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# Spin Physics with eRHIC

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DIS 2004  
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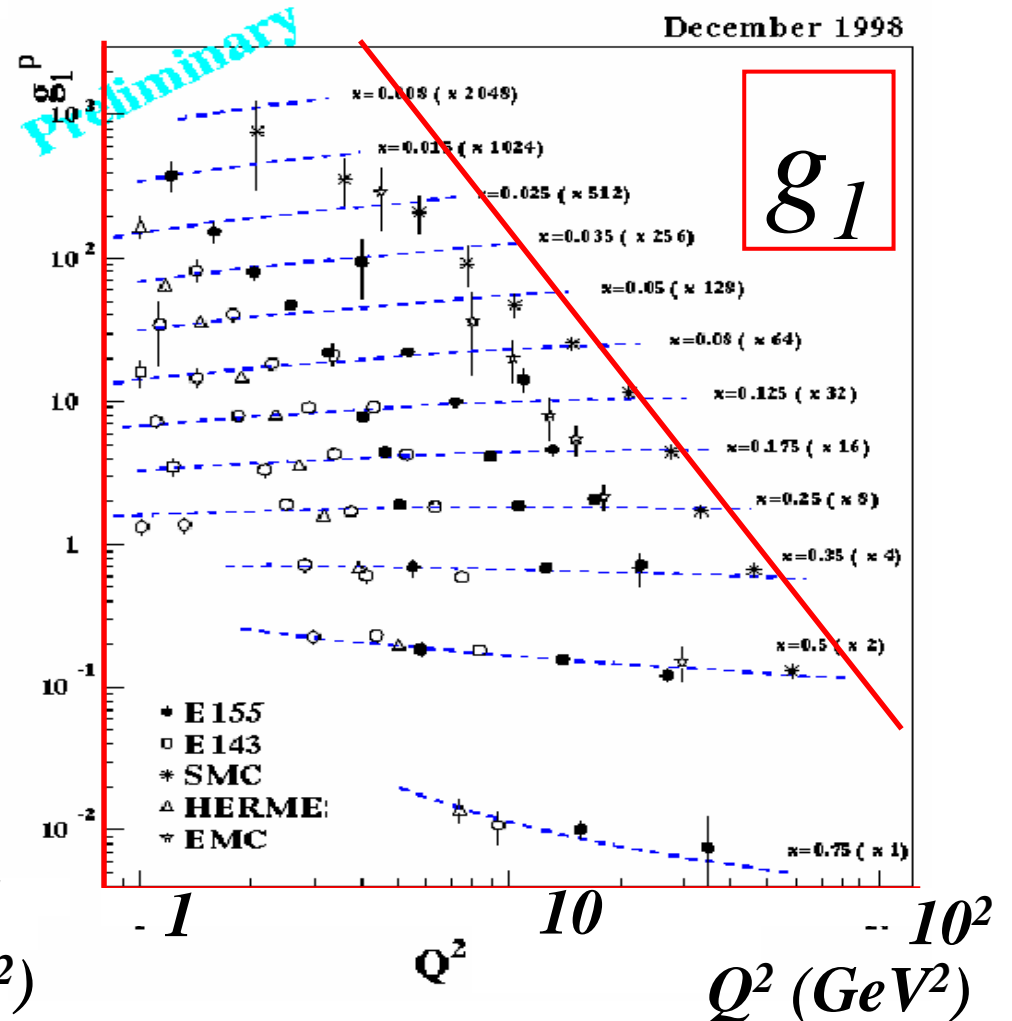
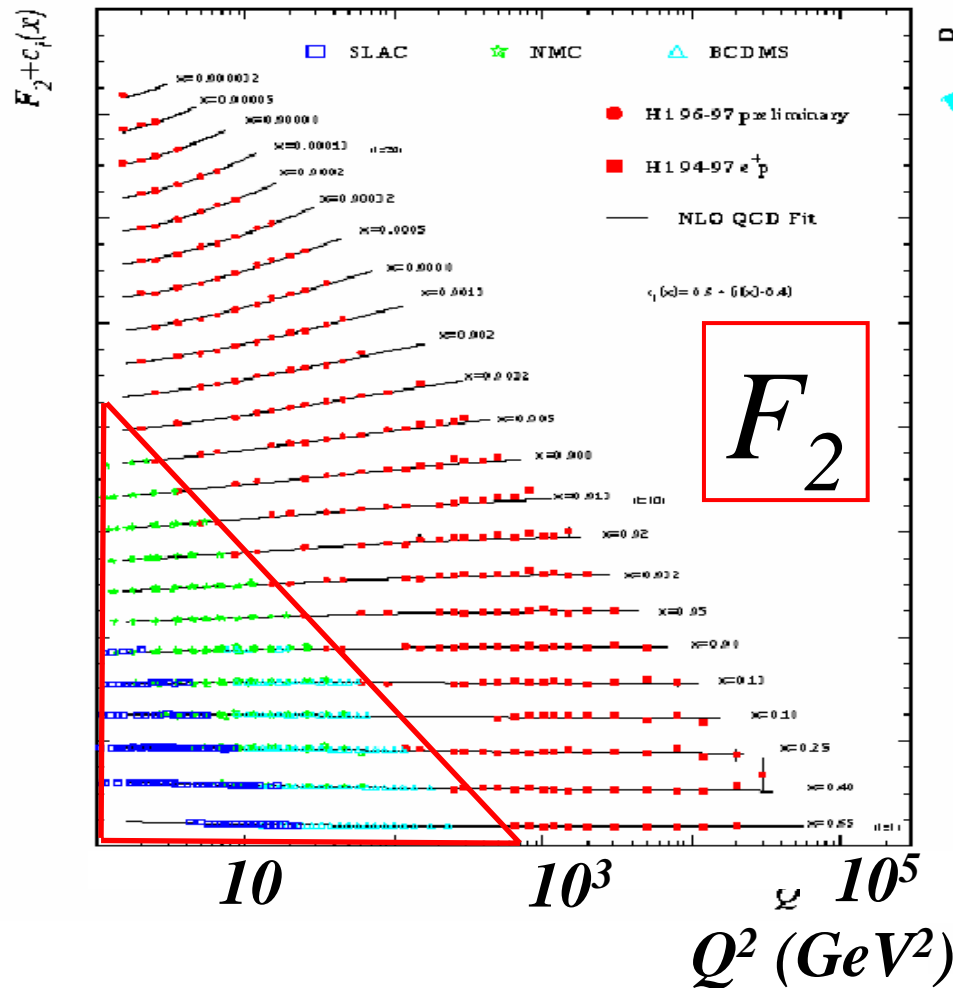
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# Some spin & Low x-high $Q^2$ surprises...

- Stern & Gerlach (1921) Space quantization associated with direction
- Goudschmidt & Uhlenbeck (1926): Atomic fine structure & electron spin magnetic moment
- Stern (1933) Proton anomalous magnetic moment  $2.79 m_N$
- Kusch(1947) Electron anomalous magnetic moment  $1.00119m_0$
- Prescott & Yale-SLAC Collaboration (1978) EW interference in polarized e-d DIS, parity non-conservation
- **European Muon Collaboration (1988/9) Spin Crisis/Puzzle**
- Transverse single spin asymmetries: E704, AGS pp scattering, HERMES (1990s) RHIC Spin (2001)
  - single spin neutron production(PHENIX)
  - pion production (STAR) at 200 GeV Sqrt(S)
- Jefferson laboratory experiments hinting at the proton shape
- Elastic e-p scattering at SLAC (1950s)  $\rightarrow Q^2 \sim 1 \text{ GeV}^2 \rightarrow$  Finite size of the proton
- Inelastic e-p scattering at SLAC (1960s) $\rightarrow Q^2 > 1 \text{ GeV}^2 \rightarrow$  Parton structure of the proton
- Inelastic mu-p scattering off p/d/N at CERN (1980s)  $\rightarrow Q^2 > 1 \text{ GeV}^2 \rightarrow$  Unpolarized EMC effect, nuclear shadowing?
- Inelastic e-p scattering at HERA/DESY (1990s) $\rightarrow Q^2 > 1 \text{ GeV}^2$ 
  - $\rightarrow$  Unexpected rise of F2 at low x
  - $\rightarrow$  Diffraction in e-p
  - $\rightarrow$  Saturation(??)

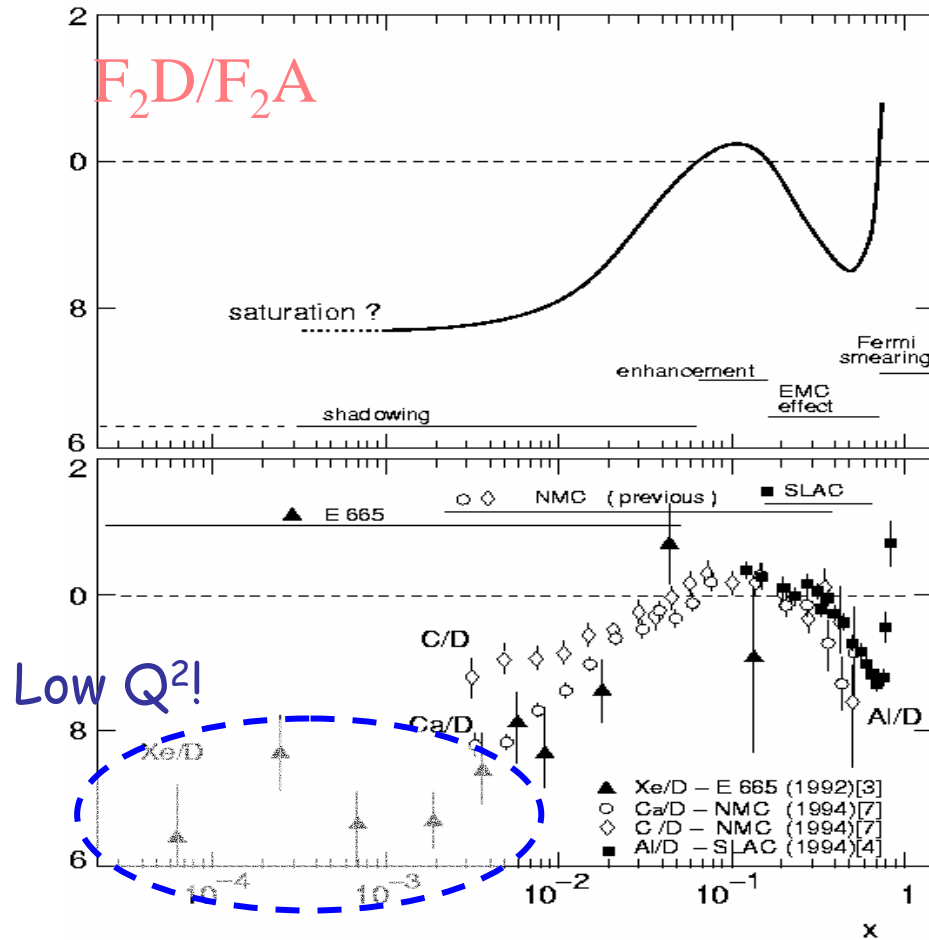
A facility that does both would be ideal....

# Our Knowledge of Structure Functions



Large amount of polarized data since 1998... but not in NEW kinematic region!

# DIS in Nuclei is Different!



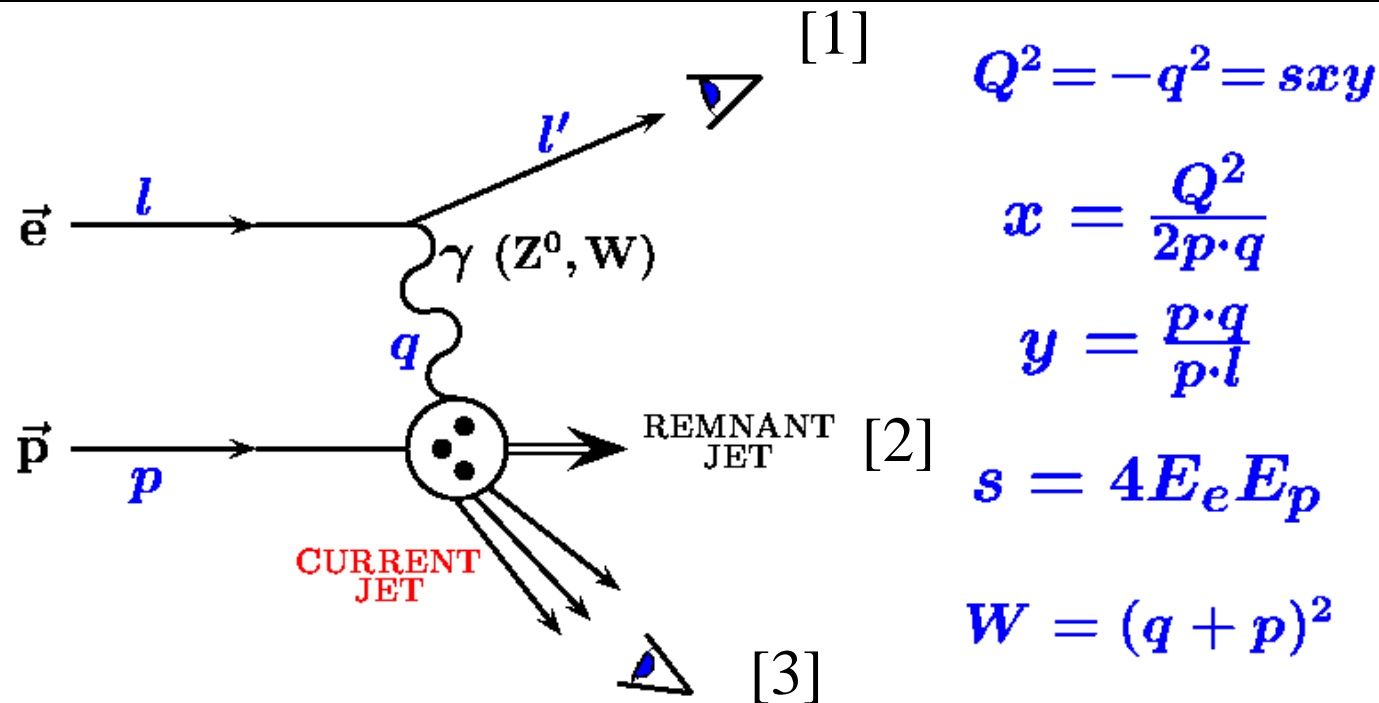
Regions of:

- Fermi smearing
- EMC effect
- Enhancement
- Shadowing
- Saturation?

Regions of shadowing and saturation mostly around  $Q^2 \sim 1 \text{ GeV}^2$

An e-A collision at eRHIC can be at significantly higher  $Q^2$

# Deep Inelastic Scattering



- Observe scattered electron [1] inclusive measurement
- Observe [1] + current jet [2] semi-inclusive measurement
- Observe [1] + [2] + remnant jet [3] exclusive measurement
- Luminosity requirements goes up as we go from [1] --> [2] --> [3]
- Exclusive measurements also puts demanding requirement on detectors, interaction region *and hence deliverable luminosity*

# Why Collider In Future?

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- Polarized DIS and e-A physics: in past only in fixed target mode
- Collider geometry--> distinct advantages (HERA Experience)



- Better angular resolution between beam and target fragments
  - Better separation of electromagnetic probe
  - Recognition of rapidity gap events (recent diffractive physics)
  - Better measurement of nuclear fragments
- Higher Center of Mass energies reachable
- **Tricky issues: integration of interaction region and detector**

# The eRHIC Proposals

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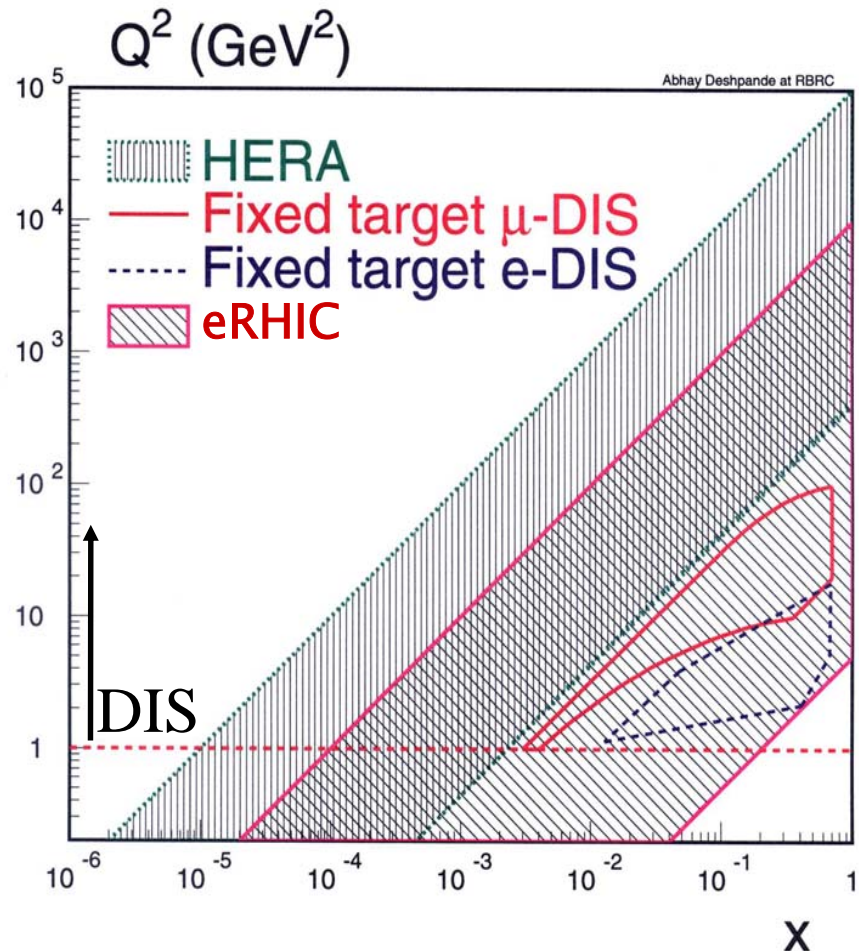
## eRHIC at BNL

A high energy, high intensity polarized electron/positron beam facility at BNL to colliding with the **existing heavy ion and polarized proton beam** would significantly enhance RHIC's ability to probe **fundamental and universal aspects of QCD**

## Jlab Upgrade II: CEBAFII/ELIC

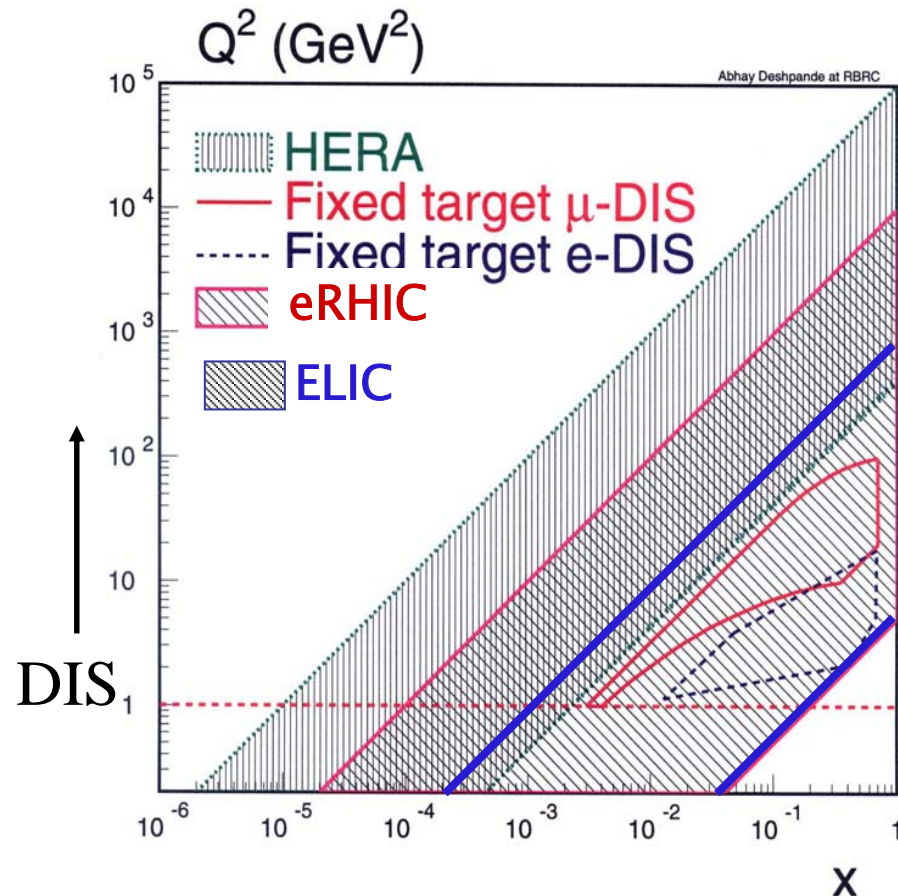
An electron-light-ion collider or/and a 25 GeV fixed target facility at Jlab will address the question of **precision measurements of nucleon spin**, including the issues related to **generalized parton distributions** with its large luminosity. The collider and fixed target facility will cover complementary kinematic regions.

# eRHIC vs. Other DIS Facilities



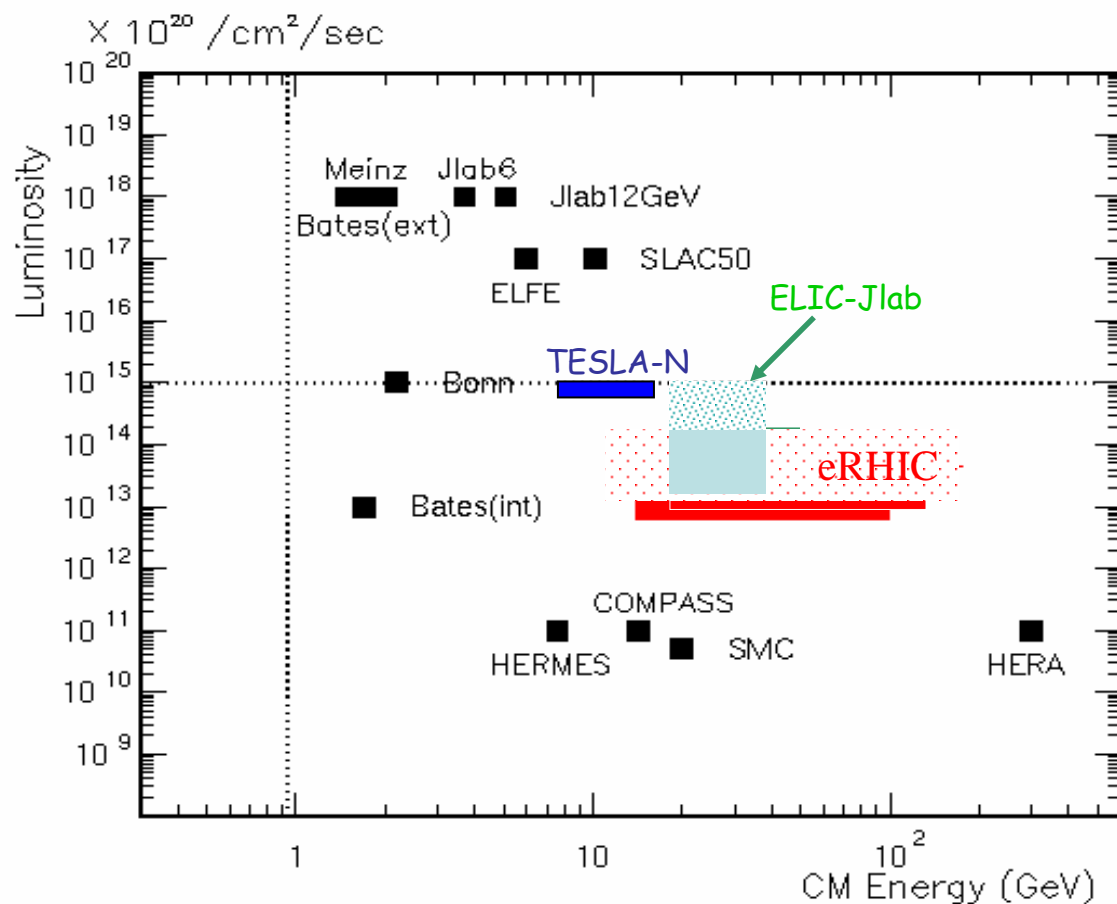
- **New kinematic region**
- $E_e = 10$  GeV (reducible to 5 GeV)
- $E_p = 250$  GeV (reducible to 50 GeV)
- $EA = 100$  GeV (reducible to 12 GeV)
- $\sqrt{S_{ep}} = 30-100$  GeV
- $\sqrt{S_{eA}} = 63$  GeV
  - Low  $x$  physics
- Kinematic reach of eRHIC:
  - $X = 10^{-4} \rightarrow 0.7$  ( $Q^2 > 1$  GeV<sup>2</sup>)
  - $Q^2 = 0 \rightarrow 10^4$  GeV<sup>2</sup>
- Polarization of e,p and light ion beams at least  $\sim 70\%$  or better
- Heavy ions of ALL species
  - High gluonic densities
- High Luminosity:
  - $L(ep) \sim 10^{33-34}$  cm<sup>-2</sup> sec<sup>-1</sup>
  - $L(eA) \sim 10^{31-32}$  cm<sup>-2</sup> sec<sup>-1</sup> N<sup>-1</sup>

# ELIC vs. Other DIS Facilities



- **Physics of Exclusive measurements**
- $E_e = 3-7$  GeV
- $E_p = 30-100$  (150) GeV
- $\sqrt{S_{ep}} = 20-45$  (65) GeV
- Kinematic reach of ELIC
  - $X = 10^{-3} \rightarrow 0.8$  ( $Q^2 > 1$  GeV<sup>2</sup>)
  - $Q^2 = 0 \rightarrow 10^3$  GeV<sup>2</sup>
- Polarization of e, p & light ion beam.  $\sim 70\%$
- High luminosity:
  - $L_{(ep)} \sim 10^{33-35}$  cm<sup>-2</sup> sec<sup>-1</sup>
  - Staged increase in luminosity

# CM vs. Luminosity



- **eRHIC**

- Variable beam energy
- P-U ion beams
- Light ion polarization
- Large luminosity

- **ELIC**

- Variable beam energy
- Light ion polarization
- Huge luminosity

# Scientific Frontiers Open to eRHIC

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- **Nucleon structure, role of quarks and gluons in the nucleons**
  - Unpolarized quark and gluon distributions, confinement in nucleons
  - Polarized quark and gluon distributions
  - Correlations between partons
    - Exclusive processes--> Generalized Parton Distributions
  - Understanding confinement with low  $x$ /low $Q^2$  measurements
- **Meson Structure:**
  - Goldstone bosons and play a fundamental role in QCD
- **Nuclear Structure, role of partons in nuclei**
  - Confinement in nuclei through comparison e-p/e-A scattering
- **Hadronization in nucleons and nuclei & effect of nuclear media**
  - How do knocked off partons evolve in to colorless hadrons
- **Partonic matter under extreme conditions**
  - For various  $A$ , compare e-p/e-A

# Unpolarized e-p at The eRHIC

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- Although large kinematic region already covered at HERA, additional studies with high luminosities desirable
- Unique features: high luminosity, variable CM energy, He beams, *and improved detectors and interaction regions*
- **Precision Measurements:**
  - With d, He beams, neutron structure [1]
  - strong coupling constant and its evolution [1]
  - photo-production physics at high energies [1]
  - gluon distribution [1]
  - $F_L$  structure function [1]
  - slopes of  $F_2$  structure function exploring confinement [1]
  - Diffractive physics [1]
  - Semi-inclusive and exclusive reactions [1,2]
  - Nuclear fragmentation region [2,3]

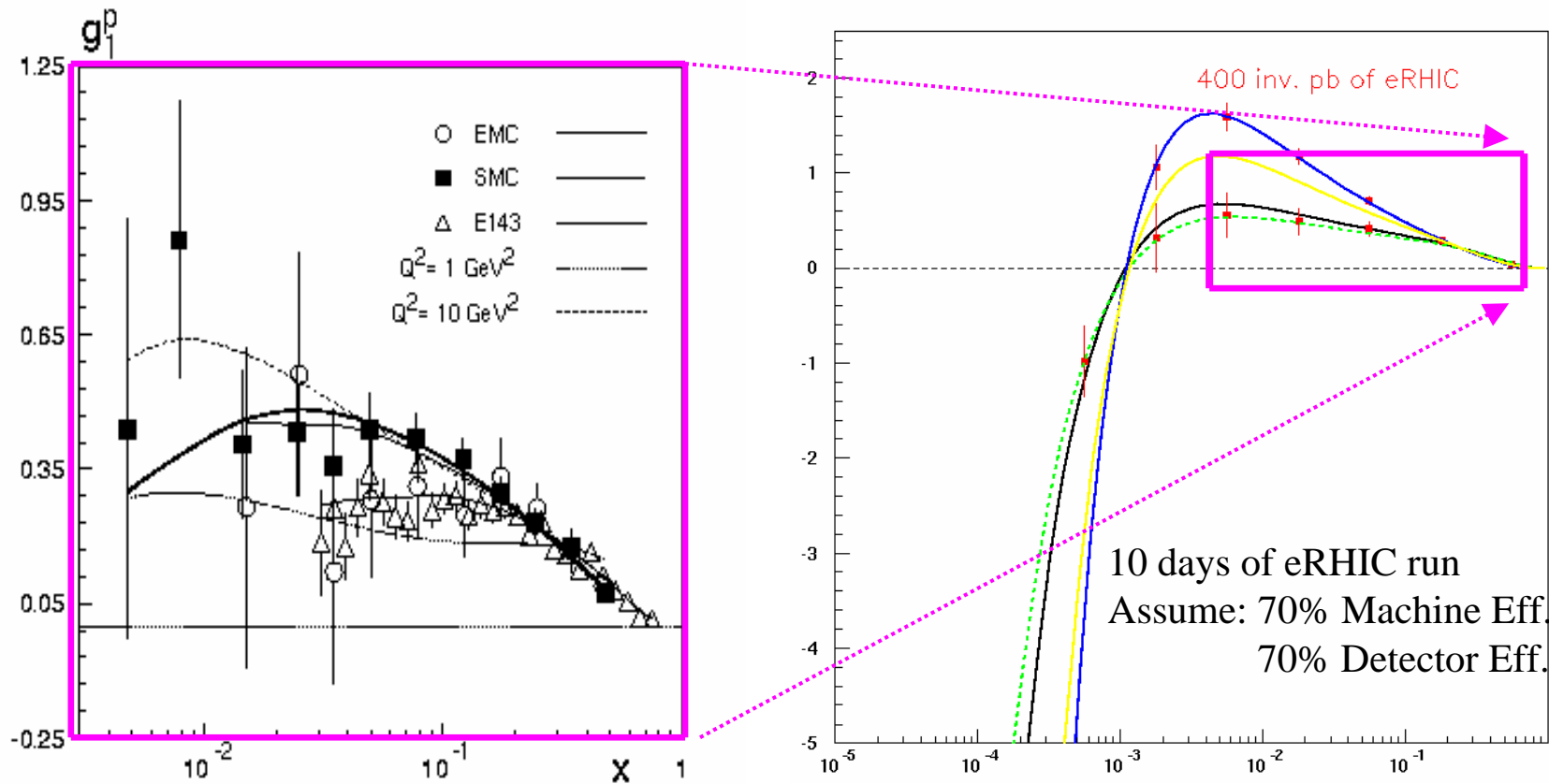
# Polarized DIS at eRHIC

- Spin structure functions  $g_1$  (p,n) at low x, high precision [1]
    - $g_1$ (p-n): Bjorken Spin sum rule better than 1% accuracy
  - Polarized gluon distribution function  $\Delta G(x, Q^2)$  [1]
    - at least three different experimental methods
  - Precision measurement of  $\alpha_s(Q^2)$  from  $g_1$  scaling violations [1]
  - Polarized s.f. of the photon from photo-production [1]
  - Electroweak s. f.  $g_5$  via  $W^{+/-}$  production [1,2]
  - Flavor separation of PDFs through semi-inclusive DIS [1]
  - Deeply Virtual Compton Scattering (DVCS) [1,2]
    - >> Generalized Parton Distributions (GPDs) [3]
  - Transversity [1]
  - Drell-Hern-Gerasimov spin sum rule test at high  $\nu$  [1]
  - Target/Current fragmentation studies [2,3]
  - ... etc.....
- Luminosity Requirement

# Proton Spin Structure at Low $x$

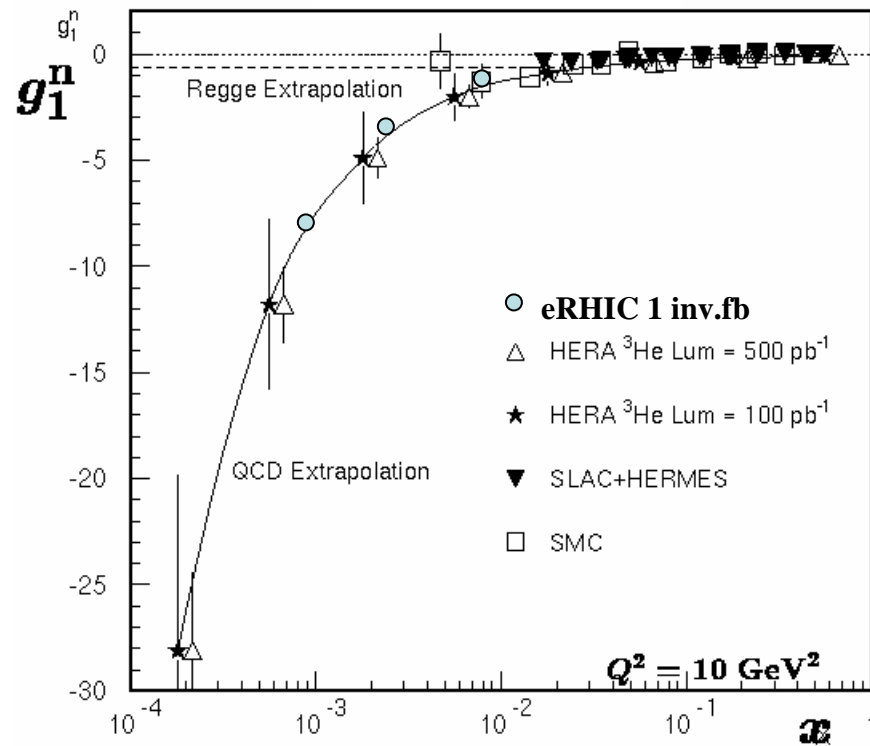
Fixed target experiments  
1989 - 1999 Data

eRHIC 250 x 10 GeV  
Luminosity =  $\sim 85$  inv. pb/day



Studies included statistical error & detector smearing to confirm that asymmetries are measurable. **No present or future approved experiment will be able to make this measurement**

# Spin Structure of Neutron at Low $x$



- With polarized He
- ~ 2 weeks of data at EIC
- Compared with SMC(past) & possible HERA data
- If combined with  $g_1$  of proton results in **Bjorken sum rule**  
**test of better than 1–2%**  
**within a couple of months of running**

# Polarized Gluon Measurement at eRHIC

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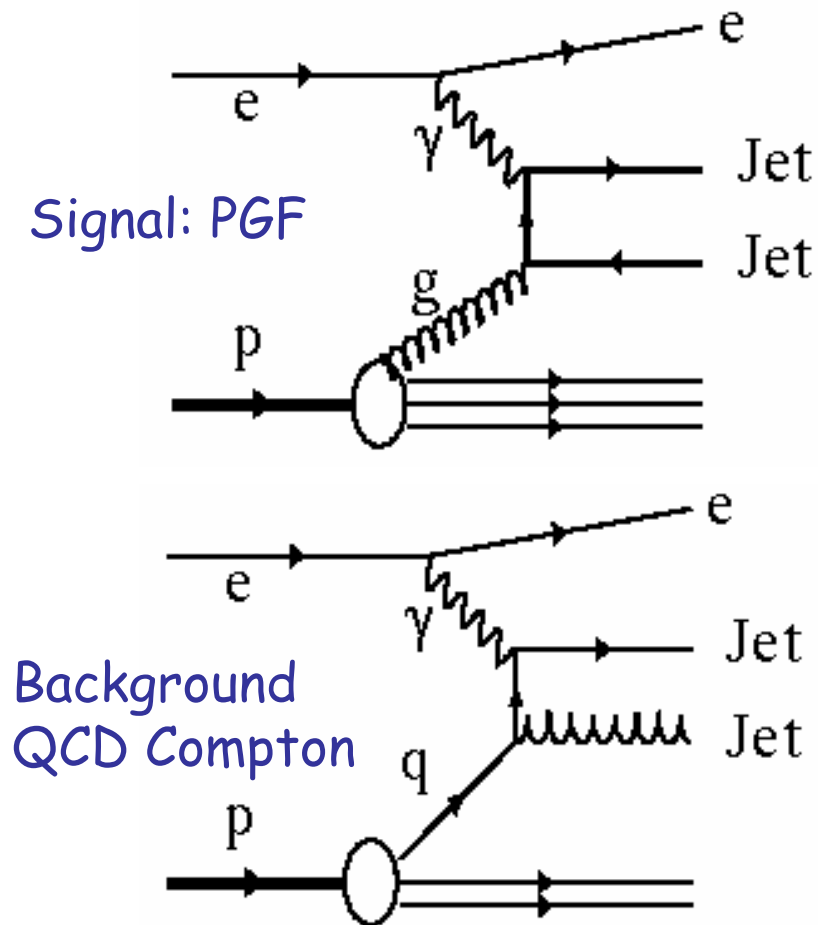
- This is the hottest of the experimental measurements being pursued at various experimental facilities:
  - HERMES/DESY, COMPASS/CERN, RHIC-Spin/BNL & E159/E160 at SLAC
  - Reliability from applicability of pQCD without doubt leaves *only RHIC*
- Measurements at eRHIC will be complimentary with RHIC
  
- Deep Inelastic Scattering kinematics at eRHIC
  - Scaling violations (pQCD analysis at NLO) of  $g_1$
  - (2+1) jet production in photon-gluon-fusion process
  - 2-high  $p_T$  hadron production in PGF
- Photo-production (real photon) kinematics at eRHIC
  - Single and di-jet production in PGF
  - Open charm production in PGF
  
- ELIC measurements possible but in limited kinematic range and would ~~result in considerable scale dependences in interpretation.~~

# $\Delta G$ from Scaling Violations of $g_1$

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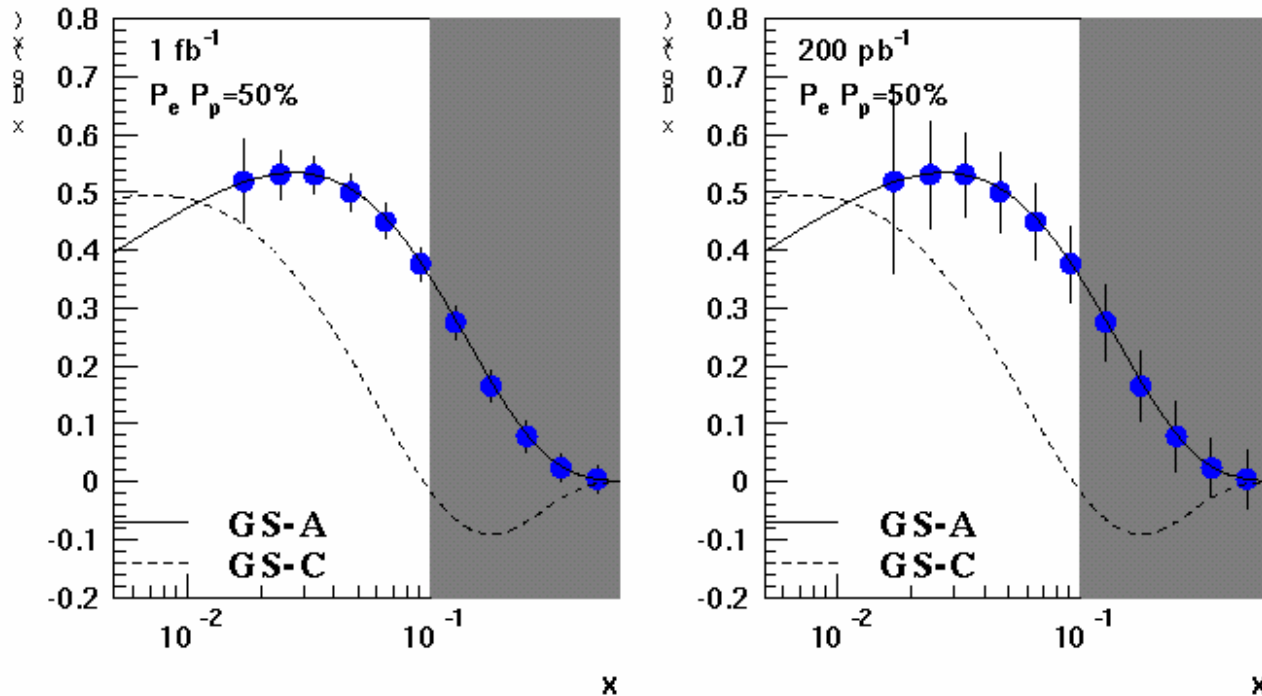
- World data (today) allows a NLO pQCD fit to the scaling violations in  $g_1$  resulting in the polarized gluon distribution and its first moment.
- SM collaboration, B. Adeva et al. PRD (1998) 112002  
 $\Delta G = 1.0 \pm 1.0$  (stat)  $\pm 0.4$  (exp. Syst.)  $\pm 1.4$  (theory)
- Theory uncertainty dominated by the lack of knowledge of the shape of the PDFs in **unmeasured low  $x$  region** where eRHIC data will play a crucial role.
- **With approx. 1 week of eRHIC statistical and theoretical uncertainties can be reduced by a factor of 3**
  - coupled to better low  $x$  knowledge of spin structure
  - less dependence on factorization & re-normalization scale in fits as new data is acquired

# Photon Gluon Fusion at eRHIC



- “Direct” determination of  $\Delta G$ 
  - Di-Jet events: (2+1)-jet events
  - High  $p_T$  hadrons
- High  $\sqrt{s}$  at eRHIC
  - no theoretical ambiguities regarding interpretation of data
- Both methods tried at HERA in unpolarized gluon determination & both are successful!
  - NLO calculations exist
  - H1 and ZEUS results
  - Consistent with scaling violation  $F_2$  results on G
- Scale uncertainties at ELIC large

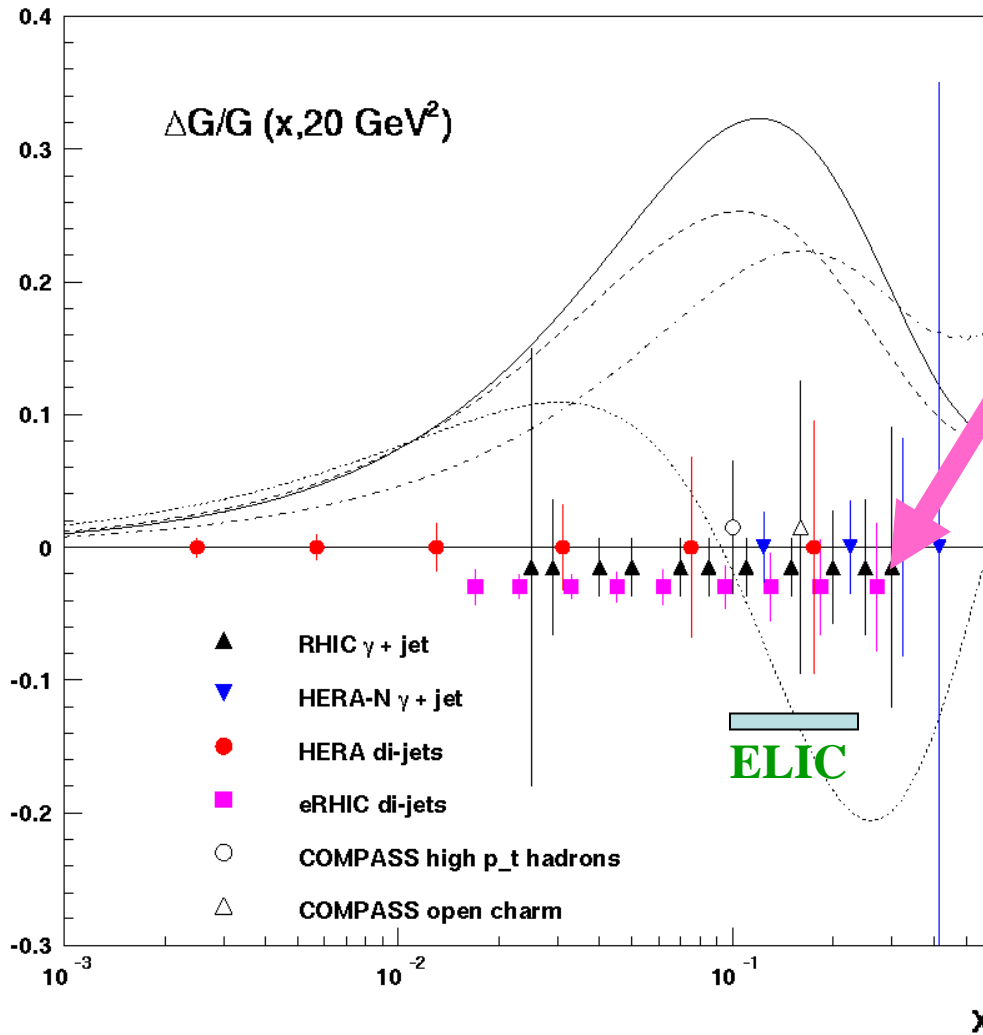
# Di-Jet events at eRHIC: Analysis at NLO



- Stat. Accuracy for two luminosities
- Detector smearing effects considered
- NLO analysis

- Easy to differentiate different  $\Delta G$  scenarios: factor 3 improvements in  $\sim 2$  weeks
- If combined with scaling violations of  $g_1$ : factors of 5 improvements in uncertainties observed in the same time.
- Better than 3–5% uncertainty can be expected from eRHIC  $\Delta G$  program

# Di-Jet at eRHIC vs. World Data for $\Delta G/G$



eRHIC Di-Jet  
DATA 2fb<sup>-1</sup>

Good precision

Clean measurement in x  
range 0.01 < x < 0.3

Constrains shape of  
 $\Delta G(x)$

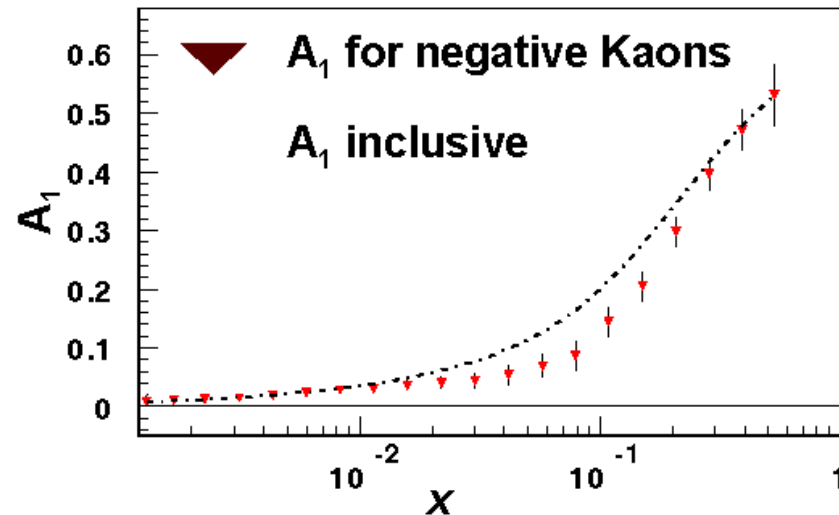
Polarization in HERA  
much more difficult

$\Delta G$  from scaling violations

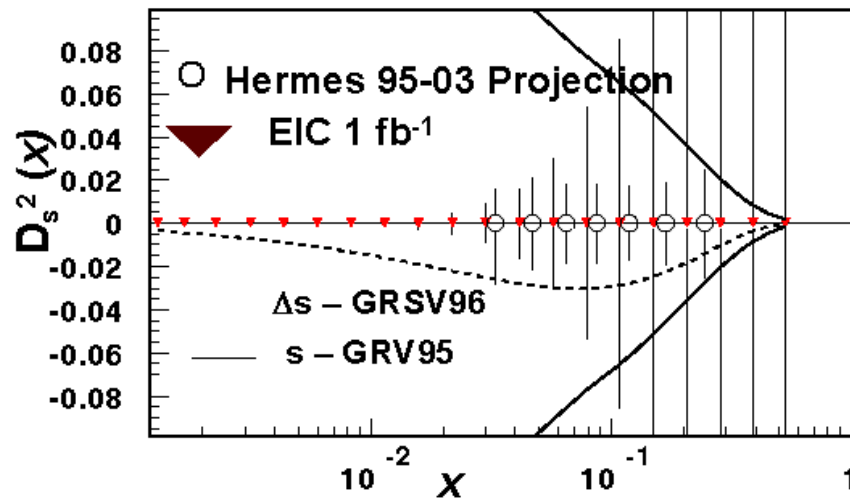
>  $x_{\min} \sim 10^{-4}$  at eRHIC

>  $x_{\min} \sim 10^{-3}$  at ELIC

# Strange Quark Distributions at eRHIC

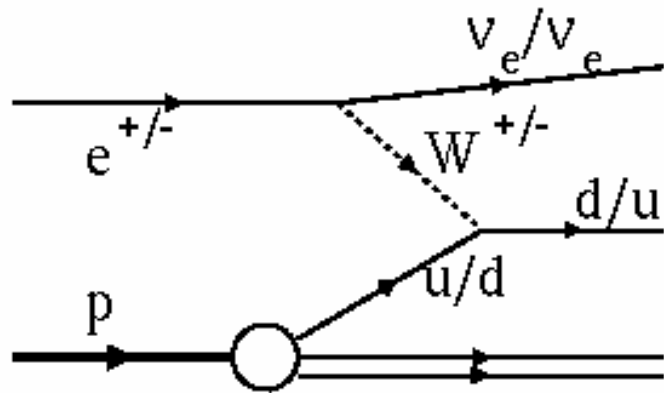


- After measuring u & d quark polarized distributions.... Turn to s quark (polarized & otherwise)
- Detector with good Particle ID: pion/kaon separation



- Upper Left: statistical errors for kaon related asymmetries shown with  $A_1$  inclusive
- Left: Accuracy of strange quark distribution function measurements possible with eRHIC and HERMES (2003–05) and some theoretical curves on expectations

# Parity Violating Structure Function $g_5$



$$\frac{d^2\sigma}{dx dQ^2} \sim \{a[F_1 - \lambda b F_3] + \delta[ag_5 - \lambda^2 b g_1]\} \frac{1}{(Q^2 + M_W^2)^2}$$

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 huge asymmetry in detector (neutrino)
- Unique measurement
- Unpolarized  $x F_3$  measurements at HERA in progress
- Will access heavy quark distribution in polarized DIS

$$A_{cc}^{W^+} = \frac{-2bg_1 + ag_5}{aF_1 - bF_3} \quad A_{cc}^{W^-} = \frac{+2bg_1 + ag_5}{aF_1 + bF_3}$$

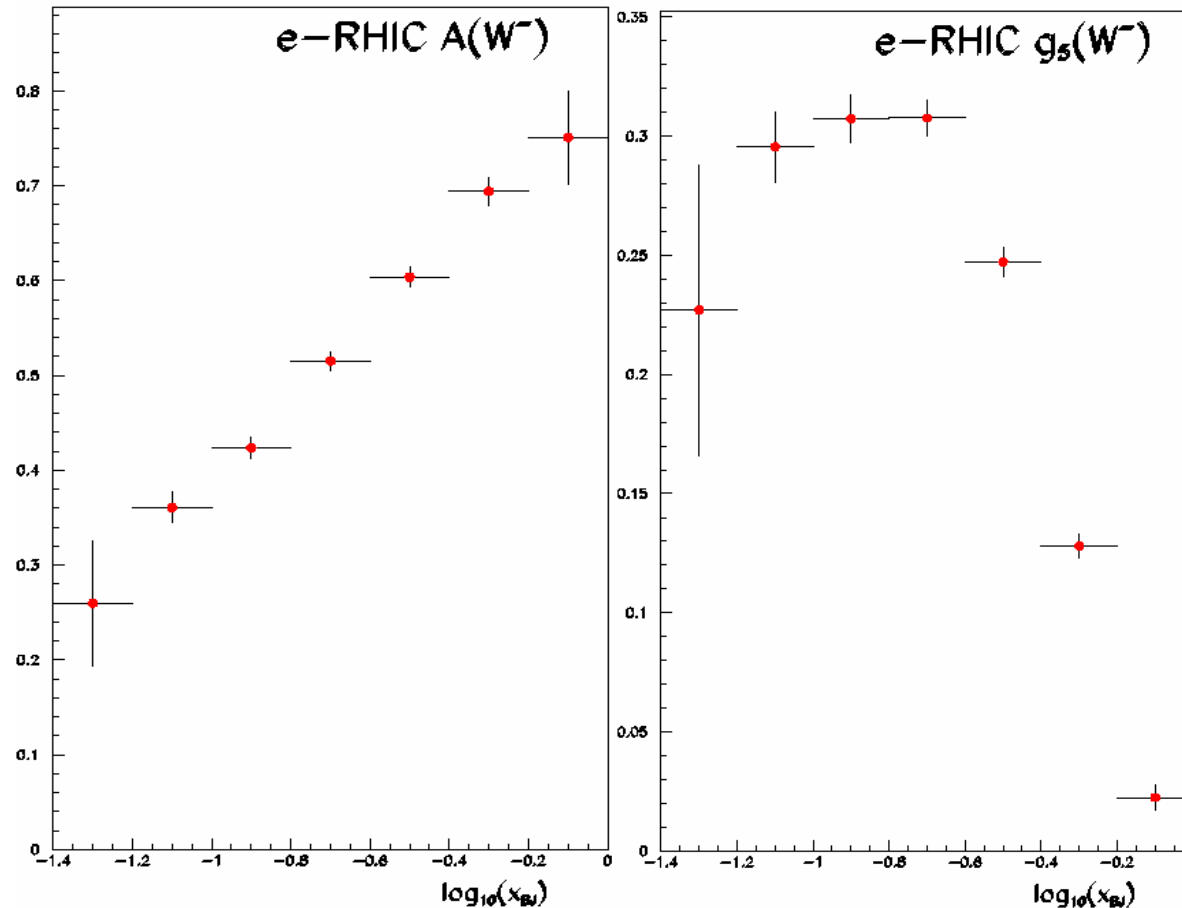
For eRHIC kinematics  $a \gg b$

$\Rightarrow g_5$  dominates  $\rightarrow$  Extract  $g_5$

$$g_5^{W^-} = \Delta u + \Delta c - \Delta \bar{d} - \Delta \bar{s}$$

$$g_5^{W^+} = \Delta d + \Delta s - \Delta \bar{u} - \Delta \bar{c}$$

# Measurement Accuracy PV $g_5$ at eRHIC



## Assumes:

1. Input GS Pol. PDFs
2.  $xF_3$  measured by then
3.  $4 \text{ fb}^{-1}$  luminosity

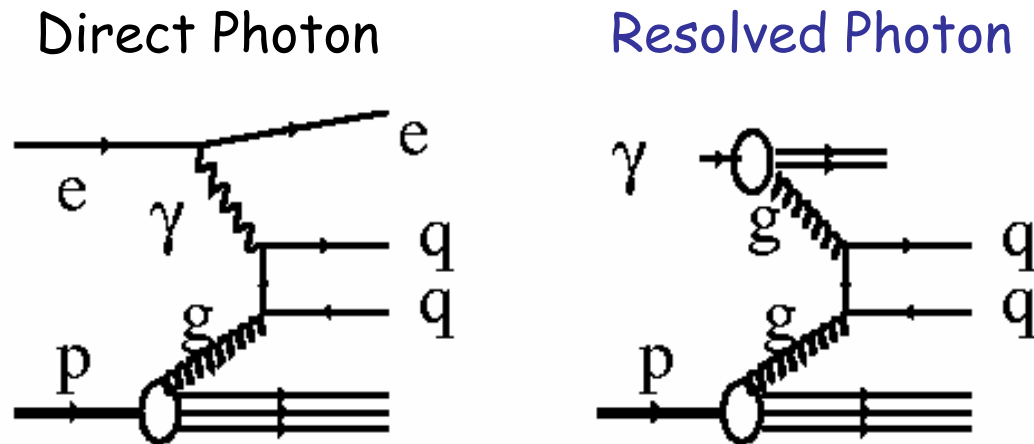
Positrons & Electrons  
in eRHIC  $\rightarrow g_5(+)$

>> reason for  
keeping the  
option of  
positrons in  
eRHIC

# Polarized PDFs of the Photons

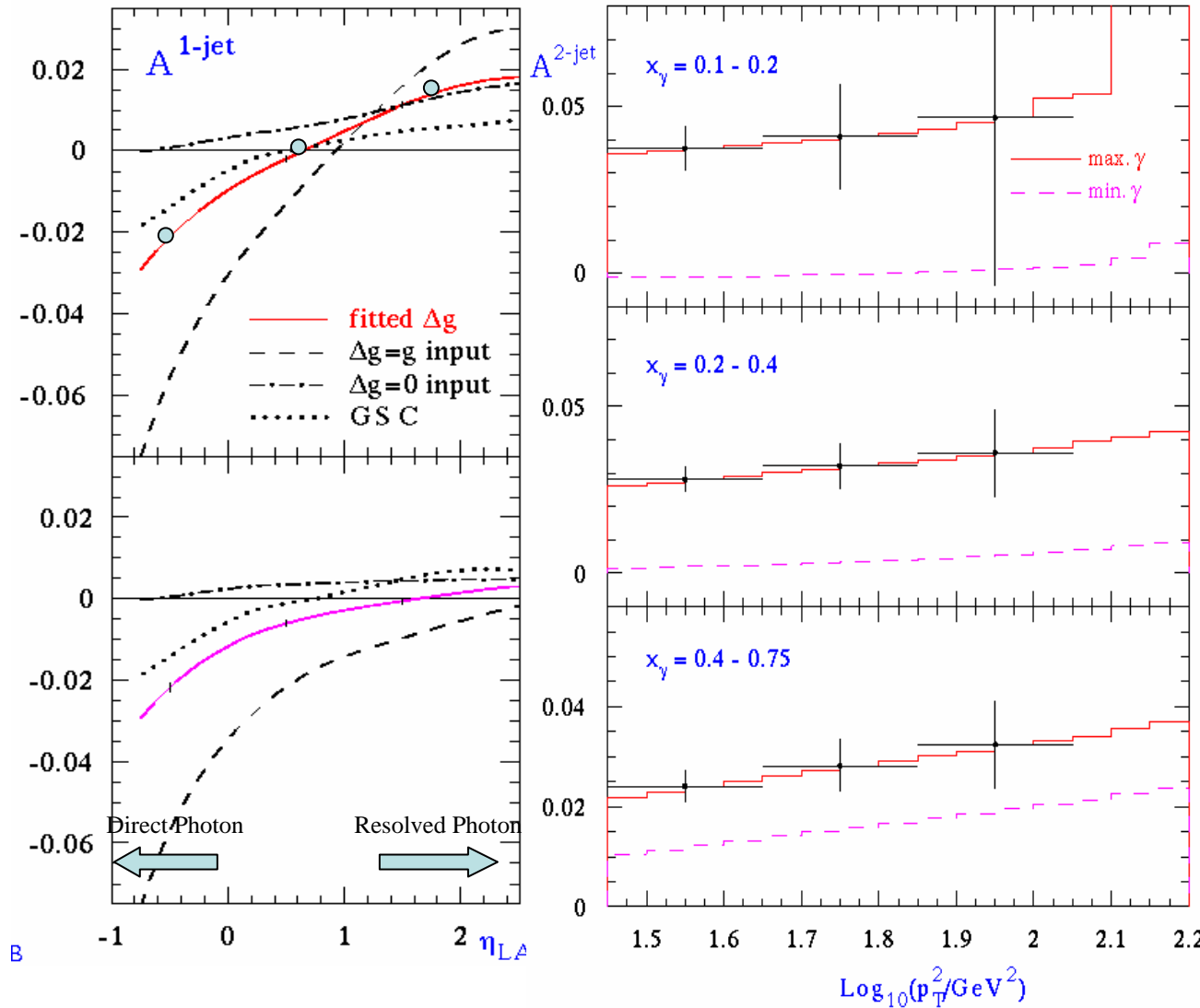
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- Photo-production studies with single and di-jet



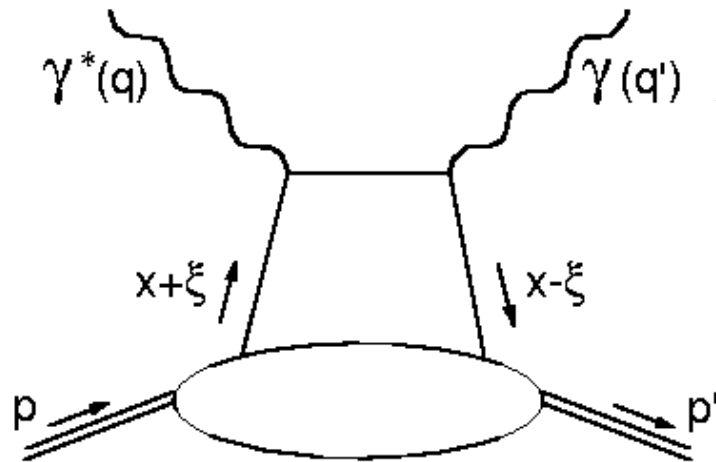
- Photon Gluon Fusion or Gluon Gluon Fusion (Photon resolves in to its partonic contents)
- Resolved photon asymmetries result in measurements of spin structure of the photon
- Asymmetries sensitive to gluon polarization as well... but we will consider the gluon polarization “a known” quantity!

# Photon Spin Structure at eRHIC



- Stat. Accuracy estimated for  $1 \text{ fb}^{-1}$  running (2 weeks at EIC)
- Single and double jet asymmetries
- ZEUS acceptance
- Will resolve photon's partonic spin contents

# DVCS/Vector Meson Production



- Hard Exclusive DIS process
- **g** (default) but also vector mesons possible
- Remove a parton & put another back in!  
→ Microsurgery of Baryons!

- Claim: Possible access to skewed or off forward PDFs?  
Polarized structure: Access to **quark orbital angular momentum?**

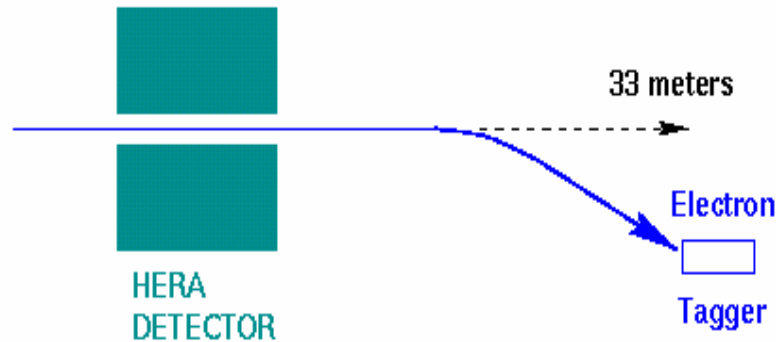
$$\int x dx [H(x, t, \xi) + E(x, t, \xi)] = 2J_{quark} = \Sigma + 2L_q$$

On going theoretical debate... experimental effort just beginning...

--A. Sandacz, AD

- M. Diehl's talk today

# Drell Hern Gerasimov Spin Sum Rule



- DHG Sum rule:

$$\int_{\nu_{th}}^{\infty} \frac{d\nu}{\nu} (\sigma_{\uparrow\downarrow}^{\gamma P} - \sigma_{\uparrow\uparrow}^{\gamma P})(\nu) = -\frac{4\pi^2 \alpha \kappa^2}{2m_p^2}$$

- Inclusive Photo-production measurement
- Using **electron tagger** in RHIC ring  
 $Q^2 \sim 10^{-6} \rightarrow 10^{-2} \text{ GeV}^2$   
 $\text{Sqrt}(s) \sim 25 \rightarrow 85 \text{ GeV}$

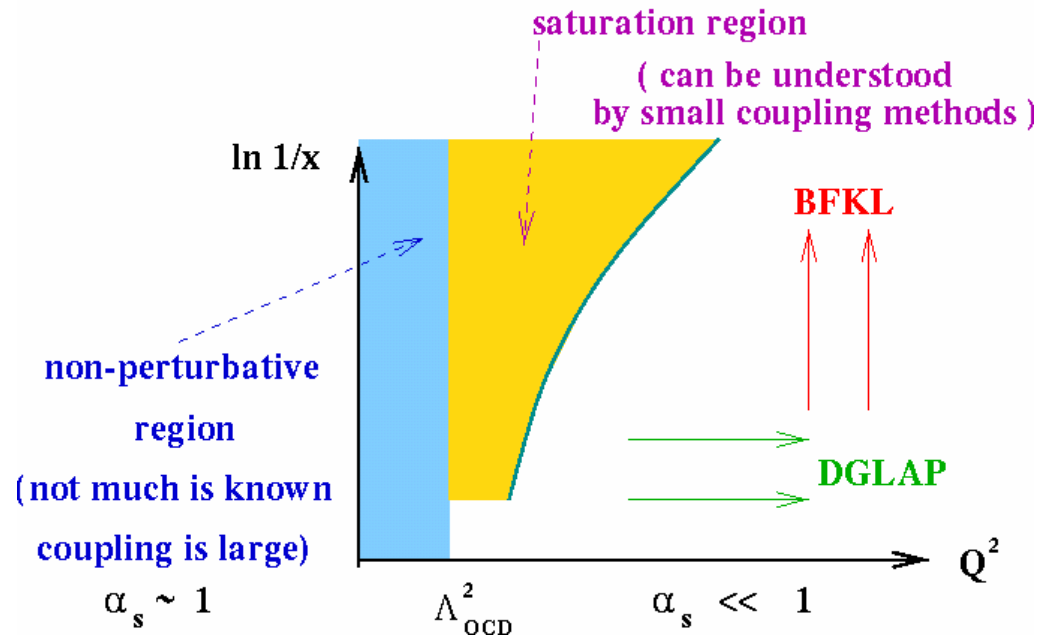
- At eRHIC range: GeV  $\rightarrow$  few TeV
- Although contribution from to the this sum rule is small, the high n behavior is completely unknown and **hence theoretically biased** in any present measurements at: Jefferson Lab., MAMI, BNL

# Highlights of e–A Physics at eRHIC

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- Study of e–A physics in Collider mode for the first time
- QCD in a different environment
- Clarify & reinforce physics studied so far in fixed target e–A &  $\mu$ –A experiments including target fragmentation
  - QCD in:  $x > [1 / (2m_N R_N)] \sim 0.1$  (high x)
  - QCD in:  $[1 / (2m_N R_A)] < x < [1 / (2m_N R_N)] \sim 0.1$  (medium x)
  - Quark/Gluon shadowing
  - Nuclear medium dependence of hadronization
- .... And extend in to a **very low x region** to explore:  
saturation effects or high density partonic matter also called the **Color Glass Condensate (CGC)**
  - QCD in:  $x < [1 / (2m_N R_A)] \sim 0.01$  (low x)

# 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???
- A. Mueller's talk today**

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

# A Color Glass Condensate?

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- At small  $x$ , partons are rapidly fluctuating gluons interacting weakly with each other, but still strongly coupled to the high  $x$  parton color charges which act as random static sources of **COLOR** charge  
→ Analogous to spin **GLASS** systems in condensed matter: a disordered spin state coupled to random magnetic impurities
- Gluon occupation number large; being bosons they can occupy the same state to form a **CONDENSATE**  
→ Bose Einstein condensate leads to a huge over population of ground states
- A new “state matter”(??): **Color Glass Condensate (CGC)** at high energy density would display dramatically different, yet simple properties of glassy condensates
- **Experimental measurements:** Gluon distributions inclusive semi-inclusive methods, specific predictions regarding enhancement of diffractive processes in  $e-A$  vs.  $e-p$  at identical  $x, Q^2$ , measurement of  $F_L$  to access gluon distribution in nuclei.

# Recent interest in eRHIC from HERA

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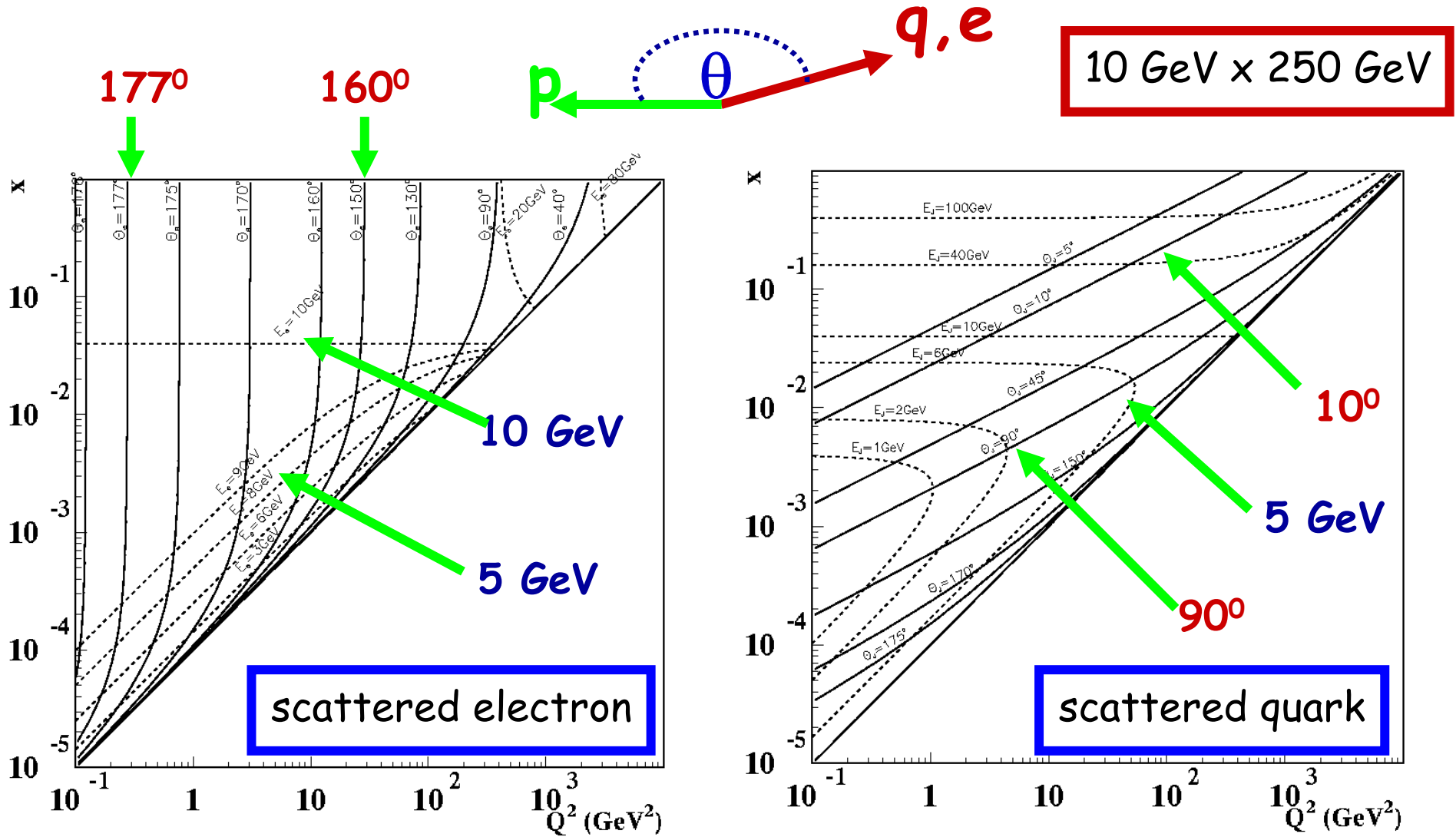
- Proposals for HERA-III have presently an uncertain future
- Physics of strong interaction, main motivation for HERA-III
  - **Understanding the radiation processes in QCD at small and large distances:**
    - Small distance scales: explores parton splitting (DGLAP, BFKL, CCFM...)
    - Large distance scales: transition from pQCD to non-pQCD regime
- Needs specially designed detector to look in to very very forward directions, unprecedented so far at HERA
- Early indications are that eRHIC energies would be sufficient to study this physics... if a specially designed detector is installed in eRHIC

# A Detector for eRHIC $\rightarrow$ A $4\pi$ Detector

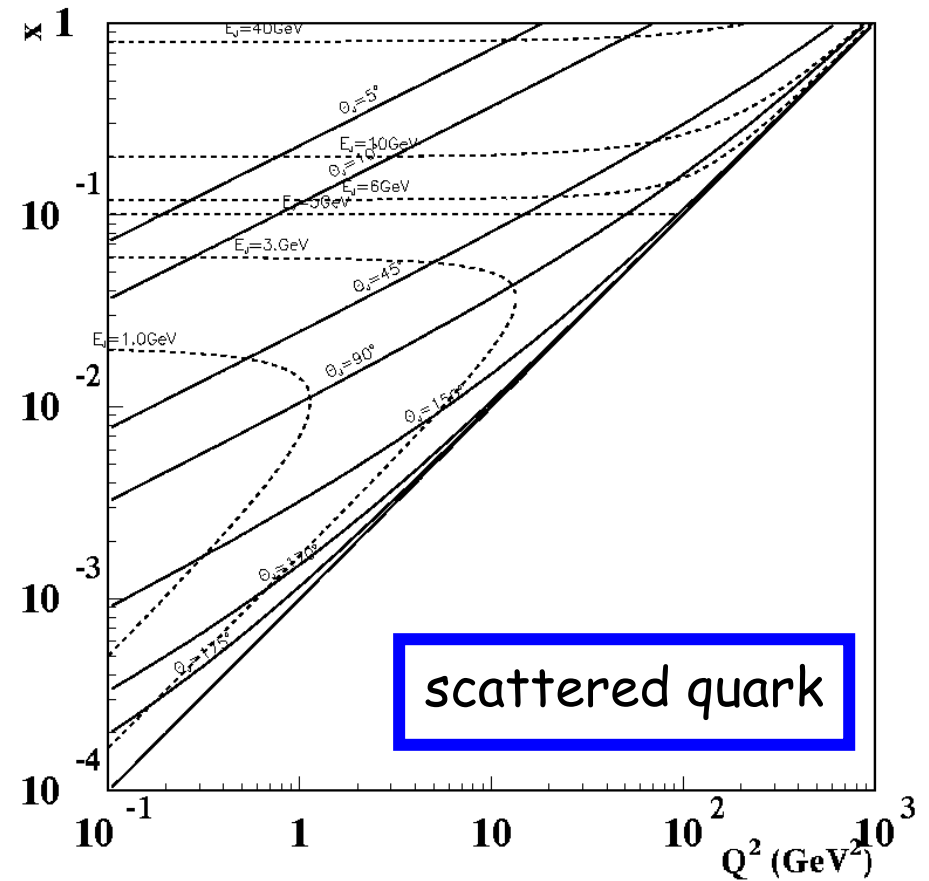
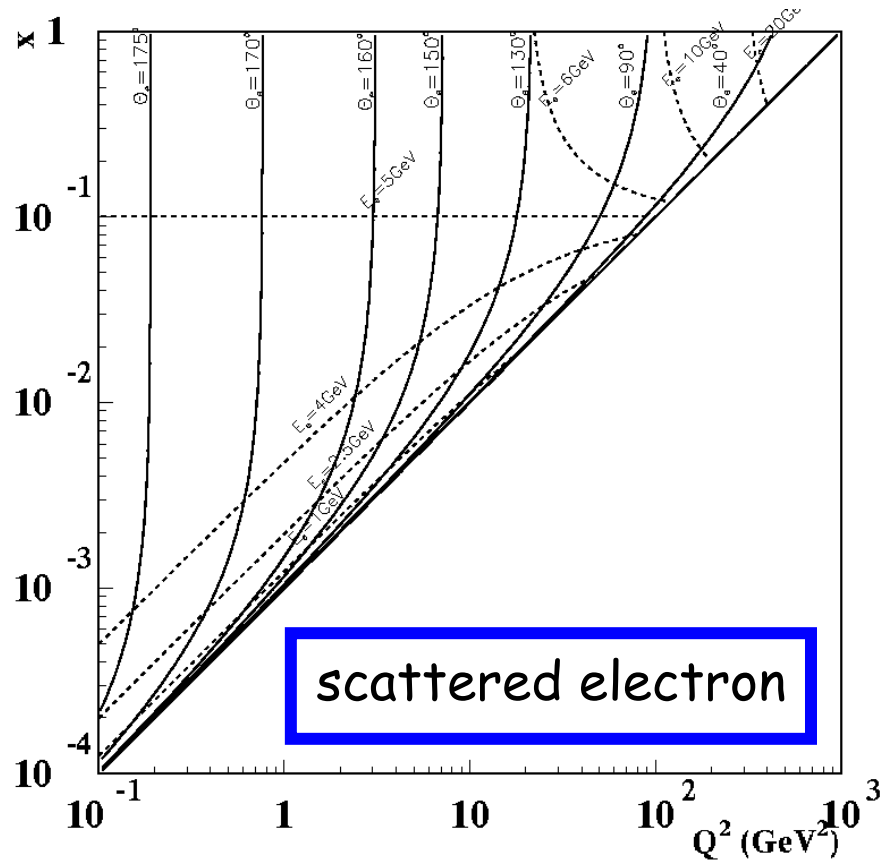
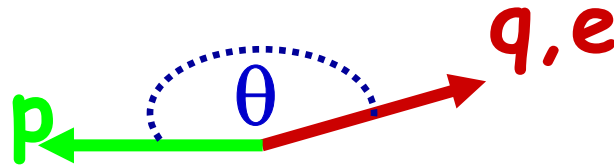
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- Scattered electrons to measure kinematics of DIS
- Scattered electrons at small ( $\sim$ zero degrees) to tag photo production
- Central hadronic final state for kinematics, jet measurements, quark flavor tagging, fragmentation studies, particle ID
- Central hard photon and particle/vector detection (DVCS)
- $\sim$ Zero angle photon measurement to control radiative corrections and in e-A physics to tag nuclear de-excitations
- Missing  $E_T$  for neutrino final states (W decays)
- Forward tagging for 1) nuclear fragments, 2) diffractive physics
- *At least one second detector should be incorporated... if not more*
  - How?
- eRHIC will provide: 1) Variable beam energies 2) different hadronic species, some of them polarization, 3) high luminosity

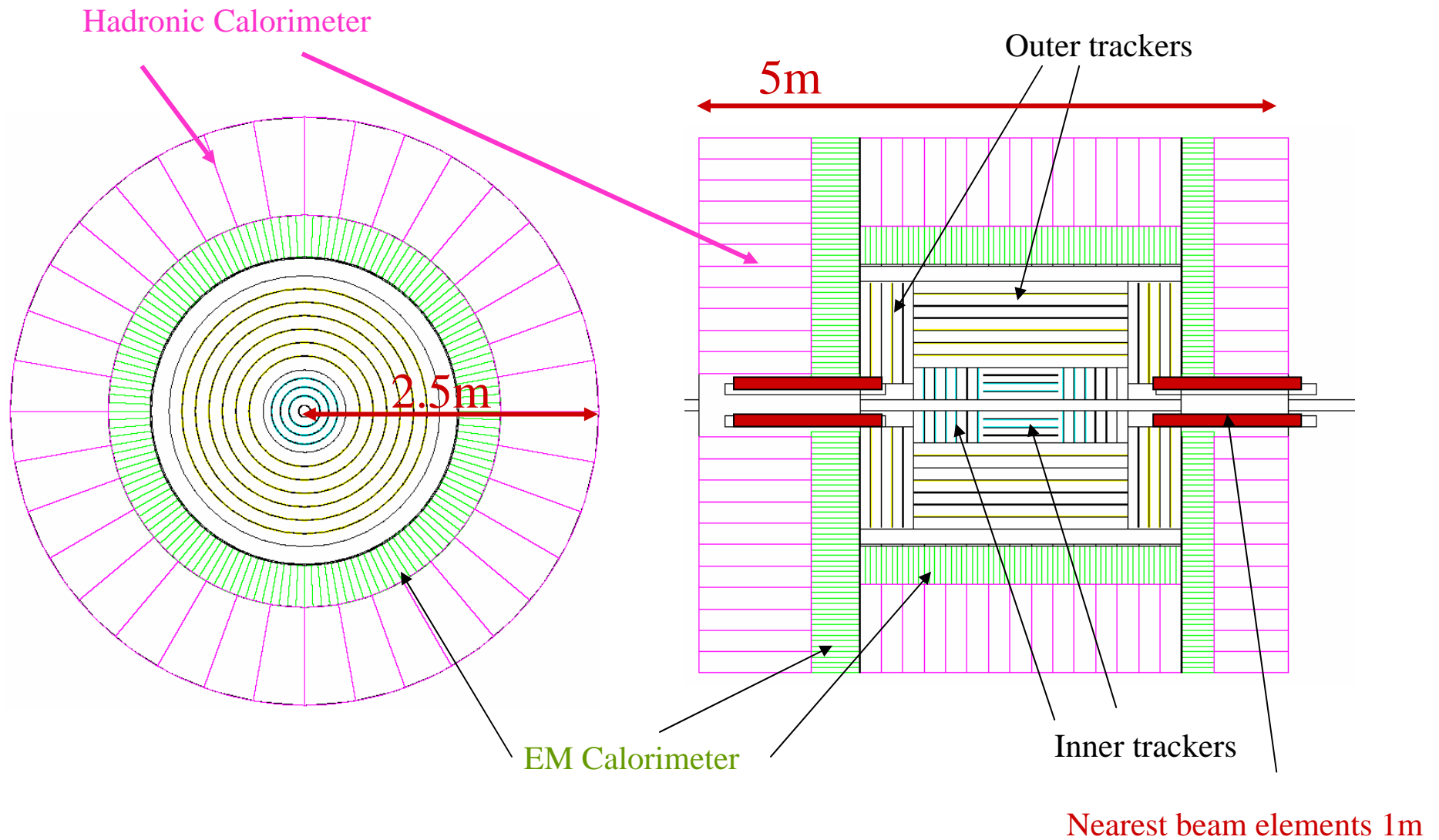
# Where do electrons and quarks go?



# Electron, Quark Kinematics

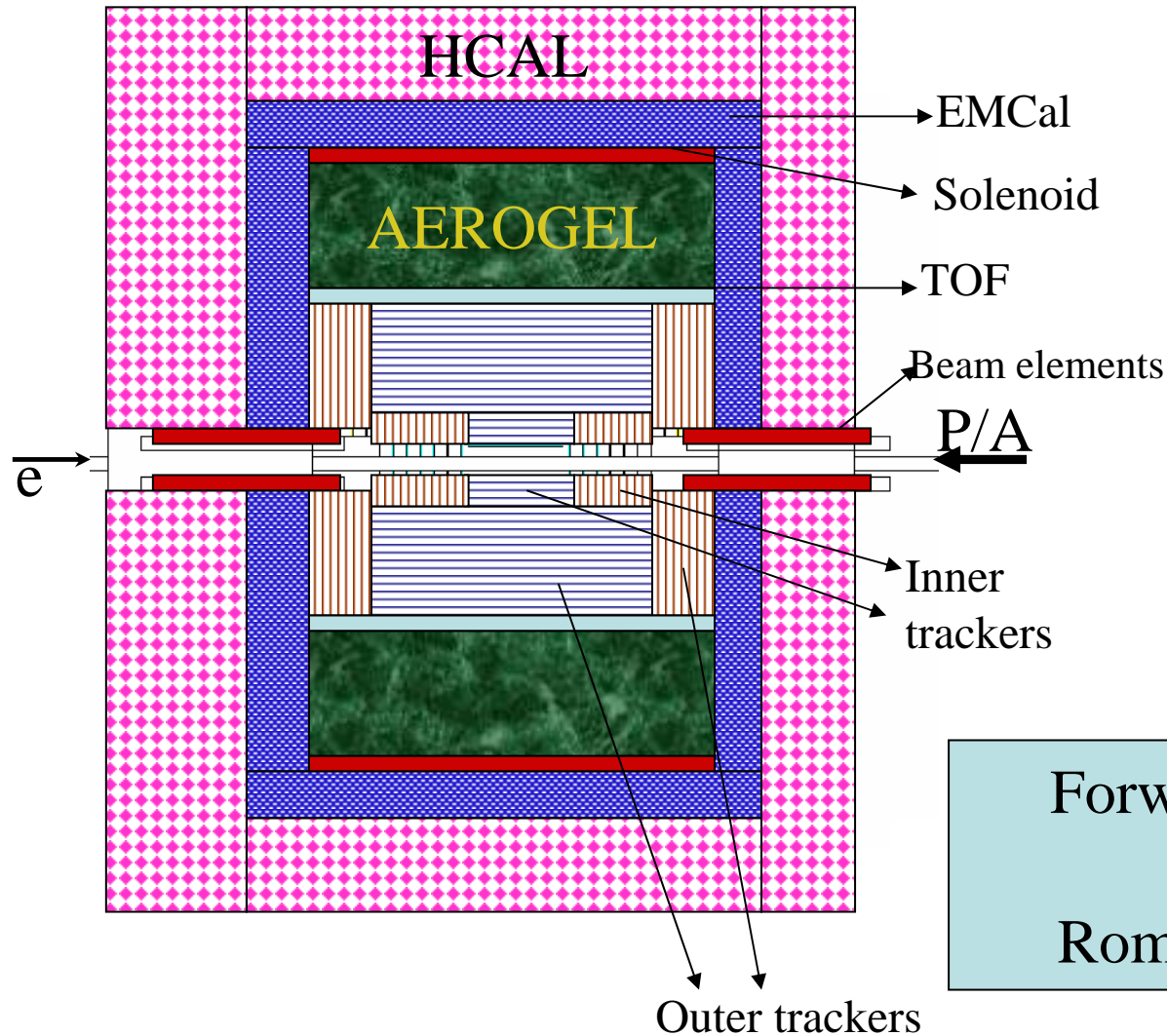


# Detector Design --- HERA like...



# Detector Design II: HERA like...+ PID

(Not to scale)



A HERA like  
Detector with  
dedicated PID:  
>>Time of flight  
>>Aerogel Ckov

AND

Forward detectors  
including  
Roman Pots etc...

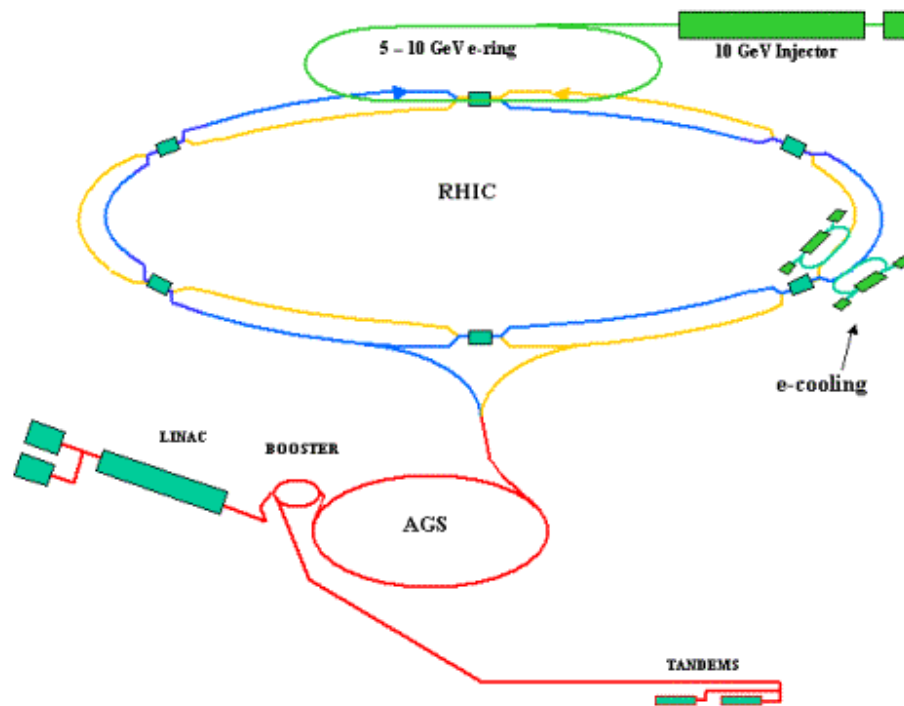
# eRHIC Status & Design Ideas

<http://www.bnl.gov/eic>

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- 2001 LRP: NSAC enthusiastically supported R&D and stated it would be the next major for nuclear physics (after 12 GeV Jlab upgrade)
- 2003 NSAC subcommittee's high recommendation
  - **Level 1 for physics, and level 2 for readiness**
- **2003 One of the 28 “must-do” projects in the next 20 yrs of the DoE list**
- BNL Management Requested a Zero<sup>th</sup> Design Report (ZDR)
  - What can be done with minimal R&D and shortest time scale?
    - **eRHIC: Ring-Ring design (presently: “main design line”)**
  - Identify parameters for enhanced machine parameters with identified R&D topics toward significant luminosity enhancement
    - **eRHIC: Ring-Ring design enhancement**
    - **eRHIC: Linac-Ring design**
  - BNL-MIT-Budker-DESY collaboration: ZDR ready NOW
  - Informal review planned in May 2004
- **Development on both projects will continue in future until the time to make the decisions to freeze technology and design option**

# The eRHIC Ring-Ring Lay Out & Plans

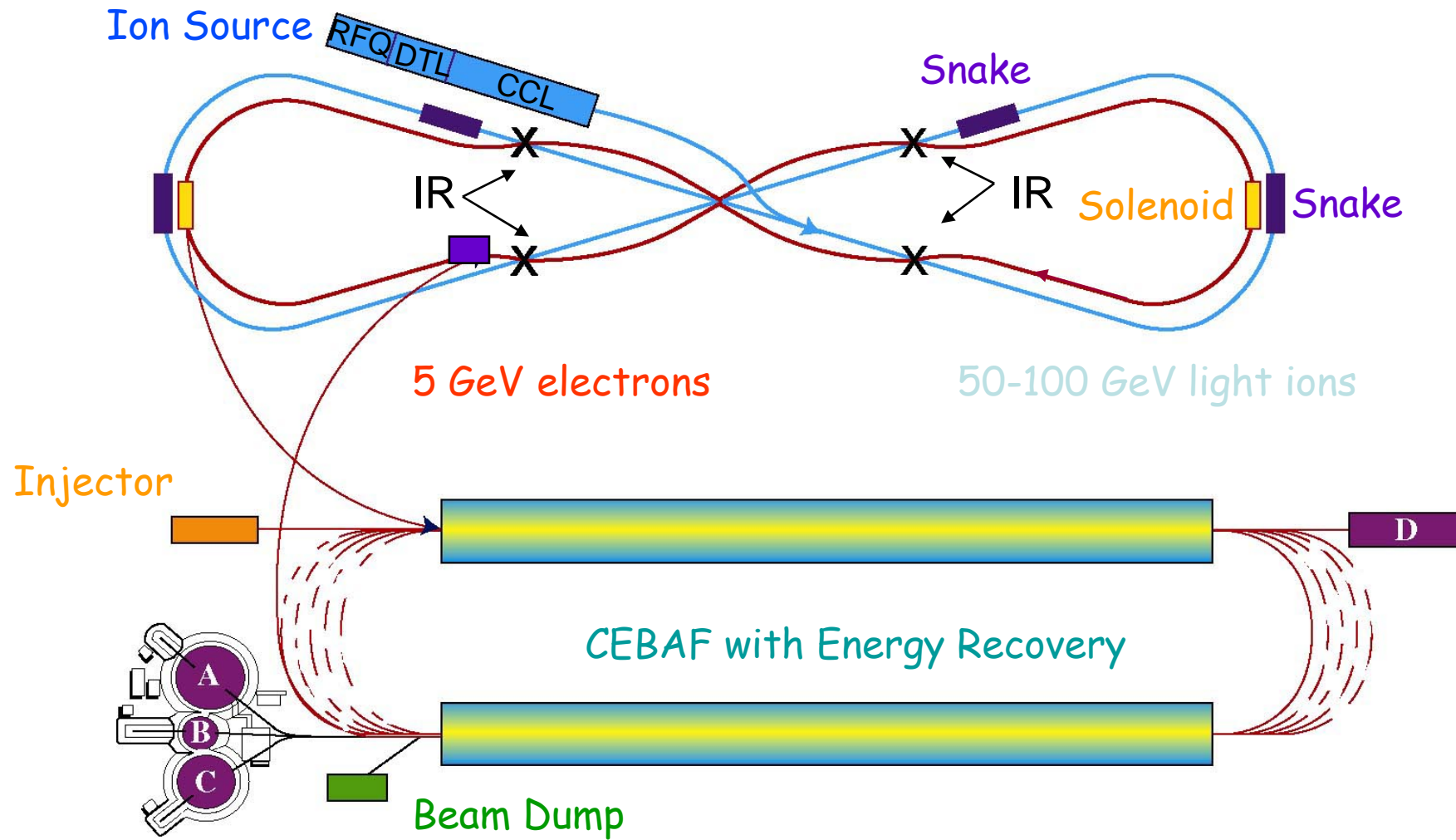


- Full energy injection
- Polarized e- source & unpolarized e+ --> (polarization via synchrotron radiation)
- 10 GeV main design but up to 5 GeV reduction possible with **minimal polarization loss**
- Fill in bunch spacing 35ns

Present conservative estimates  $L_{(ep)} \sim 4 \times 10^{32} \text{ cm}^{-2} \text{ sec}^{-1}$  **work on luminosity enhancement continues.** *Advantages:* both positrons/electrons positrons.....  
*Disadvantages:* Multiple detectors or/and Interaction Regions?

Work towards higher luminosity continues....

# Jlab Upgrade II: ELIC Layout



One accelerating & one decelerating pass through CEBAF

**NSAC Subcommittee Evaluation March 03: 1 Science, 3 for Readiness**

# JLAB/ELIC Aggressive R& D Launched

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- **Conceptual development:**
  - Circulator ring → to reduce the high current polarized photo-injector and ERL requirement
  - Highest luminosity limits
- **Analysis and simulations:**
  - electron cooling and short bunches
  - beam-beam physics
  - energy recovery linac physics
- **Experimental research effort:**
  - CEBAF-ERL to address ERL issues in large scale systems
  - JLAB FEL (10mA), Cornell/JLAB Prototypes (100 mA), BNL Cooling Prototype (100mA) to address high current ERL issues.

# Concluding thoughts....

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- The case for a future ep/eA collider is very strong already and is being continuously improved
- eRHIC at BNL, **ZDR is now ready**; will seek approval from NSAC in the next LRP (2005-2006) and prepare the CD0
  - **Advanced accelerator designs** integrating IR and Detector issues will be ready by that time after a few more iterations with the experimental physicists
- ELIC design will solidify in the next few years and a dedicated R&D program will lead and decide the details of luminosity and interaction region issues
- We hope that the collider seeking communities join forces now to realize the chances of future collider(s) for QCD studies