Experimental aspects on Low-x Physics at a Future EIC facility - Concepts / Status / Projections -

Bernd Surrow
Motivation

Structure and dynamics of proton (mass / spin) (→ visible universe) originates from QCD-interactions!

Synergy of experimental progress and theory (Lattice QCD / Phenomenology incl. phenomenological fits / Modeling) critical!

(D. Leinweber: Action (~energy) density fluctuations of gluon-fields in QCD vacuum)
**Motivation**

- The silent (low $x$) partners...: *Gluons and QCD-Sea*

**Fundamental questions:**

- What are the properties of **gluons** that bind strongly interacting particles?
- What is the **quark-gluon** internal structure of nucleons?
- What are the properties of **quark-gluon** matter at high density?

\[ W^2 \simeq \frac{Q^2}{x} \]
Outline

- Future unpolarized low-x opportunities:
  Unpolarized ep/eA physics

- Concepts and Status

- Summary and Outlook

Exploring the nature of glue
Low-$x$ kinematics

- Access higher parton density system
  - Larger center-of-mass energy ($\sqrt{s}$): Smaller $x$ at larger $\sqrt{s}$!

Fixed-target

$$\sqrt{s} = \sqrt{2EBm}$$

$$x \sim \frac{Q^2}{s}$$

Collider

$$\sqrt{s} = \sqrt{4E_{b1}E_{b2}}$$

- Forward direction: Smaller $x$ at larger $\eta$!

Central ($\eta \approx 0$)

$$x \sim \frac{2p_T}{\sqrt{s}} e^{-\eta}$$

Forward ($\eta$ large)

- $eA$ vs. $ep$ scattering: Probe higher parton density system in $eA$ compared to $ep$!

$e \rightarrow A^{1/3}$
Concepts and Status

Probing the structure and dynamics of matter in ep vs. pp scattering

\[ d\sigma_{ep} \propto F_2 = \sum_q x e_q^2 f_q(x) \]

\[ W^2 \approx Q^2 / x \]

Momentum contribution

\[ f(x) = f^+(x) + f^-(x) \]

Spin contribution

\[ \Delta f(x) = f^+(x) - f^-(x) \]

Universality

Factorization

Bernd Surrow

POETIC 2012 @ IU Bloomington Workshop
Bloomington, IN, August 20-22, 2012
### Concepts and Status

#### Picture of the proton from unpolarized ep scattering

**H1 and ZEUS**

<table>
<thead>
<tr>
<th>x</th>
<th>i</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00005</td>
<td>21</td>
</tr>
<tr>
<td>0.00008</td>
<td>20</td>
</tr>
<tr>
<td>0.00013</td>
<td>19</td>
</tr>
<tr>
<td>0.00020</td>
<td>18</td>
</tr>
<tr>
<td>0.00032</td>
<td>17</td>
</tr>
<tr>
<td>0.00050</td>
<td>16</td>
</tr>
<tr>
<td>0.00080</td>
<td>15</td>
</tr>
<tr>
<td>0.00130</td>
<td>14</td>
</tr>
<tr>
<td>0.00200</td>
<td>13</td>
</tr>
<tr>
<td>0.00320</td>
<td>12</td>
</tr>
<tr>
<td>0.00500</td>
<td>11</td>
</tr>
<tr>
<td>0.00800</td>
<td>10</td>
</tr>
<tr>
<td>0.01300</td>
<td>9</td>
</tr>
<tr>
<td>0.02000</td>
<td>8</td>
</tr>
<tr>
<td>0.03200</td>
<td>7</td>
</tr>
<tr>
<td>0.05000</td>
<td>6</td>
</tr>
<tr>
<td>0.08000</td>
<td>5</td>
</tr>
<tr>
<td>0.13000</td>
<td>4</td>
</tr>
<tr>
<td>0.18000</td>
<td>3</td>
</tr>
<tr>
<td>0.25000</td>
<td>2</td>
</tr>
<tr>
<td>0.40000</td>
<td>1</td>
</tr>
<tr>
<td>0.65000</td>
<td>0</td>
</tr>
</tbody>
</table>

**Strong violation of scaling at low x and high Q^2**

**In contrast to:**

**Low Q^2, high x!**

**Huge gluon and QCD sea contribution!**

---

**POETIC 2012 @ IU Bloomington Workshop**

Bloomington, IN, August 20-22, 2012

Bernd Surrow
Important: Complementary probes are required for unambiguous extraction of observables in high-energy density QCD region!
- **Low-\(x\) basics (1)**
  - **Dynamics: DGLAP / BFKL and CGC**

\[ Y = \ln \left( \frac{1}{x} \right) \]

- **\(Q_s^2\): Saturation scale** ⇒ Characterize transition to saturation region!
  \[ Q_s^2 \simeq \alpha_s \frac{1}{\pi R^2} x G(x, Q^2) \sim A^{1/3} x^{-\delta} \]

- Enhanced for eA compared to ep:
  \[ Q^2 > Q_s^2 \Rightarrow \alpha_s = \alpha_s(Q^2) \]
  \[ Q^2 < Q_s^2 \Rightarrow \alpha_s = \alpha_s(Q_s^2) \]
Concepts and Status

- **Low-x basics (2)**
  - **Dipole model**

Consider virtual photon-proton cross-section

Frame: Proton rest frame

Interaction time < Fluctuation time at low $x$

Dipole model: Interaction of quark/anti-quark pair with proton

\[
\sigma_{\gamma^*p}^{\text{tot}} = \int dz \int d_{r_\perp}^2 |\Psi|^2 \sigma_{(q\bar{q})p}
\]
### Concepts and Status

#### HERA: $\gamma^p$ cross-section

- **Dipole-model approach**: Successful description of both inclusive and diffractive processes at low $x$.
- **Change of $Q^2$ dependence** around $1\text{GeV}^2$!

![Graph showing $\sigma_{\gamma^p} (\text{mb})$ vs. $W^2 (\text{GeV}^2)$](image)

![Graph showing $\alpha_{\gamma^p}(x,h) (\text{scaled})$ vs. $Q^2 (\text{GeV}^2)$](image)

DRAFT
**Concepts and Status**

- **Diffraction**

  - **Ratio of diffractive to total cross-section**
    - (200 < W < 245GeV): 15% at Q^2 = 4GeV^2

  - **Dipole models**: Successful description of inclusive and various diffractive measurements (e.g. Ratio of diffractive to inclusive cross-section, Diffractive Vector-Meson production)

  ![Diagram of diffraction process](image)

  - y ≈ -3
  - Large gap in y
  - y ≈ 7

  ![Graph of y^*p → J/ψ p](image)

  - $\gamma^*p \rightarrow J/\psi p$
  - $\sigma \propto \alpha_s^2 \left[g(x, Q^2)\right]^2$

  ![Graph of cross-section vs. Q^2](image)

  - Cross-section plotted against Q^2 for J/ψ production

DRAFT
RHIC dAu scattering at forward $\eta$

Forward identified hadron production at RHIC in dAu collisions: Sizable suppression of yields for charged hadrons and neutral pions observed

pQCD+shadowing calculations over-predict hadron yield suppression. Is this an indication for gluon saturation in Au nuclei?

More RHIC dAu are expected with enhanced detector capabilities (PHENIX/STAR)
Fixed-target scattering experiments

- Inclusive structure function ratio important to constrain nuclear modifications to gluon density
- World data (Fixed target) are concentrated above $x>0.01$ in pQCD region
- For $x<0.01$ only data in non-pQCD region
Future opportunities

- **EIC facilities**
  - **eRHIC (BNL)**
    - \( \mathcal{E}_e = 10 \) (20) GeV
    - \( \mathcal{E}_A = 100 \) GeV (up to U)
    - \( \sqrt{s_{eN}} = 63 \) (90) GeV
    - \( L_{eAu} \, \text{(peak)/n} \sim 2.9 \cdot 10^{33} \, \text{cm}^{-2} \, \text{s}^{-1} \)

- **ELIC (JLAB)**
  - \( \mathcal{E}_e = 9 \) GeV
  - \( \mathcal{E}_A = 90 \) GeV (up to Au)
  - \( \sqrt{s_{eN}} = 57 \) GeV
  - \( L_{eAu} \, \text{(peak)/n} \sim 1.6 \cdot 10^{35} \, \text{cm}^{-2} \, \text{s}^{-1} \)
Future Opportunities

- **Kinematics**

  - **Comparison HERA / EIC / Fixed-target experiments**

    - **Terra incognita:**
      - small-$x$, $Q\approx Q_s$
      - high-$x$, large $Q^2$

    - Diagram showing comparison of experiments such as ZEUS SVTX 1995, HERA 1993, and EIC (eA) event topology ($E_e=10$ GeV, $E_{nA}=100$ GeV).
Future Opportunities

- Key observables in electron-proton and electron-nucleus scattering
  - **Gluon distribution:**
    - $F_L$ (Variable center-of-mass energy) and $F_2$
    - Jet rates
    - Inelastic vector meson production (e.g. J/Psi)
  - **Space-Time distribution of gluon:**
    - $F_L$ (Variable center-of-mass energy) and $F_2$
    - Deep virtual compton scattering (DVCS)
    - Exclusive final states (e.g. Vector meson production)
  - **Interaction of fast probes with matter:**
    - Hadronization, Fragmentation studies
    - Energy loss (Heavy quarks)
  - Impact of strong gluon fields on the role of color neutral excitations:
    - Diffractive structure functions
    - Diffractive vector meson production
Future Opportunities: Unpolarized eA physics

- $F_2^A / (A F_2)$ ratio at EIC vs. $A^{1/3}$

**Details**

DRAFT
Future Opportunities: Unpolarized eA physics

- Di-hadron correlation vs. x at EIC: Nuclear modification $J_{eA}$

**BNL EIC Task Force**

**Details**

**DRAFT**
Future Opportunities: Unpolarized eA physics

Di-hadron correlation at EIC

BNL EIC Task Force

\[ Q^2 = 1 \text{ GeV}^2 \]

\[ C(\Delta \varphi) \]

\[ \Delta \varphi \]

\[ e \text{Au} \]

\[ e \text{Ca} \]

\[ e \text{p} \]

BNL EIC Task Force

EIC stage-II
\[ \int L dt = 10 \text{ fb}^{-1}/A \]

\[ p_T^{\text{trigger}} > 2 \text{ GeV/c} \]

\[ 1 < p_T^{\text{assoc}} < p_T^{\text{trigger}} \]

\[ |\eta| < 4 \]

\[ C_{e \text{Au}}(\Delta \varphi) \]

\[ C_{e \text{Au}}(\Delta \varphi) \text{ - nosat} \]

\[ C_{e \text{Au}}(\Delta \varphi) \text{ - sat} \]

Details

DRAFT
Future Opportunities: Unpolarized eA physics

- Diffractive VM production at EIC: \( J/\Psi \) and \( \Phi \) (1)

BNL EIC Task Force

\[
\begin{align*}
\int L dt = 10 \text{ fb}^{-1} \\
1 < Q^2 < 10 \text{ GeV}^2 \\
x < 0.01 \\
\ln(\frac{E_{\text{Beam}}}{m}) < 4 \\
p(E_{\text{Beam}}) > 1 \text{ GeV}/c \\
\delta t/t = 5\%
\end{align*}
\]

- Details

BNL EIC Task Force

\[
\begin{align*}
\int L dt = 10 \text{ fb}^{-1} \\
1 < Q^2 < 10 \text{ GeV}^2 \\
x < 0.01 \\
\ln(\frac{E_{\text{Beam}}}{m}) < 4 \\
p(E_{\text{Beam}}) > 1 \text{ GeV}/c \\
\delta t/t = 5\%
\end{align*}
\]

DRAFT

POETIC 2012 @ IU Bloomington Workshop
Bloomington, IN, August 20-22, 2012
Bernd Surrow
Future Opportunities: Unpolarized eA physics

- Diffractive VM production at EIC: $J/\Psi$ and $\Phi$ (2)

**BNL EIC Task Force**

![Graph showing $J/\Psi$ and $\Phi$ production](image)

- Details
Summary and Outlook

- Status and Concepts
  - HERA: Precision structure function measurements ($F_2$) at low $x$
  - At low $Q^2$ and low $x$: DGLAP (Leading twist) approach leads to valence-like gluon behavior
  - Diffraction: Important contribution to overall ep event yield
  - Dipole model: Allows to describe inclusive and diffractive measurements. Reach of saturation region at low $x$ not conclusive
  - Lesson: Optimize any future EIC efforts for acceptance and luminosity
  - $eA$: No information in low-$x$ region
  - $dAu$ results at RHIC: Can saturation account for observed behavior? Complementary probes important (RHIC/LHC)!
  - Important constrain on gluon polarization at medium and higher $x$ from semi-inclusive polarized DIS and RHIC-SPIN program (Hint for $\Delta G \neq 0$) - Complementary to EIC
Future Opportunities

- **EIC**: First polarized $ep$ collider - Precision measurement of polarized gluon distribution at low-$x$ and quark flavor structure

- EIC will allow to study the physics of strong color fields

- Required: EIC at high luminosity and optimized detector

- EIC will allow to bridge several QCD communities (Hadron structure and Relativistic Heavy-Ion)