Topics:

1. Symbiosis between EIC and heavy ion physics
2. Early stages of heavy collisions
3. Generalized parton distributions - vector meson production
4. Nuclear shadowing
5. Spin dependence

1. Symbiosis between EIC and LHC heavy ions
   Not a perfect match, but not too bad

LHC heavy ion collision
2.8 TeV/proton on 2.8 TeV/proton

Suppose initial collision in central rapidity
is dominated by gluons having $p_T = 2.5$ GeV
So the nuclear wave function near $x \approx 10^{-3}$ and $Q^2 = 5 GeV^2$ is the essential region of interest.

Where is EIC?

Suppose $E_e = 10 GeV$ and

\[
\text{Energy per Nucleon in ion} = 100 GeV
\]

At $Q^2 = 5 GeV^2$

\[
\frac{Q^2}{S_{\text{max}}} = \frac{5}{4 \times 10^3} = 10^{-3}
\]

Would certainly be nice to have $x$ a bit smaller. Smaller $E_e$ will move EIC further away from the interesting overlap with the LHC.
In central unit of rapidity:

(i) At RHIC gluons produced semiclassically; Weizsäcker-Williams gluons freed in collision.

\[ k_{1,2} \gtrsim 1 \text{ GeV}, \quad x \sim 10^{-2} \]

(ii) At LHC gluons produced will have

\[ k_{1,2} \gtrsim 2 \text{ GeV}, \quad x \sim 10^{-3} \]

significant evolution (quantum) can be expected

Crude picture of initial state formation:

\[ k_{10} = k_{10} + Q_s^2 \]

IF \( k_{10} \gg Q_s^2 \) not much change. Gluon will not be freed.

IF \( k_{10} \lesssim Q_s^2 \) significant disturbance. Gluon will be freed.

So, roughly, gluons having \( k_{10} \lesssim Q_s \) will be freed and will give the initial state for the plasma.
Venugopalan and by Lappi (roughly) support this picture.

This is starting point for trying to understand thermalization theoretically. Having some experimental input on $\chi G_{\chi}(\chi Q^2)$ will be important in keeping theorists on the right track.

At present no First principles understanding of thermalization in QCD
One has formula for the $S$-matrix of a dipole of size $x_1$ scattering on a proton at impact parameter $b$.

$$S(x_1, b) = 1 - \frac{1}{2 \pi^2 N(0)} \int d^2 q \frac{e^{i x_1 b}}{\sqrt{d\sigma}}$$

with $N$ determined by the overlap of $\psi_x$ and $\psi_v$. In case $v = \frac{x_1}{4}$ or $v$ one has good control of wavefunctions so that the extraction of $S$ is not strongly model dependent.

From HERA one has some information but:

(i) $f$-production; little data.

(ii) $p$-production; only for $\Delta^2 \leq 0.6$ GeV$^2$ can one be sure proton not broken up.

(iii) $\frac{x_1}{4}$; data better, but little control of $x_1$ dependence.

Jlab will have elaborate program at intermediate energies.
(i) Measure dipole cross sections to determine shadowing and saturation.

(ii) Map out where valence quarks, sea quarks and gluons live (spatially) in the proton. Valence quarks should be done at JLab.

Hera has given nice result that small-x gluons typically live at \(0.5-0.6\) Fm in b while proton charge radius is \(0.9\) Fm. Analysis assumes\footnote{Kowalski, Motyka, Watt} Form for S-matrix of dipole on proton

\[ G(x, b) = 2(1-S) = 2 \left[ 1 - \exp \left( -\frac{\pi^2 x_i^2 \mu^2}{24 \mu_c} \right) \right] \]

\[ \mu^2 = \frac{\mu_c^2}{x_i^2} + \mu_0^2, \quad T = \frac{1}{8 \pi \mu_c} e^{-\frac{b^2}{\mu_c^2}} \]

Not unreasonable, but should be able to do \"essentially\" model independent analysis with good data.
Shadowing intimately related to but not identical to saturation

In McLerran-Venugopalan (MV) model, there is gluon saturation but no shadowing.

\[ \frac{d\sigma}{d^2k_1 d^2b} \]

\[ \text{additive} \quad \text{depletion} \]

\[ \text{excess} \quad \text{MV} \]

\[ \text{depletion} = \text{excess} \]

Quarks come in at quantum level and are shadowed

\[ \text{Nucleus at rest} \]

Dipole picture

Higher twist shadowing

Fast nucleus

Bj frame

Gauge rotations broaden gluon distribution
The distribution is also shadowed. Take DIS as an example.

\[
Q^2 \frac{\delta y}{\delta x} |(Q^2, y) \sim \int dx_F \frac{P_F(x_F)}{x_F} \Rightarrow x_F, y \approx \frac{Q^2}{x_L x_F} \quad \delta \left( x_F, A \right)
\]

\[
\left( \frac{Q_s(y)}{Q^2 x_L x_F} \right)^{\alpha_0} \quad \pi R^2 \begin{cases} 
\frac{(x_F q_s(MV))^2}{2}, & (x_L x_F q_s(MV))^2 < 1 \\
1, & (x_F q_s(MV))^2 > 1
\end{cases}
\]

\[x_F \sim \frac{1}{2} q_s(MV) \text{ is dominant value}\]

\[
Q_s(MV) \sim A^{1/3} \quad \sigma_0 \sim 0.37
\]

As soon as evolution becomes important, leading twist shadowing $\leftrightarrow$ saturation. Estimates suggest evolution sets in rapidly. [Kharzeev, Kovchegov, Tuchin]
Interesting Alternative, maybe related explanation

Enhanced energy loss of quark due to many soft gluons at the small x of BRAHMS. Observed events come from surface giving weakened A-dependence.

Physics not so dissimilar: Many low-x gluons
(i) increase energy loss
(ii) should also saturate (shadow)?

EIC should be able to study shadowing in a similar energy region. However, 10 GeV electron beam important!! When $E_\gamma$ decreases below 10 GeV one quickly loses the ability to get to interesting region for gluon shadowing.
Focus on two points

A. What is the proton made of? Better yet, what are the essential ingredients for static properties of the proton.

Not a simple question of parton distribution.

Example: At small-$x$ there are many $c\bar{c}$ pairs in the proton. This is also true at finite $x$ and at short distances. However, inclusion of $c\bar{c}$ pairs in lattice calculations will not change static properties.

What about strange quarks? Are they essential for the proton?
quite a few $\bar{s}s$ pairs in the proton. Are they short time, compact (inessential) fluctuations or longer time (essential) fluctuations?

Basic issue is whether the proton, and nuclei, are $SU(2)$ flavor or $SU(3)$ flavor objects.

What do we know:

1. Light quark sea interacts strongly with rest of proton. $\bar{u}u(x) \neq \bar{d}d(x)$. Light quark sea essential.

2. Strange quark contribution to Form Factors appears small, SAMPLE, HAPPEX, MAMI.

$\bar{s}s$ and $\bar{s}\bar{s}$ have essentially the same wavefunctions in proton. Suggests they don't interact much.

3. IF $s$ and $\bar{s}$ don't interact much then $\Delta s, \Delta \bar{s}$ should be small. Nice to have good direct determination.
Slowly getting resolved.

**Constituent quark model:**
\[ \Delta U = \frac{4}{3}, \Delta D = -\frac{1}{3} \]
\[ \Delta U - \Delta D = \frac{5}{3} \rightarrow \text{relativity} \ 1.25 \ 	ext{GAGGA} \]
\[ \Delta U + \Delta D = 1 \rightarrow \text{relativity} \ 0.75 \ 	ext{Spin Fraction} \]

Carried by quarks

*For magnetic moments and non singlet axial charge good identification of constituent and current quarks. For singlet axial current this does not seem to be the case.*

**Axial anomaly gave hope**

\[ \frac{1}{2p^+} (P/\delta + 1P) = \frac{\Delta u + \Delta d + \Delta s - \frac{3s}{5u}}{\Delta \Sigma} \Delta G \]

If \( \Delta G \) had been moderate size and positive \( \Delta \Sigma \) could have been near 0.75. But RHIC-spin says \( \Delta G \) is small. Constituent quarks \( \rightarrow \) current quarks here.

Proton spin must have significant orbital component. This should begin to tell us what constitutes a constituent quark.