Opportunities in Electroweak Physics at a future e-A Collider

Why an Electron Ion Collider (EIC)?
Role of Glue in QCD:
Structure & Dynamics of partons in nuclei & nucleons

The Science and Status of Electron Ion Collider in the US

Abhay Deshpande
Stony Brook University

Electron Ion Collider Proposals:
Machine and Detector Concepts

Early studies and possibilities of EW, BSM
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

*Gluon dominates*

*Dokshitzer, Gribov, Lipatov, Altarelli, Parisi*
Gluons at Low $x$: Color Glass Condensate(?)

McLerran, Venugopalan… See Review: F. Gelis et al., arXiv:1002.0333

- Method of including non-linear effects in DGLAP equation
- Small coupling, high gluon densities $\rightarrow$ Saturation Scale $Q_s^2(x, Q^2, A)$
  - Some form of saturation, including Color Glass Condensate
  - No unambiguous experimental evidence yet, but many smoking guns (HERA, RHIC & now LHC!)
  - Could be explored cleanly in future with a high energy electron-Nucleus Collider

$$(Q_s^A)^2 \approx cQ_0^2 \left[ \frac{A}{x} \right]^{1/3}$$

Kowalski, Teany
PRD 68:114005

Could be explored cleanly in future with a high energy electron-Nucleus Collider
UNDERSTANDING NUCLEON SPIN: WHAT ROLE DO GLUONS PLAY?
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 \( x \)
\[ \Delta g(x) \oplus Q^2 = 10 \text{ GeV}^2 \]

de Florian, Sassot, Stratmann & Vogelsang

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

\[
\frac{d g_1}{d \log(Q^2)} \propto -\Delta g(x, Q^2)
\]

Low \( x \) measurements = Opportunity!
Status of “Nucleon Spin Crisis Puzzle”

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

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- Generalized Parton Distributions: $H,E,E',H' \rightarrow$ Connection to partonic OAM
  - Quark GPDs $\rightarrow J_q$: 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!
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

Measurements:
[1] $\rightarrow$ Inclusive  

Inclusive $\rightarrow$ Exclusive  
Low $\rightarrow$ High Luminosity  
Demanding Detector capabilities
EIC: Basic Parameters

- $E_e = 10 \text{ GeV}$ (5-30 GeV variable)
- $E_p = 250 \text{ GeV}$ (50-325 GeV Variable)
- $\sqrt{s_{ep}} = 100$ (30-200) GeV
- $X_{min} = 10^{-4}$; $Q^2_{max} = 10^4$ GeV
- Beam pol. $\sim 70\%$ for e,p,D,$^3$He
- Luminosity $L_{ep} = 10^{33-34} \text{ cm}^{-2}\text{s}^{-1}$
- Minimum Integrated luminosity:
  - 50 fb$^{-1}$ in 10 yrs (100 x HERA)
  - Possible with $10^{33} \text{ cm}^{-2}\text{s}^{-1}$
  - Recent projections much higher

Nuclei:
- $p -> U$; $E_A = 20-100$ (140) GeV/N
- $\sqrt{s_{eA}} = 12-63$ (75) GeV
- $L_{eA}/N = 10^{33} \text{ cm}^{-2}\text{s}^{-1}$
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
### ELIC: High Energy & Staging

**Serves as a large booster to the full energy collider ring**

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**Straight section**

**Arc**

Abhay Deshpande: EW Physics Opportunities at the EIC
eRHIC: polarized electrons with $E_e \leq 30$ GeV will collide with either polarized protons with $E_e \leq 325$ GeV or heavy ions $E_A \leq 130$ GeV/u

eRHIC staging: All energies scale proportionally

Linac 2.45 GeV

Coherent e-cooler

Linac 2.45 GeV

Beam dump

0.6 GeV

Polarized e-gun

5 mm gap

0.3 T @ 30 GeV

Small gap magnets

5 mm gap

0.3 T @ 30 GeV

30 GeV

30.0 GeV

25.1 GeV

20.2 GeV

15.3 GeV

10.4 GeV

5.50 GeV

3.05 GeV

7.95 GeV

12.85 GeV

17.75 GeV

22.65 GeV

27.55 GeV

100 m

V.N. Litvinenko

ePHENIX

eSTAR

Abhay Deshpande: EW Physics Opportunities at the EIC

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Forward / Backward Spectrometers:

- Central detector
- EM Calorimeter
- Hadron Calorimeter
-Muon Detector
-TOF
-HTCC
-RICH or DIRC/LTCC
-Tracking

BNL EIC Task Force

JLab EIC WG

Fix similar!
Science of EIC:
Institute of Nuclear Theory (INT) Program at U. of Washington: Sep-Nov 2010
Organizers: D. Boer, M. Diehl, R. Milner, R. Venugopalan, W. Vogelsang

Impact of EIC....
“golden measurements”

See the INT workshop for details of all studies
http://www.int.washington.edu/PROGRAMS/10-3/

Nucleon Spin: Precision measurement of $\Delta G$

Yellow band (left) reduces to the band shown with red dashed line (right)

Sassot & Stratmann

small-$x$
$0.001 \leq x \leq 0.05$

RHIC range
$x \geq 0.2$

large-$x$
$0.05 \leq x \leq 0.2$
EIC:
1) $x < 0.1$: gluons!
2) $\xi \sim 0 \rightarrow$ the “take out” and “put back” gluons act coherently.

Fourier transform in momentum transfer

"Diffusion"

$\xi \sim 0.001 \quad \xi < 0.1 \quad \xi \sim 0.3 \quad \xi \sim 0.8$
Some measurements considered so far for the EIC:

- Push the luminosity requirements $\sim 10^{34} \text{ cm}^{-2}\text{s}^{-1}$
  - Recall that although lower in luminosity than fixed target experiments, the collider is at (high) 100-200 GeV in CM Energy

- Push the polarimetry and beam quality requirements to the extreme:
  - $(d\text{Pol}/\text{Pol}) \sim 1\%$
  - Ultra low beam divergence for DVCS/Diffractive...

Why not consider using this machine for precision EW-Physics measurements?
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 $e^- + p \rightarrow \tau^- + X$
The main objective / why interesting 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

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

unexplored so far - unique opportunity for an EIC
in the parton model (for simplicity)

NC:

\[
\begin{align*}
[g_1^\gamma, g_1^{\gamma Z}, g_1^Z] &= \frac{1}{2} \sum_q \left[ e_q^2, 2e_q g_q^V, (g_q^V)^2 + (g_q^A)^2 \right] (\Delta q + \Delta \bar{q}) \\
[g_5^\gamma, g_5^{\gamma Z}, g_5^Z] &= \frac{1}{2} \sum_q \left[ 0, e_q g_q^A, g_q^V g_q^A \right] (\Delta q - \Delta \bar{q})
\end{align*}
\]

CC:

\[
\begin{align*}
g_1^{W^-} &= (\Delta u + \Delta \bar{d} + \Delta \bar{s} + \Delta c) \\
g_1^{W^+} &= (\Delta \bar{u} + \Delta d + \Delta s + \Delta \bar{c}) \\
g_5^{W^+} &= (\Delta \bar{u} - \Delta d - \Delta s + \Delta \bar{c}) \\
g_5^{W^-} &= (-\Delta u + \Delta \bar{d} + \Delta \bar{s} - \Delta c)
\end{align*}
\]

- NLO QCD corrections all available
- can be easily put into global QCD analysis
- enough combinations for a flavor separation (no fragmentation)

requires a positron beam

de Florian, Sassot; MS, Vogelsang, Weber; van Neerven, Zijlstra; Moch, Vermaseren, Vogt

Abhay Deshpande: EW Physics Opportunities at the EIC 9/6/11 22
feasibility - 1st exploratory studies

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

\[ \sigma (\text{pb}) \]

\[ NC(e^-) \approx NC(e^+) \]

\[ CC(e^-) \]

\[ CC(e^+) \]

no \( \gamma \) cut
\( \gamma > 0.1 \)

2nd indep. study: Kumar, Riordan, Deshpande, Taneja, Paschke

20x250
30x325

HERA
Charged & Neutral Currents...

20 \times 250 \text{ GeV}, Q^2 > 1 \text{ GeV}^2, 0.1 < y < 0.9, 10 \text{ fb}^{-1}, \text{DSSV PDFs}

(Could begin the program with 5\times250 \text{ GeV} )

Two studies: (1) Ringer & Vogelsang (these figures),

(2) Taneja, Riordin, Deshpande, Kumar & Paschke

\begin{align*}
\frac{\sigma(p_R) - \sigma(p_L)}{\sigma(p_R) + \sigma(p_L)} & \quad W^+ \\
\frac{\sigma(p_R) - \sigma(p_L)}{\sigma(p_R) + \sigma(p_L)} & \quad e^- \text{ av.}
\end{align*}

\begin{align*}
\frac{\sigma(p_R) - \sigma(p_L)}{\sigma(p_R) + \sigma(p_L)} & \quad g_1 \\
g_{4,5} & \quad x
\end{align*}
Experimental Studies of LFV

- Lepton flavor violation searches have predominantly been in 1\textsuperscript{st}, and 2\textsuperscript{nd} generation leptons ($\mu, e \rightarrow \text{“LFV(1,2)“}$)

- SINDRUM ($\mu \rightarrow 3e$)
- SINDRUM II ($\mu \rightarrow e$)
- MEGA ($\mu \rightarrow e\gamma$)

- LFV(1,3) limits few orders of magnitudes weaker than LFV(1,2)
  - BaBar ($\tau \rightarrow e\gamma$)
  - BELLE ($\tau \rightarrow 3e$)

- Future measurements at Mu2e@FNAL, MEG@PSI also focus on LFV(1,2)
Opportunity for EIC

• Limits on $\text{LFV}(1,3)$ experimental searches are significantly worse than those for $\text{LFV}(1,2)$

• Especially if there are BSM models which specifically allow and enhance $\text{LFV}(1,3)$ over $\text{LFV}(1,2)$
  – Minimal Super-symmetric Seesaw model
  – SU(5) GUT with leptoquarks
• M. Gonderinger & M. Ramsey Musolf, JHEP 1011 (045) (2010); arXive: 1006.5063 [hep-ph]
• Clearly there is an opportunity for EIC: if a search can be effectively launched with it’s planned (high luminosity) and large large acceptance detector suitable for the GPD/Exclusive physics program
**LFV phenomenology**

- LPQ event topologies studied with:
  - LQ generator for e-p processes using BRW effective model
- To increase efficiency of calculations: BW-LO propagator replaced with a constant.
  - \( m_{LQ} = 200 \text{ GeV}, \lambda = 0.3 \) (for example one particular LQ…)
  - Then go over various values of \( M_{LQ} \) i.e. ratios: \( z = \lambda i \lambda j / M_{LQ}^2 \)
How does EIC compare with HERA?

Private communications: M. Gonderinger

Lepto-Quark: $e \ q_i \rightarrow \tau \ q_j$

Mass for $(q_i, q_j)$ generation (GeV)
Tau Jet identifiers and selections

- Reconstructed $D_{NN}$ variable for Tau into hadronic channel
- $p_T^{\text{miss}}$ distribution
- $\Delta\phi_{\text{miss-TauJet}}$
MC generator level studies…. So far

- **Standard model backgrounds generated**: Neutral & Charged current DIS, photo-production, lepton-pair production & W production…. *Compare event topologies* with the LQ events

- τ has a clean signature: repeated similar set of analyses as performed for such analyses in H1 and ZEUS analyses at HERA: *Established that*: Clean identification of Tau is certainly possible both for
  - Leptonic Decays of τ
  - Hadronic Decays: Narrow “pencil” like jets with 1-3 pions

- Very clear differences in topologies of SM and LQ events established. Realistic (GEANT) detector simulations now underway.
SM vs. LPQ

\[ p_T^{\text{miss}} = \sqrt{\left( \sum P_{x,i} \right)^2 + \left( \sum P_{y,i} \right)^2} \]

Acoplanarity: \( \Delta \phi_{\text{miss}} - \tau_{\text{jet}} \)

Abhay Deshpande: EW Physics Opportunities at the EIC

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\( A_{PV} \) in Deep Inelastic Scattering

\[ A_{PV} = \frac{G_F Q^2}{\sqrt{2}\pi\alpha} \left[ a(x) + f(y)b(x) \right] \]

**A\(_{PV}\) in e-N DIS:**

\[ a(x) = \frac{\sum_i C_{1i} Q_i f_i(x)}{\sum_i Q_i^2 f_i(x)} \quad b(x) = \frac{\sum_i C_{2i} Q_i f_i(x)}{\sum_i Q_i^2 f_i(x)} \]

For a \(^2\)H target, assuming charge symmetry, structure functions largely cancel in the ratio

\[ a(x) = \frac{3}{10} \left[ (2C_{1u} - C_{1d}) \right] + \ldots \]

\[ b(x) = \frac{3}{10} \left[ (2C_{2u} - C_{2d}) \frac{u_v(x) + d_v(x)}{u(x) + d(x)} \right] + \ldots \]

\( C_{1u} = (1 - 8 \sin^2 \theta_W/3)/2 \sim 0.20 \) Hadronic

\( C_{1d} = (1 - 4 \sin^2 \theta_W/3)/2 \sim -0.32 \) Hadronic

\( C_{2u} = (1 - 4 \sin^2 \theta_W)/2 \sim 0.04 \) Leptonic

\( C_{2d} = -(1 - 4 \sin^2 \theta_W)/2 \sim -0.04 \) Leptonic

\( C_{2q} \) sensitive to RC & New Physics

Measure \( A_{PV} (C_{2q}) \) to better than 0.5% (1-2%)?
Prospects: near and far future....

Jefferson Laboratory:

• 6 GeV DIS $eD \rightarrow eX$ proceeding
• 12 GeV DIS $eD$ in future (after 2015)
  – Measure $C_{2q}$’s New Physics, Charge Symmetry violation
  – Effective luminosity (fixed target) $10^{38}$ cm$^{-2}$sec$^{-1}$

Future $ep$, $eD$ collider:

• Asymmetry: $FOM \sim A^2N$; $A \sim Q^2$ & $N \sim 1/Q^2$, Acceptance
• **Collider: higher $Q^2$ but luminosity(?)**
• Need accumulate $> 100$ fb$^{-1}$ (possible with $10^{34}$ cm$^{-2}$sec$^{-1}$)

Y. Li & W. Marciano studied this at $\sqrt{s} = 140$ GeV ($ep$ or $eD$)
$\sin^2 \Theta_W$ with the EIC

- Deviation from the “curve” may be hints of BSM scenarios including: Lepto-Quarks, RPV SUSY extensions, $E_6/Z'$ based extensions of the SM
EIC Project status and plans

A “collaboration” of highly motivated people/groups intends to take this project to realization:

- 100+ dedicated physicists from 20+ institutes
- Details of many recent studies: Recent Workshop @ INT at U. of Washington: [http://www.int.washington.edu/PROGRAMS/10-3/](http://www.int.washington.edu/PROGRAMS/10-3/)
- Working groups/Task Forces at BNL and at Jefferson Laboratory
- Steering Committee (coordinators: A. Deshpande & R. Milner)

International Advisory Committee formed by the BNL & Jlab Management to steer this project to realization: 

**W. Henning (ANL, Chair), J. Bartels (DESY), A. Caldwell (MPI, Munich) A. De Roeck (CERN), R. Gerg (ANL), D. Hetrzog (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)**


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

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

**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
Summary

Science Case for EIC: → “Understand QCD”
“Precision study of the role of gluons & sea quarks in QCD”
Many body dynamics in QCD is an essential focus of this study
Exciting new possibilities are also emergent on the EW and BSM front, if at highest levels of EIC luminosities and energies and accuracy of polarization can be achieved.

The Collaboration & the BNL+Jlab managements are moving (together) towards realization: NSAC approval 2013 → Next Milestone

• Machine R&D, detector discussions, simulation studies towards making the final case including detailed detector design and cost considerations

INVITATION: Ample opportunities to get involved and influence the design of this machine according to your own physics interests and participate in this exciting quest.
Thank You!
### Activity Name

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Time line at BNL not *too* different

### Notes

- H. Montgomery, Jeff. Laboratory Director

- Abhay Deshpande: EW Physics Opportunities at the EIC
Luminosity upgrade:
Further luminosity upgrades (pp, low-E)

Staged approach to eRHIC

RHIC-II science by-passing RHIC-II project

Opportunity for upgrade* or 1st EIC stage (eRHIC-I)

EIC = Electron-Ion Collider; eRHIC = BNL realization by adding e beam to RHIC

Legend:
- R&D
- Construction
- Multiple small projects
- CD0: DOE Critical Decision, mission need

* New PHENIX and STAR Decadal Plans provide options for this period.
Why search for Lepton Flavor Violation?

- Every conservation law in the SM of Physics is anticipated to have a "symmetry" associated with it.
- We have no knowledge of a symmetry that asserts Lepton Flavor Conservation, and yet its violation has not been seen.

Although neutrino oscillation implies charged lepton flavor violation within the SM, observation of processes such as $\mu \rightarrow e\gamma$, very challenging due to smallness of neutrino mass.

$$BR(\mu \rightarrow e\gamma) = \frac{3\alpha}{32\pi} \sum_{i=2,3} |U_{\mu i}^* U_{ei}|^2 \frac{\Delta m_{1i}^2}{M_W^2} < 10^{-54}$$

Many models of physics beyond the SM predict rates of charged LFV larger than those within the SM and within reach of existing and near-future experiments.

LVF is hence considered an important probe of physics beyond the Standard model.