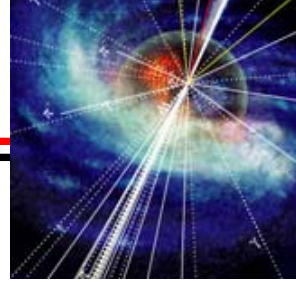


Physics & Status of the Electron Ion Collider

Abhay Deshpande
SUNY-Stony Brook
RIKEN BNL Research Center

EIC 2004 at Jefferson Laboratory
March 15th, 2005

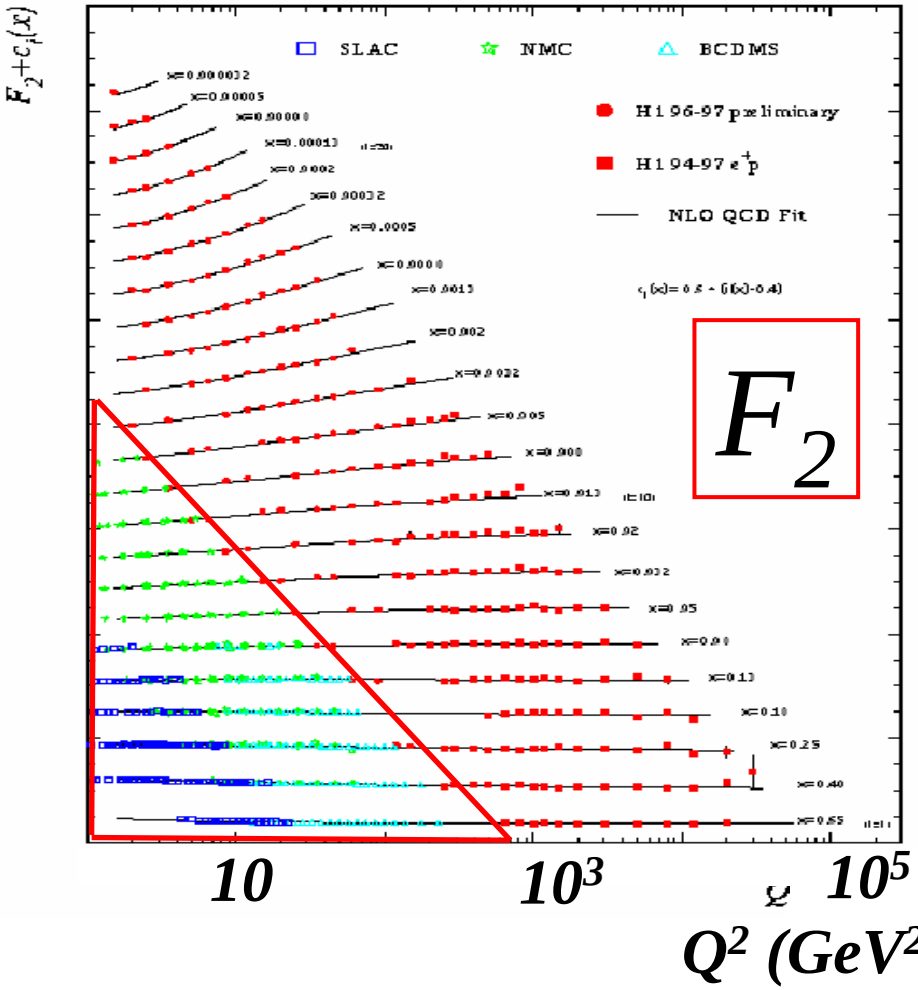
Some spin & Low x-high Q^2 surprises…

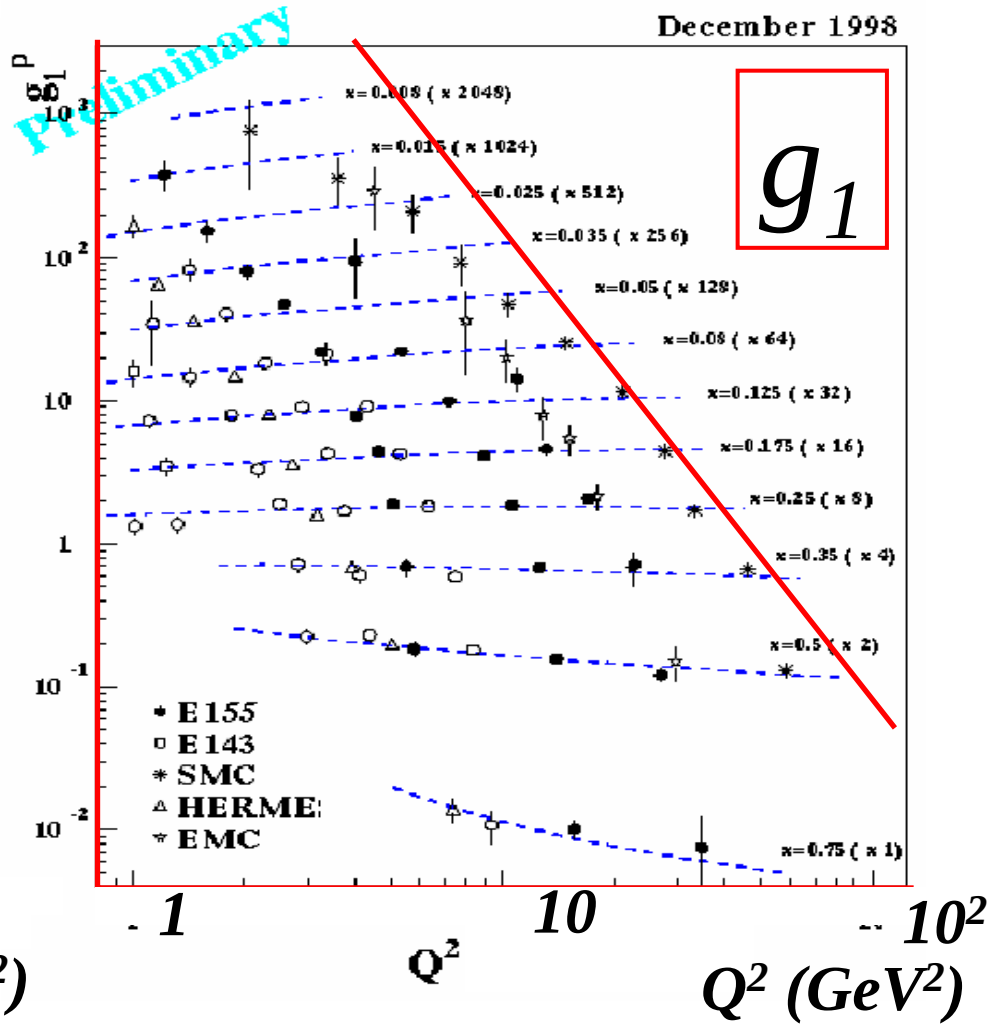
- Stern & Gerlach (1921) Space quantization associated with direction
- Goudschmidt & Ulhenbeck (1926): Atomic fine structure & electron spin magnetic moment
- Stern (1933) Proton anomalous magnetic moment 2.79 $\mathbf{m}_N$
- Kusch(1947) Electron anomalous
- magnetic moment 1.00119$\mathbf{m}_0$
- 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) → Q2 ~ 1 GeV2 ➔ Finite size of the proton
- Inelastic e-p scattering at SLAC (1960s)→ Q2 > 1 GeV2 ➔ Parton structure of the proton
- Inelastic mu-p scattering off p/d/N at CERN (1980s) → Q2 > 1 GeV2 ➔ Unpolarized EMC effect, nuclear shadowing?
- Inelastic e-p scattering at HERA/DESY (1990s)→ Q2 > 1 GeV2
  - ➔ Unexpected rise of F2 at low x
  - ➔ Diffraction in e-p
  - ➔ Saturation(??)

A facility that does both would be ideal….

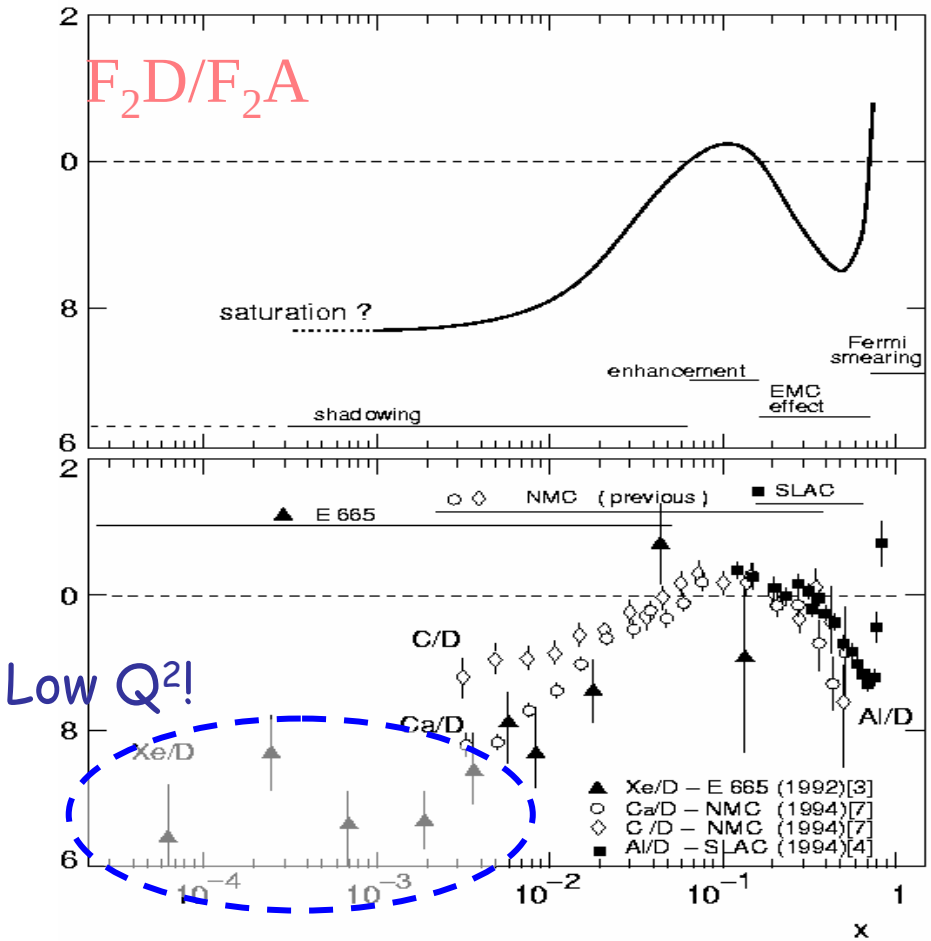
Our Knowledge of Structure Functions





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

DIS in Nuclei is Different!



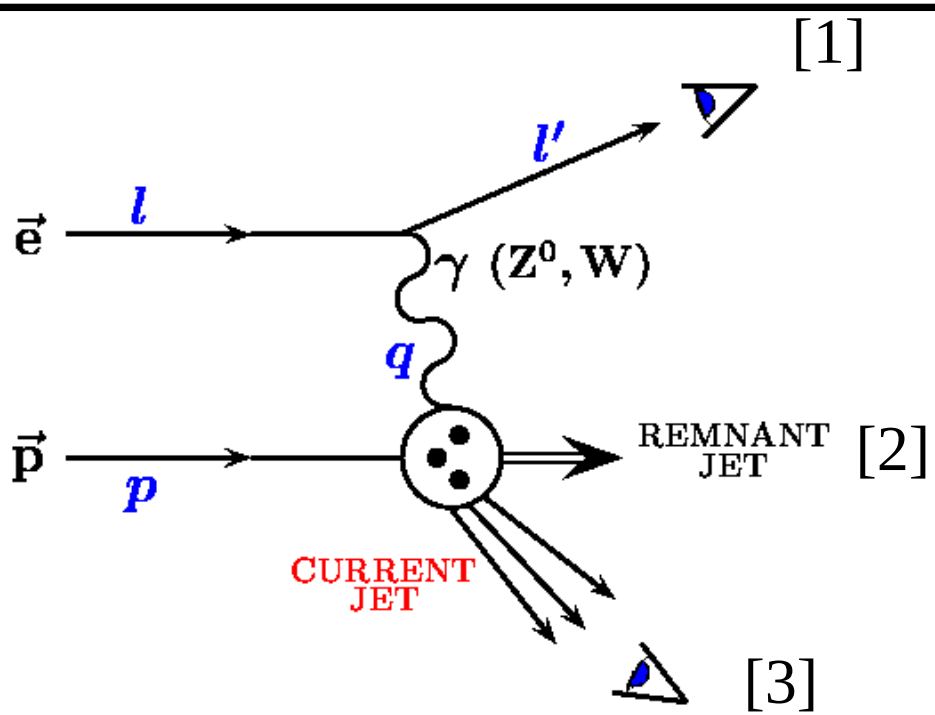
Regions of:

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

Regions of shadowing and saturation mostly around Q^2 ~1 GeV^2

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

Deep Inelastic Scattering



$$Q^2 = -q^2 = sxy$$

$$x = \frac{Q^2}{2p \cdot q}$$

$$y = \frac{p \cdot q}{p \cdot l}$$

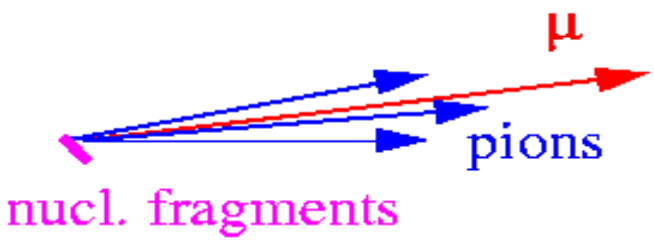
$$s = 4E_e E_p$$

$$W = (q + p)^2$$

- 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?

- 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 EIC Proposals

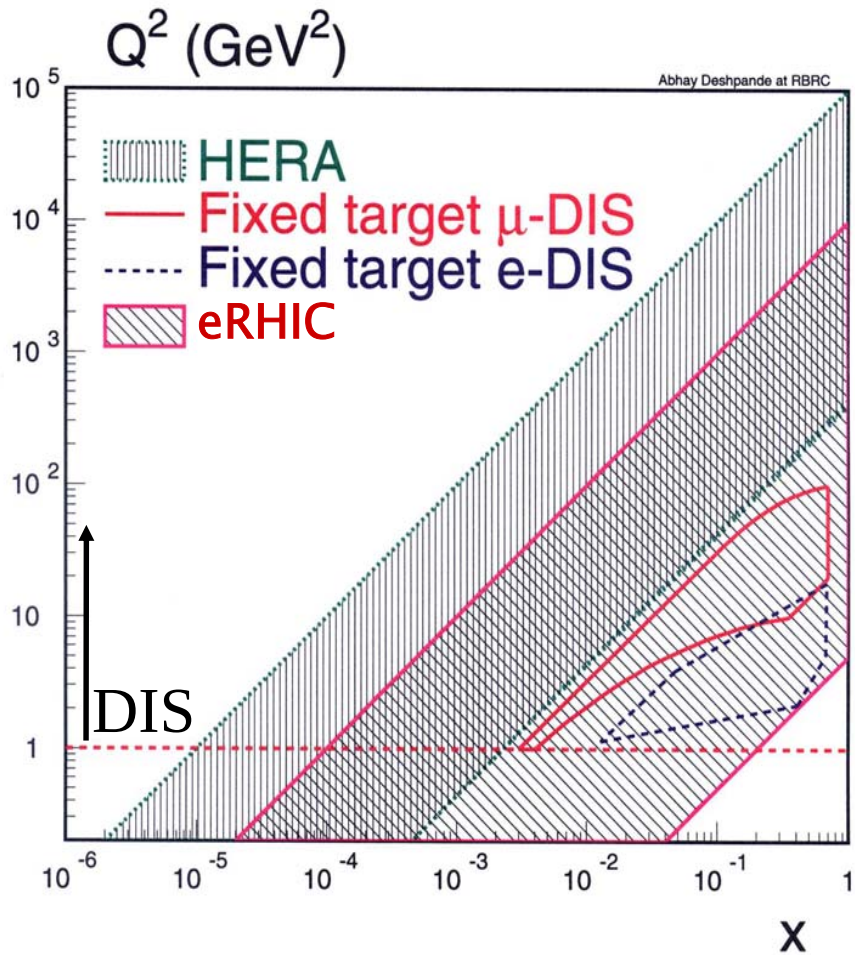
eRHIC at BNL

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

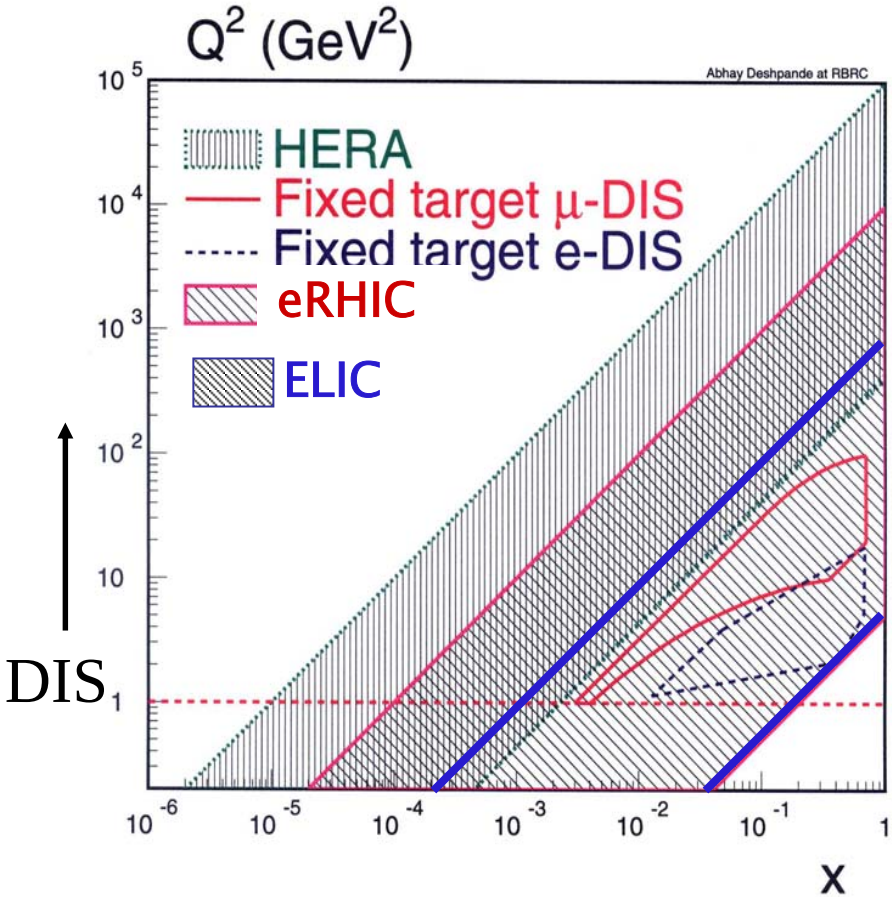
An electron-light-ion collider or/and a 25 GeV fixed target facility at Jlab will address the question of **precision measurements of nucleon spin**, including the issues related to generalized parton distributions with its large luminosity. The collider and fixed target facility will cover complementary 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} --> 0.7 (Q^2 > 1 GeV^2)
  - Q^2 = 0 --> 10^4 GeV^2
- Polarization of e,p and light ion beams at least ~ 70% or better
- Heavy ions of ALL species
  - High gluonic densities
- High Luminosity:
  - **L(ep) ~10^{33-34} cm^{-2} sec^{-1}**
  - **L(eA) ~10^{31-32} cm^{-2} sec^{-1} N^{-1}**

ELIC vs. Other DIS Facilities



- **Physics of Exclusive measurements**

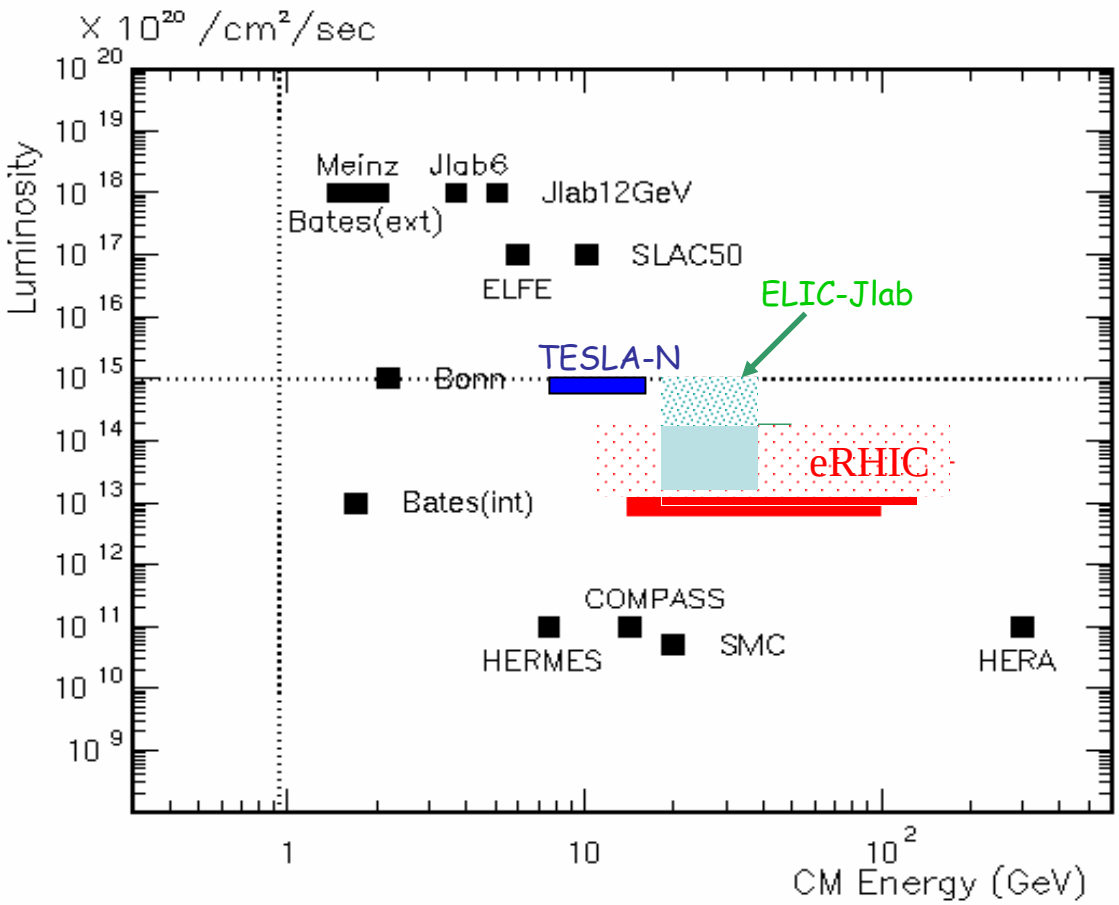
- Ee = 3-7 GeV
- Ep = 30-100 (150) GeV
- **Sqrt[S_ep] = 20-45 (65) GeV**

- Kinematic reach of ELIC
  - $X = 10^{-3}$ --> 0.8 ($Q^2 > 1$ GeV^2)
  - $Q^2 = 0$ --> 10^3 GeV^2

- Polarization of e, p & light ion beam ~ 70%

- **High luminosity:**
  - **L_(ep) ~10^{33-35} cm^{-2} sec^{-1}**
  - **Staged increase in luminosity**

CM vs. Luminosity



- **eRHIC**
  - Variable beam energy
  - P-U ion beams
  - Light ion poalrization
  - Large luminosity
- **ELIC**
  - Variable beam energy
  - Light ion polarization
  - Huge luminosity

Scientific Frontiers Open to EICs

eRHIC

- **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/lowQ^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

ELIC

Light nuclei

Unpolarized e-p at The EIC

- 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 α_S(Q2) 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 ν [1]
- Target/Current fragmentation studies [2,3]
- … etc….

ELIC

ELIC

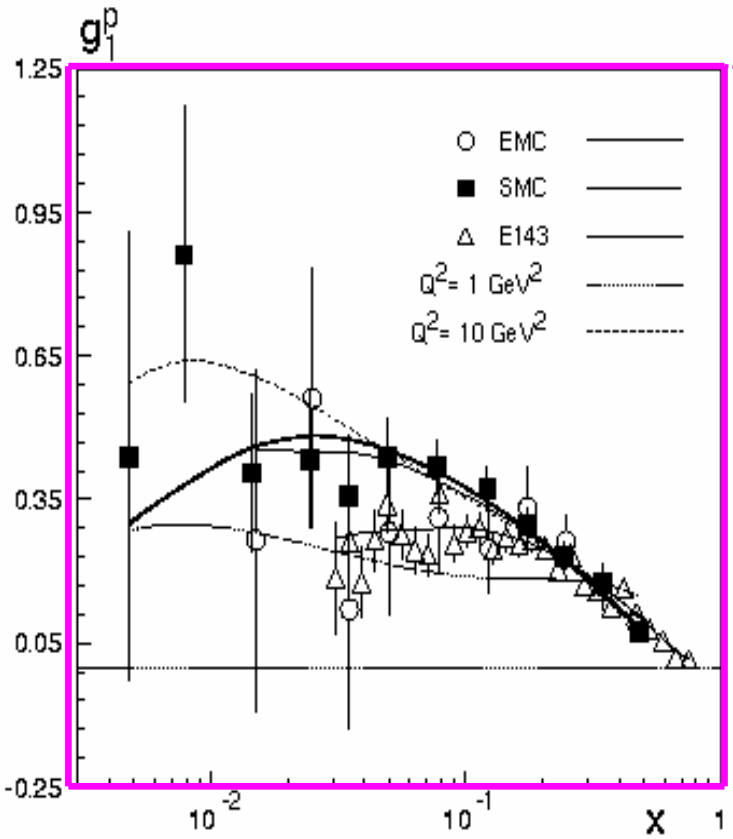
Luminosity Requirement

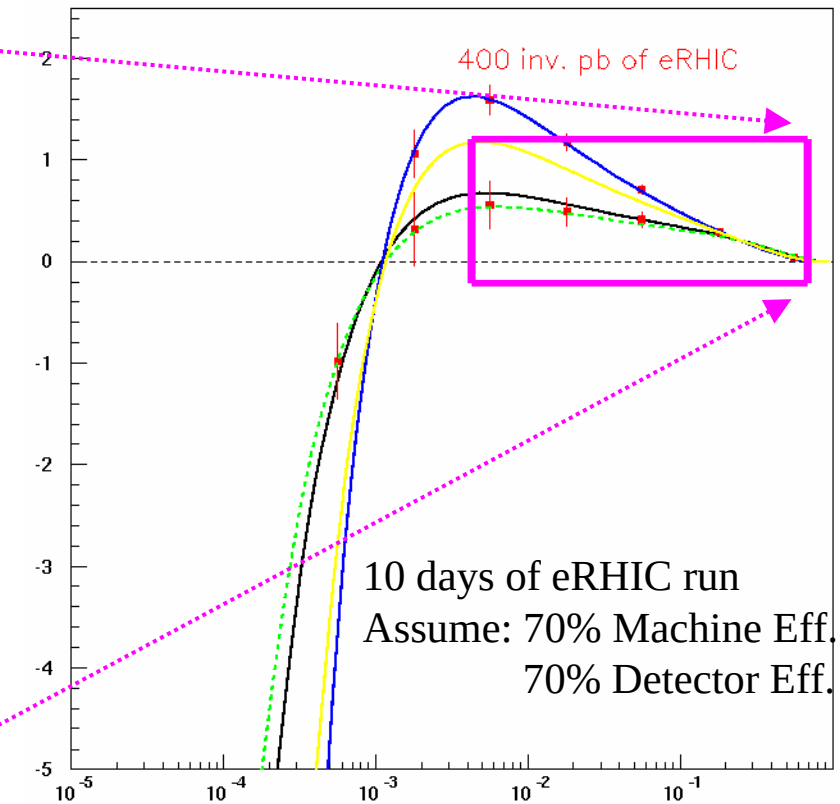
A.D. & V. W. Hughes

Proton Spin Structure at Low x

Fixed target experiments
1989 – 1999 Data

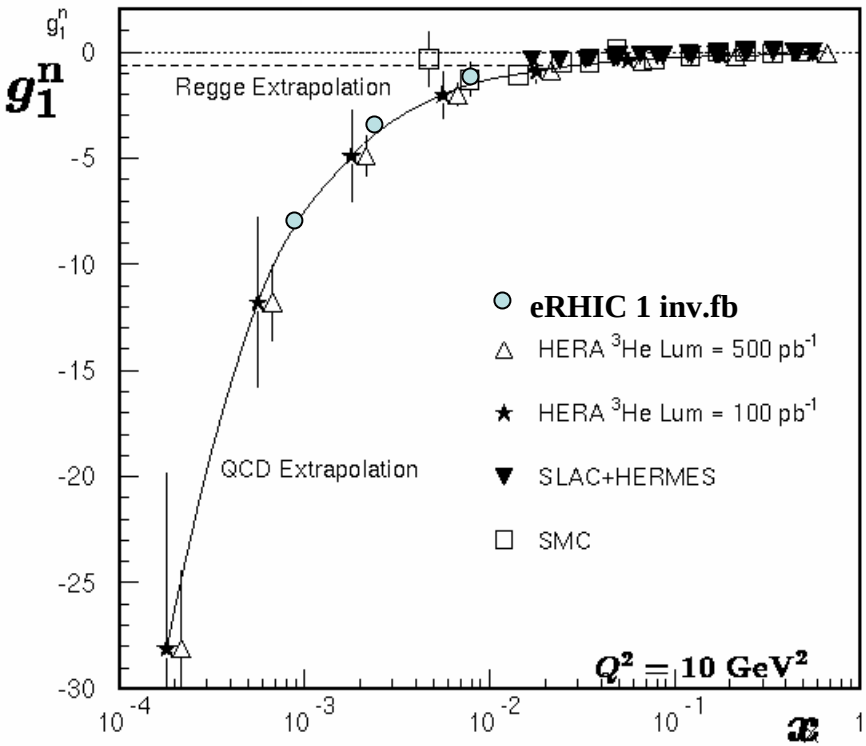
eRHIC 250 x 10 GeV
Luminosity = ~85 inv. pb/day





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

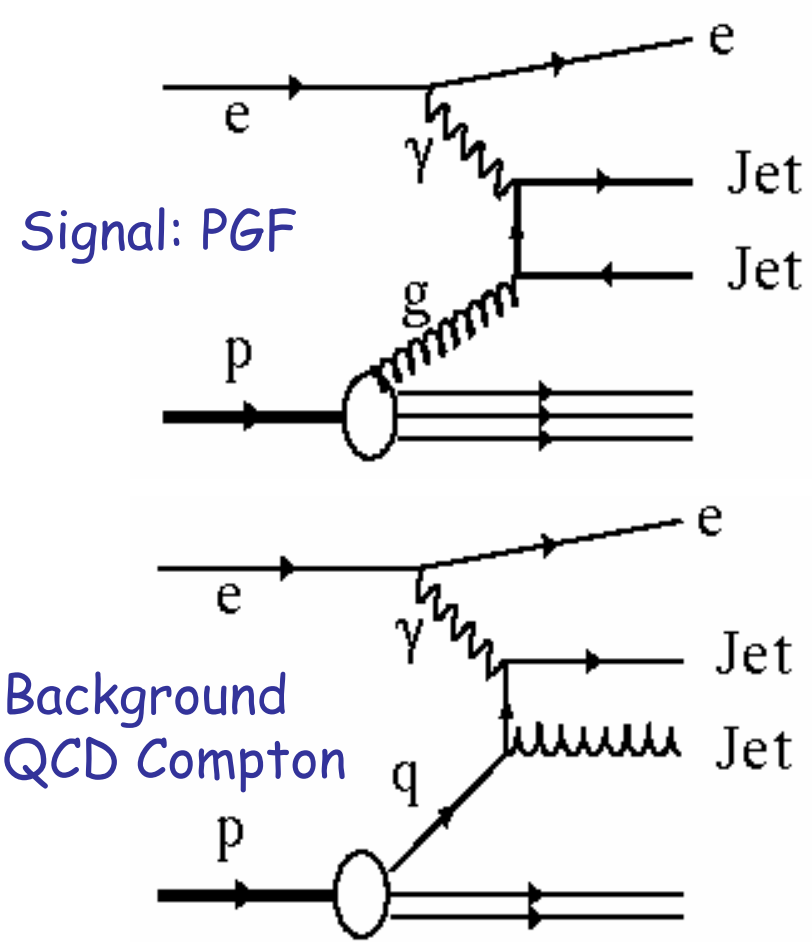
Spin Structure of Neutron at Low x



- With polarized He
- ~ 2 weeks of data at EIC
- Compared with SMC(past) & possible HERA data
- **If combined with g1 of proton results in Bjorken sum rule**

  test of better than 1–2% within a couple of months of running

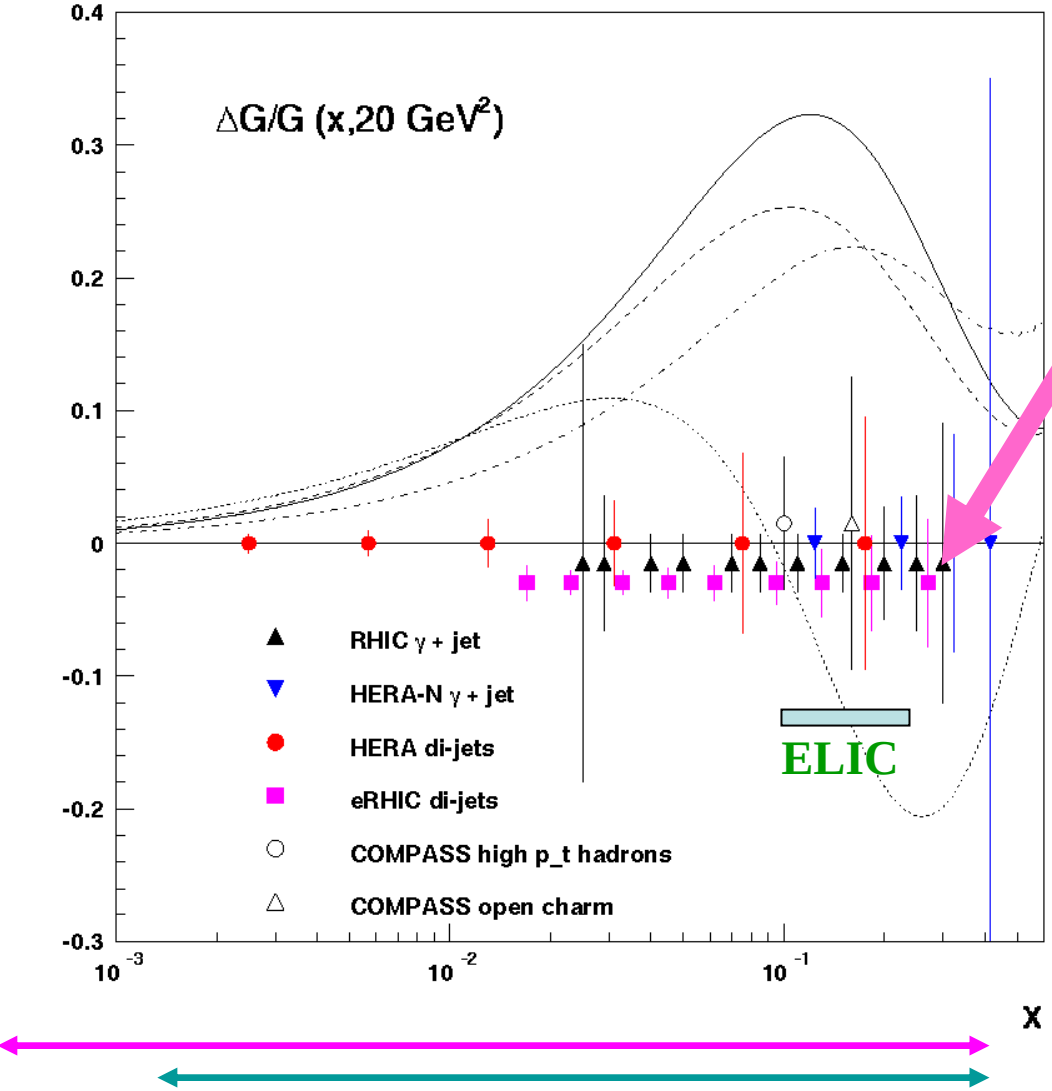
Photon Gluon Fusion at eRHIC



- "Direct" determination of ΔG
  -- Di-Jet events: (2+1)-jet events
  -- High pT hadrons
- High Sqrt(s) at eRHIC
  -- no theoretical ambiguities regarding interpretation of data
- Both methods tried at HERA in un-polarized 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

G. Radel, A. De Roeck
AD

Di-Jet at eRHIC vs. World Data for ΔG/G

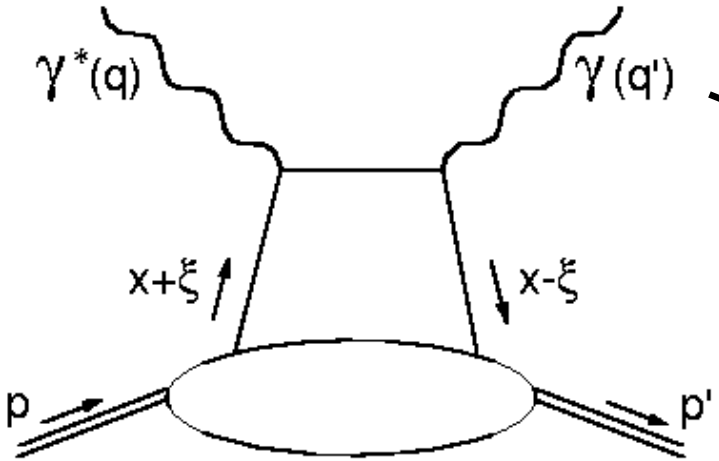


eRHIC Di-Jet DATA 2fb^{-1}

- Good precision
- Clean measurement in x range $0.01 < x < 0.3$
- Constrains shape of $\Delta G(x)$
- Polarization in HERA much more difficult

ΔG from scaling violations
$> x_{min} \sim 10^{-4}$ at eRHIC
$> x_{min} \sim 10^{-3}$ at ELIC

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

Highlights of e-A Physics at eRHIC

- 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 & μ-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

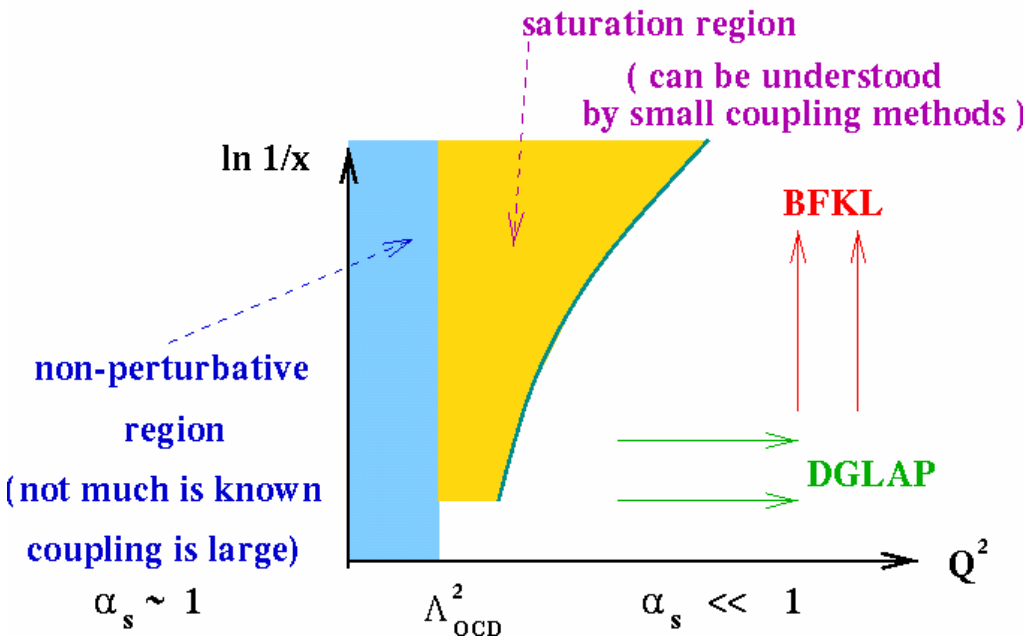
  Nuclear medium dependence of hadronization

- …. 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?

- 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

- 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

  See details in talk by **A. Caldwell et al.**

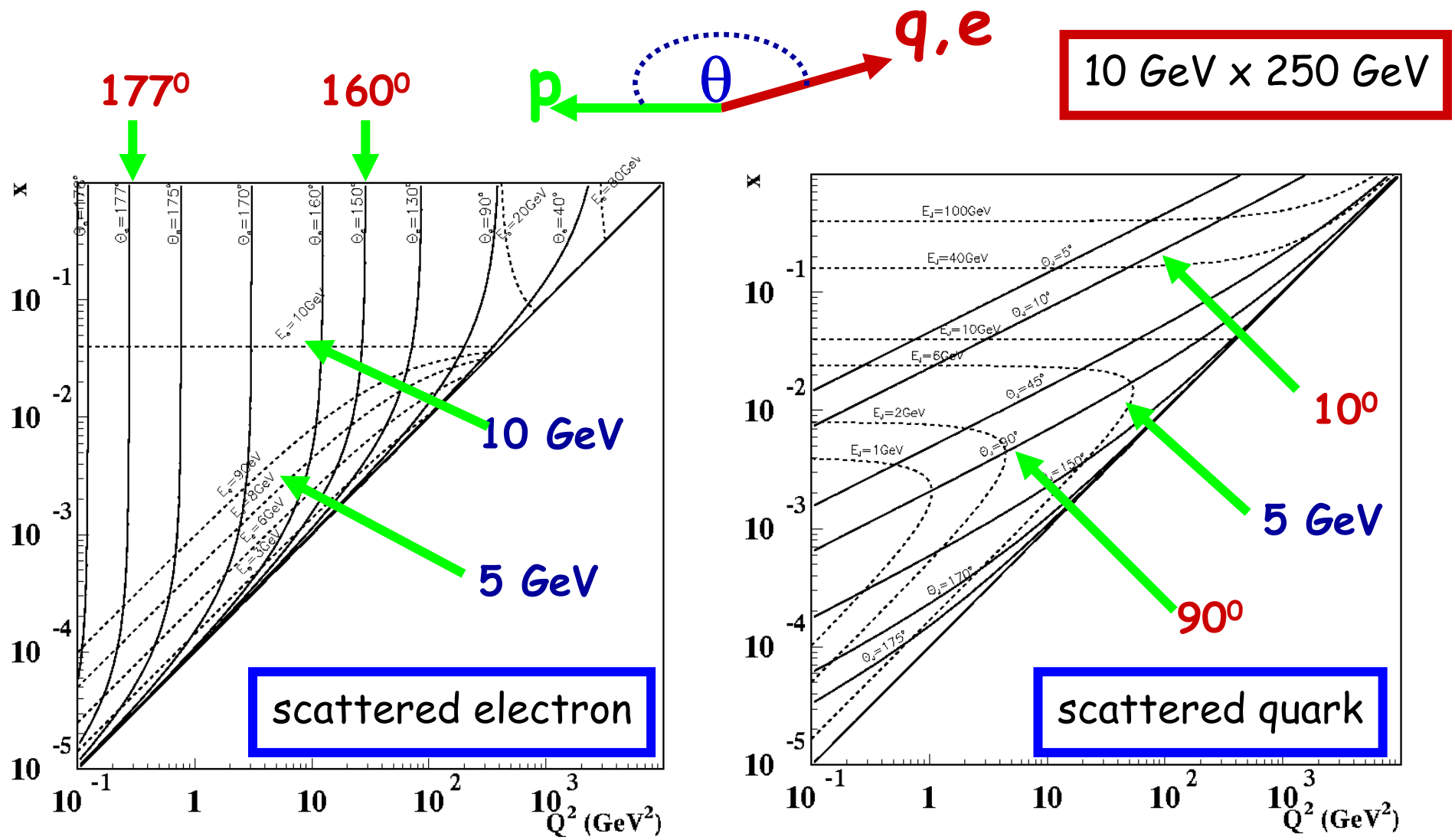
A Detector for EIC → A 4π Detector

- Scattered electrons to measure kinematics of DIS
- Scattered electrons at small (~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)
- ~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

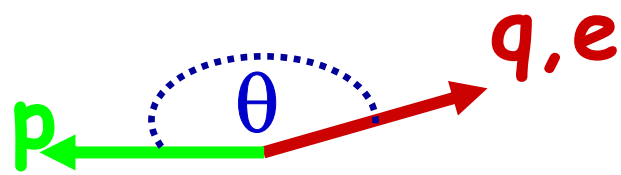
- *At least one* second detector should be incorporated… if not more
  - How?

- EIC/eRHIC will provide: 1) Variable beam energies 2) different hadronic species, some of them polarization, 3) high luminosity

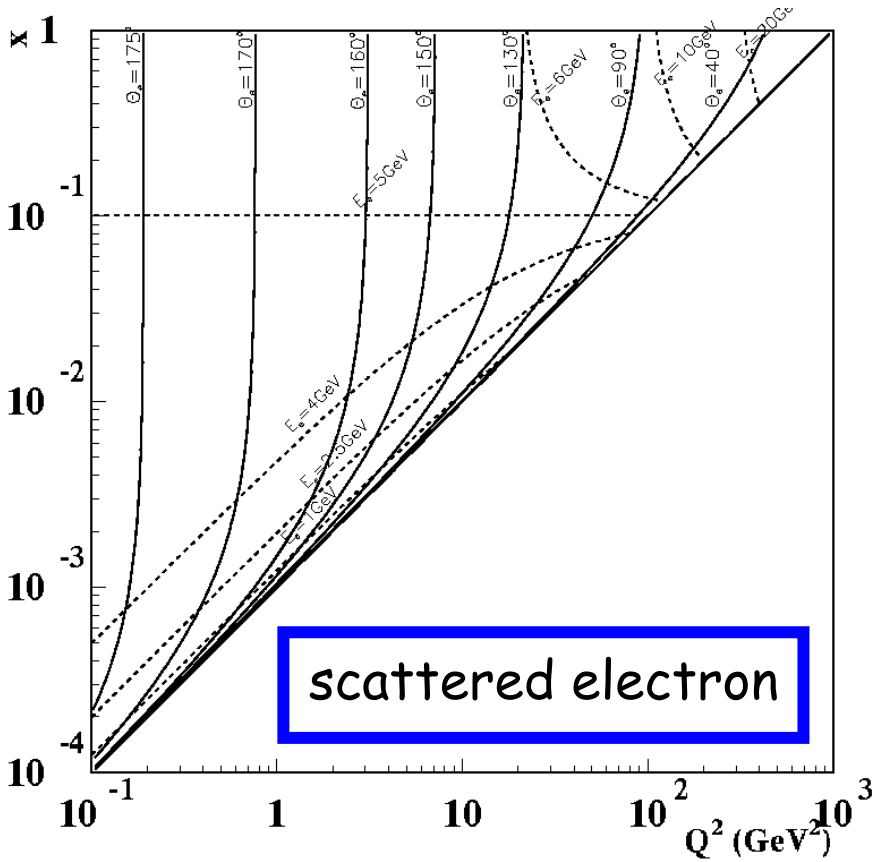
Where do electrons and quarks go?

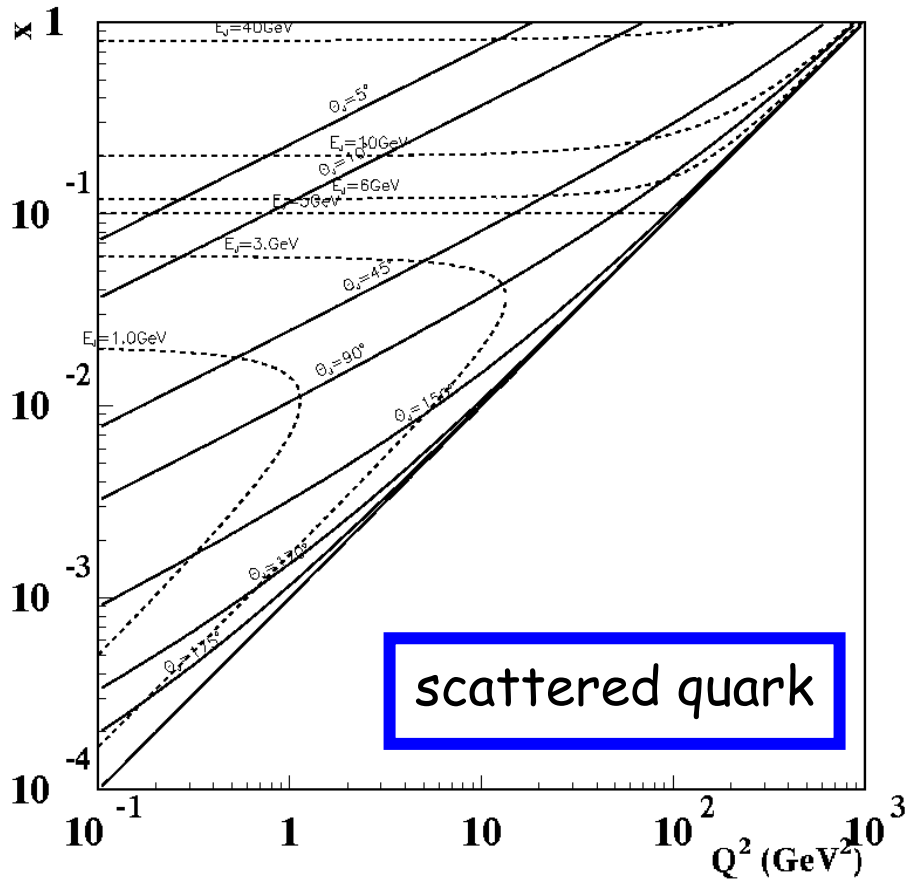


Electron, Quark Kinematics

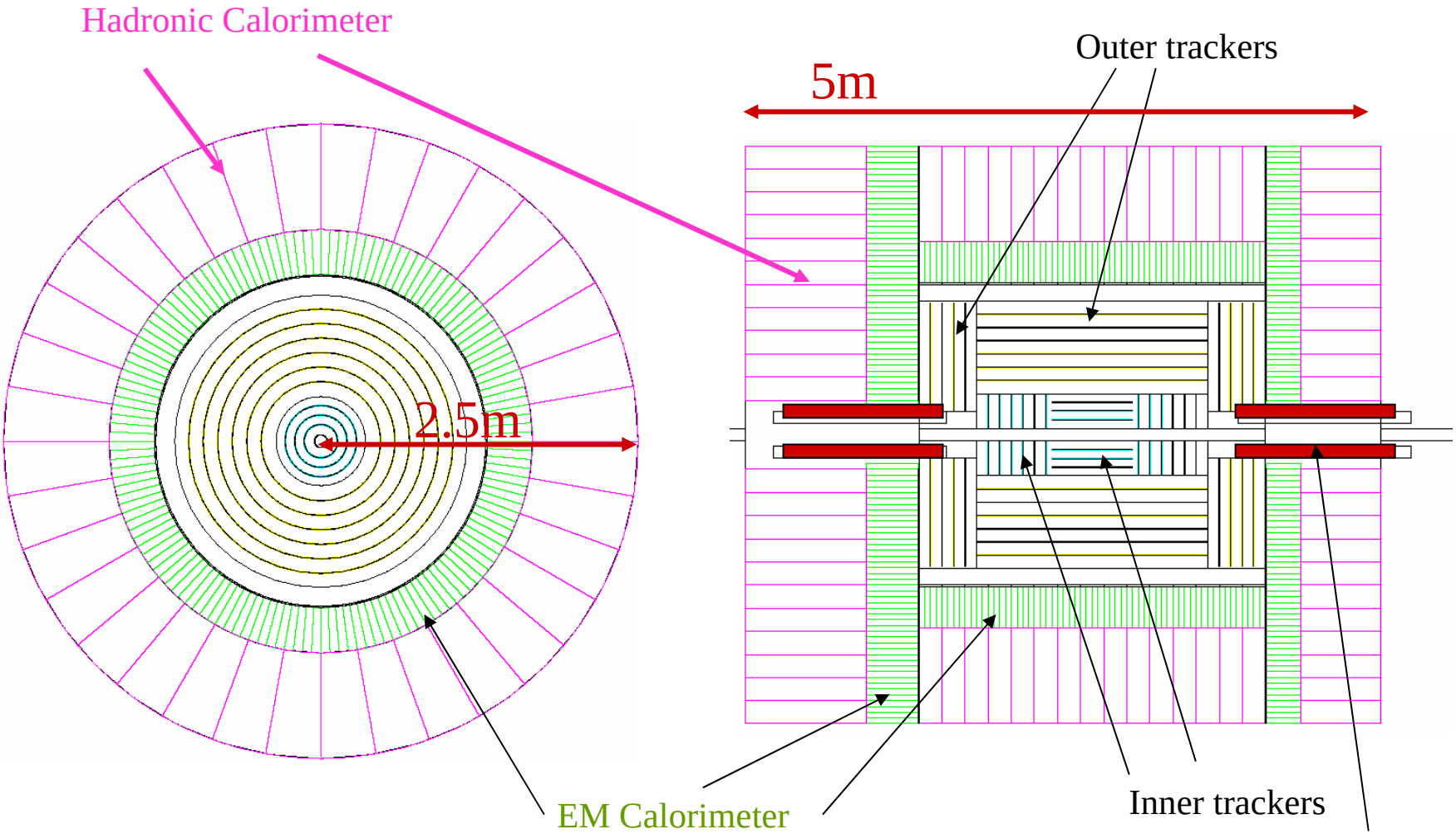


5 GeV x 50 GeV





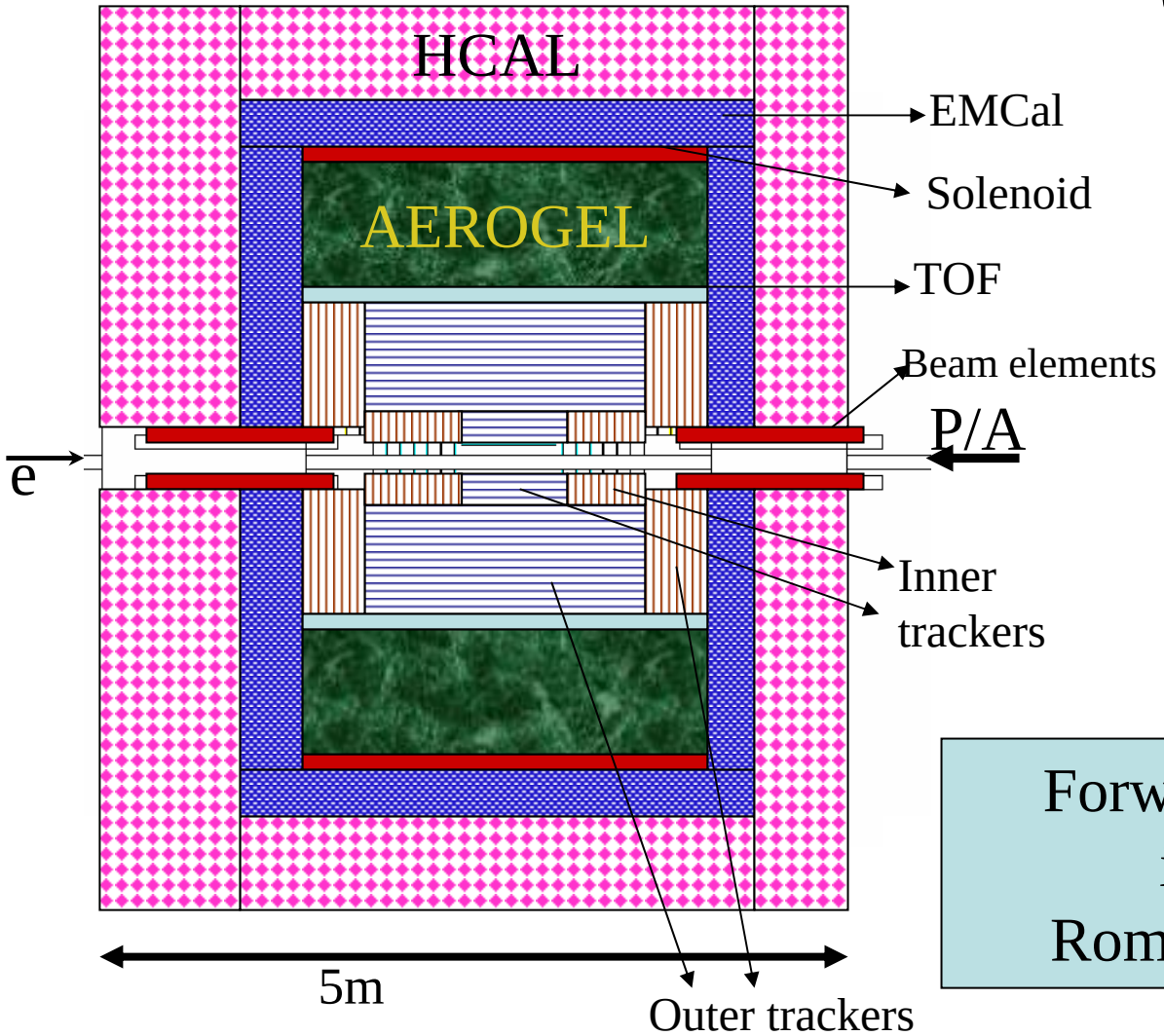
Detector Design --- HERA like…



Nearest beam elements 1m

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

- 2001 LRP: NSAC enthusiastically supported R&D and stated its 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 Zeroth 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

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

- 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)~ 4 x 10^{32} cm^{-2} sec^{-1} **work on luminosity enhancement continues**. *Advantages:* both positrons/electrons positrons….. *Disadvantages:* Multiple detectors or/and Interaction Regions?

Details in talks by: **V. Ptitsyn(BNL) and many in parallel sessions**

IR, Synchrotron Radiation, other Hadron Beam Modification

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C. Montag's Talk this meeting

eRHIC: Linac-Ring Option

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are needed to see this picture.

Features:

- Up to L(ep) ~10^{34} $cm^{-2}sec^{-1}$
- Polarization transparency at all energies
- Multiple IRs and detectors
  - Long element free regions
- STAR & PHENIX still run
- Full range of CM Energies
- Future upgrades to 20 GeV seem straightforward

Limitations:

Positron beams not possible

Physics implications?

More details in: **I. Ben-Zvi & V. Litvinenko's** talk

eRHIC Linac-Ring

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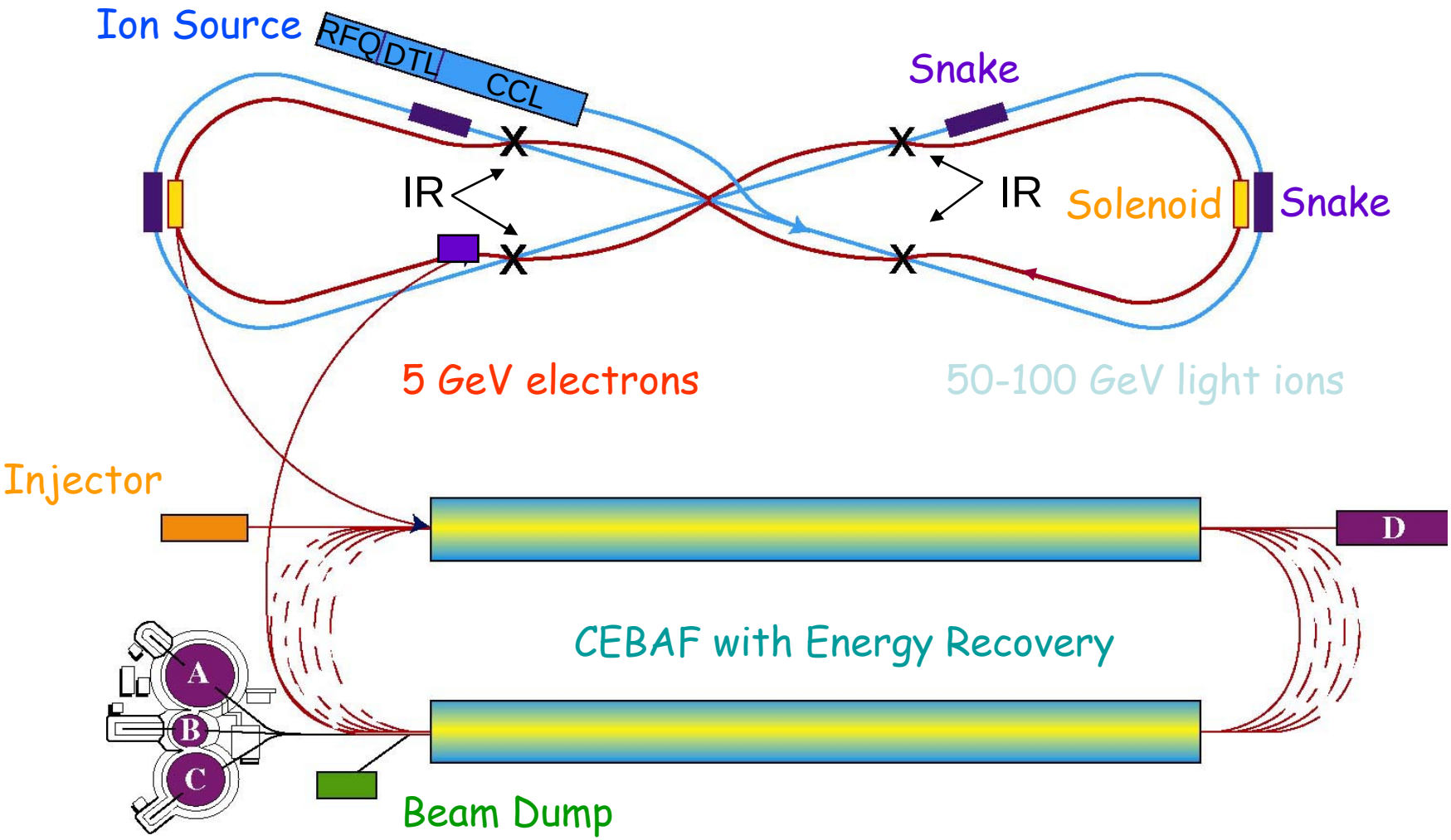
TIFF (LZW) decompressor
are needed to see this picture.

Up to 4 Irs
Up to 20 GeV
Electron beams

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

- **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….

- 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

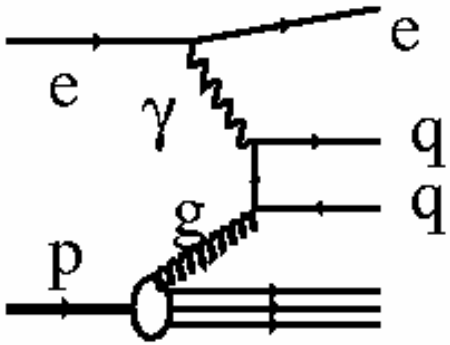
- We hope that the collider seeking communities join forces now to realize the chances of future collider(s) for QCD studies

Detailed backup slides….

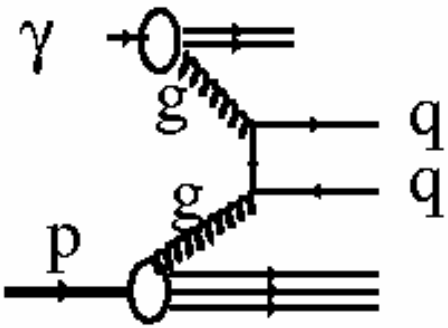
Polarized PDFs of the Photons

- Photo-production studies with single and di-jet

Direct Photon

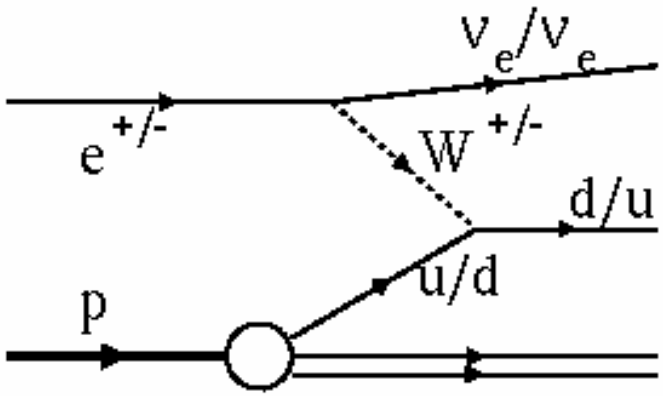


Resolved Photon



- 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!

Parity Violating Structure Function g_5



$$\frac{d^2\sigma}{dx\,dQ^2} \sim \{a\,[F_1 - \lambda b F_3] + \delta\,[a g_5 - \lambda^2 b g_1]\}\frac{1}{(Q^2 + M_W^2)^2}$$

where

$a = 2(y^2 - 2y + 2)$; $b = y(2 - y)$; $\lambda = \pm 1$ for $e^{\pm}$

$\delta = \pm 1$ for $\uparrow\downarrow$ and $\uparrow\uparrow$ spin orientations

- Experimental signature is a huge asymmetry in detector (neutrino)
- Unique measurement
- Unpolarized xF_3 measurements at HERA in progress
- Will access heavy quark distribution in polarized DIS

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

For eRHIC kinematics $a \gg b$

$\Longrightarrow g_5$ dominates $\rightarrow$ Extract g_5

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

AD, V.W.Hughes, J.Lichtenstadt

ΔG from Scaling Violations of g_1

- 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

  ΔG = 1.0 +/- 1.0 (stat) +/- 0.4 (exp. Syst.) +/- 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

Polarized Gluon Measurement at eRHIC

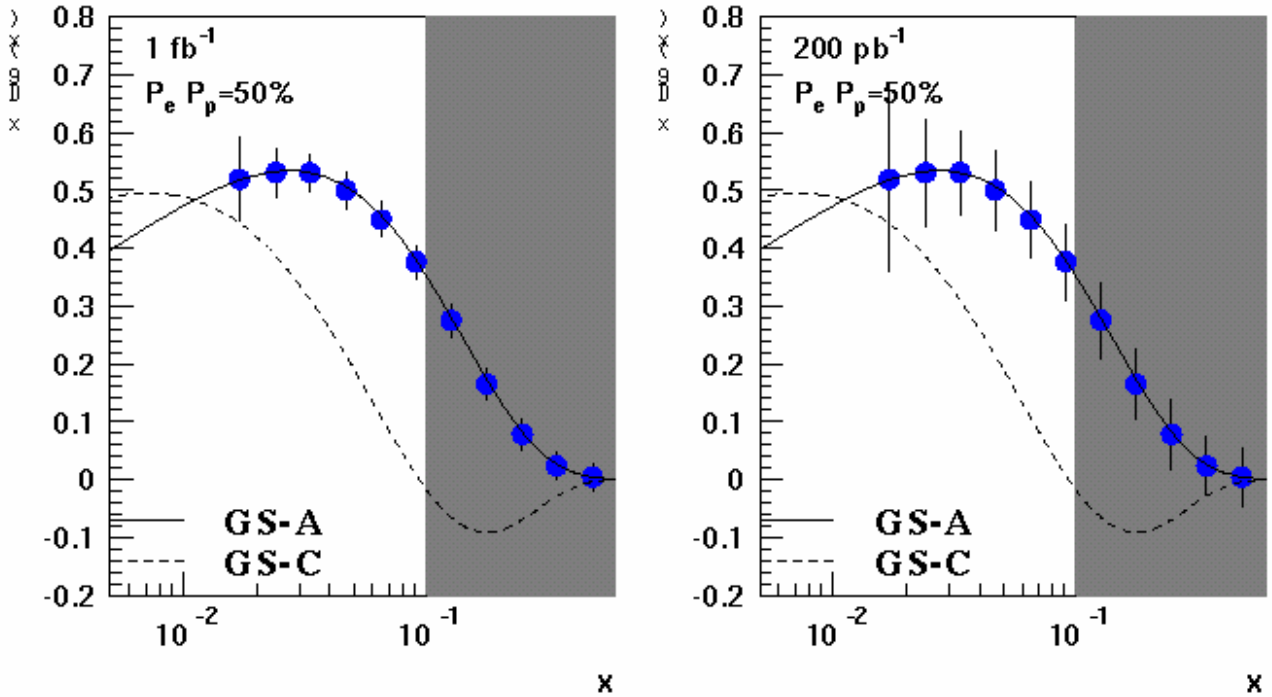
- This is the hottest of the experimental measurements being pursued at various experimental facilities:
  -- HERMES/DESY, COMPASS/CERN, RHIC-Spin/BNL & E159/E160 at SLAC
  -- Reliability from applicability of pQCD without doubt leaves *only RHIC*
- Measurements at eRHIC will be complimentary with RHIC

- 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 pT 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.

G. Radel & A. De Roeck,A.Deshpande, V. Hughes, J. Lichtenstadt

Di-Jet events at eRHIC: Analysis at NLO

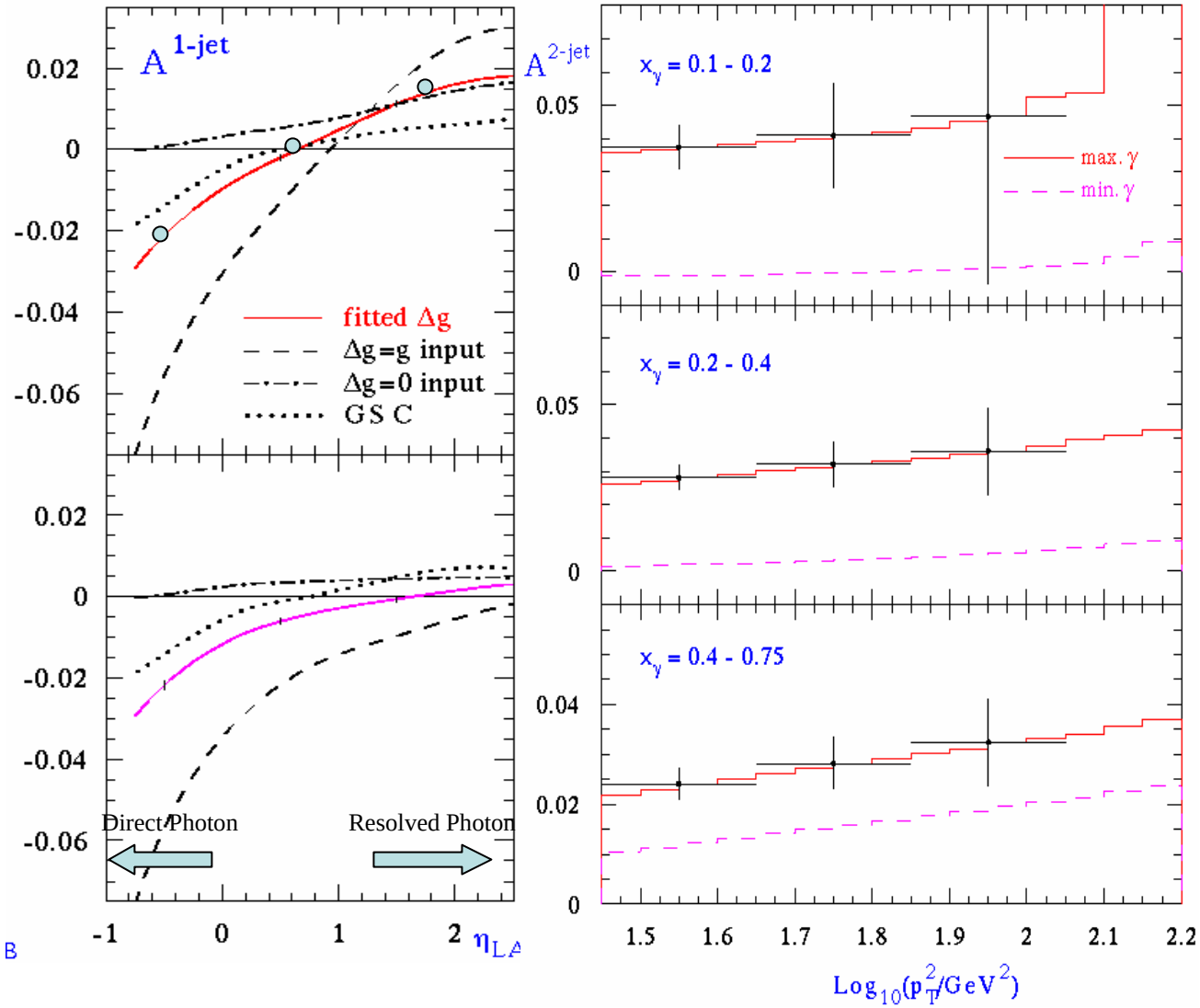


- Stat. Accuracy for two luminosities
- Detector smearing effects considered
- NLO analysis

- Easy to differentiate different ΔG scenarios: factor 3 improvements in ~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 ΔG progra

M. Stratmann, W. Vogelsang

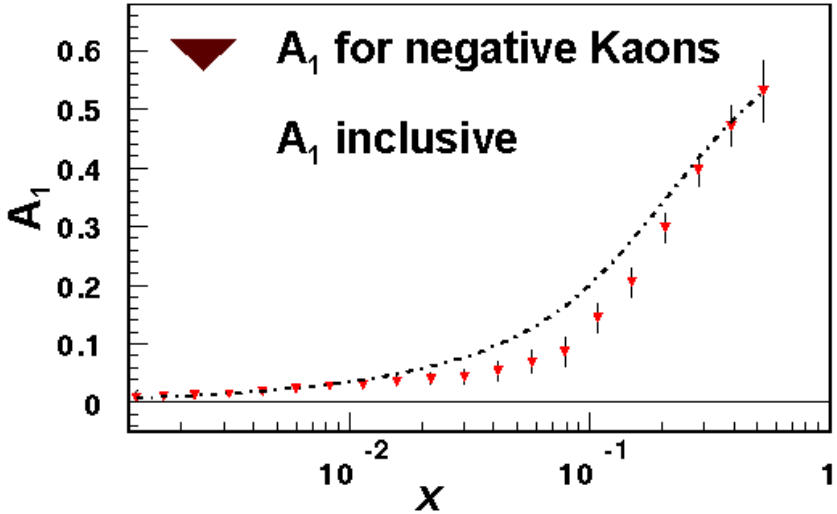
Photon Spin Structure at eRHIC

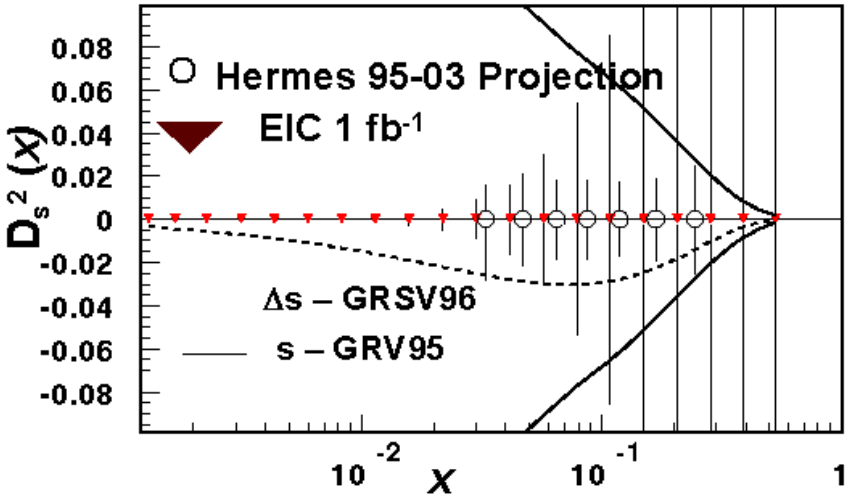


- Stat. Accuracy estimated for 1 fb^{-1} running (2 weeks at EIC)
- Single and double jet asymmetries
- ZEUS acceptance
- Will resolve photon's partonic spin contents

U. Stoesslein, E. Kinney

Strange Quark Distributions at eRHIC



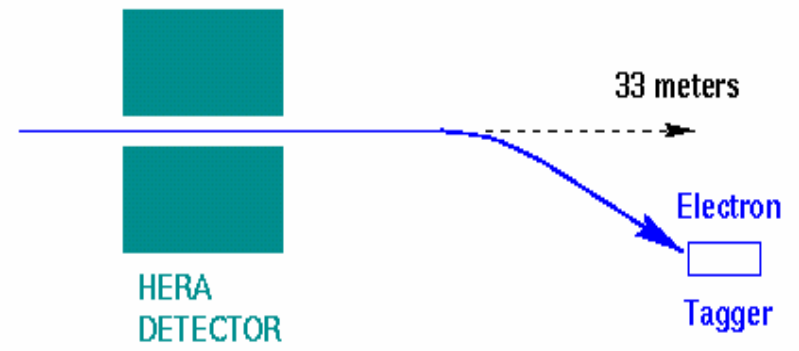


- After measuring u & d quark polarized distributions…. Turn to s quark (polarized & otherwise)
- Detector with good Particle ID: pion/kaon separation

- 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

S.D.Bass, A. De Roeck,AD

Drell Hern Gerasimov Spin Sum Rule



- DHG Sum rule:

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

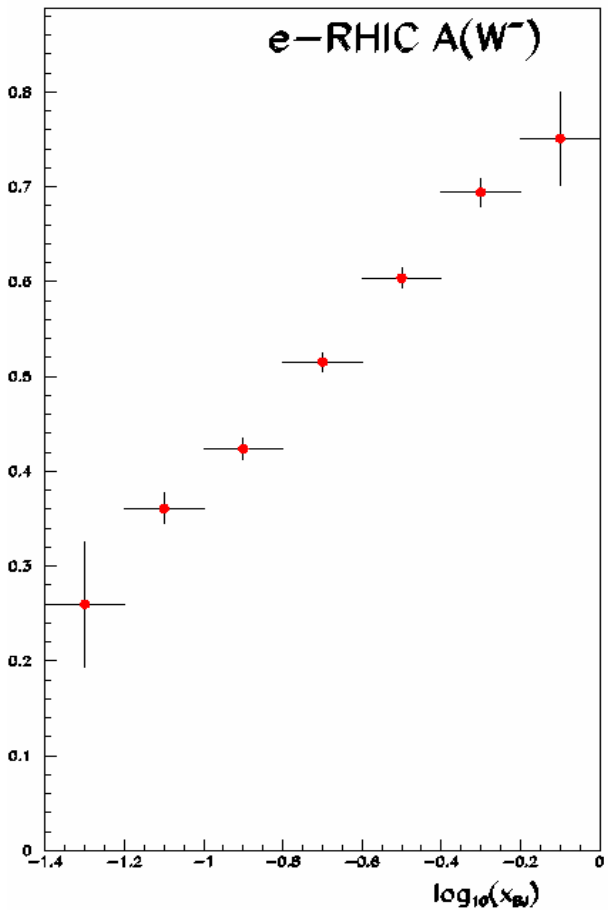
- At eRHIC range: GeV → few TeV

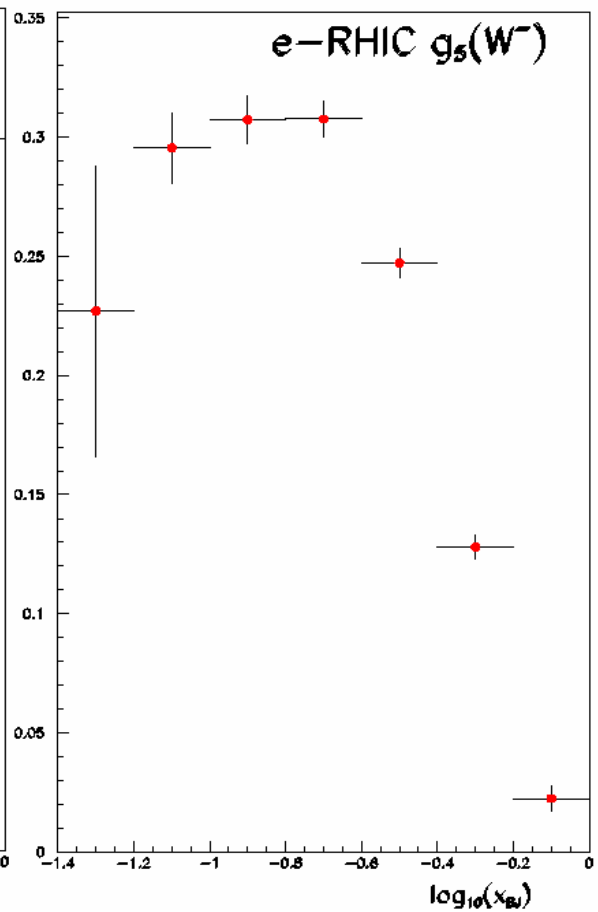
- Inclusive Photo-production measurement
- Using electron tagger in RHIC ring
  $Q^2 \sim 10^{-6} \rightarrow 10^{-2}$ GeV^2
  Sqrt(s) ~ 25 → 85 GeV

- 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

J. Contreras, A. De Roeck

Measurement Accuracy PV g_5 at eRHIC





Assumes:

1. Input GS Pol. PDfs
2. xF_3 measured by then
3. 4 fb^{-1} luminosity

Positrons & Electrons in eRHIC ➔ $g_5(+)$

>> reason for keeping the option of positrons in eRHIC

Luminosities e-p and e-A from eRHIC ZDR

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

Luminosity Comparison Table

JLAB/ELIC

Parameter	Units	Design	
		e^-	Ions
Energy	GeV	5	50/100
Electron Cooling	-	-	Yes
Circulator Ring	-	Yes	-
Luminosity	cm^{-2} sec^{-1}	$6x10^{34}$ / $1x10^{35}$	
I_{ave}	A	2.5	2.5
f_c	MHz	1500	

eRHIC (ring-ring)

Parameters	e-ring	ion ring	
		p	Au
C, m	1022	3833	
E, GeV	5–10	250	100/u
n_b	96	360	
N_b	$1\cdot10^{11}$	$1\cdot10^{11}$	$1\cdot10^{9}$
I, A	0.45	0.45	
ε_{rms},mm rad	45–25	17–9	
β^*, cm	10	27	
σ^*, mm	0.07–0.05	0.07–0.05	
ξ, cm^{-2} s^{-1}	0.05	$(0.5-0.9)\cdot10^{33}$	$(0.5-0.9)\cdot10^{31}$

eRHIC Ring-Ring parameters

Now

With future development

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

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TIFF (LZW) decompressor
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M. Stratmann & W. Vogelsang

Scale Dependence: NLO/LO K factor