Opportunities in ep Physics at an Electron-Ion Collider

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INT Program 10-3 (Sep 13 to Nov 19, 2010)

Gluons and the quark sea at high energies:
distributions, polarization, tomography

organizers: D. Boer, M. Diehl, R. Milner, R. Venugopalan, W. Vogelsang

convenors: D. Hasch, M.S., F. Yuan spin, PDFs, TMDs M. Burkardt, V. Guzey, F. Sabatie imaging
A. Accardi, M. Lamont, C. Marquet eA K. Kumar, Y. Li, W. Marciano beyond SM

main goal: sharpen the physics case for an EIC for next NSAC long range plan

• identify outstanding open questions in hadronic physics still relevant in 10+ years
• devise key “golden” measurements in ep and eA to address these questions
• quantify experimental needs & requirements and study feasibility

very successful, well attended program: most goals accomplished
detailed 500+ pages write-up is in its finishing stages – to appear on the arXiv soon

joint BNL/INT/JLab publication

but no time to sit & relax

• studies for identified “golden measurements” need to be substantiated & feasibility demonstrated

• input for community wide white paper (draft by end of 2011)
Physics Questions to be addressed at an EIC
spin physics

what is the polarization of gluons at small $x$ where they are most abundant

what is the flavor decomposition of the polarized sea depending on $x$

determine quark and gluon contributions to the proton spin at last
most compelling physics questions

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**imaging**
- what is the spatial distribution of quarks and gluons in nucleons/nuclei
- understand deep aspects of gauge theories revealed by $k_T$ dep. distr'n
- possible window to orbital angular momentum
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**physics of strong color fields**
- quantitatively probe the universality of strong color fields in AA, pA, and eA
- understand in detail the transition to the non-linear regime of strong gluon fields and the physics of saturation
- how do hard probes in eA interact with the medium
Prerequisites: Machine, Kinematics
• most design parameters converging (likewise for detector concepts)
• both machines have staged approach

eRHIC:
up to 30 GeV electrons (stage-1: 5 GeV)
up to 325 GeV protons
up to 130 GeV/u ions

MEIC: (stage-1)
3-11 GeV electrons
20-100 GeV protons (full ELIC: 250 GeV)
12-40 GeV/u ions (full ELIC: 100 GeV/u)

• luminosities of few × 10^{33} cm^{-2}s^{-1} sufficient to perform most “golden” measurements (often quickly systematics limited)
• small x reach critical to achieve goals (saturation regime, spin, …)
key to EIC program: large & variable kinematic coverage

EIC stage-1 (ep):
\[ \sqrt{S} = 32 \quad 45 \quad 71 \quad 81 \]
\[ x_{\text{min}} \approx 10^{-3} \quad 2 \times 10^{-4} \quad 1.6 \times 10^{-4} \]
small x pol. DIS
lever arm for \( F_L \)

eRHIC 5x50, 5x100, ..., 5x250, 5x325
MEIC 11x60
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small x pol. DIS

\[ \sqrt{S} \approx 80 \quad \sqrt{S} \approx 50 \]

\[ Q^2 = x y S \]

**EIC stage-1 (eA):** \( \sqrt{S} \approx 50 \) sufficient?

benefit from nuclear enhancement factor

\[ Q^2_s(eA) \approx A^{1/3} Q^2_s(ep) \]

Kowalski, Lappi, Venugopalan

to reach saturation regime much earlier in eA

however, little lever-arm at stage-1

full EIC \( \sqrt{S} \approx 120 \) will allow us to go “in and out” of saturation regime; \( F_L^{eA} \) measurement possible

eRHIC 5x50, 5x100, ..., 5x250, 5x325

MEIC 11x60
Some “golden Measurements”
the quest for the spin of the proton: $\Delta g$

**current status:**

- Low x behavior unconstrained
  - Significant polarization still possible
- No reliable error estimate for 1st moment $\int_0^1 dx \Delta g(x, Q^2)$ (enters spin sum rule)
- RHIC will continue to improve our knowledge at medium x

DSSV global fit
de Florian, Sassot, MS, Vogelsang

\[
\Delta f(x) \equiv f_+^N(x) - f_-^N(x)
\]

\[
\frac{1}{2} \Delta \Sigma = \frac{1}{2} \Delta \Sigma + \Delta g + L_{q,g}
\]

- Quarks
- Gluons
- OAM
**the quest for the spin of the proton: $\Delta g$**

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**DSSV global fit**
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**best probe for small $x$ gluons**
pQCD scaling violations

$$\frac{d g_1(x, Q^2)}{d \ln Q^2} \propto -\Delta g(x, Q^2)$$

**$\frac{1}{2} \hbar = \frac{1}{2} \Delta \Sigma + \Delta g + L_{q,g}$**
quarks gluons OAM
polarized DIS @ EIC and impact on \( \Delta g(x, Q^2) \)

strategy to quantify impact: global QCD fits with realistic pseudo-data

measurements limited by systematics – need to control them very well

issues: bunch-by-bunch polarimetry, relative luminosity, detector performance, ...
how effective are scaling violations?

quantitative studies based on simulated data for eRHIC stage-1: 5 x (50, 100, 250, 325) GeV

\[ \chi^2 \text{ profile for } \int_{10^{-4}}^{1} \Delta g(x, Q^2) \, dx \]

from current ep & RHIC data

Sassot, MS
how effective are scaling violations?  
quantitative studies based on simulated data for eRHIC stage-1: 5 x (50, 100, 250, 325) GeV

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χ² profile for

\[
\int_{10^{-4}}^{1} \Delta g(x, Q^2) \, dx
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χ² profile slims down significantly already for eRHIC stage-1
how effective are scaling violations? quantitative studies based on simulated data for eRHIC stage-1: 5 x (50, 100, 250, 325) GeV

Sassot, MS

$x^2$ profile for $\int_{10^{-4}}^{1} \Delta g(x, Q^2) \, dx$

uncertainties on the x-shape of $\Delta g(x, Q^2)$

DSSV $\Delta x^2 / x^2 = 2\%$ band

$Q^2 = 10 \text{ GeV}^2$
how effective are scaling violations?  
quantitative studies based on simulated data for eRHIC stage-1: 5 x (50, 100, 250, 325) GeV

\[ \chi^2 \text{ profile for } \int_{10^{-4}}^{1} \Delta g(x, Q^2) \, dx \]

uncertainties on the x-shape of \( \Delta g(x, Q^2) \)

expect to determine \( \int_{0}^{1} dx \Delta g(x, Q^2) \) at about 10% level (or better - more studies needed)

kinematic reach down to \( x = 10^{-4} \) essential to determine integral
how effective are scaling violations? 

quantitative studies based on simulated data for eRHIC stage-1: $5 \times (50, 100, 250, 325) \text{ GeV}$

$x^2$ profile for

$$\int_{10^{-4}}^{1} \Delta g(x, Q^2) \, dx$$

uncertainties on the $x$-shape of $\Delta g(x, Q^2)$

similar improvements can be expected

for all quark flavors by studying SIDIS

(work in progress: eRHIC TF + MS, Sassot)

expect to determine

$$\int_{0}^{1} dx \, \Delta g(x, Q^2)$$

at about 10% level (or better - more studies needed)

kinematic reach down to $x = 10^{-4}$ essential to determine integral
strangeness is one of the least known quantities in hadronic physics
- both unpolarized and polarized - where significant progress is difficult w/o an EIC

\[ x[s(x) + \bar{s}(x)]/2 \]

\[ x \Delta s(x) = x \Delta \bar{s}(x) \]

• substantial uncertainties
• known issues with HERMES data at large \( x \)
• hot topic: \( s(x) - \bar{s}(x) \)

• surprise: \( \Delta s \) small & positive from SIDIS data
• but 1st moment is negative and sizable due to “constraint” from hyperon decays (F,D) (assumed SU(3) symmetry debatable M. Savage)
• drives uncertainties on \( \Delta \Sigma \) (spin sum)

we really need to determine it better! (including their u,d quark colleagues)
feasibility study: $K^+$ yields in unpol. ep at NLO based on 100 NNPDF replicas $z$ integrated to minimize FF uncertainties

actual uncertainties much smaller than points one month of running

PYTHIA MC points agree well with NLO (despite very different hadronization model)

work in progress: quantify impact (requires full global analyses); pion yields, SIDIS in polarized ep
at high enough $Q^2$ electroweak probes become relevant

- **neutral currents** ($\gamma$, $Z$ exchange, $\gamma Z$ interference)
- **charged currents** ($W$ exchange)

parameterized by new structure functions which probe combinations of PDFs different from photon exchange

--> flavor decomposition without SIDIS; e-w couplings

**hadron-spin averaged case:** studied to some extent at HERA (limited statistics)

**hadron-spin difference:**

contains e-w propagators and couplings

\[
\frac{d\Delta\sigma^{e^\pm,i}}{dx dy} = \frac{4\pi\alpha^2}{xyQ^2} \left[ \pm y(2 - y)x\hat{g}_1 - (1 - y)\hat{g}_4 - y^2 x\hat{g}_5 \right] \quad i = NC, CC
\]

**unexplored so far - unique opportunity for the EIC**
large $Q^2$: novel electroweak probes for $\Delta q's$

Key for e-w measurements at an EIC:
derop in cross section more than compensated by luminosity increase

unexplored so far - unique opportunity for the EIC
most promising: charged current DIS

\[ \frac{\sigma(p_R) - \sigma(p_L)}{\sigma(p_R) + \sigma(p_L)} \]

measurement is a single-spin asymmetry

requires an unpolarized positron beam

\[ A_W^- = \frac{(\Delta u + \Delta c) - (1 - y)^2(\Delta \bar{d} + \Delta \bar{s})}{(u + c) + (1 - y)^2(\bar{d} + \bar{s})} \]
\[ A_W^+ = \frac{(1 - y)^2(\Delta d + \Delta s) - (\Delta \bar{u} + \Delta \bar{c})}{(1 - y)^2(d + s) + (\bar{u} + \bar{c})} \]

Cabibbo suppressed contributions neglected

20 \times 250 \text{ GeV}

DIS cuts

10 \text{ fb}^{-1}

need to be able to reconstruct \( x, Q^2 \) from hadronic final-state

separate up-type and down-type PDF combinations by varying \( y \)
**DIS structure fct. $F_L$ at an EIC**

**recall:** hard to measure \[ \sigma_r = F_2(x, Q^2) - \frac{y^2}{Y_+} F_L(x, Q^2) \]

contributes mainly at large $y$ (= lowest $x$ for any given $Q^2$)

strategy: slope of $y^2/Y_+$ for different $S$ at fixed $x$ and $Q^2$  

largely missed at HERA (limited statistics for different $E_p$)

**very relevant:** strong sensitivity to gluons -> saturation effects

at LO \[ F_L = \frac{\alpha_s}{4\pi} x^2 \int_x^1 \frac{dz}{z^3} \left[ \frac{16}{3} F_2(z) + 8 \sum_q e_q^2 \left( 1 - \frac{x}{z} \right) zg(z) \right] \]
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**1st feasibility study for ep**

5x50 - 5x325
running combined
(about 1 month each)

needs to be refined:
- detector resolution
- systematic uncertainties
- QED radiative corrections
- extend to eA

Aschenauer, Debbe, MS
Bartels, Golec-Biernat, Motyka

**ratio** = \( \frac{F_L^{\text{tot}} - F_L^{\text{leading twist}}}{F_L^{\text{tot}}} \)

quantitative estimate based on phenomenological successful dipole model description of DIS data

compute non-linear effects in

recall: DIS in the proton rest frame: photon splits into a quark-antiquark pair ("*color dipole*) which scatters off the target proton (= "slow" gluon field)
"3D imaging" of nucleons and nuclei

**goal:** going beyond longitudinal momentum structure & collinear factorization
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TMDs

2+1 D picture in momentum space

Bacchetta, Conti, Radici
goal: going beyond longitudinal momentum structure & collinear factorization

TMDs
2+1 D picture in momentum space

GPDs
2+1 D picture in impact-parameter space

Bacchetta, Conti, Radici

QCDSF collaboration
relativistic system/uncertainty principle: can localize only in *two* dimensions

<table>
<thead>
<tr>
<th>TMDs</th>
<th>GPDs</th>
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<td>• intrinsic transverse motion</td>
<td>• collinear but long. momentum transfer</td>
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transverse structure: momentum vs. position

relativistic system/uncertainty principle: can localize only in \textit{two} dimensions

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- intrinsic transverse motion
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\textbf{gluon and sea distributions largely unknown $\rightarrow$ EIC}

no direct, model-indep. connection known between TMDs and GPDs

average transverse mom. and position \textit{not} Fourier conjugates

“high level connection” through \textit{Wigner phase space distr.} $W(x,k_T, b_T)$
relativistic system/uncertainty principle: can localize only in two dimensions

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**next talk**

**gluon and sea distributions largely unknown \(\rightarrow \text{EIC}\)**

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average transverse mom. and position not Fourier conjugates

“high level connection” through Wigner phase space distr. $W(x,k_T, b_T)$
suite of observables accessible in azimuthal ($\phi$) asymmetries in SIDIS related to entire zoo of TMD functions (PDFs & FFs) measured at large $x$ by HERMES & COMPASS.

focus on unpolarized $f_1$ and Sivers function to illustrate underlying physics:

$$f_{q/P\uparrow}(x, k_\perp, S) = f_1(x, k_\perp^2) - \frac{S \cdot (\hat{P} \times k_\perp)}{M} f_{1T}(x, k_\perp^2)$$
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"unintegrated PDFs"

k_T dep. gluon plays prominent role at small x rather direct access to saturation scale Q_s(x) (e.g. through di-jet correlations in eA)
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"Sivers effect"

access to 3D imaging in momentum space non-trivial role of Wilson lines role of spin-orbit correlations & OAM correlation of transverse spin of proton with $k_T$ of unpolarized quark
never been measured before; excellent signature for saturation in eA

Dominguez, Xiao, Yuan

2 < pT1 < 3 GeV
1 < pT2 < 2 GeV

\( Q^2 = 4 \text{ GeV}^2 \)

systematic depletion of away-side peak with increasing nuclear size/energy

can be also obtained in TMD factorization

\( \leftrightarrow \) unintegrated gluon at small x
profound consequence of gauge invariance: colored partons “surrounded” by gluons
(technically realized by Wilson lines; also leads to issues with factorization in some pp processes)

Collins; Belitsky, Ji, Ma, Yuan; Boer, Mulders, Pijlman; Mulders, Rogers; Aybat, Rogers; ...
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Collins; Belitsky, Ji, Ma, Yuan; Boer, Mulders, Pijlman; Mulders, Rogers; Aybat, Rogers; ....

\[ f_{1T}^{\perp \text{SIDIS}} = - f_{1T}^{\perp \text{DY}} \]

Sivers fct. has opposite sign when gluons couple “after” quark scatters (SIDIS) or “before” quark annihilates (DY) (and would be zero without gluons)
**TMDs: physics of Wilson lines**

**Profound consequence of gauge invariance:** colored partons "surrounded" by gluons (technically realized by Wilson lines; also leads to issues with factorization in some pp processes)

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**Rough analogy:**

P. Mulders

importance of phases in physics

\[ \psi' = e^{ie\int ds A} \psi \]

\[ \psi_i(x)|P\rangle = e^{-ig\int ds A} \psi_i(x')|P\rangle \]
• multi-dim. binning possible (here 30fb\(^{-1}\) = few months of running) - similarly for kaons
• pseudo-data being used in global fits of TMDs (work in progress) Prokudin et al
• TMDs encode physics for small transverse momenta (or $p_T$ differences) and $Q \gg p_T$
• if $p_T$ is large, it can be treated perturbatively
• no sharp boundary between “intrinsic” and “radiative” $p_T$ --> matching region

example: SIDIS (hadron mass $M$, $q_T^2 \approx p_{T,H}^2/z$)

---

**TMD factorization**

**collinear factorization**

$\text{twist-3 parton-parton correlation}$

$\text{Efremov, Teryaev; Qiu, Sterman}$

the leading high-$p_T$ part should match with the $p_T$ tail of the TMD

$\text{Collins, Soper, Sterman; Ji, Qiu, Vogelsang, Yuan}$
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TMD factorization
collinear factorization
can be studied in detail at an EIC
requires about 100fb$^{-1}$

the leading high-$p_T$ part should match with the $p_T$ tail of the TMD

Collins, Soper, Sterman; Ji, Qiu, Vogelsang, Yuan
• latest twist: “sign mismatch” Kang, Qiu, Vogelsang, Yuan

$1^{st} k_T$ moment of Sivers fct and twist-3 analogue related at operator level

$$g_s T_{q,F}(x, x) = - \int d^2k_T \frac{|k_T|^2}{M} f_{1T}(x, k_T^2) |_{SIDIS}$$

both sides have been extracted from data

**find:** similar magnitude ✓ but wrong sign ✗

inconsistency in formalism?
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possible resolutions: (1) data constrain Sivers fct only at low $k_t$; function has a node

phenomenological studies with more flexible Sivers fct. under way

(2) analysis of $T_{q,F}$ neglects possible final-state contributions to $A_N$

need data for $A_N$ which are insensitive to fragmentation: photons, jets, DY

• on the bright side: recent progress on evolution for Sivers fct Kang, Xiao, Yuan

crucial for consistent phenomenology - properly related experiments at different scales
general complication: QED radiative corrections

precision measurements in ep/eA require good understanding of QED corrections

problem: photon radiation strongly affects exp. determination of kinematics
e.g. \[ Q^2 = -(1 - l')^2 \rightarrow \tilde{Q}^2 = -(1 - l' - k)^2 \]
effects are large but we can benefit from HERA experience

H. Spiesberger

extraction of “true” structure functions requires unfolding procedure:

\[
F_{i}^{\text{obs}}(x, Q^2) = \int d\tilde{x} d\tilde{Q}^2 \ R_i(x, Q^2; \tilde{x}, \tilde{Q}^2) \ F_{i}^{\text{true}}(\tilde{x}, \tilde{Q}^2)
\]

“radiator function” calculable
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\]

“radiator function” calculable
other opportunities in ep scattering

• watch out for "surprises" at small-\( x = \) deviations from polarized DGLAP
  might set in earlier than in unpol. DIS: \([\alpha_s \ln^2(1/x)]^k\) 
  Bartels, Ermolaev, Ryskin; Ermolaev, Greco, Troyan

• tag on \( g_1^{\text{charm}} \) - irrelevant so far (<< 1%), driven by \( \Delta g \) at small \( x \), NLO in progress 
  Kang, MS

• extract (anti-)strangeness from CC charm production \( W^+ s' \rightarrow c \) NLO 
  Kretzer, MS

• Bjorken sum rule:
  \[
  \int_0^1 dx \left[ g_1^p(x, Q^2) - g_1^n(x, Q^2) \right] = \frac{1}{6} C_{Bj} \left[ \alpha_s(Q^2) \right] \ g_A
  \]
  known to \( O(\alpha_s^4) \)
  Kodaira; Gorishny, Larin; Larin, Vermaseren; Baikov, Chetyrkin, Kühn, ...

  • experimental challenge: effective neutron beam \((^3\text{He})\), very precise polarimetry, ...

  • theor. motivation for precision measurement: Crewther relation

  Adler function \( D(Q^2) \) in \( e^+e^- \) \( \xrightarrow{\text{deviation from}} \) Bj sum \( C_{Bj}(Q^2) \) in DIS

  \[ \sim 1 + \frac{\beta(\alpha_s)}{\alpha_s} K(\alpha_s) \]
  exact conformal symmetry

• detailed study of heavy quark production: \( F_2, F_L \), and intrinsic charm ?

• host of photoproducion measurements (access to photon PDFs needed at an ILC)

  and many other topics ...
- goal: measure running of $\sin^2 \Theta_W$ over a wide range of scales $Q$

- other avenues pursued: electron-tau conversion
Summary & Outlook
overarching theme of an EIC
from testing QCD to a detailed understanding of QCD

an EIC is the Über-microscope for precision QCD studies

can explore the rich science of QCD many-body dynamics of “cold” nuclear matter complementary to pp / pA / AA physics

made quite some headway in identifying the “golden measurements”
details need to be worked out now (realistic feasibility studies & “impact plots”)

detailed write-up of INT program will appear very soon - stay tuned
serves as input to a White Paper anticipated for the end of the year
BACKUP SLIDES
can we finally settle this?
• shown:
  \( F_{2c} \) ~ BMSN
  (close to \( m_c \neq 0 \))

• \( F_{Lc} \) is not small
  (\( m_c \neq 0 \))

TO DO:

det. simulations & optimize extraction of \( F_{2, Lc} \)
• many observables possible in $lp \rightarrow lhX$ if intrinsic $k_T$ included and $\Phi$ kept e.g. “left-right asymmetries” in the direction of produced hadron
• seen at HERMES and COMPASS (but mainly valence quark region & large uncertainties)

SIDIS cross section: 

$$d\sigma^h(x, Q^2, z, P_T^h, \phi, \phi_S, \lambda) = d\sigma_{UU} + \cos 2\phi d\sigma_{UU} + S_L \sin 2\phi d\sigma_{UL} + \frac{\lambda S_L d\sigma_{LL}}{\Delta q \otimes D}$$

$$+ S_T [\sin(\phi + \phi_S) d\sigma_{UT} + \sin(\phi - \phi_S) d\sigma_{UT} + \sin(3\phi - \phi_S) d\sigma_{UT}]$$

$$+ \lambda S_T \cos(\phi - \phi_S) d\sigma_{LT} + \frac{1}{Q} ...$$

$f_{1T} \otimes D$ “Sivers effect”

correlation of transverse spin of proton with $k_T$ of unpolarized quark