scale partons + Saturation Scale
Figure 1.19: 

**Fluctuations inside Nucleons**

Two different fluctuations: 
**Around low scale partons** + Saturation Scale

\[ Au + Au \rightarrow J/\psi + Au + Au, \sqrt{s_{NN}} = 200 \text{ GeV}, y = 0 \]

Summary

The EIC provides the only way to measure the Nuclear Initial State: Saturation Gluon Fluctuations Nuclear Imaging Constrict Nuclear PDFs

Essential for limiting major uncertainties in many AA observables
**Going from \( e\rho \) to \( eA \)**

**\( e\rho \):**

\[
\text{Re}(S) = 1 - \mathcal{N}^{(p)}(x, r, b) = 1 - \frac{1}{2} \frac{d\sigma^{(p)}_{q\bar{q}}(x, r, b)}{d^2b}
\]

**\( eA \):** Independent scattering approximation

\[
1 - \mathcal{N}^{(A)} = \prod_{i=1}^{A} \left( 1 - \mathcal{N}^{(p)}(x, r, |b - b_i|) \right)
\]

**Assume the Woods-Saxon distribution**

**\( b\text{Sat}: \)**

\[
\frac{d\sigma^{A}_{q\bar{q}}}{d^2b} = 2 \left[ 1 - \exp \left( -\frac{\pi^2}{2N_c} r^2 \alpha_s(\mu^2) x g(x, \mu^2) \sum_{i=1}^{A} T_p(b - b_i) \right) \right]
\]
### What we learn from diffraction:

<table>
<thead>
<tr>
<th>Observable</th>
<th>Process</th>
<th>What we learn</th>
<th>Coh./Inc.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\frac{\sigma_{\text{diff}}}{\sigma_{\text{tot}}}$</td>
<td>Inclusive</td>
<td>Level of saturation</td>
<td>Coherent</td>
</tr>
<tr>
<td>$\frac{d\sigma}{dt}$</td>
<td>Exclusive</td>
<td>Spatial gluon density $\rho_G(b)$, important for e.g. $\eta/S$</td>
<td>Coherent</td>
</tr>
<tr>
<td>No breakup</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$d\sigma/dt$</td>
<td>Exclusive</td>
<td>Fluctuations and lumpiness of gluons in ions</td>
<td>Incoherent</td>
</tr>
<tr>
<td>Breakup</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\frac{d\sigma}{dt}$</td>
<td>Exclusive</td>
<td>Level of saturation</td>
<td>Coherent</td>
</tr>
<tr>
<td>DIS</td>
<td>DIS</td>
<td>Level of saturation vs. shadowing</td>
<td>Coherent &amp; Incoherent</td>
</tr>
</tbody>
</table>

ΔΦ of dihadrons
Detecting Nuclear Breakup

- Detecting **all** fragments $p_{A'} = \sum p_n + \sum p_p + \sum p_d + \sum p_\alpha$ ... not possible
- Focus on $n$ emission
  - Zero-Degree Calorimeter
  - Requires careful design of IR

**Additional measurements:**
- Fragments via Roman Pots
- $\gamma$ via EMC

**Traditional modeling done in pA:**

**Intra-Nuclear Cascade**
- Particle production
- Remnant Nucleus (A, Z, E*, ...)
- ISABEL, INCL4

**De-Excitation**
- Evaporation
- Fission
- Residual Nuclei
- Gemini++, SMM, ABLA (all no $\gamma$)
What has been measured?

Hahn, Ravenhall, and Hofstadter, Phys Rev 101 (1956)

Electron colliding with fixed ion target, large $x$ charge distribution - no gluons!