Summary of the Electron Ion Collider Possibilities

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Hall-C Summer Physics Workshop 2004

1) The Electron-Ion Collider Project
2) Science at the EIC
3) Ongoing Accelerator R&D
4) Summary of the Summary

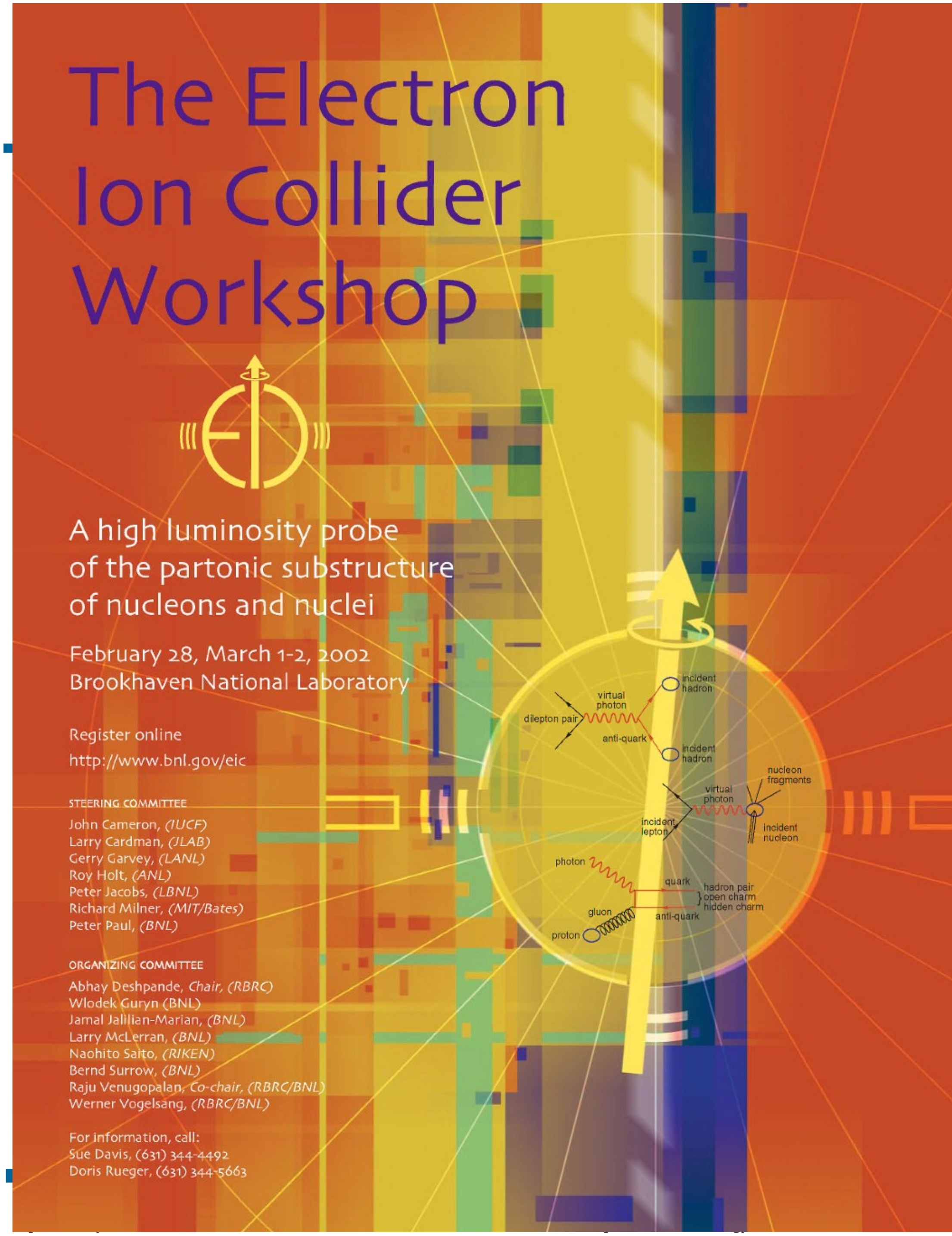
The Electron Ion Collider Project

A large community believes a high luminosity polarized electron ion collider is the ultimate tool to understand the structure of quark-gluon systems, nuclear binding, and the conversion of energy into matter to such detailed level that we can use/apply QCD.

Several workshops have already taken place:
- DESY/GSI/NuPECC Workshop at Darmstadt (1997) – 100 attendants
- EPIC99 Workshop at IUCF (1999)
- eRHIC Workshop at BNL (1999)
- Second eRHIC Workshop at Yale (2000)
- EPIC 2000 Workshop at MIT (2000) – 108 attendants
- Electron Ion Collider Workshop at BNL (2002) – 119 attendants

History

- March 15-17: 2nd Electron Ion Collider Workshop at JLab (2004) – 122 attendants



Associated white paper was submitted to last NSAC cycle

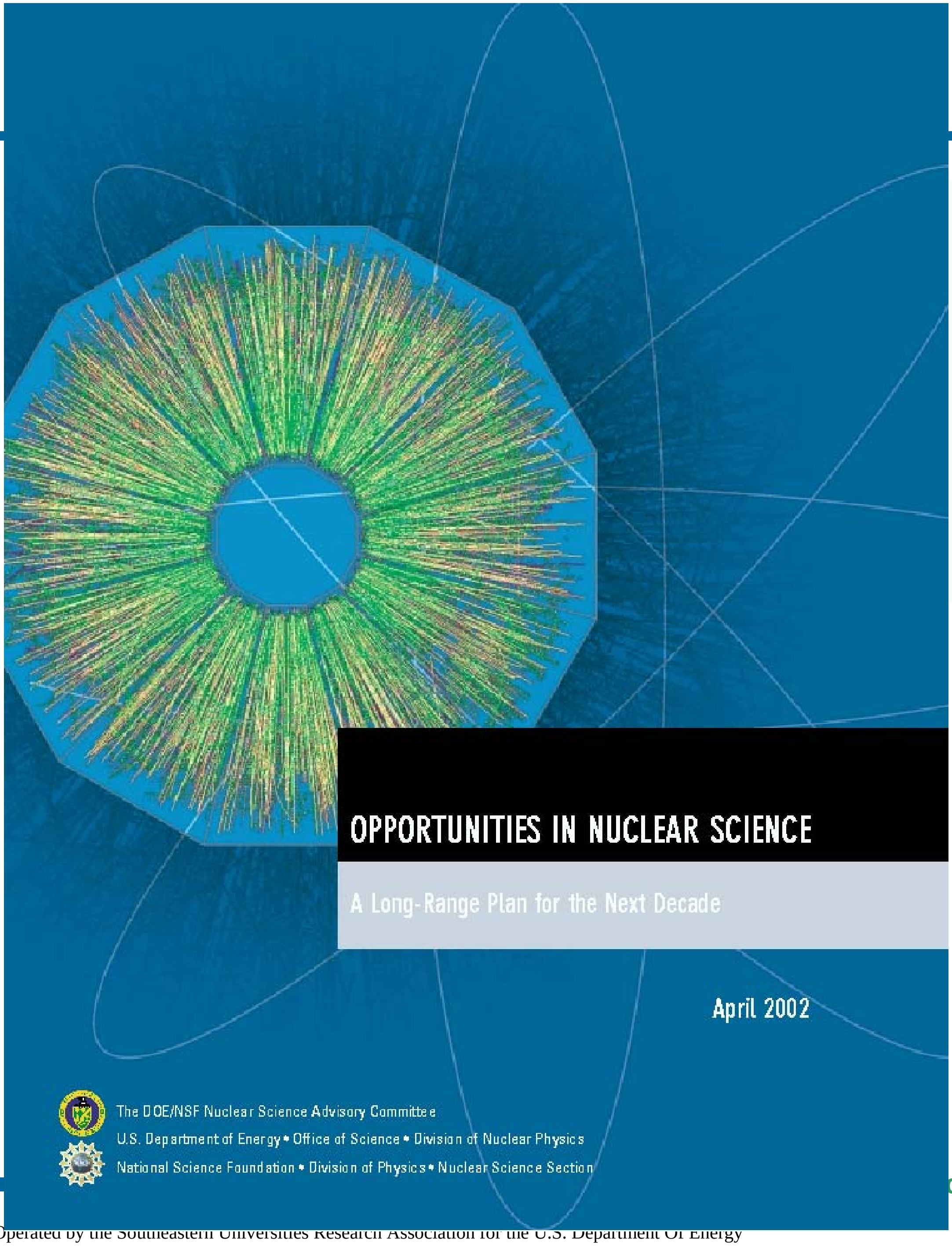
The Electron Ion Collider

A high luminosity probe of the partonic substructure of nucleons and nuclei

"A white paper summarizing the scientific opportunities and the preliminary detector and accelerator options"

February 2002

BNL-68933-02/07-REV.

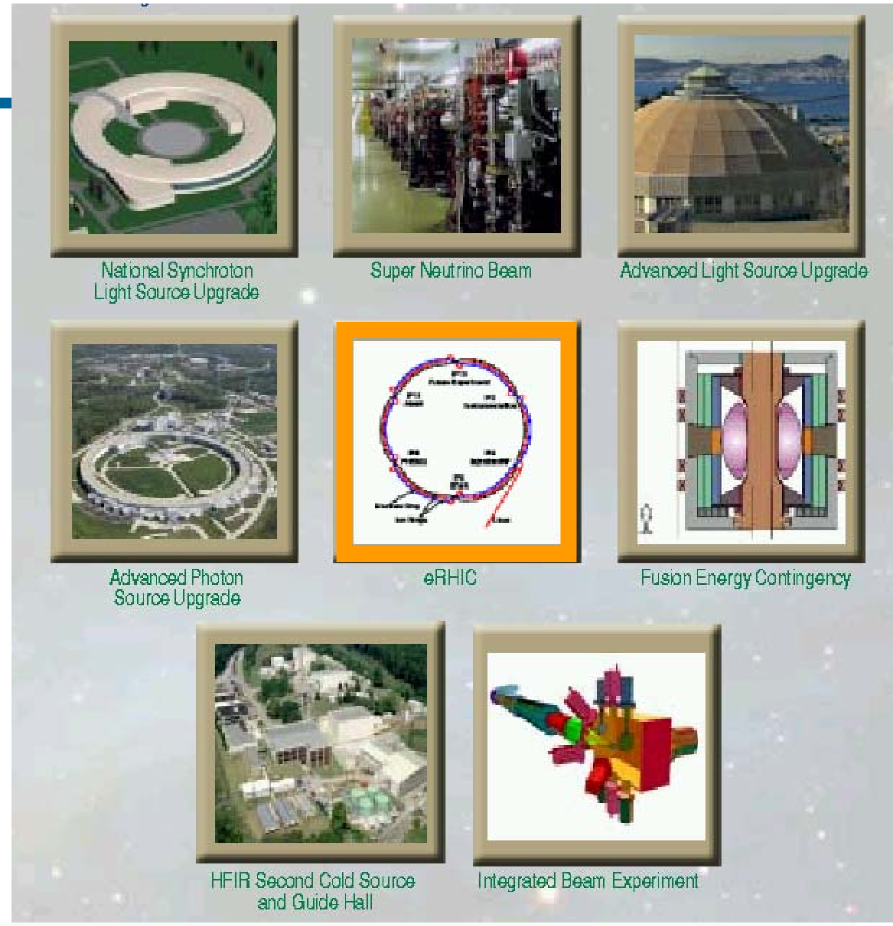


NSAC Report 2002

Other initiatives. Even under the tightest budget constraints, a fraction of the nuclear physics budget must be set aside to provide the flexibility to fund smaller new initiatives. The following initiatives were identified by the Long-Range Plan Working Group as having great promise but were not prioritized. Those that may be accommodated within the existing budget will be implemented, while others, at earlier stages of development, may be promoted to the status of strong recommendations in a subsequent long-range plan.

- **The Electron-Ion Collider (EIC).** The EIC is a new accelerator concept that has been proposed to extend our understanding of the structure of matter in terms of its quark and gluon constituents. Two classes of machine design for the EIC have been considered: a ring-ring option where both electron and ion beams circulate in storage rings, and a ring-linac option where a linear electron beam is incident on a stored ion beam.

Electron-Ion Collider …



Far-Term Priorities

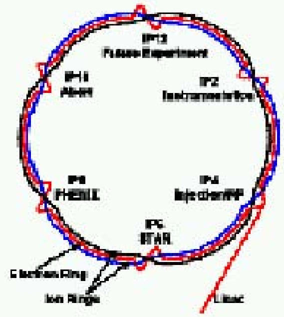
Priority: Tie for 21	National Synchrotron Light Source (NSLS) Upgrade
	Super Neutrino Beam
Priority: Tie for 23	Advanced Light Source (ALS) Upgrade
	Advanced Photon Source (APS) Upgrade
	eRHIC
	Fusion Energy Contingency
	High-Flux Isotope Reactor (HFIR) Second Cold Source and Guide Hall
	Integrated Beam Experiment (IBX)

Priority: Tie for 23
eRHIC

(From Orbach's 20-year Plan)

The Facility: An electron accelerator ring added to the existing Relativistic Heavy Ion Collider (RHIC) would create the world's first electron-heavy ion collider (eRHIC). The facility will enable scientists to learn things about the structure of protons, and the subatomic particles that bind them, that they could learn in no other way.

Background: Current theory holds that atoms are composed of protons and neutrons, which in turn are composed of particles called quarks, held together by gluons. Both quarks and gluons are little understood. While most existing and contemplated nuclear physics facilities are designed for the study of quarks, eRHIC is intended to create and study gluons, which bind subatomic particles.



Schematic layout of the injection linac, electron ring and the two ion rings. "Ring-Ring" Option

Schematic of electron-proton/ion collider based on the recirculating "linac-on-ring" concept.

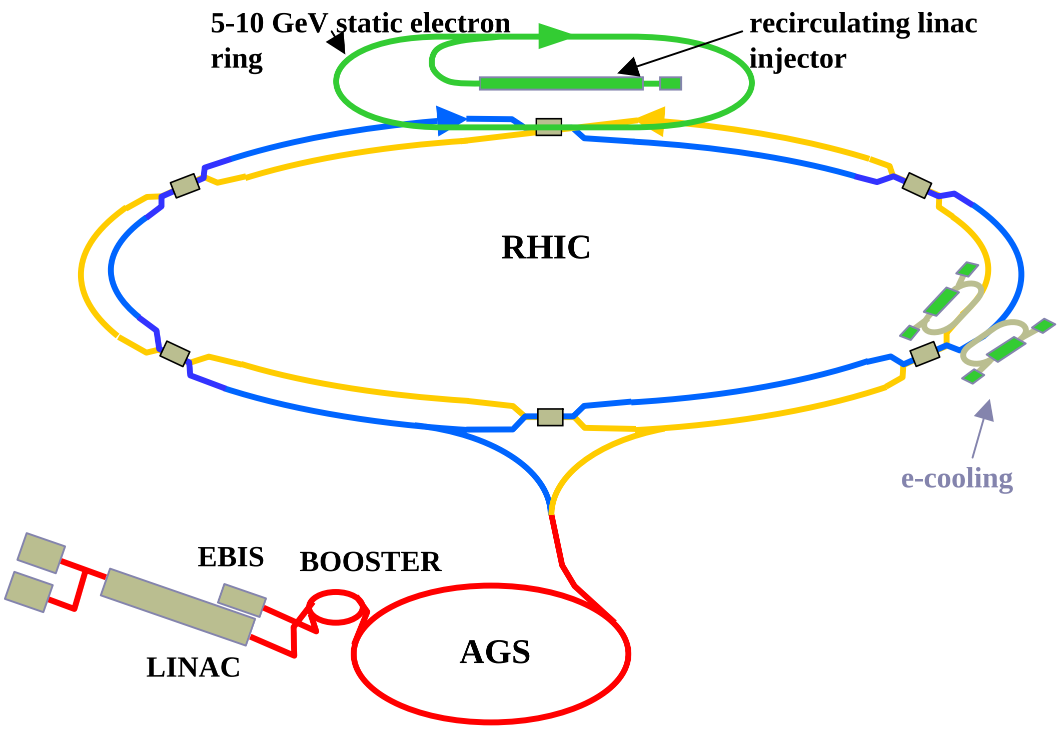
Adding an electron accelerator ring to the existing RHIC at Brookhaven National Laboratory will create eRHIC, the world's first electron-heavy ion collider, which in turn will create enormous numbers of gluons for scientists to study.

What's New: The addition of a polarized electron source and 10 GeV energy electron ring to the current RHIC facility will enable eRHIC to create enormous numbers of gluons—in effect a saturated "gluonic" state of matter—giving scientists a unique opportunity and approach to probe the substructure of particles.

Applications: Einstein's famous equation, $E=mc^2$, predicts that small amounts of mass can be transformed into large amounts of energy, and that the reverse is also possible. Although we have demonstrated this prediction and its practical applications (nuclear weapons, among other things, are based on this principle), the truth is that we do not yet understand *how* the process works—the underlying mechanisms by which mass is transformed into energy and vice versa. eRHIC will allow scientists to tackle this very fundamental question in physics.

Main design option

eRHIC Layout
(V.Ptitsyn, EIC2004)



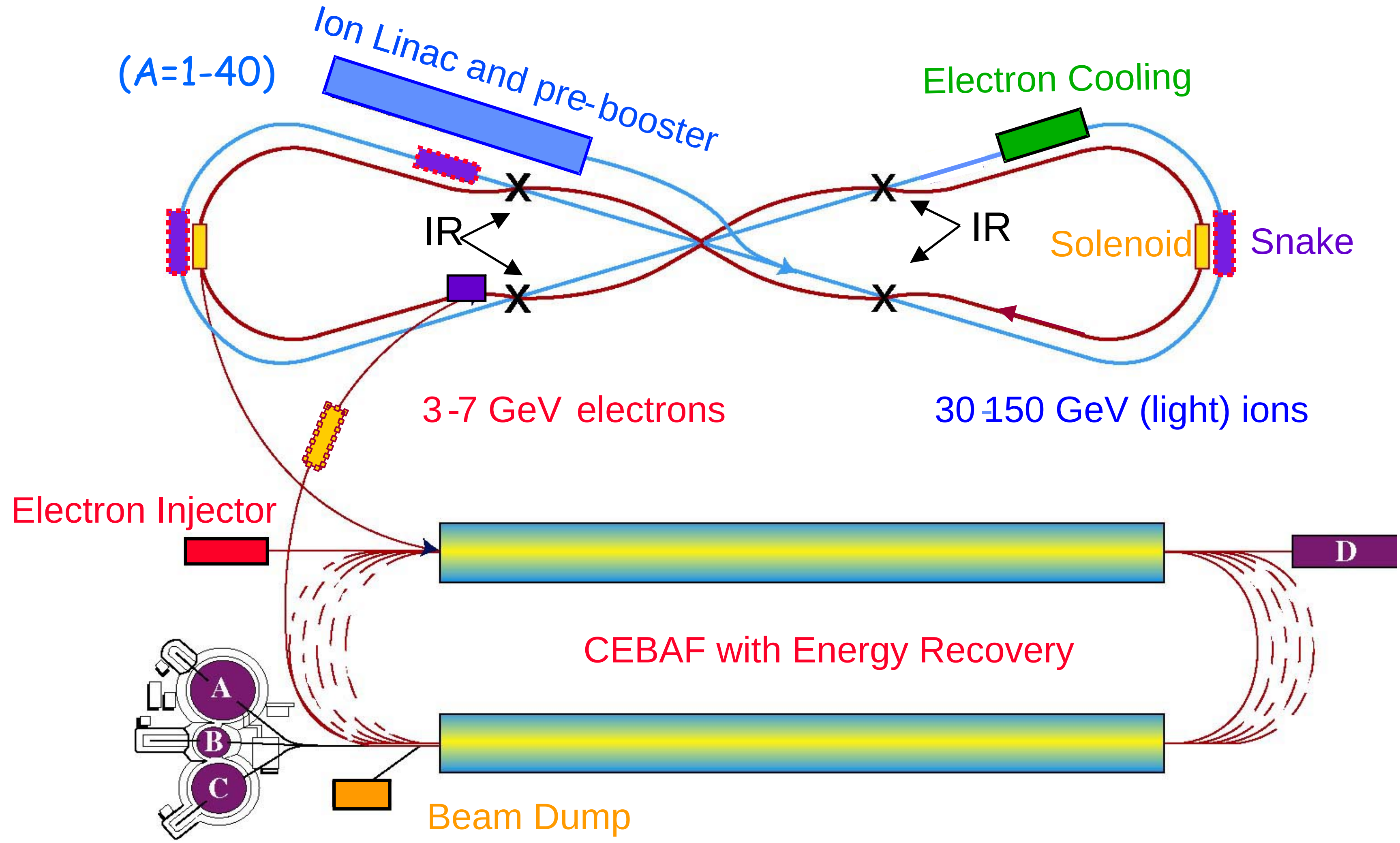
(Main design option as also alternative Linac-Ring design under consideration)

- The electron ring of 1/3 of the RHIC ion ring circumference
- Full energy injection using polarized electron source and 10 GeV energy linac.
- e-ion collisions in one interaction point.

  Ion-ion collisions in two other IPs at the same time.
- Longitudinal polarization produced by local spin

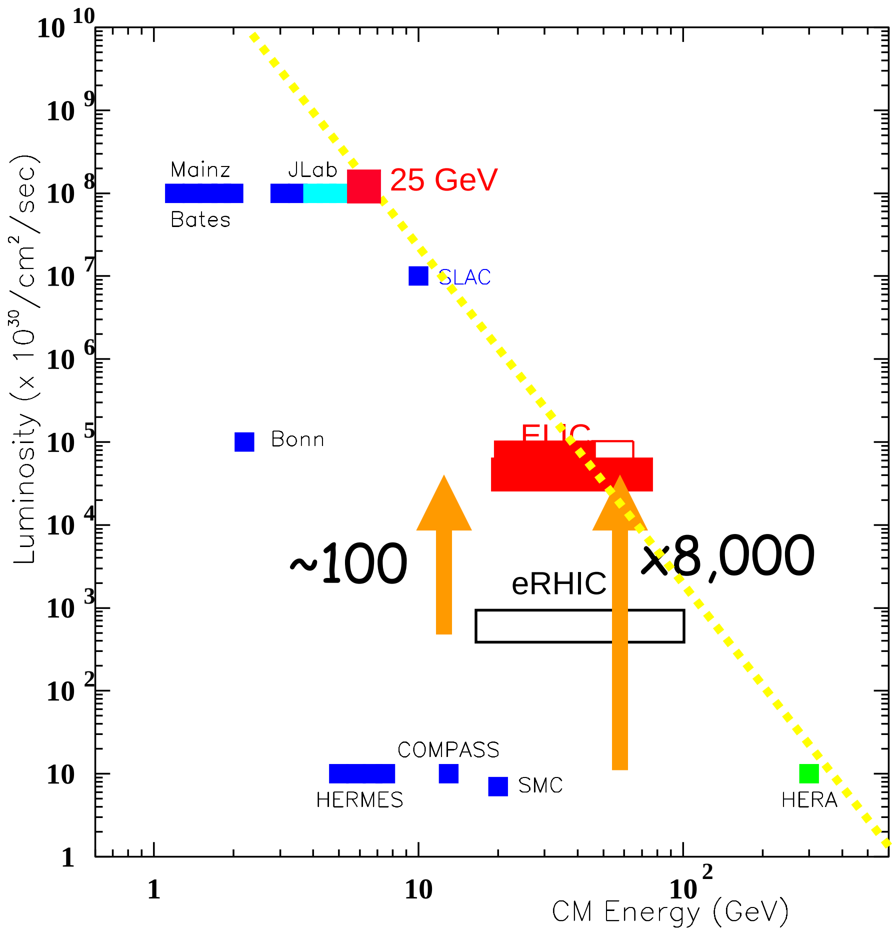
ELIC Layout *(Derbenev, Chattopadhyay, Merminga et al.)*

One accelerating & one decelerating pass through CEBAF



Luminosity Potential with eRHIC/ELIC

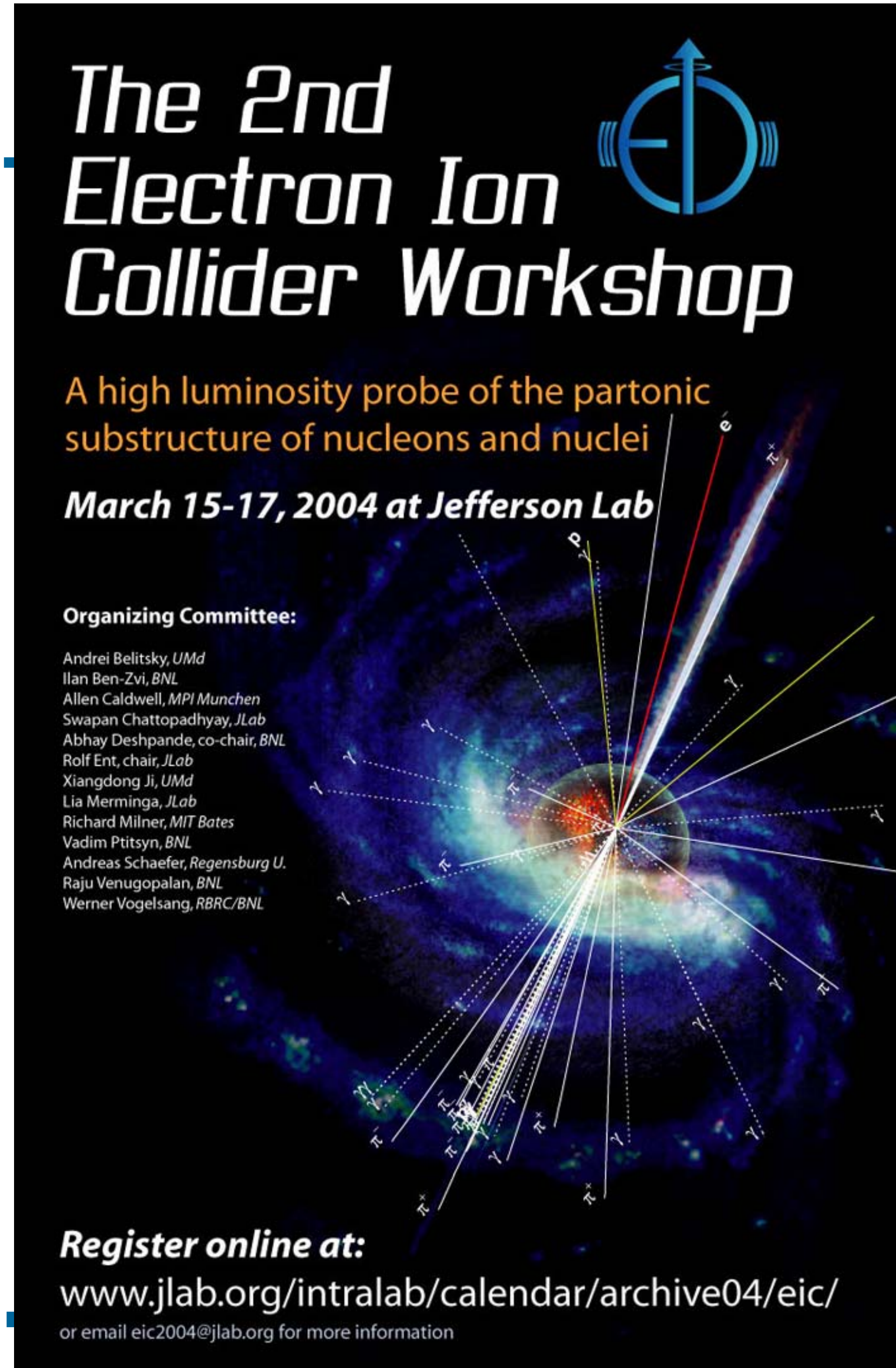
eRHIC: 10 GeV Electrons on 250 GeV Protons (up to Pb)
ELIC : 7 GeV Electrons on 150 GeV Protons (up to Ca)



ELIC Luminosity

$8x10^{34}$ $cm^{-2}sec^{-1}$
(per interaction point, one day lifetime)

Precision Frontier

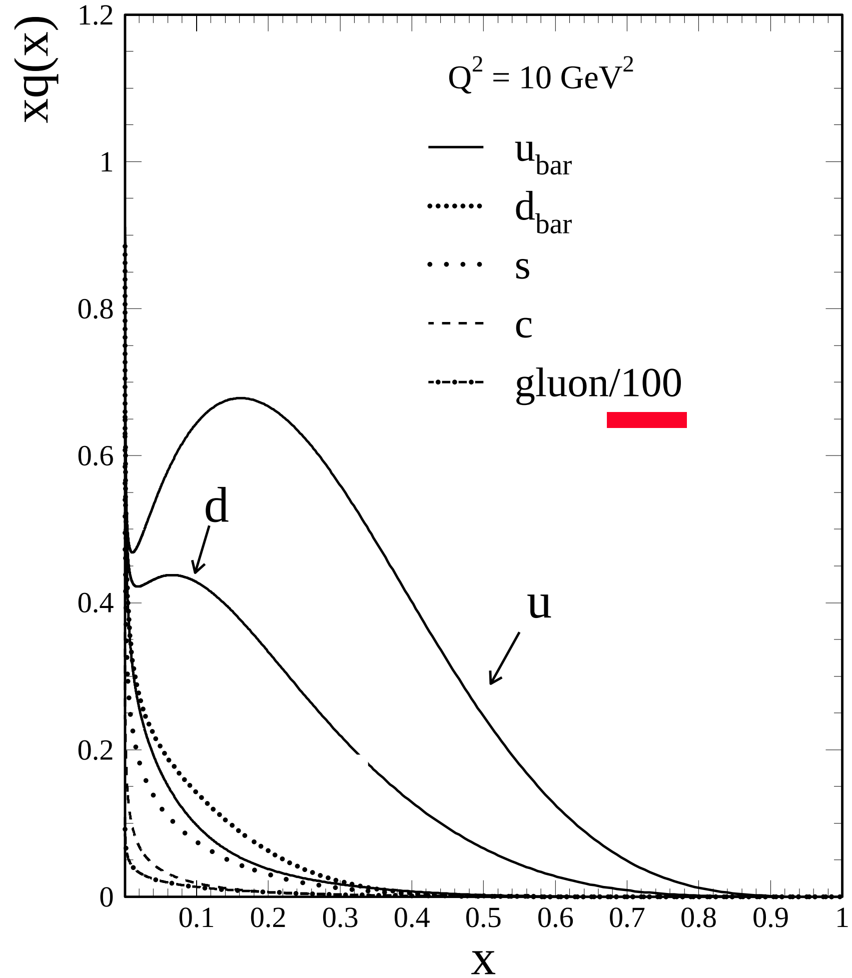


March 15-17, 2004: 2nd Electron Ion Collider Workshop

General Strategy: Prepare White Paper with significantly refined physics case for an electron ion collider, including realistic accelerator and IR detector designs for next NSAC Long Range Plan.

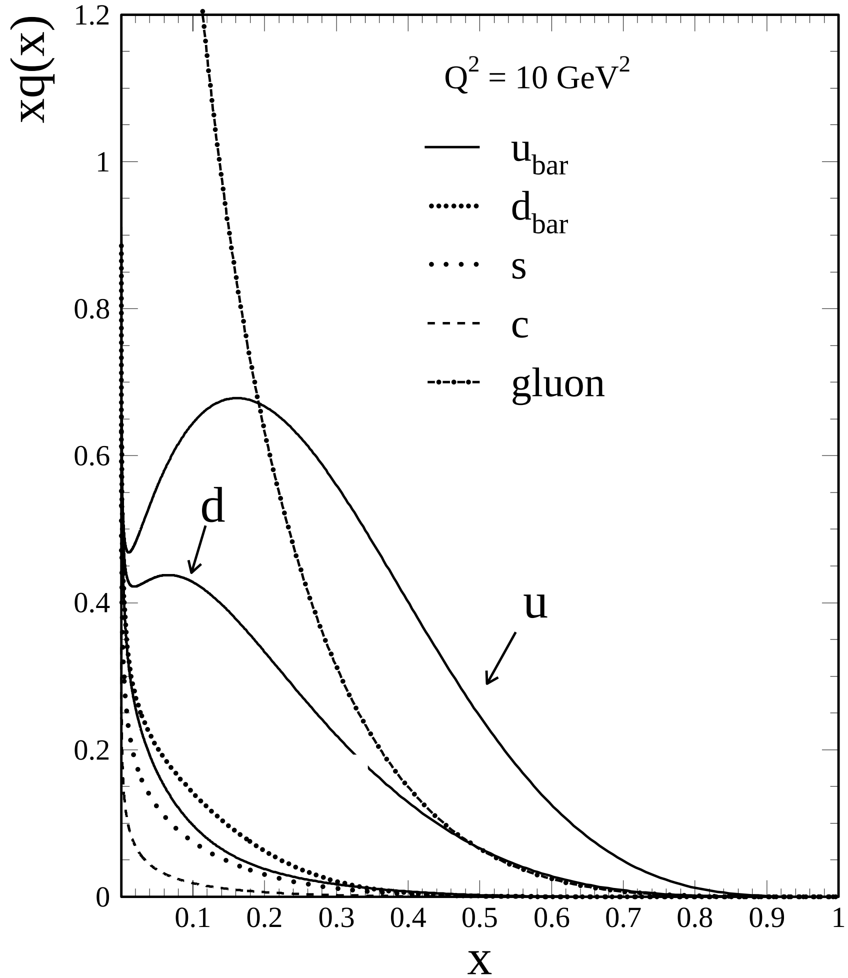
1) EIC Monte Carlo Group formed that transformed the HERMES Physics Monte Carlo to collider kinematics
   Meetings at Boulder (August 03)
   JLab (October 03)
   Goal: what energy and luminosity is really required to access the key physics issues
2) eRHIC Collaboration Meeting at BNL (January 04)
3) 2nd EIC Workshop at JLab (March 04)
   Main idea: join interested physicists from eRHIC and ELIC projects
4) eRHIC Steering Committee has several follow-up meetings planned
   Sept. (?) 04 Topical Workshops (CGC/GPDs) followed by Global Workshop
   December 04 Physics Priority and Machine/Detector Costs
   January-April 05 White Paper Writing

EIC - Science



EIC is the ultimate gluon spin machine?

EIC - Science

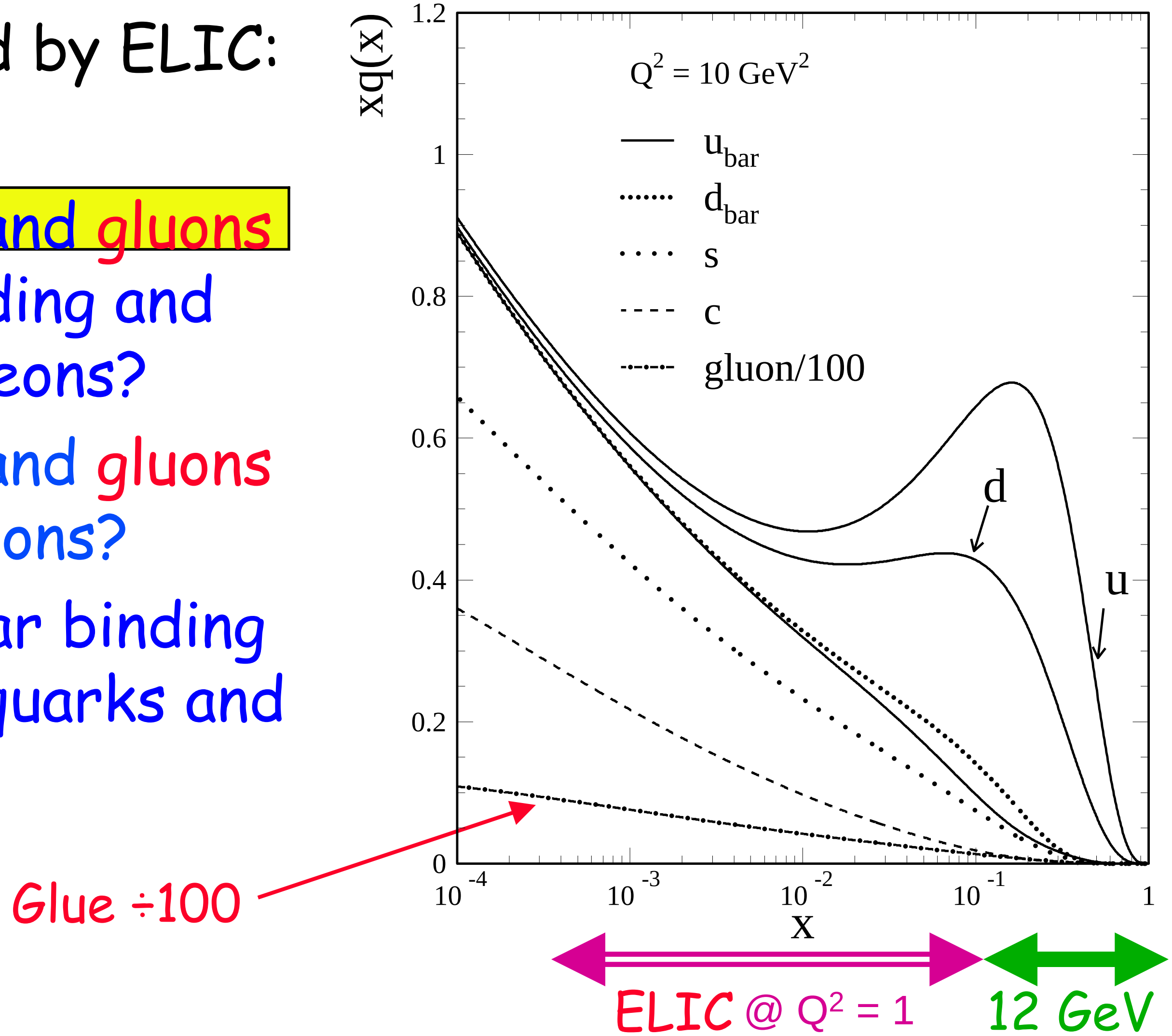


EIC is the ultimate gluon spin machine!

EIC - Science

Science addressed by ELIC:

- How do quarks and gluons provide the binding and spin of the nucleons?
- How do quarks and gluons evolve into hadrons?
- How does nuclear binding originate from quarks and gluons?



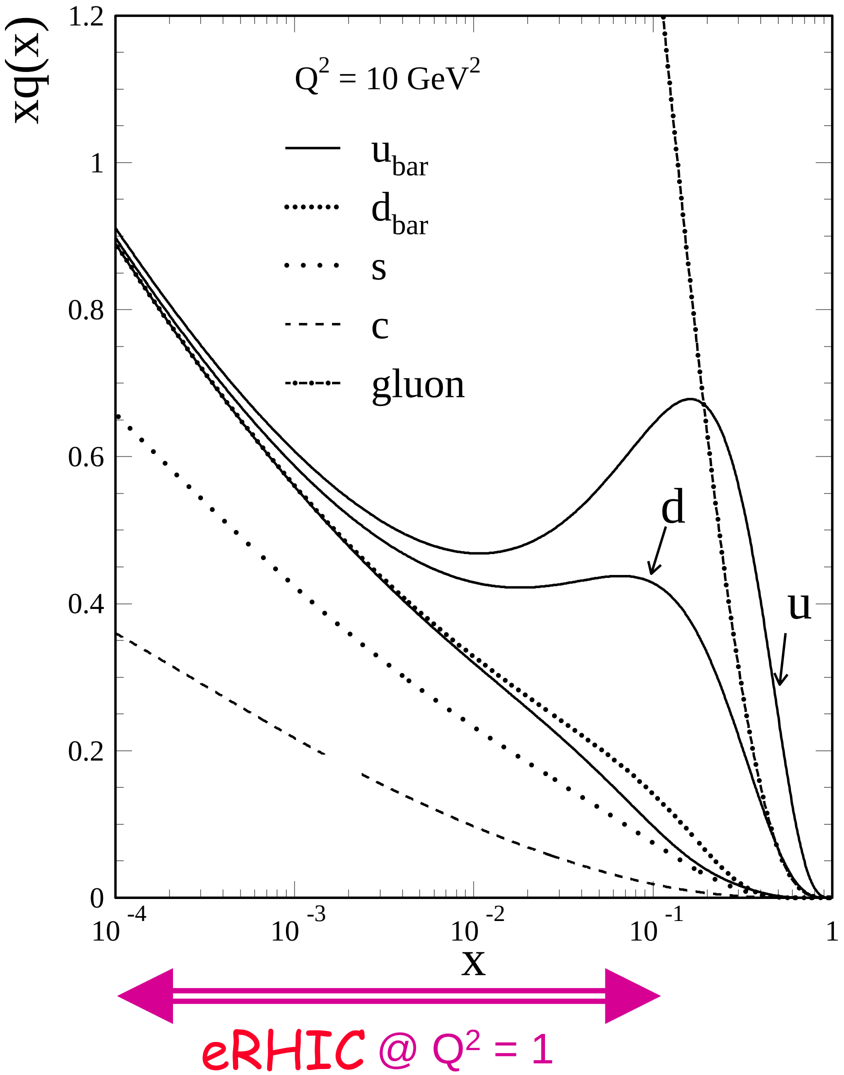
Operated by the Southeastern Universities Research Association for the U.S. Department Of Energy

EIC - Science

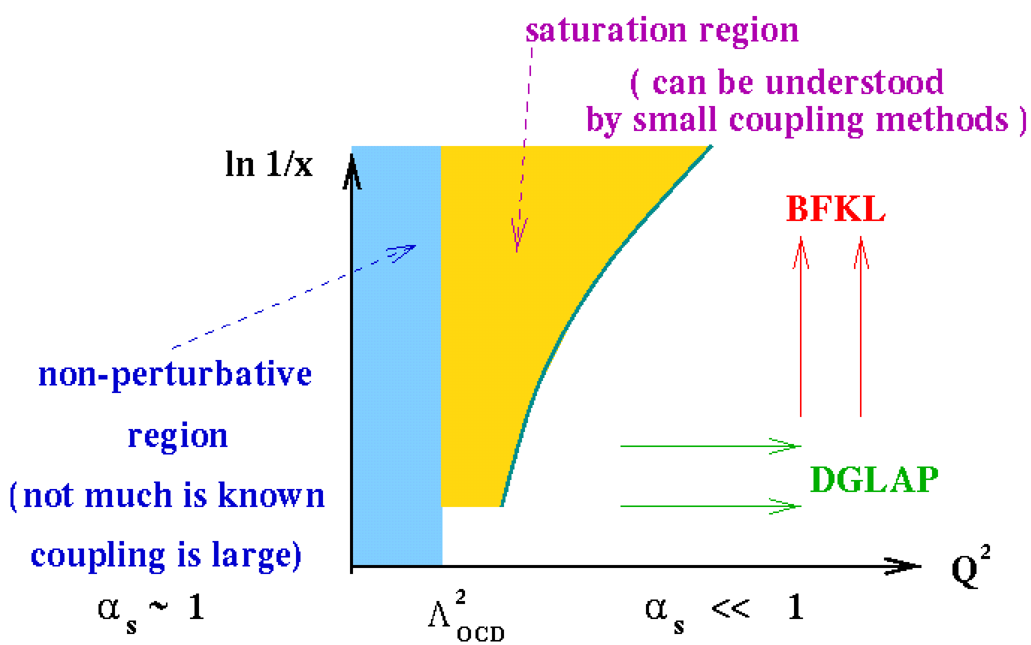
How many gluons can you stuff in a unit area? At high enough density saturation must set in!

Gluon density (@Q^2=10) ~ $x^{-0.3}$
For e-A collisions will get an amplification in gluon density with factor $A^{1/3}$
→ Lower x better to reach this saturation region
→ Large A also better

(eRHIC ~ factor of 2 x ELIC)



The Saturation Region…

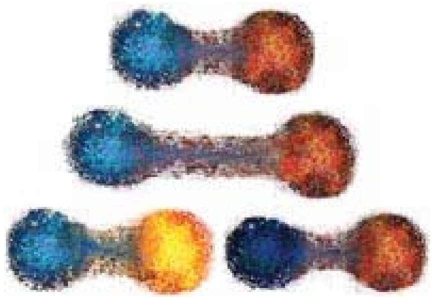


- As parton densities grow, standard pQCD break down.
- Even though coupling is weak, physics may be non-perturbative due to high field strengths generated by large number of partons.
- A new state of matter???

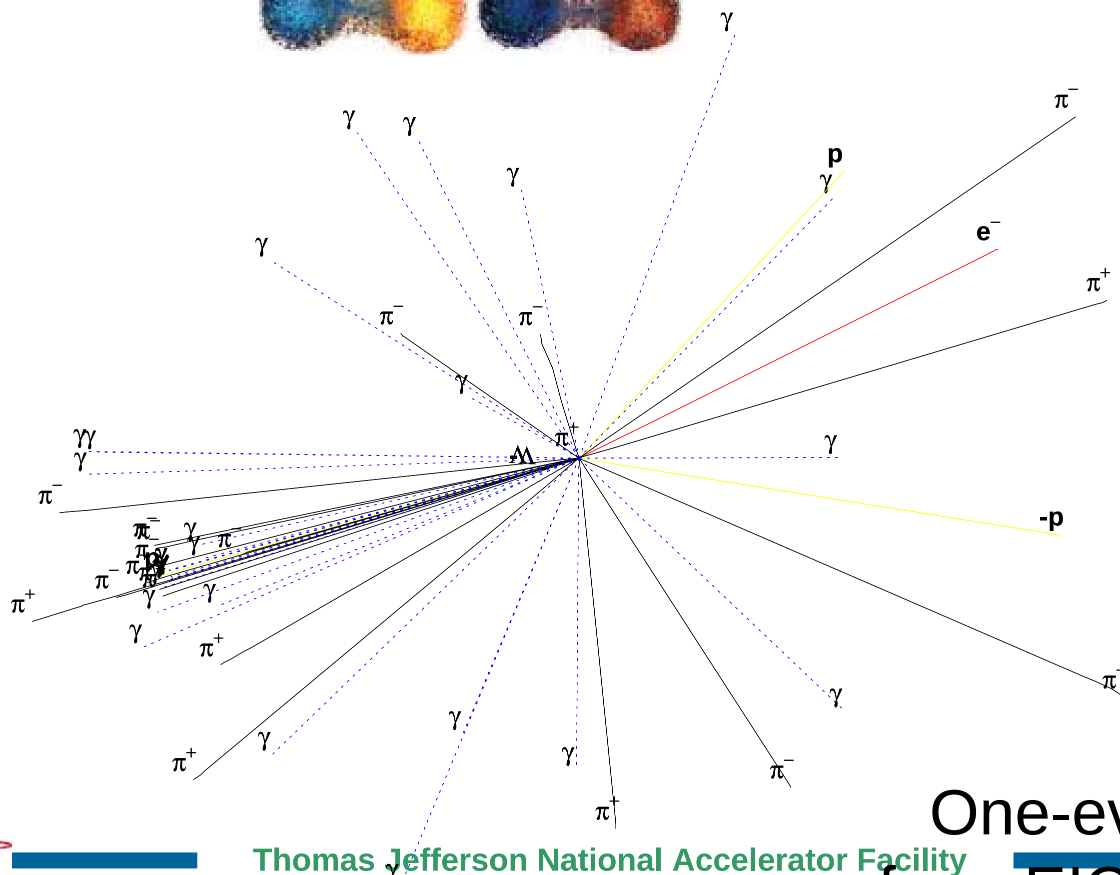
An e-A collider/detector experiment with high luminosity and capability to have different species of nuclei in the same detector would be ideal… ➔ Low x --> Need the eRHIC at BNL

An Electron Ion Collider will allow to look in detail into the sea of quarks and gluons, to create and study gluons, and to discover how energy transforms into matter

$$E = Mc^2$$



150 GeV proton

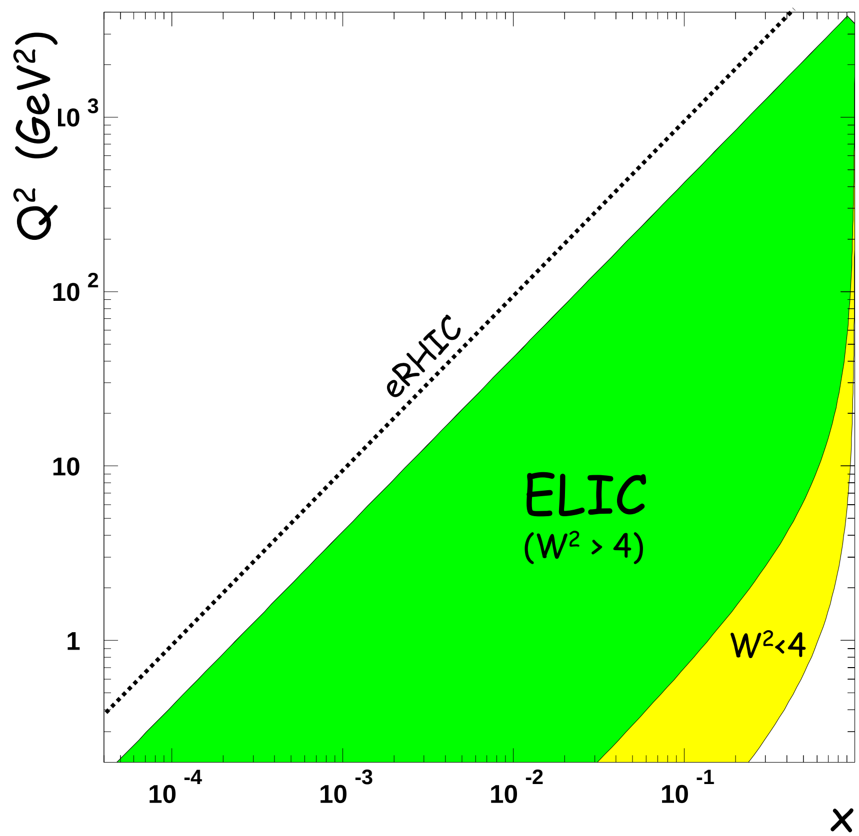


7 GeV electron

One-event display from EIC Monte Carlo

Kinematics at an Electron Light Ion Collider

ELIC kinematics at E_{cm} = 65 GeV, and beyond the resonance region.

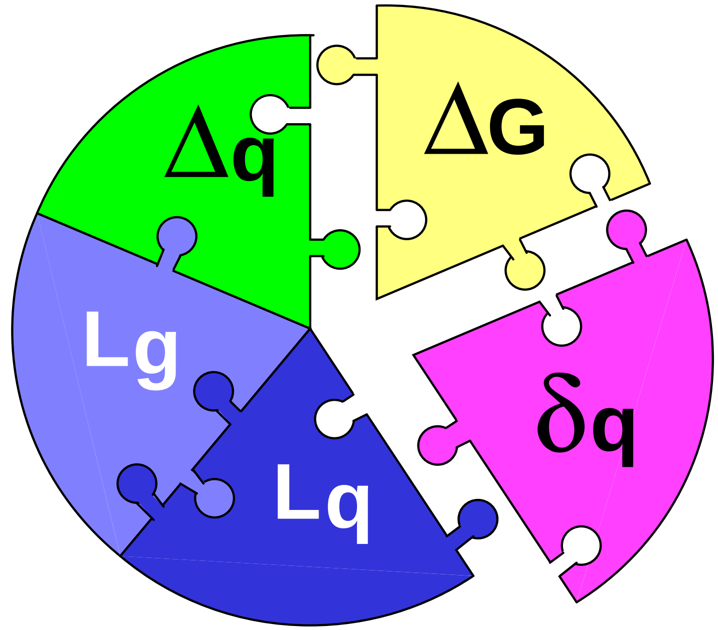


- Luminosity of up to 8×10^{34} cm^{-2} sec^{-1}
  - One day → 4,000 events/pb
  - Supports Precision Experiments
- Lower value of x scales as s^{-1}
- DIS Limit for $Q^2 > 1$ GeV^2 implies x down to 2.5 times 10^{-4}
  - Significant results for 200 events/pb for inclusive scattering
- If $Q^2 > 10$ GeV^2 required for Deep Exclusive Processes can reach x down to 2.5 times 10^{-3}
  - Typical cross sections factor 100-1,000 smaller than inclusive scattering → high luminosity essential
- For $Q^2 > 200$ GeV^2, typical cut required for Electroweak Processes, can reach x down to 4 times 10^{-2}

The Spin Structure of the Proton

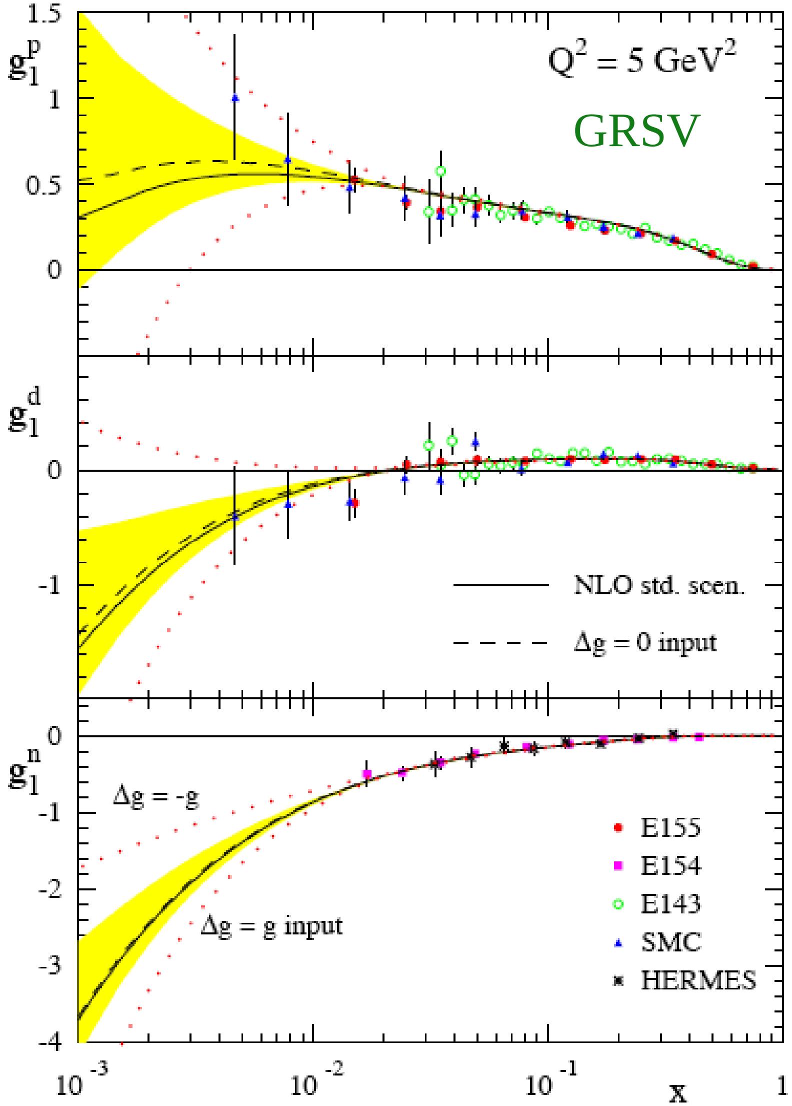
- From NLO-QCD analysis of DIS measurements … (SMC analysis)
  $\Delta\Sigma = 0.38$ (in AB scheme)
  $\Delta G = 1.0^{+1.9}_{-0.6}$ "
- quark polarization $\Delta q(x)$
  → first 5-flavor separation from HERMES
- transversity $\delta q(x)$
  → a new window on quark spin
  → azimuthal asymmetries from HERMES and JLab-6
  → future: flavor decomposition
- gluon polarization $\Delta G(x)$
  → RHIC-spin and COMPASS will provide some answers!
- orbital angular momentum L
  → how to determine? → GPD's

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g$$



ELIC@JLab can solve this puzzle due to large range in x and Q^2 and precision due to high luminosity

Examples: g_1^p



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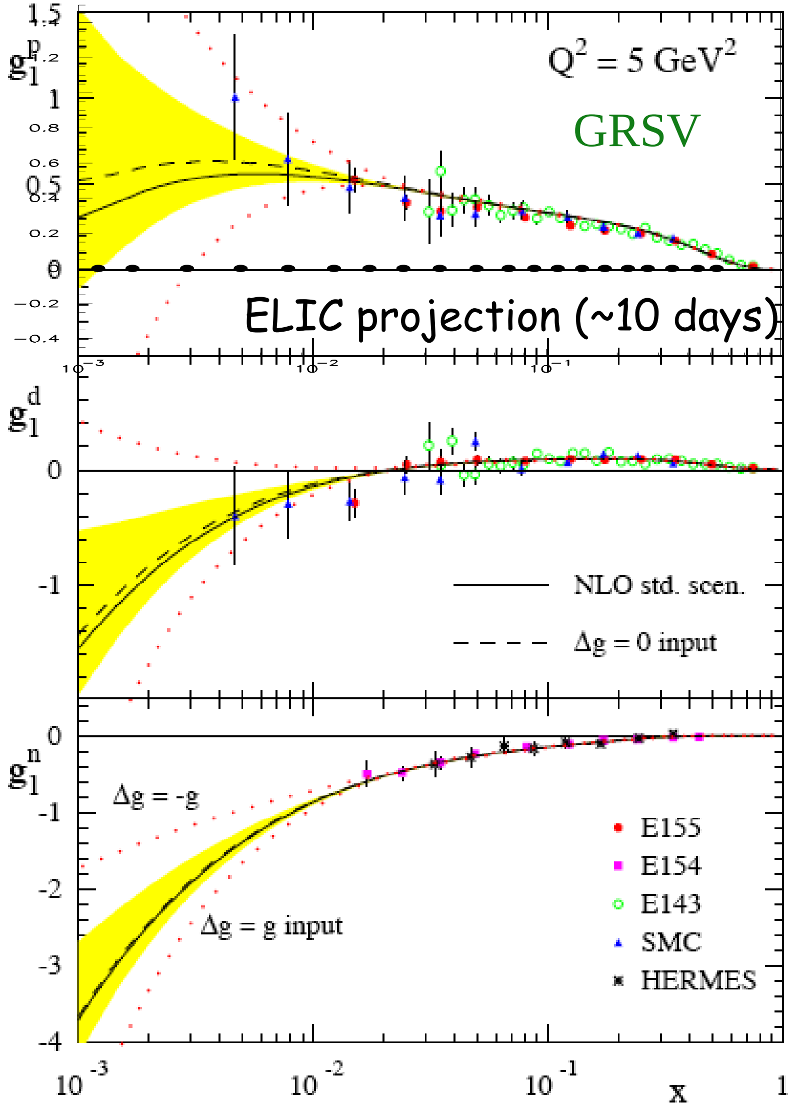
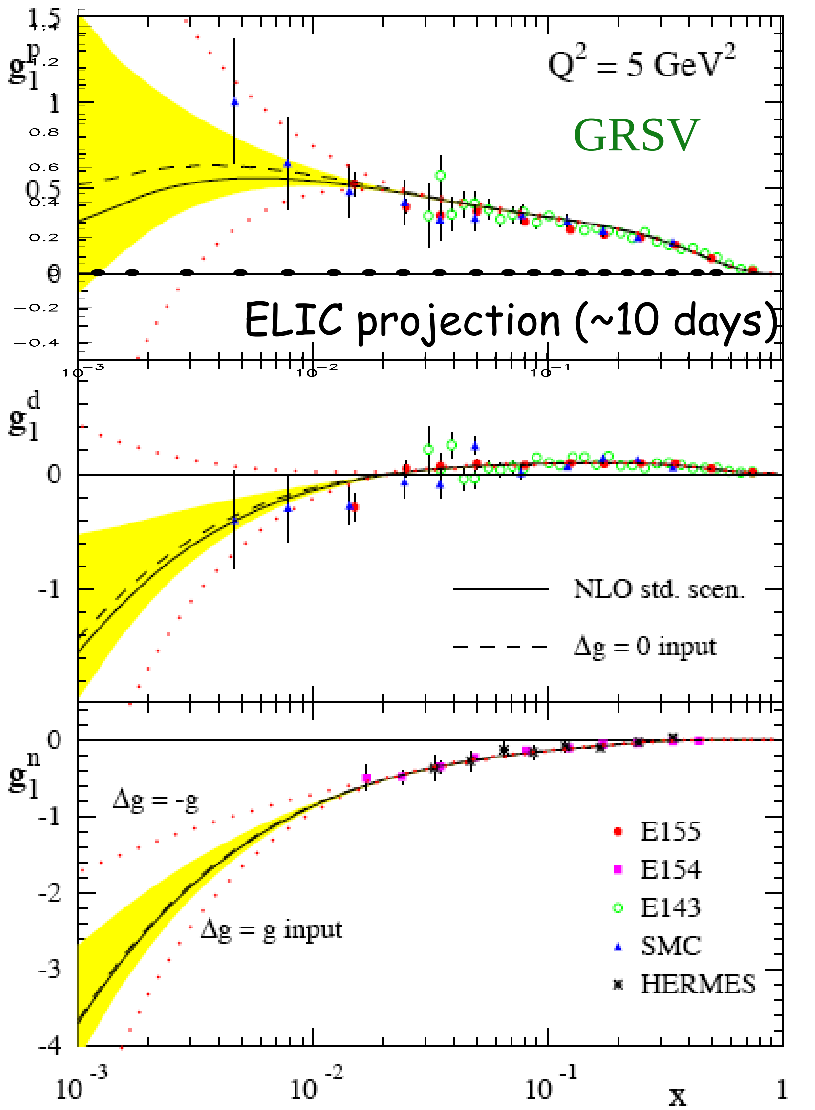
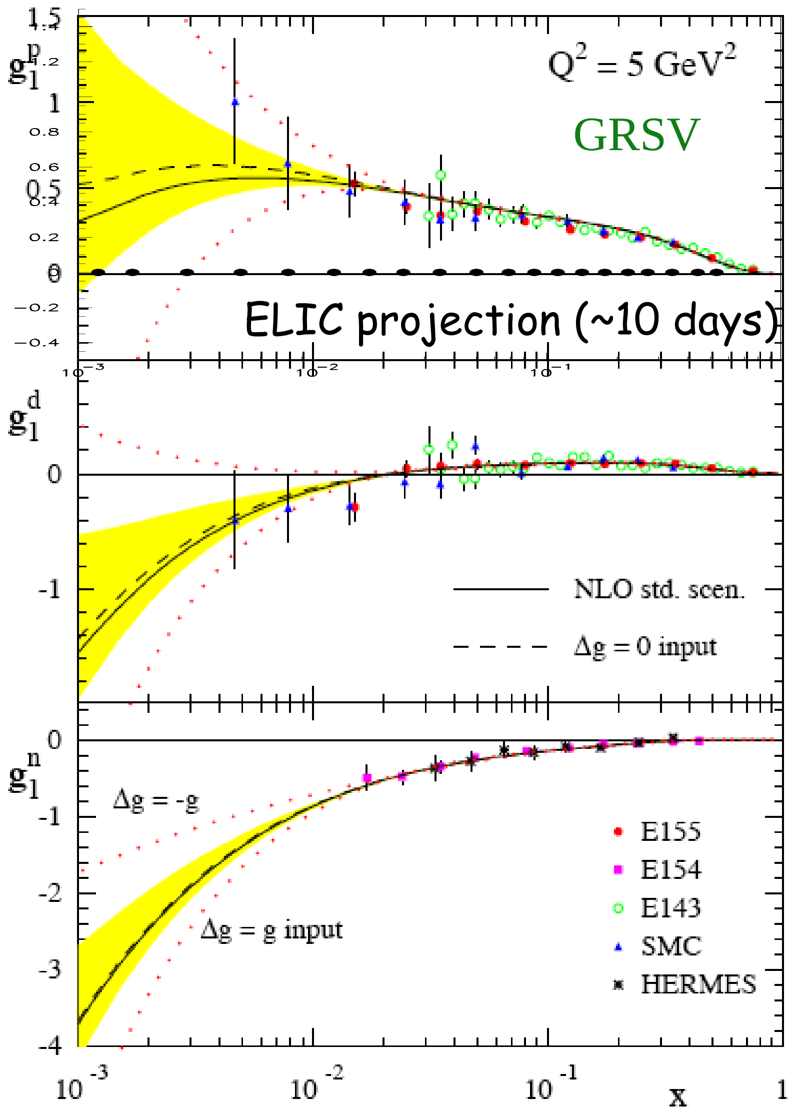


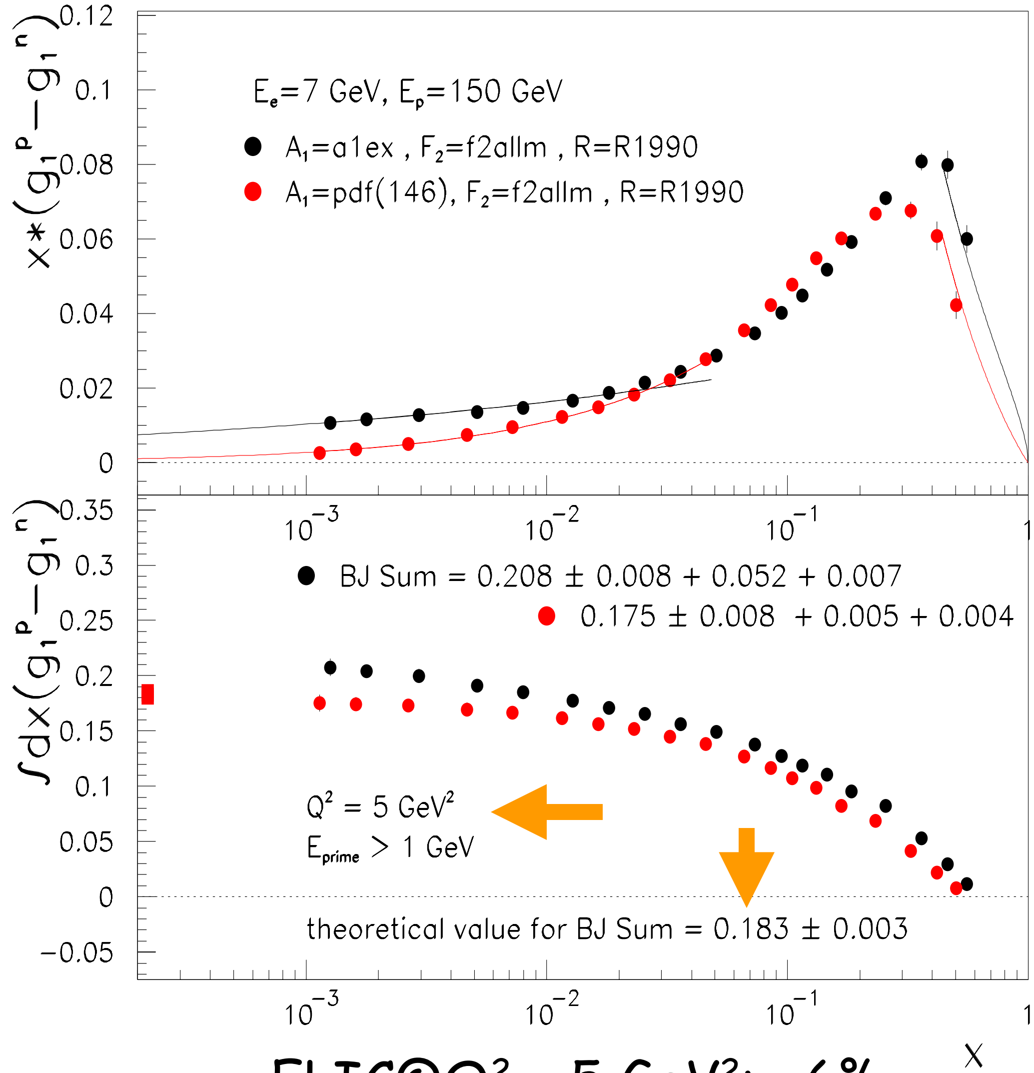
Examples: g_1^p



How about Bjorken Sum Rule?
(Present uncertainty: 10-15%)

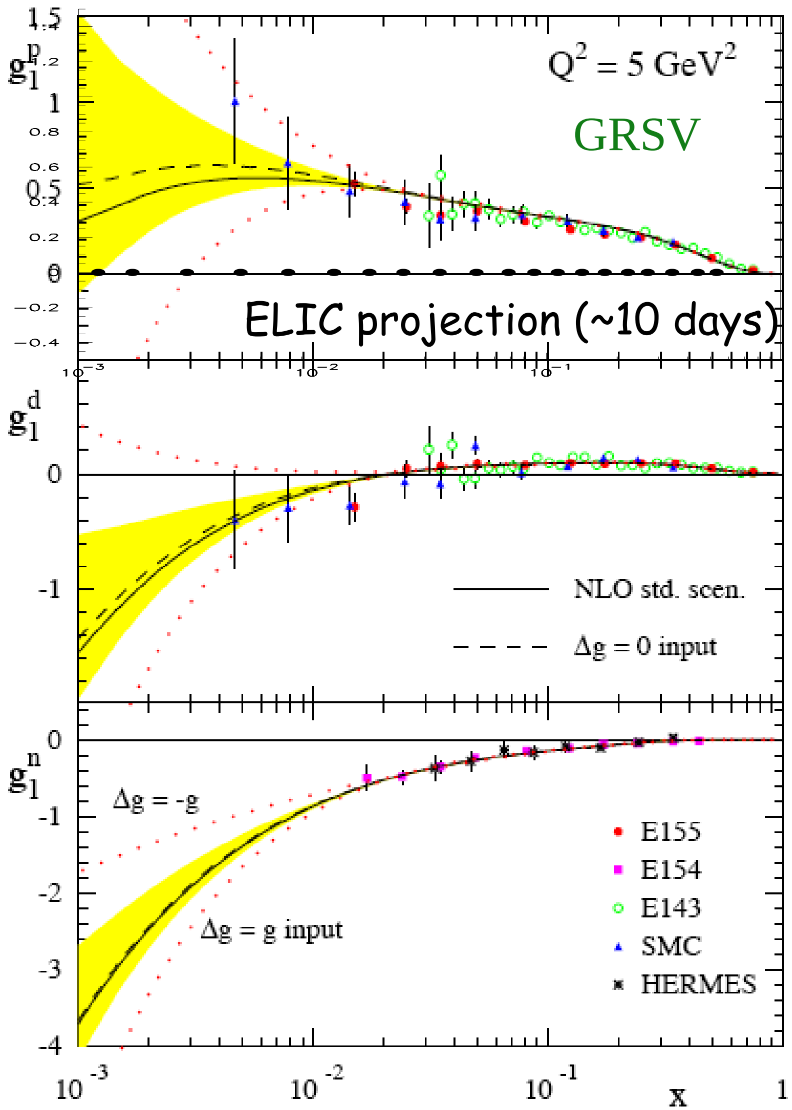
Examples: g_1^p, Bjorken Sum Rule

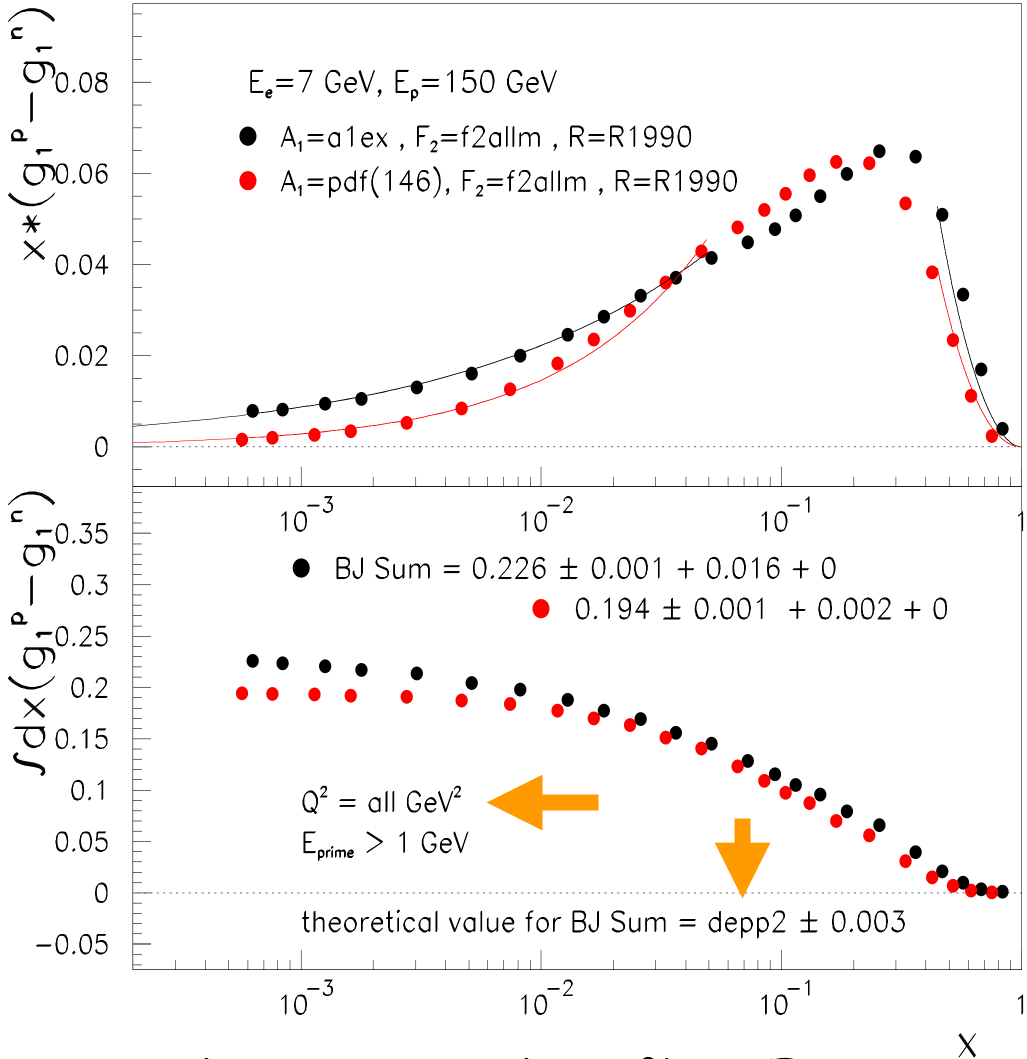




ELIC@Q^2 = 5 GeV^2: ~6%

Examples: g_1^p, Bjorken Sum Rule

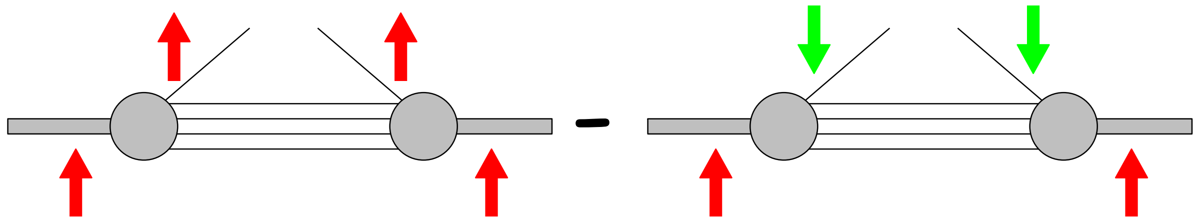




Work in progress! 2-3% at ELIC?

New Spin Structure Function: Transversity

$\delta q(x) \sim$ (in transverse basis)



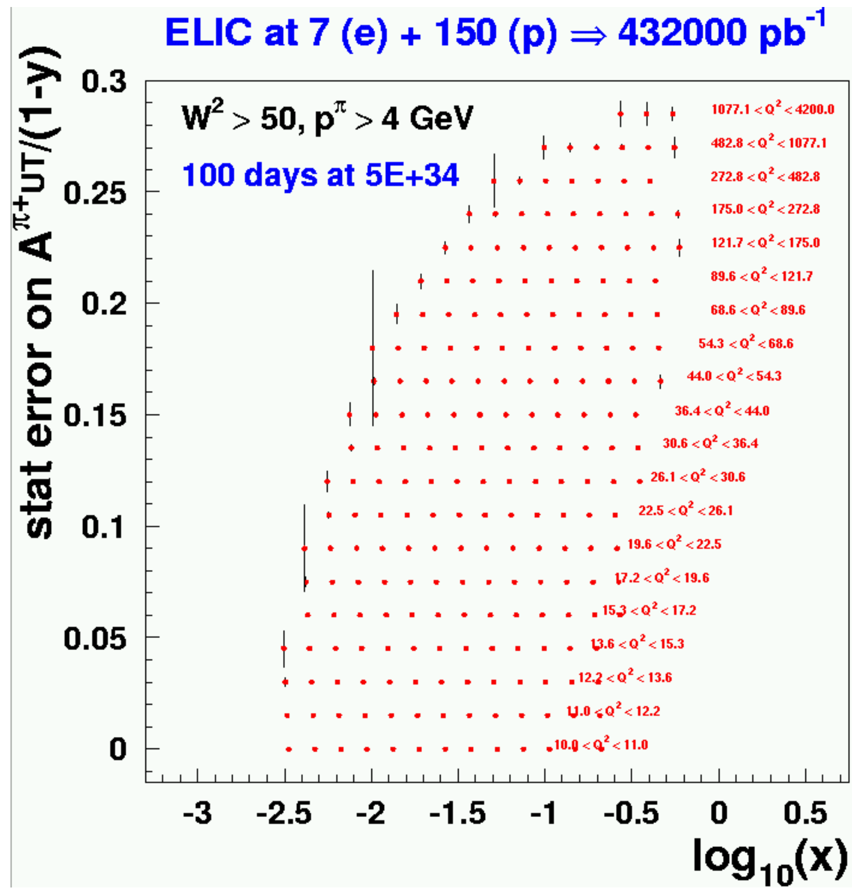
- Nucleon's transverse spin content → "tensor charge"
- No transversity of Gluons in Nucleon → "all-valence object"
- Chiral Odd → only measurable in semi-inclusive DIS

→ first glimpses exist in data (HERMES, JLab-6)

→ Later work: more complicated

→ COMPASS 1st results: ~0 @ low x

→ Future: Flavor decomposition



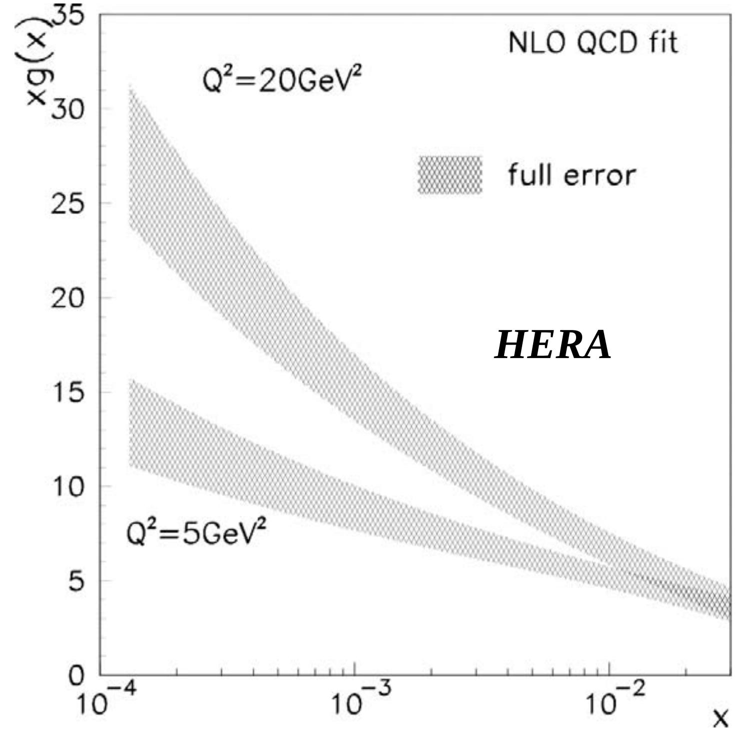
Gluon Spin in the Nucleon

$$s = \frac{1}{2} = \frac{1}{2}\Delta\Sigma + L_q + \Delta G + L_G$$

$$\Delta\Sigma = 0.25 \pm 0.1$$

Gluon contribution is likely to be substantial: Profound implications for our basic understanding of the nucleon which must be directly measured by experiment

The gold standard: measure ΔG from a variety of experiments, where the dominant theoretical input is NLO QCD and residual model dependence is negligible and non-controversial



The dream is to produce a similar plot for $x\Delta g(x)$ vs x

$\Delta G/G$ from open charm: ~RHIC-SPIN precision down to x = 0.001

Orbital Angular Momentum

Analysis of hard exclusive processes leads to a new class of generalized parton distributions

Four new distributions:

helicity conserving →	$H(x,\xi,t)$, $E(x,\xi,t)$
helicity-flip →	$\tilde{H}(x,\xi,t)$, $\tilde{E}(x,\xi,t)$

"skewedness parameter" ξ
→mismatch between quark momenta
→sensitive to partonic correlations

3-dimensional GPDs give spatial distribution of partons and spin

- Angular Momentum $J_q = \frac{1}{2}\,\Delta\Sigma + L_q$!

$$J_q = \frac{1}{2}\int_{-1}^{1} x\,dx \left[H_q(x,\xi,t=0) + E_q(x,\xi,t=0)\right]$$

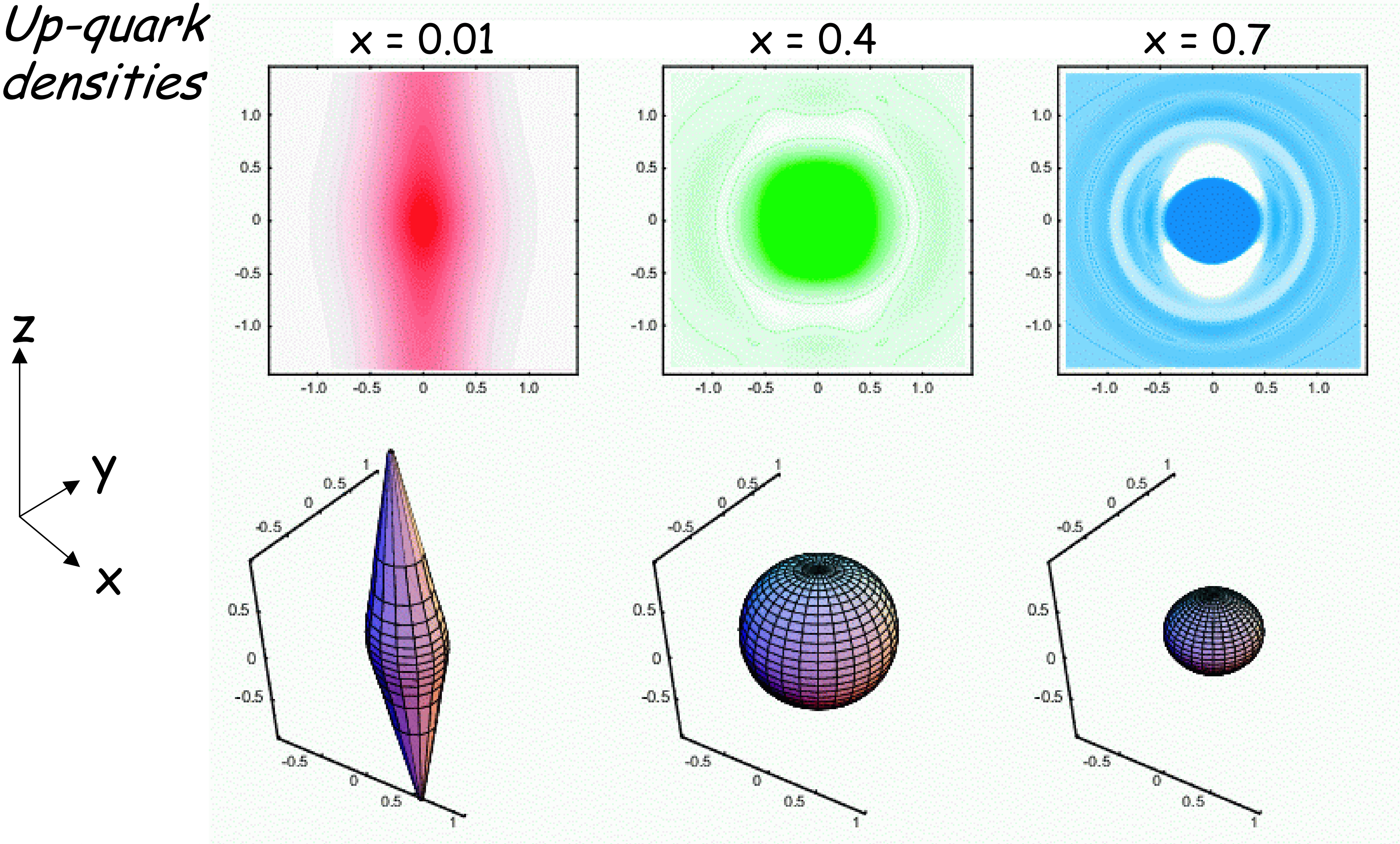
New Roads:

- Deeply Virtual Meson Production @ $Q^2 > 10$ GeV^2
  → disentangles flavor and spin!
- ρ and ϕ Production give access to gluon GPD's at small x (<0.2)

Can we achieve same level of understanding as with F_2?

Proton Images at Fixed x

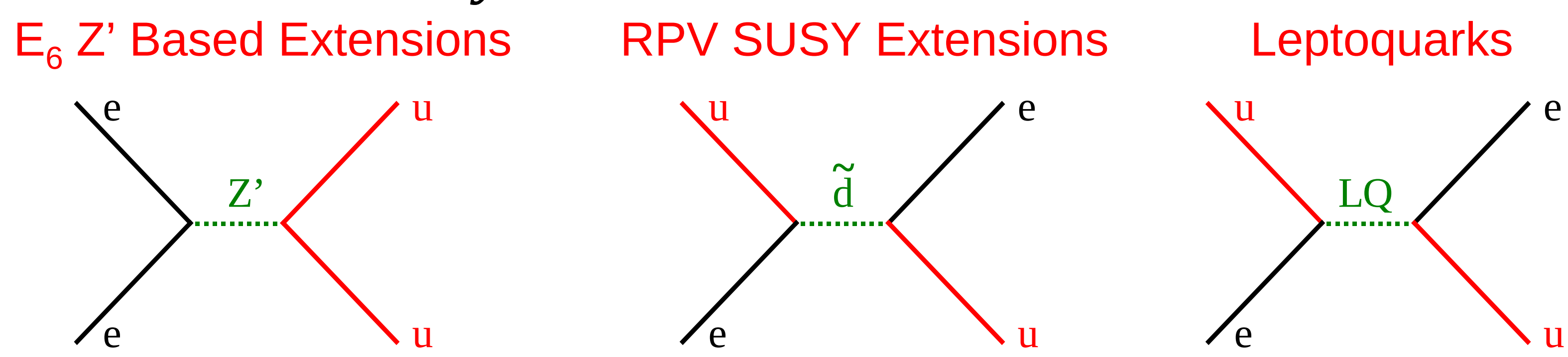
Up-quark densities



Parity Violation

Ent

Beyond the Standard Model



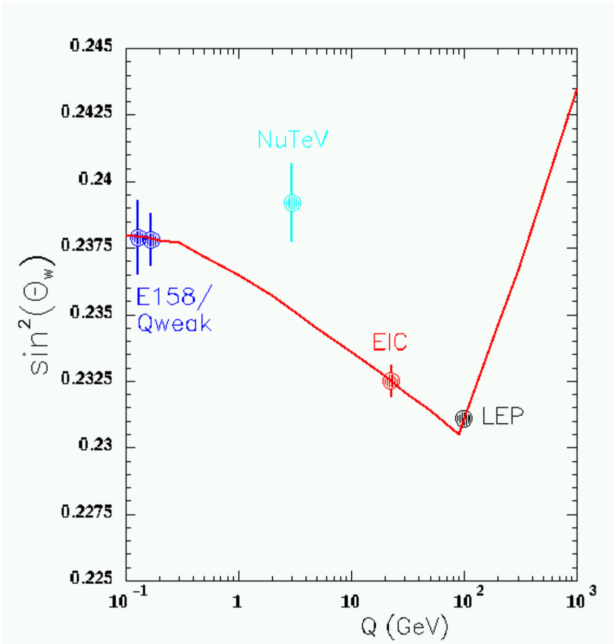
Due to finite Y

$$\frac{\delta \sin^2\theta_W}{\sin^2\theta_W}\bigg|_{Y=0.46} \approx \frac{1}{2}\left(\frac{\delta A_d}{A_d}\right)$$

$$A_d \approx 2.9 \times 10^{-4}$$

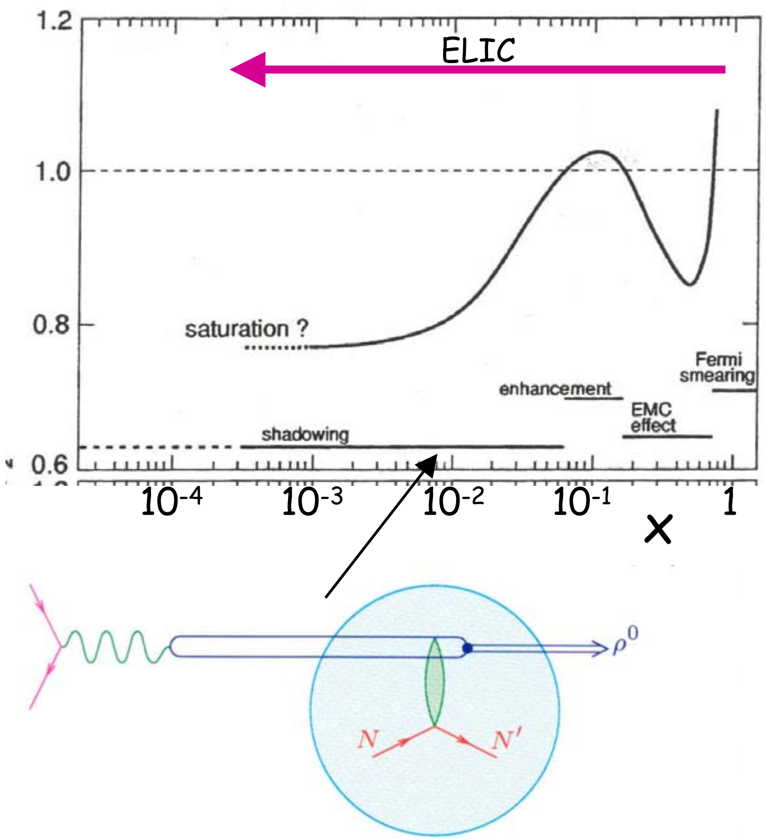
10^{35} /cm²/s

Sub 0.5% polarimetry



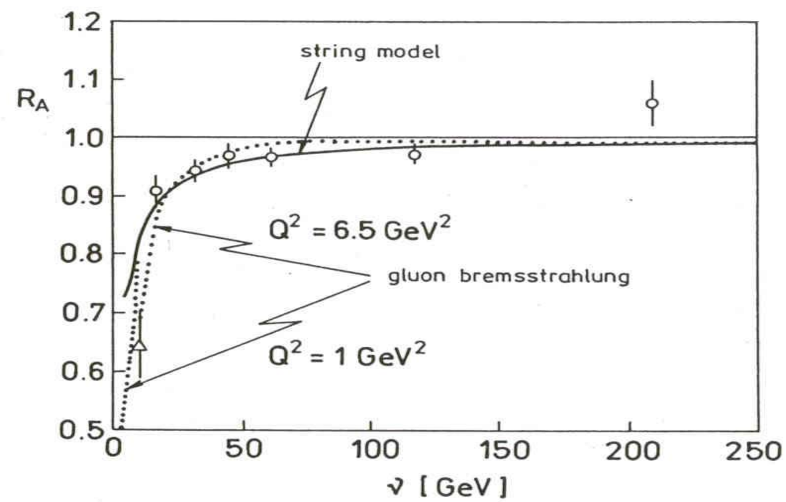
Quarks in a Nucleus

F_2^A/F_2^D "EMC Effect"



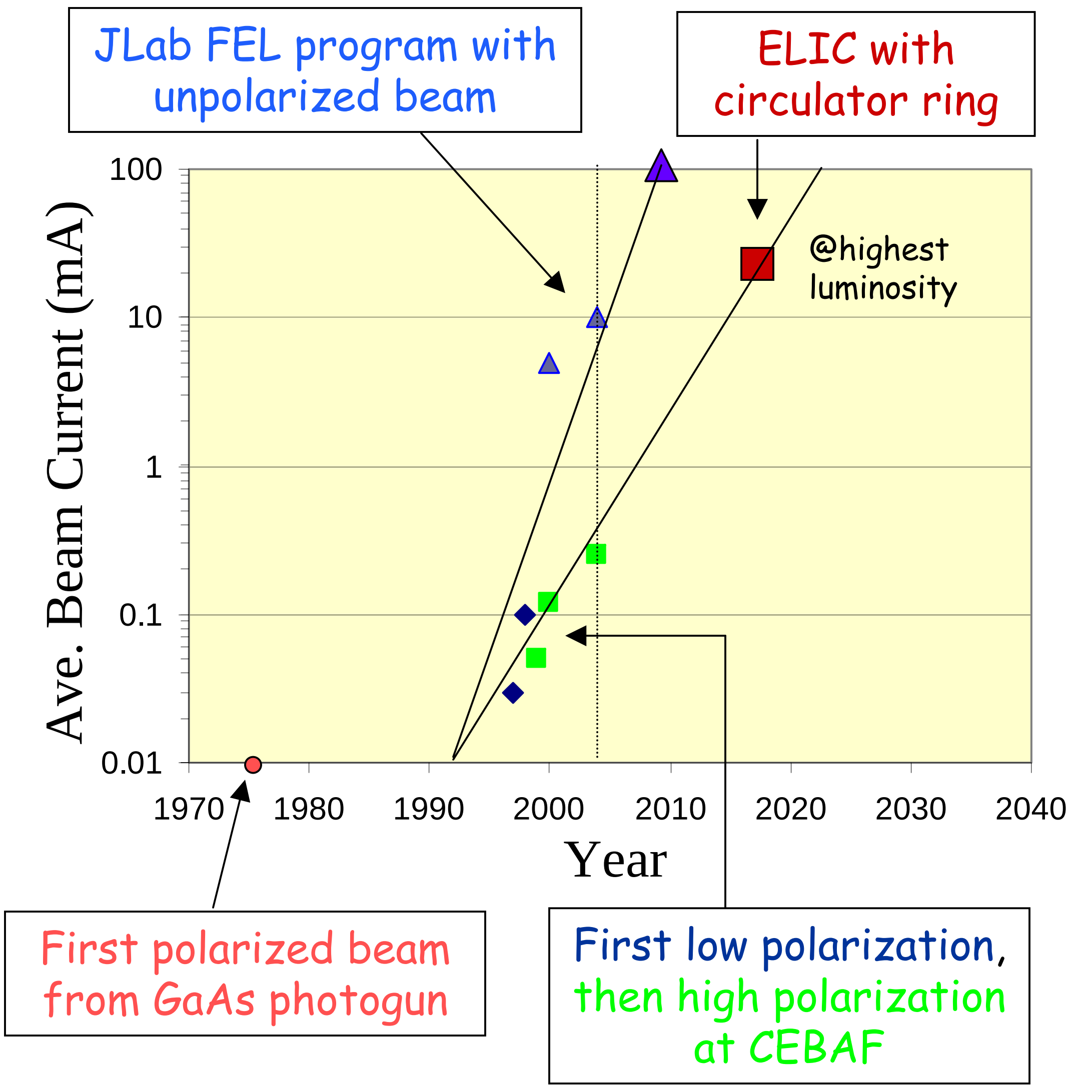
Space-Time Structure of Photon

Can pick apart the spin-flavor structure of EMC effect by technique of flavor tagging, in the region where effects of the space-time structure of hadrons do not interfere (large ν!)



Nuclear attenuation negligible for ν > 50 GeV →hadrons escape nuclear medium undisturbed

Towards Higher Electron Beam Current



Source requirements for ELIC less demanding with circulator ring! Few mA's versus >> 100 mA of highly polarized beam.

Lifetime Estimate @ 25 mA:

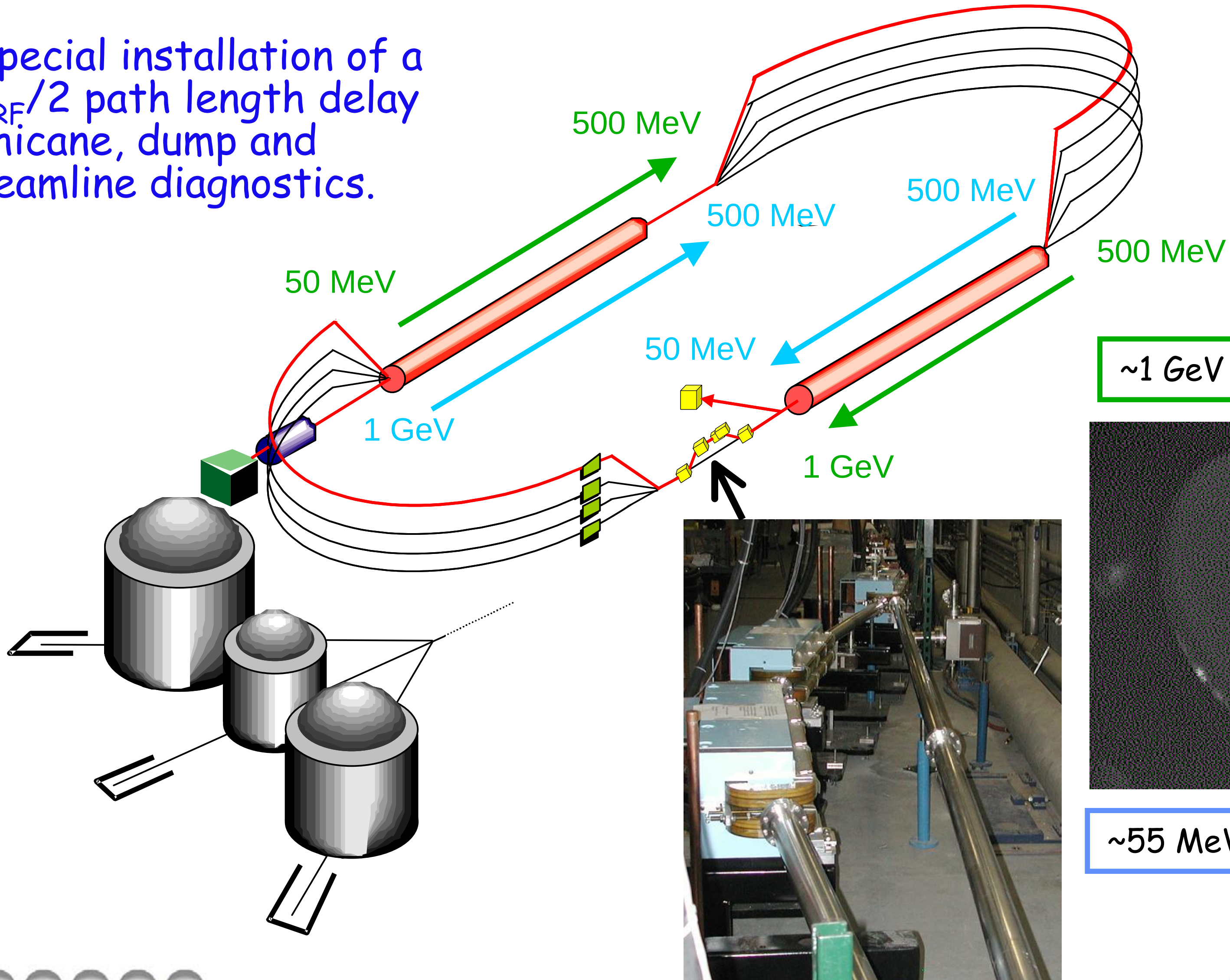
CEBAF enjoys excellent gun lifetime:
~200 C charge lifetime
(until QE reaches 1/e of initial value)
~100,000 C/cm^2 charge density lifetime
(we use a ~0.5 mm dia. spot)

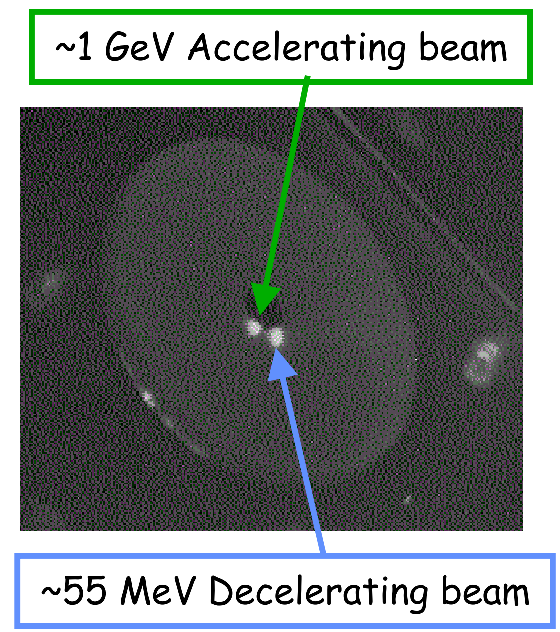
If Charge-Lifetime assumption valid:
With ~1 cm dia. spot size lifetime of 36 weeks at 25 mA!

Need to test the scalability of charge lifetime with laser spot diameter → Measure charge lifetime versus laser spot diameter in lab. *(Poelker, Grames)*

ERL Technology demonstrated at CEBAF @ 1 GeV

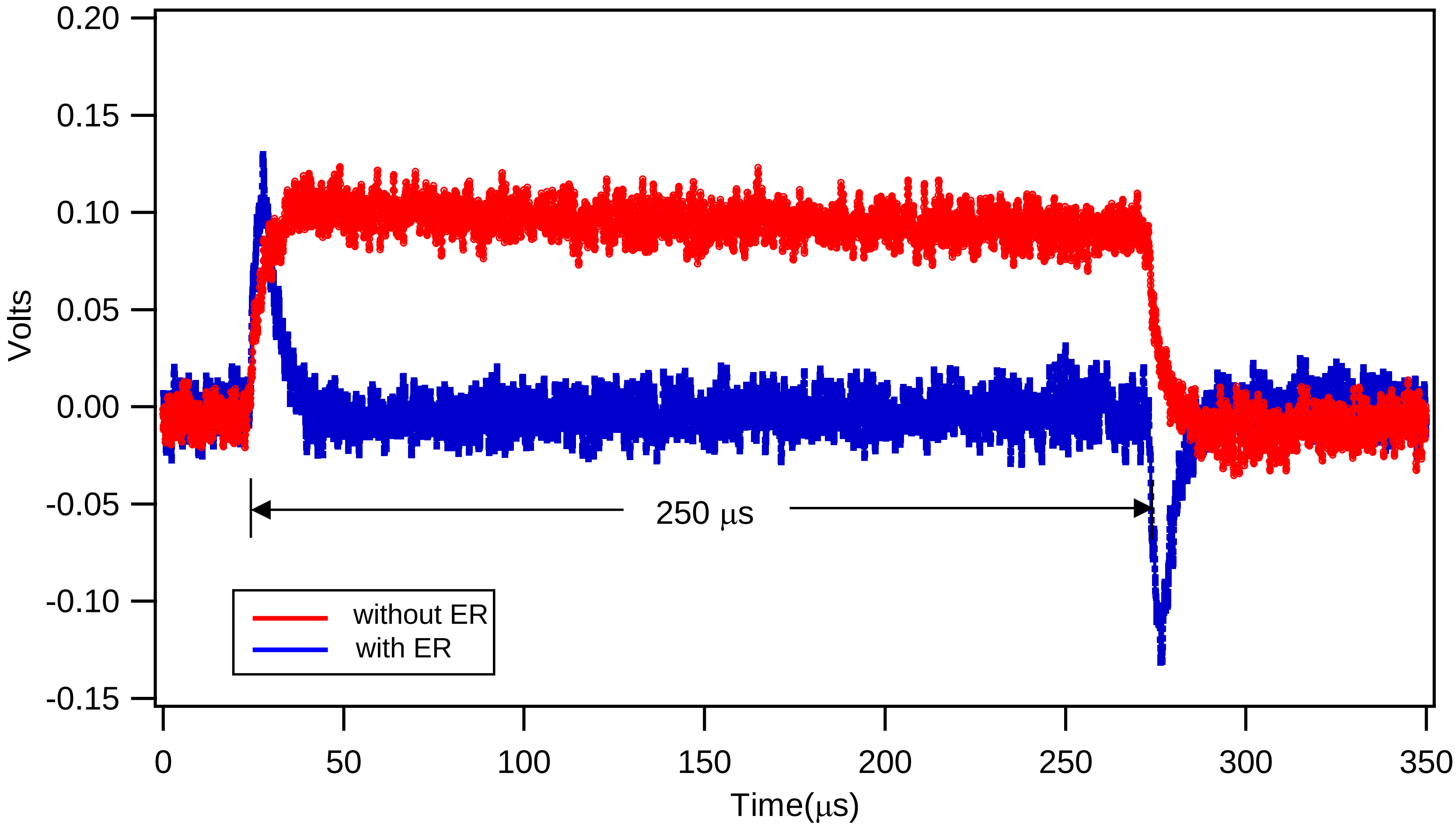
Special installation of a $\lambda_{RF}/2$ path length delay chicane, dump and beamline diagnostics.





RF Response to Energy Recovery

- Gradient modulator drive signals **with** and **without** energy recovery in response to 250 μsec beam pulse entering the RF cavity *(SL20 Cavity 8)*



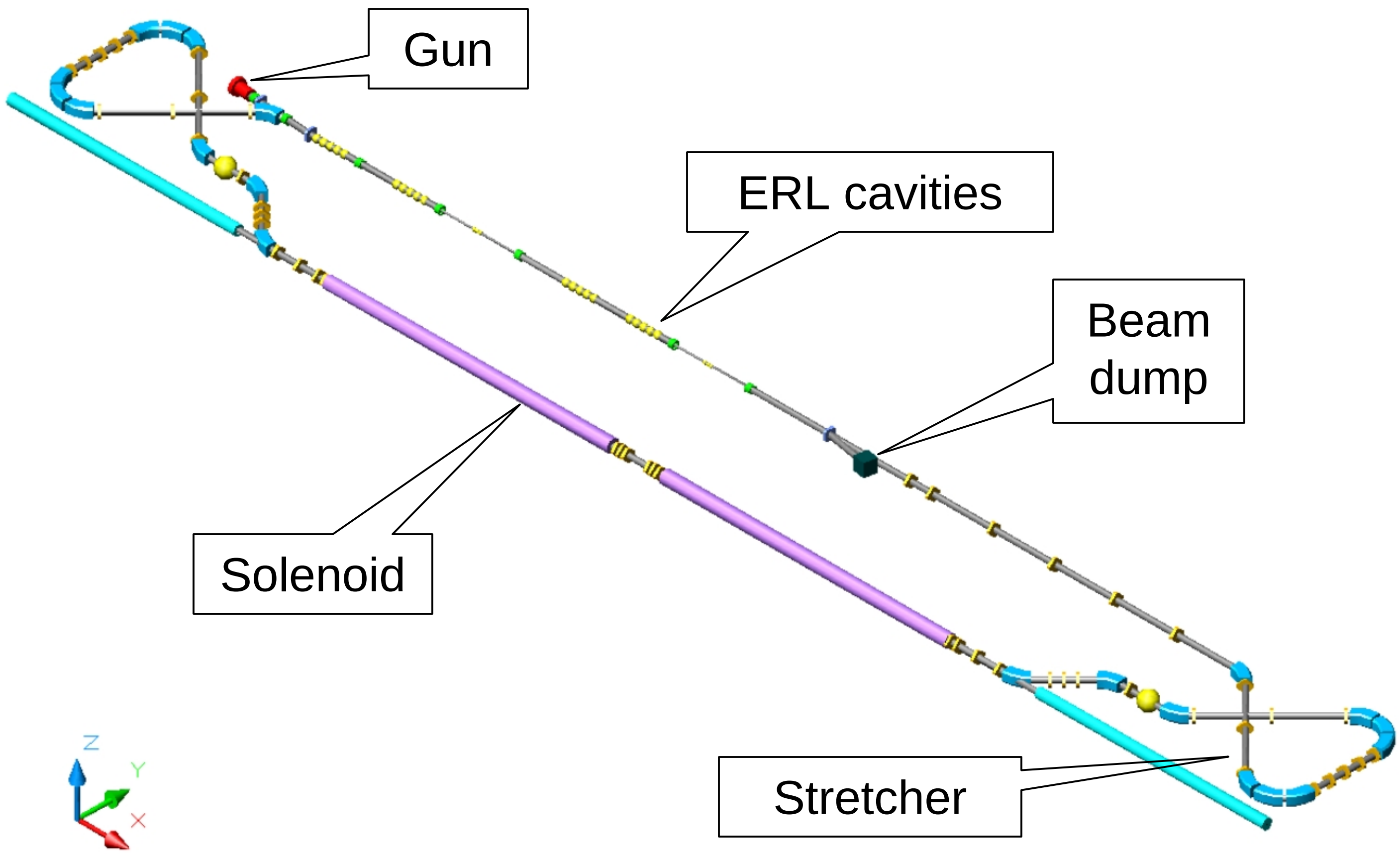
Summary of the EIC Possibilities – Summary!

1) The Electron-Ion Collider Project
- Part of DOE 20-year Plan
- Two options: eRHIC – Zero Design Report Available
  ELIC – Push parameters, R&D Ongoing
- Prepare White Paper for next NSAC Long-Range Plan Cycle

2) Science at the EIC
- Will be the ultimate gluon machine
- Solve the Spin Puzzle
- New state of matter? (Colored Glass Condensate)
- How does Energy convert into Matter?
- What is the Partonic Origin of Nuclear Binding?

3) Ongoing Accelerator R&D
- High Energy Electron Cooling of Protons/Ion
  Practical only if based on SRF-ERL technology. Rigorous e-cooling R&D program established at BNL
- High Charge per Bunch and High Average Current Polarized Electron Source
  Measure charge lifetime versus laser spot diameter at JLab
- High Current and High Energy demonstration of Energy Recovery
  ERL Technology demonstrated at CEBAF @ 1 GeV; High E + High I still to be demonstrated
- Integration of Interaction Region Design with Detector Geometry
  eRHIC has preliminary design

Layout of RHIC electron cooler



Each electron bunch is used just once.