The Electron Ion Collider: Why? How? When?

Precision study & understanding the role of gluons (& sea quarks) in QCD

Abhay Deshpande
January 30, 2012
CPTEIC Workshop @ STIfS, Stellenbosch, South Africa

What distinguishes QCD from QED?

Asymptotic Freedom ⇔ antiscreening

QCD: \( \frac{\partial \alpha_s(Q^2)}{\partial \ln Q^2} = \beta(\alpha_s) < 0 \)

Compare

QED: \( \frac{\partial \alpha_{EM}(Q^2)}{\partial \ln Q^2} = \beta(\alpha_{EM}) > 0 \)


2004 Nobel Prize in Physics
QCD: The SM of Strong Interactions

For the discovery of asymptotic freedom in QCD

“Folks, we need to stop “testing” QCD and start understanding it”
Yuri Dokshitzer

1998, ICHEP Vancouver, BC, Conference Summary Talk

Success of pQCD at High Q: Jet Cross section

- Input:
  - $F_2(x,Q^2)$
  - Next to LO QCD

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A. Deshpande, Science of EIC & the Path to Realization
QCD definitely correct

Lattice QCD
- Starting from QCD lagrangian → Static properties of hadrons: hadron mass spectrum
  BUT, No guidance on partonic dynamics

Perturbative QCD
- Calculations possible when coupling is small, at high Q
  BUT, problematic at low Q → fast rise of $\alpha_s(Q)$

Generation of Mass – Gluons in QCD
- Protons and neutrons form most of the mass of the visible universe
- 99% of the nucleon mass is due to self generated gluon fields
  - Similarity between p, n mass indicates that gluonic interactions are identical & overwhelmingly important

  • Lattice QCD supports this

  Higgs Mechanism, often credited with mass generation, is of no consequence
Gluon self-interaction in QCD
Dynamical generation & self-regulation of hadron masses

F. Wilczek in “Origin of Mass”

*Its enhanced coupling to soft radiation… means that a ‘bare’ color charge, inserted in to empty space will start to surround itself with a cloud of virtual color gluons. These color gluon fields themselves carry color charge, so they are sources of additional soft radiation. The result is a self-catalyzing enhancement that leads to a *runaway growth*. A small color charge, in isolation builds up a big color thundercloud….theoretically the energy of the quark in isolation is infinite… having only a finite amount of energy to work with, nature always finds a way to short cut the ultimate thundercloud”*

![Diagram of electric charge and color charge](image)

What limits the “thundercloud”?

- Partial cancellation of quark-color-charge in color neutral finite size of the hadron (confinement) is responsible, *but*
- Saturation of gluon densities due to $gg \rightarrow g$ (gluon recombination) must also play a critical role regulating the hadron mass

**Need to experimentally explore and study many body dynamics**
- a) regions of quark-hadron transition and
- b) non-linear QCD regions of extreme high gluon density
What is the role of gluons at high energy?

**HOW WELL DO WE UNDERSTAND GLUONS?**

Measurement of Glue at HERA

- Scaling violations of $F_2(x, Q^2)$
  $$\frac{\partial F_2(x, Q^2)}{\partial \ln Q^2} \propto G(x, Q^2)$$
- NLO pQCD analyses: fits with linear DGLAP* equations

*Dokshitzer, Gribov, Lipatov, Altarelli, Parisi
Gluon distribution at low-\(x\) understood?

- Indefinite rise: Infinite high energy hadron cross section?
  - Could this be an artifact of using linear DGLAP in gluon extraction?

No higher energy e-p collider than HERA! \(\rightarrow\) other than “LHeC”

\(\rightarrow\) Nuclei: naturally enhance the densities of partonic matter

**Why not use Nuclear DIS at high energy?**

Physics at Low \(x\) & Color Glass Condensate


- Method of including non-linear effects
  - McLerran & Venugopalan
  - Small coupling, high gluon densities
  - BK/JMWLK equations lead to a Saturation Scale \(Q_s(Y)\)
  - Wave function: Color Glass Condensate in infinite momentum frame

Infinite Momentum Frame (IMF)

- BFKL (linear QCD) gluon splitting functions \(\rightarrow\) higher gluon density
- BK (non linear) recombination of gluons \(\rightarrow\) restricts gluon density

**At \(Q_s\) gluon emission balances the recombination**
How to reach the high gluon density regions?

More powerful e-p collider
CME~ 1-2 TeV instead of
HERA’s 300 GeV

Alternatively,
Probe the nucleons in
NUCLEI coherently…. 

\[
L \sim (2m_N x)^{-1} > 2 R_A \sim A^{1/3}
\]

Enhancement of \(Q_s\) with \(A\), not energy

EIC and RHIC/LHC (Heavy Ion)

A decadal plan is being launched to characterize the “QGP”
To understand “QGP” fully, we need to understand:

The initial state i.e. the nucleus & hadronization

Deeper Connection: many body interactions of parton in QCD
UNDERSTANDING NUCLEON SPIN: WHAT ROLE DO GLUONS PLAY?

Evolution: Our Understanding of Nucleon Spin

We have come a long way, but do we understand nucleon spin?
Status of “Nucleon Spin Crisis Puzzle”

\[ \frac{1}{2} = \frac{1}{2} \Delta \Sigma + L_q + \Delta g + L_g \]

- We know how to determine \( \Delta \Sigma \) and \( \Delta g \) precisely: data+pQCD
  - \( \frac{1}{2} (\Delta \Sigma) \sim 0.15 \): From fixed target pol. DIS experiments
  - RHIC-Spin: \( \Delta g \) not large as anticipated in the 1990s, but measurements \& precision needed at low \& high \( x \)

\[ \Delta g(x) @ Q^2=10 \text{ GeV}^2 \]

de Florian, Sassot, Stratmann \& Vogelsang

- Global analysis: DIS, SIDIS, RHIC-Spin
- Uncertainly on \( \Delta G \) large at low \( x \)

\[ \frac{d g_1}{d \log(Q^2)} \propto -\Delta g(x, Q^2) \]
Status of “Nucleon Spin Crisis Puzzle”

\[
\frac{1}{2} = J_q + J_g = \frac{1}{2} \Delta \Sigma + L_q + \Delta g + L_g
\]

- We know how to measure $\Delta \Sigma$ and $\Delta G$ precisely using pQCD
  - $\frac{1}{2} (\Delta \Sigma) \sim 0.15$ : From fixed target pol. DIS experiments
  - RHIC-Spin: $\Delta G$ not large as anticipated in the 1990s, but measurements & precision needed at low & high $x$

- Generalized Parton Distributions: $H,E,E',H' \rightarrow$ Connection to partonic OAM
  - Quark GPDs $J_q$: 12GeV@JLab & COMPASS@CERN
  - Gluons @ low $x \rightarrow J_g \rightarrow$ will need the future EIC!

- (2+1)D tomographic image of the proton…. Transverse Mom. Distributions
  - 2: $x,y$ position and +1:momentum in $z$ direction

Towards Full understanding of transverse and longitudinal hadron structure including spin!

Beyond form factors and quark distributions

**Generalized Parton Distributions**


Proton form factors, transverse charge & current densities

Correlated quark momentum and helicity distributions in transverse space - GPDs

Structure functions, quark longitudinal momentum & helicity distributions
Do we really “understand” QCD?

While there is no reason to doubt QCD, our level of understanding of QCD remains extremely unsatisfactory: both at low & high energy

- Can we explain basic properties of hadrons such as mass and spin from the QCD degrees of freedom at low energy?
- What are the effective degrees of freedom at high energy?
- How do these degrees of freedom interact with each other and with other hard probes?
- What can we learn from them about confinement & universal features of the theory of QCD?

After ~20+ yrs of experimental & theoretical progress, we are only beginning to understand the many body dynamics of QCD
The Proposal:

**Future DIS experiment at an Electron Ion Collider:** A high energy, high luminosity (polarized) ep and eA collider and a suitably designed detector

![Diagram of DIS experiment]

**Measurements:**

1. Inclusive
2. Semi-Inclusive
3. Exclusive

**EIC : Basic Parameters (e-p)**

- $E_e = 10 \text{ GeV} \ (5-30 \text{ GeV variable})$
- $E_p = 250 \text{ GeV} \ (50-275 \text{ GeV Variable})$
- $\sqrt{S_{ep}} = 100 \ (30-180) \text{ GeV}$
- $x_{\text{min}} \sim 10^{-4} \ ; \ Q^2_{\text{max}} \sim 10^4 \text{ GeV}$
- Polarization $\sim 70\%$: e,p, D/He
- **Luminosity** $L_{ep} = 10^{33-34} \text{ cm}^{-2}\text{s}^{-1}$
- **Minimum Integrated luminosity:**
  - $50 \text{ fb}^{-1} \text{ in 10 yrs (100 x HERA)}$
  - Possible with $10^{33} \text{ cm}^{-2}\text{s}^{-1}$
  - Recent projections much higher
EIC : Basic Parameters (e-A)

- $E_e = 10$ GeV (5-30 GeV variable)
- $E_A = 100$ GeV (20-110 GeV Variable)
- $\sqrt{s_{eA}} = 63 (20-115)$ GeV
- $x_{\text{min}} \sim 10^{-4}$;
- $Q^2_{\text{max}} \sim 8 \times 10^3$ GeV

Nuclei:
- Proton $\rightarrow$ Uranium
- $L_{eA}/N = 10^{33-34}$ cm$^{-2}$s$^{-1}$

Machine Designs

eRHIC at Brookhaven National Laboratory using the existing RHIC complex

ELIC at Jefferson Laboratory using the Upgraded 12GeV CEBAF

Both planned to be STAGED
RHIC as a Polarized Proton Collider

Without Siberian snakes: \( \nu_{sp} = G_f = 1.79 \text{ E/m} \rightarrow ~1000 \) depolarizing resonances
With Siberian snakes (local 180° spin rotators): \( \nu_{sp} = \frac{1}{2} \rightarrow \) no first order resonance
Two partial Siberian snakes (11° and 27° spin rotators) in AGS

STONY BROOK
A. Deshpande, Science of EIC & the Path to Realization
1/31/12 27

Staging of eRHIC: \( E_0 : 5 \rightarrow 30 \text{ GeV} \)

ERL: 6 electron beam passes thru SRF linacs precede (accel) and follow (decel) e-p/e-A collisions
New detector

All energies scale proportionally by adding SRF cavities to the injector

V. Litvinenko

Technical design review
Aug. 1-3, 2011; Aim for cost review Spring 2012

eRHIC design has evolved to make optimal use of existing RHIC infrastructure, and to permit straightforward (multi-step) upgrades from Phase 1 to eventual full electron energy
ARC’s

Recent developments: lattice of recirculating passes for 20-30 GeV electron energy; spreader/combiners (D. Trbojevic, N. Tsoupas)

30 GeV e+ ring
30 GeV ERL
HE ERL passes
LE ERL passes

1.27 m beam high

CENTER OF RING

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MEIC: Medium Energy EIC

Three compact rings:
• 3 to 11 GeV electron
• Up to 12 GeV/c proton (warm)
• Up to 60 GeV/c proton (cold)

Exists

12 GeV CEBAF

prebooster
Ion Sources
SRF Linac
medium-energy IPs
Low-to-medium collider ring
polarimetry
low-energy IP

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Deep Inelastic Scattering

**Kinematics:**

- Kinematic variables:
  - $k_\mu$: momentum of the incident lepton
  - $k_{\mu'}$: momentum of the scattered lepton
  - $E_e$: energy of the incident lepton
  - $E_e'$: energy of the scattered lepton
  - $\theta_e$: scattering angle
  - $y = \frac{pq}{pk} = 1 - \frac{E_e'}{E_e} \cos^2\left(\frac{\theta_e}{2}\right)$: kinematic variable

- Formulae:
  - $Q^2 = -q^2 = -(k_\mu - k_{\mu'})^2$
  - $Q^2 = 2E_eE_e'(1 - \cos\theta_e)$
  - $x = \frac{Q^2}{2pq}$
  - $z = \frac{E_h}{\nu} : p_t$ with respect to $\gamma$

- Measure of resolution power
- Measure of inelasticity
- Measure of momentum fraction of struck quark

**Inclusive events:**

- $e+p/A \rightarrow e+X$

- detect only the scattered lepton in the detector

**Semi-inclusive events:**

- $e+p/A \rightarrow e'+h(\pi,K,p,\text{jet})+X$

- detect the scattered lepton in coincidence with identified hadrons/jets in the detector
**Deep Inelastic Scattering**

**Kinematics:**

\[
Q^2 = -q^2 = -(k_\mu - k'_\mu)^2 \\
Q^2 = 2E_eE'_e(1 - \cos \Theta'_e) \\
y = \frac{pq}{pk} = 1 - \frac{E'_e}{E_e} \cos^2 \left(\frac{\Theta'_e}{2}\right) \\
x_B = \frac{Q^2}{2pq} = \frac{Q^2}{sy} \\
t = (p - p')^2, \xi = \frac{x_B}{2 - x_B}
\]

Measure of resolution power

Measure of inelasticity

Measure of momentum fraction of struck quark

Exclusive events:
\[e + (p/A) \rightarrow e^- + (p'/A') + \gamma / J/\psi / \rho / \phi \]
detect all event products in the detector

Special sub-event category **rapidity gap events**
\[e + (p/A) \rightarrow e^- + \gamma / J/\psi / \rho / \phi / \text{jet} \]
Don't detect \((p'/A')\) in final state

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**Emerging eRHIC Detector Concept**

- High acceptance: \(-5 < \eta < 5\) central detector
- Good PID and vertex resolution (< 5\(\mu\)m)
- Tracking and calorimeter coverage the same \(\rightarrow\) good momentum resolution, lepton PID
- Low material density \(\rightarrow\) minimal multiple scattering and bremsstrahlung
- Very forward electron and proton detection \(\rightarrow\) maybe dipole spectrometers
**Detector & IR Design: ELIC**

- **Central detector**
  - Detect particles with angles **down to 0.5°** before ion FFQs.
  - Need 1-2 Tm dipole.

- **Very-forward detector**
  - Large dipole bend @ 20 meter from IP (to correct the 50 m rad ion horizontal crossing angle)
  - Allows for **very-small angle detection (<0.3°)**

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**A set of meetings on the Physics of EIC: 1999-2010**
http://web.mit.edu/eicc/Meetings.html

**A series of Users Workshops at Jefferson Lab in 2010:**
Users Workshops Organizer by the Users of Jeff Lab:
http://michael.tunl.duke.edu/workshop
http://www.phy.anl.gov/mep/EIC-NUC2010/

**An International Group met at the INT September – December 2010 to define: The Science of EIC “Golden Measurements”**
Institute of Nuclear Theory (INT) at U. of Washington: Sep-Nov 2010
Organizers: D. Boer, M. Diehl, R. Milner, R. Venugopalan, W. Vogelsang

See the INT WebPage for details of all studies:
http://www.int.washington.edu/PROGRAMS/10-3/
INT Workshop Write-up: http://arxiv.org/abs/1108.1713v2
Science of EIC:
Precise Investigations of the “Glue & Sea Quarks”

- Precision measurements of *Sea Quarks* and *Gluon's Spin* via inclusive and semi-inclusive DIS including EW probes of the hadron structure

- Measurement of (gluon) GPDs & TMDs: via semi-inclusive and exclusive DIS (nucleons and nuclei) \( \rightarrow \) wide range in \( x \) and \( Q^2 \)
  - 3D momentum and position (correlations) of the nucleon/nuclei
  - Possibly leading to orbital angular momentum in nucleons

- Study of extreme high gluon densities via inclusive and semi-inclusive DIS off a wide range of nuclei and energies

- High energy, beam polarization, and a full acceptance detector: why not explore precision electroweak physics and EW (spin) structure functions

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**Nucleon Spin: Precision measurement of \( \Delta G \)**

![Diagram showing precision measurement of \( \Delta G \)]

Sassot & Stratmann

Yellow band (left) reduces to the band shown with red dashed line (right)
GPDs → Orbital Angular Momenta?

Nucleon Spin = \( \frac{1}{2} \) = \( J_{\text{quark}} + J_{\text{gluons}} \)

\[ J_q = \frac{1}{2} \Delta \Sigma + L_q \]

\[ J_q = \frac{1}{2} \int_0^1 x \, dx \left[ H(x, t, \zeta) + E(x, t, \zeta) \right] \]

Similar expression for gluon \( J_g \) total spin contribution through DVVM

Needs measurements over a wide range in each of the variables

Simulations and eRHIC impact studies: underway in BNL Task Force

Transverse Parton Imaging & GPDs

Fourier transform of momentum transfer

EIC:
1) \( x < 0.1 \): gluons!
2) \( x \sim 0 \) → the “take out” and “put back” gluons act coherently.
Measurement of Gluons at Low x

- **Diffractive cross section**
- $F_2(x, Q^2)$ and its *scaling violations* of Nucleons & Nuclei
- Structure function $F_L(x, Q^2)$

\[
\frac{d^2\sigma^{eh\rightarrow eX}}{dx dQ^2} = \frac{4\pi\alpha_e^2}{xQ^4} \left[ \left( 1 - y + \frac{y^2}{2} \right) F_2(x, Q^2) - \frac{y^2}{2} F_L(x, Q^2) \right]
\]

$Q^2 = S x y$

- Needs *change of beam energies* to directly measure $F_L$

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**$F_{2,L}$ sensitivity studies**

$F_{2,L}$ extracted from pseudo-data generated for 1 month running at 3 eRHIC energies

- 5+100 GeV
- 5+250 GeV
- 5+325 GeV

Data points added to theoretical expectations from ABKM09 PDF set to visualize stat. errors

- valid for $Q^2 > 2.5$ GeV$^2$
How does e-A really help?

Nuclear Oomph Factor:

\[
(Q_s A)^2 \approx c Q_0^2 \left( \frac{A}{x} \right)^{1/3}
\]

Instead of extending \( x \), \( Q \) reach increased \( Q_s \).

\( \sim sx \): EIC factor 27 behind (10+100 GeV)

\[
Q_s^2(Hera) = Q_s^2(EIC) \rightarrow Q_0^2 x_e^{-1/3} = c Q_0^2 A^{1/3} x_e^{-1/3}
\]

\[
x_{EIC} = x_{Hera} \cdot c^3 A
\]

\[
c^3 A = 0.5^3 \cdot 197 \approx 25
\]

Small \( x \) and saturation

\( F_L \)

\( F_2 \)

plots: T. Lappi

- EIC: \( E_p = 300 \) GeV, \( E_A = 130 \) GeV/nucleon, \( E_x = 30 \) GeV
- mEIC: \( E_A = 130 \) GeV/nucleon, \( E_x = 5 \) GeV
- always cut \( y < 0.9 \)
Diffraction: A robust signature for CGC

- Diffraction → in the final state, the proton remains intact
- Pomeron exchange: → low-x issue
- Surprise: ~14% of the time, the proton remain intact. Completely unanticipated, astonishing phenomena

- CGC attempts to give quantitative description
  - CGC predicts in e-A, DIFFRACTION: 14% → 30%-40%
  - Needs to be experimentally verified...

Requires tagging of the nucleus: Can it be successfully done?
- Low angle
- Low binding energy of the nucleon
- Prone to break-up

Experimental simulation studies
In progress

DIS vs. Diffractive events in ZEUS
**Diffractive vector meson production in eA**

Precise transverse imaging of the gluons in protons & nuclei
Later, how low x dynamics modifies this transverse gluon distribution

Toll and Ullrich (2011)

![Graph](image)

Exclusive coherent (at small t) and incoherent (intermediate t) Diffraction
Experimental challenges being Studied.

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**Electroweak & beyond... (?)**

BNL LDRD: Deshpande, Marciano, Kumar & Vogelsang

- High energy collisions of polarized electrons and protons and nuclei afford a unique opportunity to study electro-weak deep inelastic scattering
  - **Electroweak structure functions (including spin)**
  - Significant contributions from W and Z bosons which have different couplings with *quarks and anti-quarks*

- **Parity violating DIS**: a probe of beyond TeV scale physics
  - Measurements at higher $Q^2$ than the PV DIS 12 GeV at Jlab
  - Precision measurement of $\sin^2 \Theta_W$

- **New window for physics beyond SM?**
  - Lepton flavor violation search $e^- + p \to \tau^- + X$

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*arXiv: 006.5063v1 [hep-ph]*

M. Gonderinger et al.
EW Physics Highlights

Deviations from the curve may hint at existence of BSM scenarios including: Lepto-Quarks, RPV SUSY extensions, E₆/Z’ based extensions of the SM.

Electroweak CC and NC structure functions: access to spin properties of quarks and anti-quarks over a wide x, Q² range.

EIC Luminosity vs. Time (Detector)

eRHIC/ELIC detector with good PID & full acceptance

Stage 1 Physics ePHENIX/eSTAR MEIC Detector

Inclusive

Semi-Inclusive

Exclusive
EIC Project status and plans

• A “collaboration” of highly motivated people:
  – 100+ dedicated physicists from 20+ institutes
  – Task Forces at BNL (Aschenauer & Ullrich) and at Jefferson Laboratory (Ent)
  – Steering Committee (co-ordinators/contacts persons: Milner & AD)

• **EIC International Advisory Committee** formed by the BNL & Jlab Management to steer this project to realization: *W. Henning (ANL/RIKEN, Chair), J. Bartels (DESY), A. Caldwell (MPI, Munich), A. De Roeck (CERN), R. Gerig (ANL), D. Hetzog (U of W), X. Ji (Maryland), R. Klanner (Hamburg), A. Mueller (Columbia), S. Nagaitsev (FNAL), N. Saito (J-PARC), Robert Tribble (Texas A&M), U. Wienands (SLAC), V. Shiltev (FNAL)*

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**A White for NSAC Long Range Plan 2012/2013 to be produced by early 2012**

**Writing Group:** E; Aschenauer, M. Diehl, H. Gao, A. Hutton, T. Horn, K. Kumar, Y. Kovchegov, M. Ramsey-Musolf, T. Roser, F. Sabatie, E. Sichtermann, T. Ullrich, W. Vogelsang, F. Yuan

**Senior Advisors:** A. Mueller, R. Holt

**Co-Chairs/Editors:** A. Deshpande, J. Qiu, Z.E. Meziani

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**H. Montgomery, Jeff. Laboratory Director**

EIC Realization Possible Time Line

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*Construction Schedule Highly Site Dependent*
**EIC: Status in US NP & Path Forward**

- "An EIC with polarized beams has been embraced by the US nuclear science community as embodying the vision for reaching the next QCD frontier"

- EIC was not ready for construction in 2007, hence no recommendation

- Highest priority for accelerator and detector R&D

**Approval in the next LRP (2012/2013/?) needs: articulation of the science case for a broad NP community**

**Summary**

The science case for EIC is strong. Best possible articulation of it for the wider NP audience (and beyond) is now being developed.

Science Case for EIC: → “Understand QCD” via

*“Precision study of the role of gluons & sea quarks in QCD”*

For this the EIC, with its parameters & flexibility, will be superior to any other existing or future planned QCD facilities in the world

The EIC Enthusiasts & the BNL+Jlab managements are moving *(together)* towards its realization: *Milestone: NSAC approval 2013*

• Machine R&D, detector discussions, simulation studies towards making the final case including detailed detector design & cost: underway…