The Electron Ion Collider (EIC)

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Lecture 4:
What else can the EIC address?
How does one design a detector for the EIC?

EIC: how? When?
QCD Physics at the EIC:

- Pushes the luminosity requirements ~ few $10^{34}$ cm$^{-2}$s$^{-1}$
  - Recall that although lower in luminosity than fixed target experiments, the collider is at (high) 100-140 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/Diffraction…

Why not consider using this machine for precision EW & BSM Physics?
Weak probes of nucleon helicity

\[ \frac{d^2\sigma}{dxdQ^2} \sim \left\{ a \left[ F_1 - \lambda b F_3 \right] + \delta \left[ a g_5 - \lambda^2 b g_1 \right] \right\} \frac{1}{(Q^2 + M_W^2)^2} \]

where

\[ a = 2(y^2 - 2y + 2); \quad b = y(2 - y); \quad \lambda = \pm 1 \text{ for } e^\pm \]

\[ \delta = \pm 1 \text{ for } \uparrow\downarrow \text{ and } \uparrow\uparrow \text{ spin orientations} \]

Experimental signature is a large asymmetry (due to missing neutrino)

HERA used this to probe \( xF_3 \), \( W^\pm \) combination of quark, anti-quark Distributions, using electron and positron beams

EIC’s Polarized beam \( g_5^{W^+/ -} \)

First studied: J. Contreras & A. De Roeck 2002
A more recent study....

E. Aschanauer et al. PRD 88 114025 (2013)

$g_{1}^{W^{-},p}(x) = \Delta u(x) + \Delta \bar{d}(x) + \Delta c(x) + \Delta \bar{s}(x),$

$g_{5}^{W^{-},p}(x) = -\Delta u(x) + \Delta \bar{d}(x) - \Delta c(x) + \Delta \bar{s}(x),$

$g_{1}^{W^{+},p}(x) = \Delta \bar{u}(x) + \Delta d(x) + \Delta \bar{c}(x) + \Delta s(x),$

$g_{5}^{W^{+},p}(x) = \Delta \bar{u}(x) - \Delta d(x) + \Delta \bar{c}(x) - \Delta s(x)$

A full unfolding of $Q$ and $\bar{Q}$bars will require polarized electron and positron beams at high luminosity.

High luminosity positron beams is a challenge

EIC provides independent weak probes of the nucleon spin constitution, Including separation between quarks and anti-quarks
Physics vs. Luminosity & Energy

- QCD at Extreme Parton Densities - Saturation
- Spin and Flavor Structure of the Nucleon and Nuclei
- Transverse Momentum Distribution and Spatial Imaging
- Electroweak (CLFV, $\sin^2\Theta_W$)
- Internal Landscape of the Nucleus
- Tomography ($p/A$)

Luminosity ($cm^{-2}sec^{-1}$)

$\sqrt{S}$ (GeV)

arXiv: 1212.1701.v3
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 through LFV search
  M. Gonderinger & M. Ramsey-Musolf, JHEP 1011 (045) (2010); arXive: 1006.5063 [hep-ph]
  $e^- + p \rightarrow \tau^- + X$
\[ A_{PV} \text{ in Deep Inelastic Scattering} \]

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

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

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

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

\[ C_{1u} = (1 - 8 \sin^2 \theta_W / 3) / 2 \approx 0.20 \text{ Hadronic} \]
\[ C_{1d} = (1 - 4 \sin^2 \theta_W / 3) / 2 \approx -0.32 \text{ Hadronic} \]
\[ C_{2u} = (1 - 4 \sin^2 \theta_W) / 2 \approx 0.04 \text{ Leptonic} \]
\[ C_{2d} = -(1 - 4 \sin^2 \theta_W) / 2 \approx -0.04 \text{ Leptonic} \]

\[ C_{2q} \text{ sensitive to RC & New Physics} \]

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

Jefferson Laboratory:
- 6 GeV DIS eD→eX proceeding
- 12 GeV SoLID experiment at JLab12 in future (2020-2025)
  - Measure C_2q's New Physics, Charge Symmetry violation
  - Effective luminosity (fixed target) $10^{38}$ cm$^{-2}$sec$^{-1}$

Future ep, eD → Electron Ion Collider:
- Asymmetry: FOM $\sim A^2 N$; $A \sim Q^2$ & $N \sim 1/Q^2$, 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)
Recent: Y. Zhao, A.D. & K. Kumar revisited this....
$\sin^2 \Theta_W$ with the EIC: Physics Beyond SM

- Precision parity violating asymmetry measurements $e/D$ or $e/p$
- Deviation from the “curve” may be hints of BSM scenarios including: Lepto-Quarks, RPV SUSY extensions, $E_6/Z'$ based extensions of the SM
Low $Q^2$ Weak Mixing Angle Measurements and Rare Higgs Decays

and William J. Marciano

**Dark Z Study: arXiv:1507.00352**

EIC Study .

**Y. Zhao, A. Deshpande & K. Kumar et al.**
Opportunity for EIC

- Limits on LFV\((1,3)\) experimental searches are significantly worse than those for LFV\((1,2)\)
- There are BSM models which specifically allow and enhance LFV\((1,3)\) over LFV\((1,2)\)
- M. Gonderinger & M. Ramsey Musolf, JHEP 1011 (045) (2010); arXive: 1006.5063 [hep-ph]
  - 10 fb\(^{-1}\) e-p luminosity @ 90 GeV CM would have potential
  - Detector & analysis efficiencies assumed 100%
  - HERA experience: effective efficiencies 5-15%
- Clearly there is an opportunity for EIC: “icing on the cake”
Detector Design:
Some General Considerations

See details about design strategy, technology and integration with accelerator design (IR) in Prof. Aschenauer’s lectures tomorrow.
• \(4.1 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}\) for \(\sqrt{s} = 126 \text{ GeV}\) (15.9 GeV e\(\uparrow\) on 250 GeV p\(\uparrow\))
The eRHIC Interaction Region (IR)
EIC at Jlab: JLEIC
JLEIC Interaction Region (IR)

Extended detector: 80+ m

Electron crab cavities
Compton polarimetry
Forward $e^-$ detection
Forward ion detection
IP
Ion crab cavities
Common characteristics:

• Both eRHIC and JLEIC are planned to measure the whole event: “Exclusive Measurement” of DIS
  • Measure scattered electron, measure and identify beam and target fragments (remnants)

• Both have beam crossing angles (collisions not head-on)
  • Initially dictated by “lessons from HERA” where e-/e+ beams were brought in and taken out creating a “fan of intense synchrotron radiation” which made detectors difficult (impossible) to operate
  • Electron beam in the EIC era will have no bends before the Interaction Region.

• Many more will be discussed in dedicated lectures….
Aim of EIC is nucleon and nuclear structure beyond the longitudinal description. This makes the requirements for the machine and detector different from all previous colliders including HERA.
Final State Particles in the Central Rapidity

Products of the hard electron-quark collision

Transverse and flavor structure measurement of the nucleon and nuclei: The particles associated with struck parton must have its species identified and measured.
Final State Particles in the Central Rapidity

Asymmetric collision energies will boost the final state particles in the ion beam direction:

Detector requirements change as a function of rapidity
Particles Associated with the Initial Ion

For EIC, particles of the “target remnant” is as important as the struck parton.

- Was not considered at HERA initially.
- Close to the beamline
- Not analyzed by central solenoid.
- **Aim for ~100% acceptance and good resolution at EIC.**
Particles Associated with the Initial Electron

Forward Electron area:
- Tag photoproduction ($Q^2 \approx 0$)
- Measure Luminosity
- Measure electron polarization

Apply lessons from HERA, JLab and elsewhere
The aim is to get ~100% acceptance for all final state particles, and measure them with good resolution.
Interaction Region Concept

Beam crossing angle creates room for forward dipoles

Dipoles analyze the forward particles and create space for detectors in the forward direction
Interaction Region Concept

Possible to get ~100% acceptance for the whole event

Total acceptance detector (and IR)
JLEIC IR Layout

Extended detector: 80+ m

e⁻ crab cavities
Compton polarimetry

forward e⁻ detection

forward ion detection

IP

ions
e⁻

ion crab cavities

R. Yoshida, EICUG @ ANL
Electron Isoline Plot

Isolines of the scattered electron energy $E'_e$

- $0 < E' < 20$ GeV (2 GeV steps)
- $20 < E' < 100$ GeV (5 GeV steps)

$(10 \text{GeV} \times 100 \text{GeV})$
Quark(Jet) Isoline Plot

Isolines of the struck quark energy $F_h (E_{\text{jet}})$

- $1 < F_h < 20$ GeV (2 GeV steps)
- $30 < F_h < 100$ GeV (10 GeV steps)

(10 x 100 GeV)

Barrel

Hadron Endcap

Far-forward Hadron (Out of central detector)
Day-1 Detector: CELESTE
A.K.A. “ePHENIX” with BaBar Solenoid
arXiv: 1402.1209

EIC IR & Detector Ideas at eRHIC

Detector: Low mass tracking technology, particle ID, asymmetric collisions (moving CM) are all in!
Opportunities for HQ and Quarkonium physics.

BEAST by BNL’s EIC Task Force
arXiv: 1409.1633
EIC at JLab: Integrated IR & Detector

Cartoon of central detector based on dual solenoid a la ILC4 detector, but using the previous iteration interaction region design.

Beamline functions as spectrometer: \( \frac{d\beta}{\beta} < 3 \times 10^{-4} \)
EIC Realization Time
Line And Planning
RECOMMENDATION:
We recommend a high-energy high-luminosity polarized EIC as the highest priority for new facility construction following the completion of FRIB.

Initiatives:
Theory
Detector & Accelerator R&D
T. Hallman, Office of NP at the NSAC meeting March 23, 2016

Next Formal Step on the EIC Science Case

THE NATIONAL ACADEMIES OF SCIENCES, ENGINEERING, AND MEDICINE
Division on Engineering and Physical Science
Board on Physics and Astronomy
U.S.-Based Electron Ion Collider Science Assessment

Summary
The National Academies of Sciences, Engineering, and Medicine (“National Academies”) will form a committee to carry out a thorough, independent assessment of the scientific justification for a U.S. domestic electron ion collider facility. In preparing its report, the committee will address the role that such a facility would play in the future of nuclear science, considering the field broadly, but placing emphasis on its potential scientific impact on quantum chromodynamics. The need for such an accelerator will be addressed in the context of international efforts in this area. Support for the 18-month project in the amount of $540,000 is requested from the Department of Energy.

Mail reviews received; proposal approved for funding in PAMS; PR package in PAMS being processed.

Progress is also being made on a second Joint NAS study on Space Radiation Effects Testing
Innovative Accelerator Science

On going R&D on accelerator concepts and technologies:

- High current polarized electron gun
- High current Energy Recovery Linac (ERL)
- Coherent electron cooling
- Fixed Field Acceleration Gradient beam transport
- High gradient crab cavities
- Super-ferric magnets
- Figure-8 shaped e/h rings to aid polarization of beams

Most of these are of global interest!

Realizing these for the US EIC requires cutting edge accelerator science
T. Hallman, Office of NP at the NSAC meeting March 23, 2016

Seeding the Possibility of a Future Electron Ion Collider

NP Planning for EIC Accelerator R&D

In view of Recommendation III in the 2015 LRP report on the realization of an EIC, NP is fomenting a plan in discussion with EIC stakeholders:

18 months NAS study: US-BASED ELECTRON ION COLLIDER SCIENCE ASSESSMENT

March - July 2016: Competitive FOA published this month, proposals due May 2 to select and fund accelerator R&D for Next Generation NP Facilities for 1 year only.

Summer 2016: Conduct an NP community EIC R&D panel (EIC-R&D) Review charged with generating a report as basis for FY17-FY20+ EIC accelerator R&D funding. NP to appoint Chair of the panel.

Late Fall 2016: Use the EIC panel report from the panel to publish a new Accelerator R&D FOA for FY2017 funding.

Funding amount and source for EIC accelerator R&D in FY17 and beyond:

**Funding level:** Aiming for $7M, exact amount to be guided by EIC-R&D Review’s report

**Funding sources:** ~$1.9M from NP competitive pot, the rest generated by percentage tax to RHIC and CEBAF Accelerator Operations budgets (~2.6% FY17 president request for each Lab).
Community/Collaboration building:
EIC User Group → eicug.org (contact me!)

Ample opportunities for contributions & participation!
EICUG Today: 651 Users, 142 Institutes, 27 Countries
350 experimentalists, 111 theorists, 141 accelerator-physicists, 43 unknowns
What’s in the immediate future for EIC?

- Science Review by National Academy of Science (Engineering & Arts) (National Research Council)
  
- Positive NAS review will trigger the DOE’s CD process
  - CD0 (acceptance of the critical need for science by DOE) FY18
  - EIC-Proposal’s Technical & Cost review → FY19 (site selection)
  - CD2 requires site selection
  - Major Construction funds ("CD3") by 2022/23"
  - Assuming 1.6% sustained increase over inflation of the next several years (Long Range Plan)
**21st Century Nuclear Science:**

Probing nuclear matter in all its forms & exploring their potential for applications

**Key Questions:**
- How are the nuclear building blocks manifested in the internal structure of compact stellar objects, like neutron stars?
- How can the properties of nuclei be used to reveal the fundamental processes that produced an imbalance between matter and antimatter in our universe?
- How can technologies developed for basic nuclear physics research be adapted to address society's needs?
- Where in the universe, and how, were the heavy elements formed? How do supernovae explode?
- Where are the limits of nuclear existence, and what is the structure of nuclei near those limits?
- What is the nature of the different phases of nuclear matter through which the universe has evolved?
- Do nucleons and all nuclei, viewed at near light speed, appear as walls of gluons with universal properties?
Summary:

The EIC will profoundly impact our understanding of the structure of nucleons and nuclei in terms of sea quarks & gluons (SM of Physics).

- The bridge between sea quark/gluons to Nuclei

The EIC will enable IMAGES of yet unexplored regions of phase spaces in QCD with its high luminosity/energy, nuclei & beam polarization

- High potential for discovery

Outstanding questions raised by world wide experiments at CERN, BNL and Jeff Lab, have naturally led us to the science and design parameters of the EIC:

World wide interest and opportunity in collaborating on the EIC

Accelerator scientists at RHIC, Jlab in collaboration with many from outside accelerator experts will provide the intellectual and technical leadership for to realize the EIC -- a frontier accelerator facility.

Future QCD studies, particularly for Gluons, demands an Electron Ion Collider

NSAC Agrees nad we are moving forward!
THANK YOU

Thanks to many of my EIC Collaborators and Enthusiasts who led many of the studies presented in this talk

Without the EIC White Paper Writing Group the EIC White Paper would not have existed.
Special thanks to Dr. Jian-Wei Qiu and Prof. Zein-Eddine Meziani, my Co-Editors for the EIC White Paper
See: arXiv:1212.1701.v3

The eRHIC and JLEIC machine design teams

Also gratefully acknowledge recent input from: E. Aschenauer, M. Diefenthaler, R. Ent, R. McKeown, B. Mueller, R. Milner, R. Yoshida
LFV phenomenology

\[ \frac{d^2\sigma_s}{dx dy} = \frac{1}{32\pi \hat{s}} \cdot \frac{\lambda_{eq}^2 \lambda_{\ell q} \hat{s}^2}{\left(\hat{s}^2 - m_{LQ}^2\right)^2 + m_{LQ}^2 \Gamma_{LQ}^2} \cdot q_i(x, \hat{s}) \times \left\{ \frac{1}{2} \frac{1}{2(1 - y)^2} \right\} \]

- Leptoquark (LQ) event topologies studied with:
  - LQ generator for e-p processes using BRW effective model
- In this study to increase efficiency: 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:** \( z = \lambda_i \lambda_j / M_{LQ}^2 \)
- \( \tau \) has a clean characteristic decay signature:
  - 3\( \pi \) decay in a **narrow pencil like jet**
  - Leptonic decays with neutrinos (missing mom.) with **different angular correlations** in SM vs. LQ
CENTRAL DETECTOR
Final State Particles in the Central Detector

Products of the hard electron-quark collision

Took away radiated photon for simplicity

Took away the (exaggerated) beam crossing for simplicity
Basic Kinematic Reconstruction

$E'_e, \theta_e, E_{jet}, \theta_{jet}$: any two of these, in principle, sufficient to reconstruct $x$ and $Q^2$.

$Q^2 \rightarrow$ Measure of resolution
$y \rightarrow$ Measure of inelasticity
$x \rightarrow$ Measure of momentum fraction of the struck quark in a proton

$Q^2 = s \times y$

What are the detector requirements?

R. Yoshida, EICUG @ ANL

7/19/16

EIC Lecture 4 at NNPSS 2016 at MIT
Reconstruction for Transvers Structure

Looking at out-of–plane component in the final state

What are the detector requirements?

Need to identify and measure these particles

Note: multiplicities are low (~20 for ep)
Cross-sec x Lumi < 0.01 x HLLHC
< 0.1 interaction/crossing
How Boosted is the Final State?

No Monte Carlo needed to Determine

Boosted towards ion beam

\[ E_{\text{ion}} = 100 \text{ GeV} \]

\[ E_{\text{electron}} = 10 \text{ GeV} \]

Given \( x \) and \( Q^2 \), \( E', \theta_e, E_{\text{jet}}, \theta_{\text{jet}} \) are all fixed.

\( E'_e, \theta_e, E_{\text{jet}}, \theta_{\text{jet}} \): any two of these, in principle, sufficient to reconstruct \( x \) and \( Q^2 \).
EICUG Today: 651 Users, 142 Institutes, 27 Countries
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Distribution of users by country
Assumption: “Modest Growth” →
1.6% growth/year above constant effort

The 2015 Long Range Plan for Nuclear Science

Figure 10.4: DOE budget in FY 2015 dollars for the Modest Growth scenario.