eRHIC: Science and Perspective

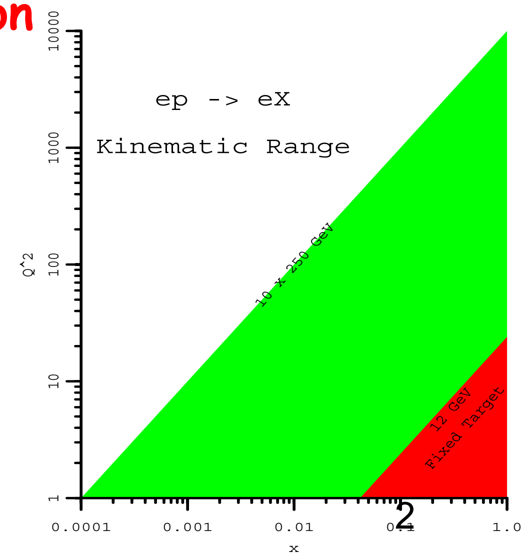
Study of the Fundamental Structure of Matter with an Electron-Ion Collider
A. Deshpande, R. Milner, R. Venugopalan, W. Vogelsang
hep-ph/0506148, Ann. Rev. Nucl. Part. Sci. **55**, 165 (2005)

The fundamental structure of matter

- QCD tells us that the nucleon and atomic nuclei are made of pointlike constituents bound by powerful gluon fields
- The valence quark region is well explored experimentally and reasonably well understood theoretically **JLab@12 GeV**
- The discovery of the perfect liquid at RHIC raises important questions, e.g. the nuclear initial state and the passage of fast partons through nuclear matter
- Frontier research in QCD demands a concerted experimental effort directed at the role of the gluons and sea quarks
- A new accelerator which directly probes the quarks and gluons is required

  Lepton probe
  High center of mass energy
  High luminosity $\Rightarrow$ precision
  Polarized lepton, nucleon
  Optimized detectors

X 100 times luminosity of HERA
+ Polarized nucleon
+ Nuclei

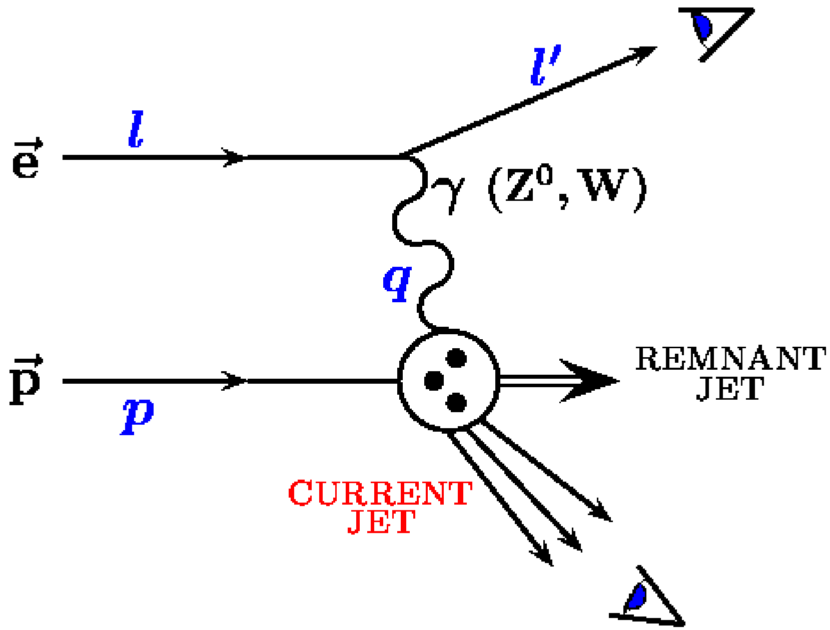


- This accelerator is urgently needed to make progress in this field of research and has substantial discovery potential

Why eRHIC?

- At BNL using RHIC
  - Have discovered the perfect fluid, a new and exciting phenomenon in high temperature QCD
  - Have realized the world's first polarized proton collider and are measuring the contribution of the gluon to the spin of the proton
- With increased luminosity (RHIC II) and detector upgrades of STAR and PHENIX, will study both the perfect fluid and the structure of the proton over the next 6-7 years.
- The addition of eRHIC (~10^{33} $cm^{-2}s^{-1}$) can greatly enhance these programs and open a new window to fundamental problems essential to the understanding of the structure of matter.
- Together with eA, eN, NN, AA, NA at RHIC physicists will truly have a laboratory for the first time that can explore QCD in all its richness and complexity

High Energy Lepton Scattering



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

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

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

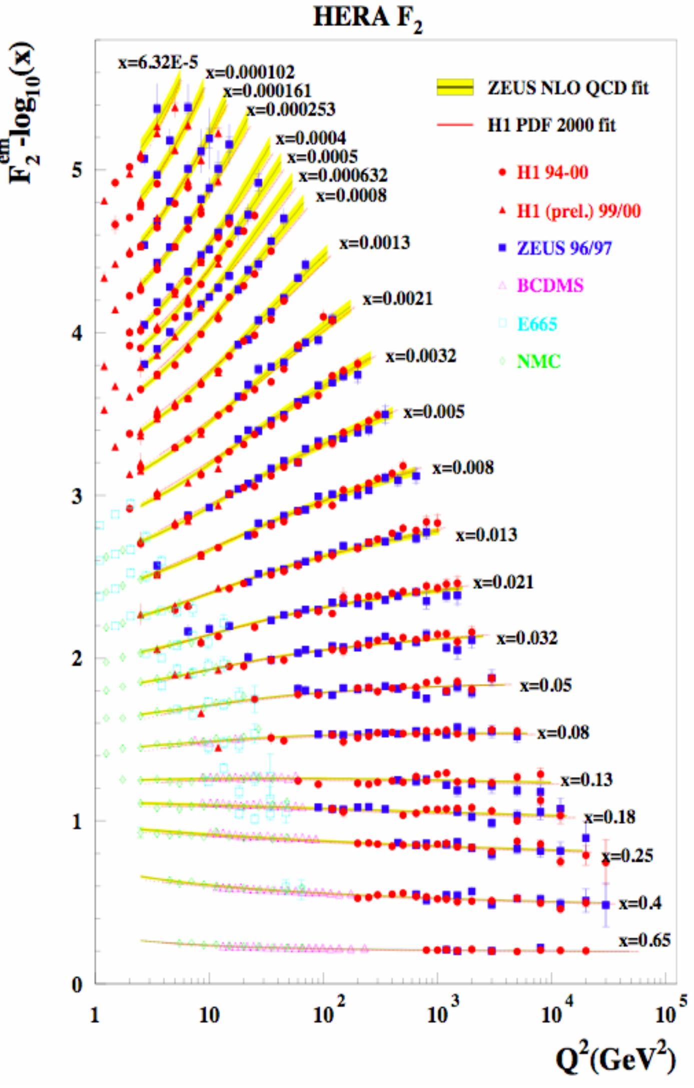
$$s = 4E_e E_p$$

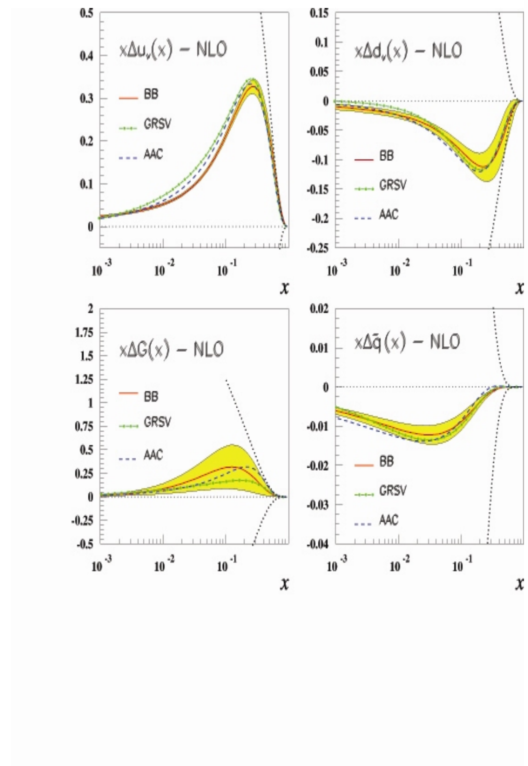
$$W = (q + p)^2$$

- Interpretable within a rigorous QCD framework
- Directly probes quarks and gluons
- Virtual photon imparts energy and momentum to quark in a completely controllable way

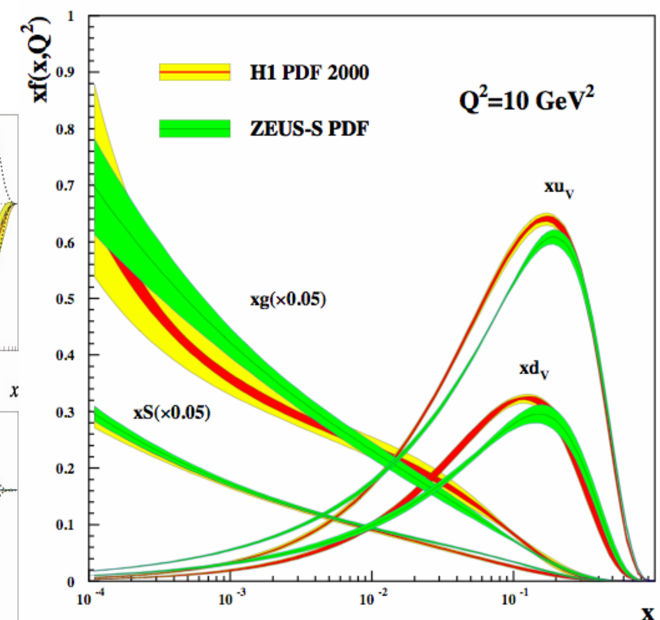
QCD remarkably successful

Bjorken scaling
DGLAP evolution

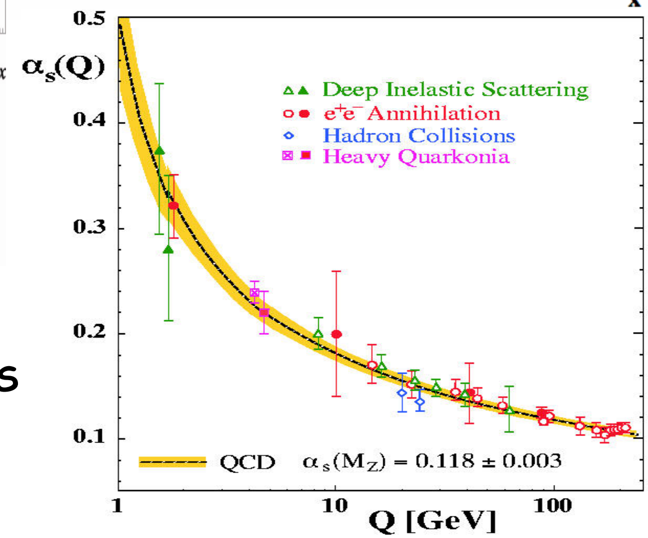




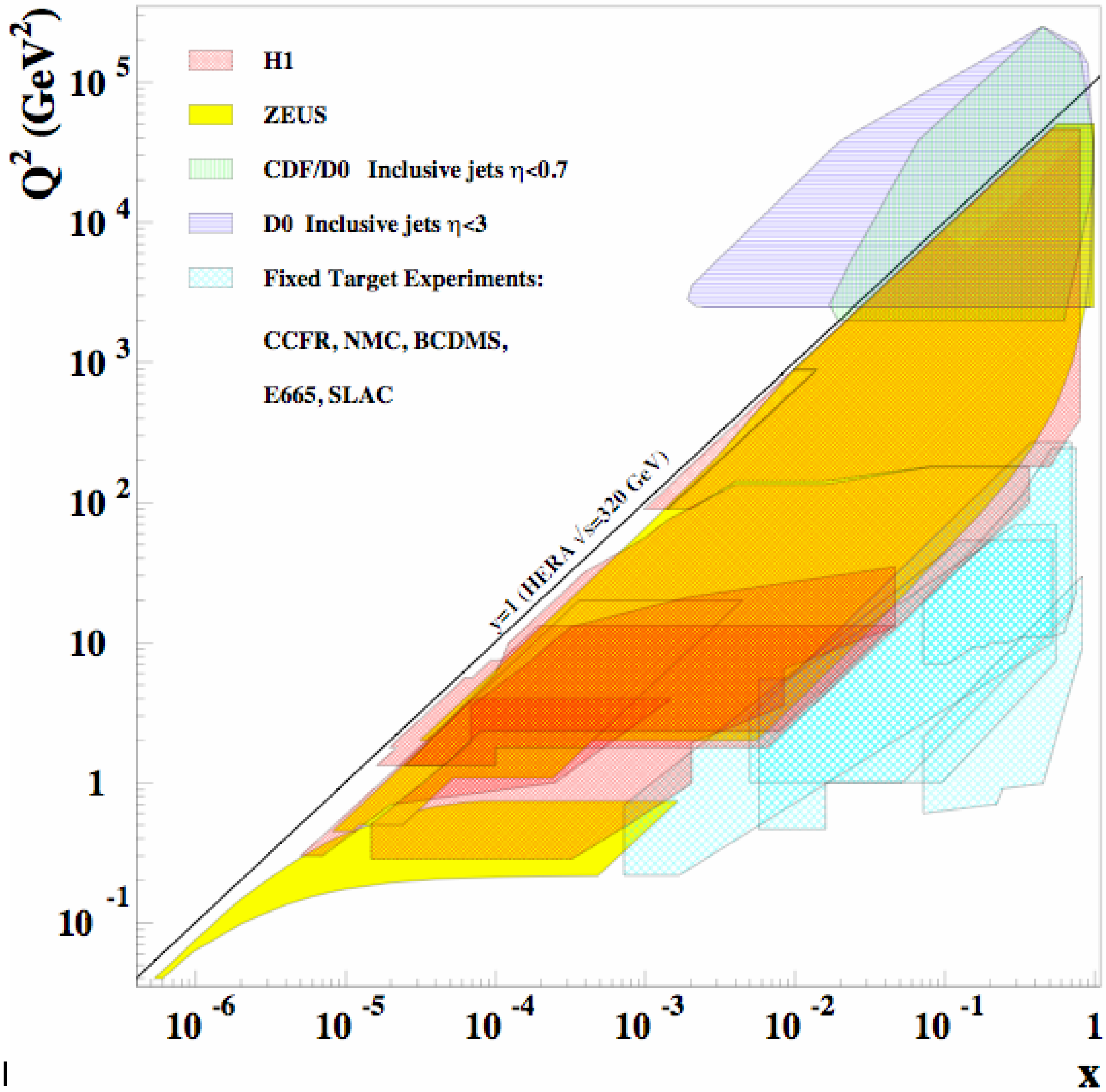
PDF's



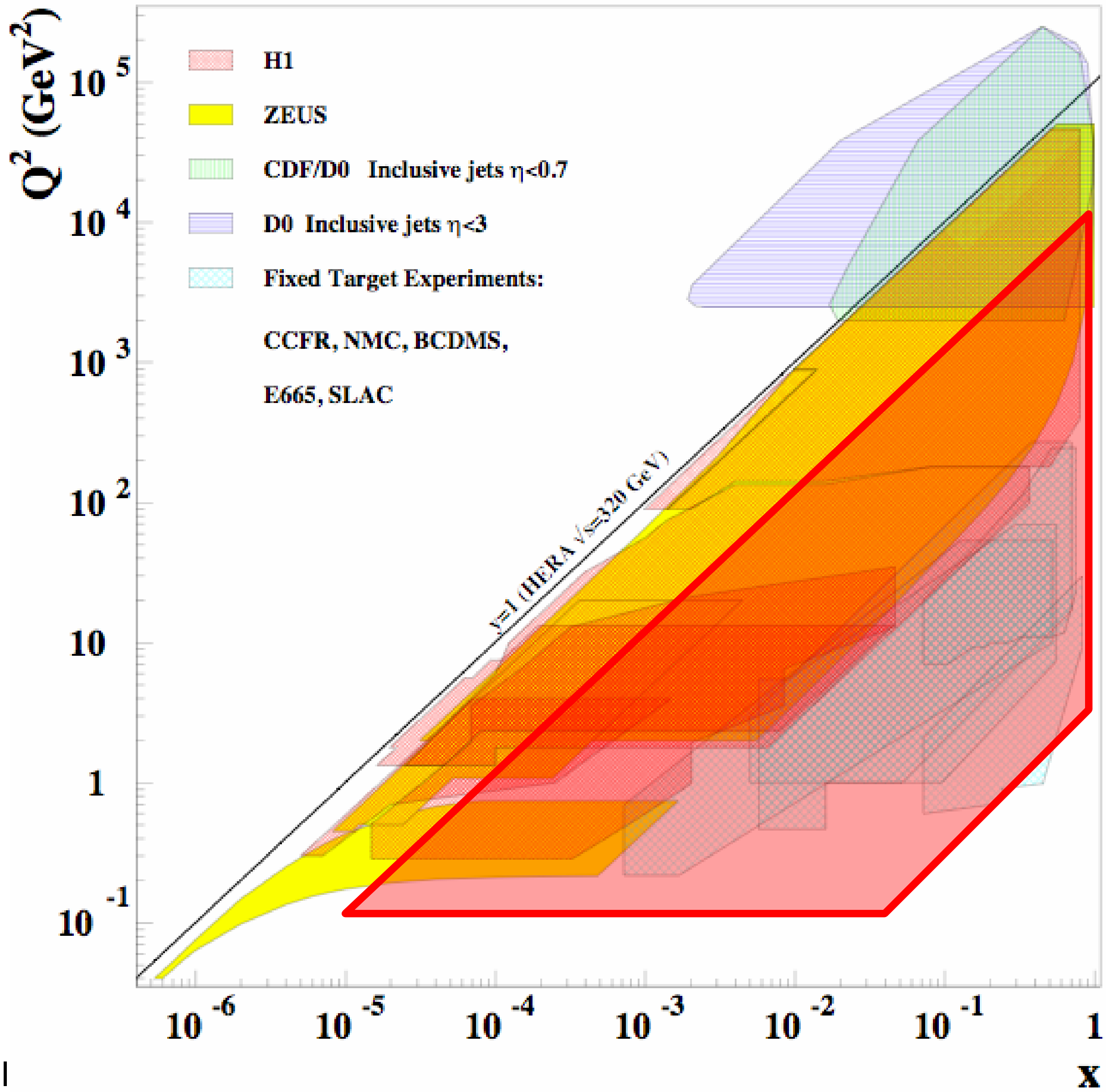
Running coupling α_s



Existing Kinematic Range-Mostly Unpolarized



eRHIC - polarized nucleon + nuclei



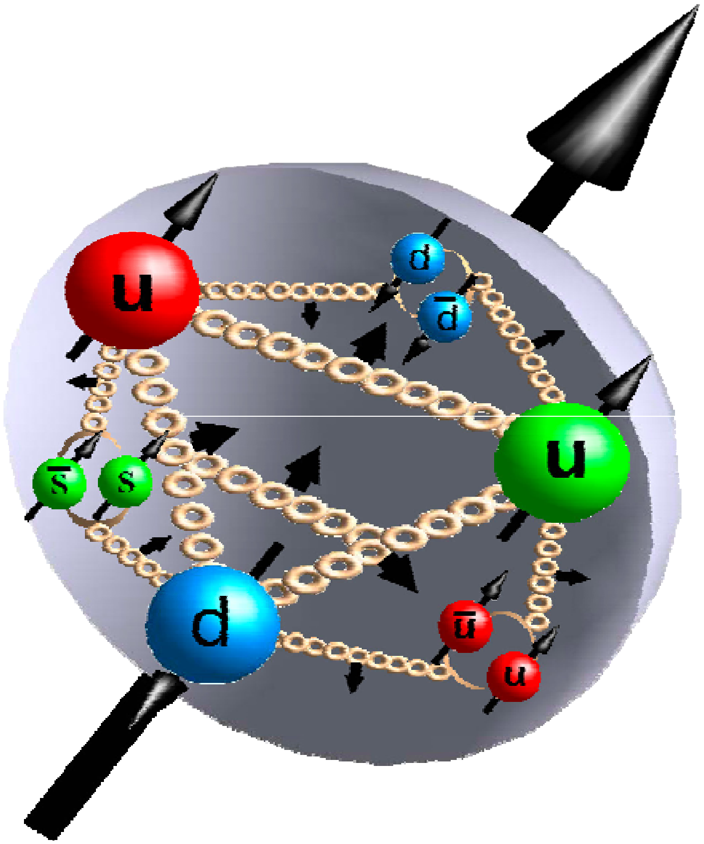
Scientific frontiers at RHIC

- **Spin structure of nucleon**
  - $g^p_1(x)$ at low x **dramatic QCD prediction**
  - gluon and sea quark polarization
  - Bjorken sum rule **QCD test**
  - new (GPD, transversity) parton distributions

- **Partonic understanding of nuclei**
  - gluon momentum distribution in nuclei: **essential to understand hot QCD in RHI collisions**
  - fundamental explanation of nuclear binding
  - saturation

The Spin Structure of the Nucleon

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



What we know:

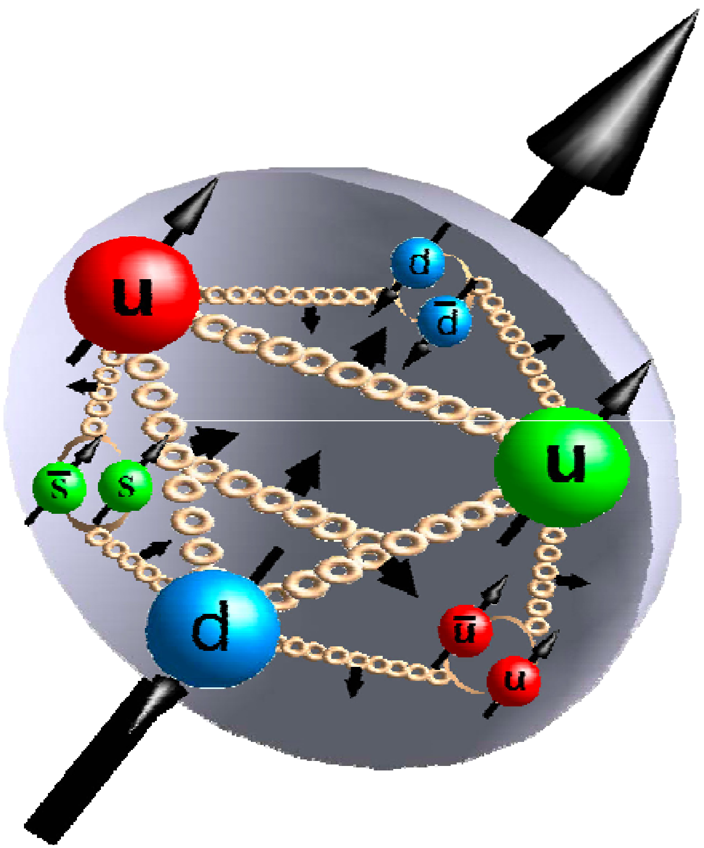
- $\Delta\Sigma \approx 0.2$
- From NLO-QCD analysis of DIS measurements

  $\Delta G \approx 1 \pm 1$
- Quark polarizations Δu_V, Δd_V determined

  anti-quark polns. consistent with zero
- Transversity $\delta q(x)$: first data from HERMES
- Gluon polarization $\Delta G(x)$: RHIC-spin starting to produce data

The Spin Structure of the Nucleon

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

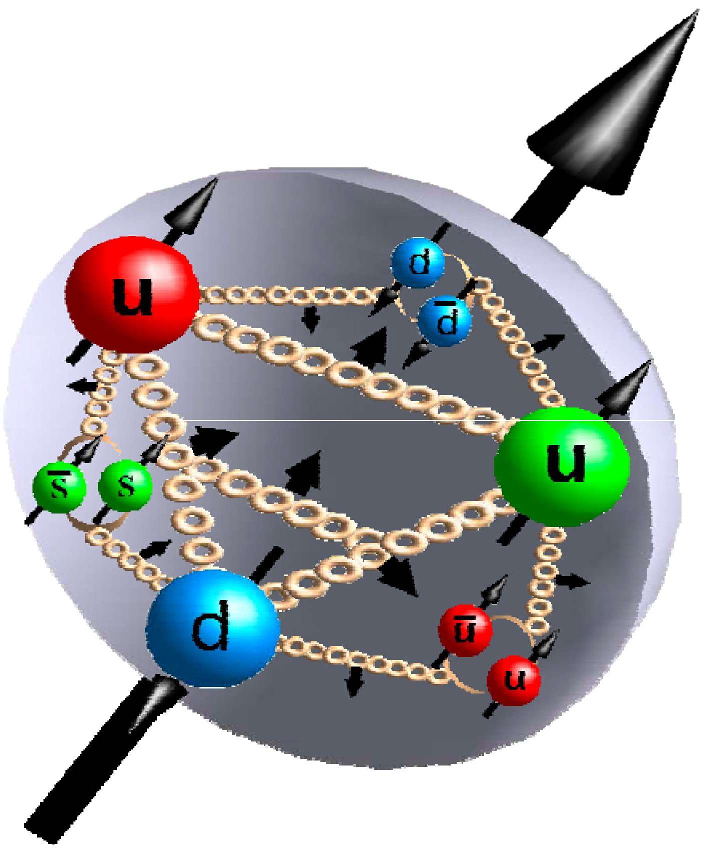


What we would like:

- ΔG accurately determined
- Anti-quark polns. accurately determined
- Bj. SR tested to ~ 1%
- Transversity $\delta q(x)$ fully explored
- x-dependence of gluon polarization $\Delta G(x)$ and $g_1^p(x)$ determined
- Contribution of orbital angular momentum $L_{q,g}$ determined

The Spin Structure of the Nucleon

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



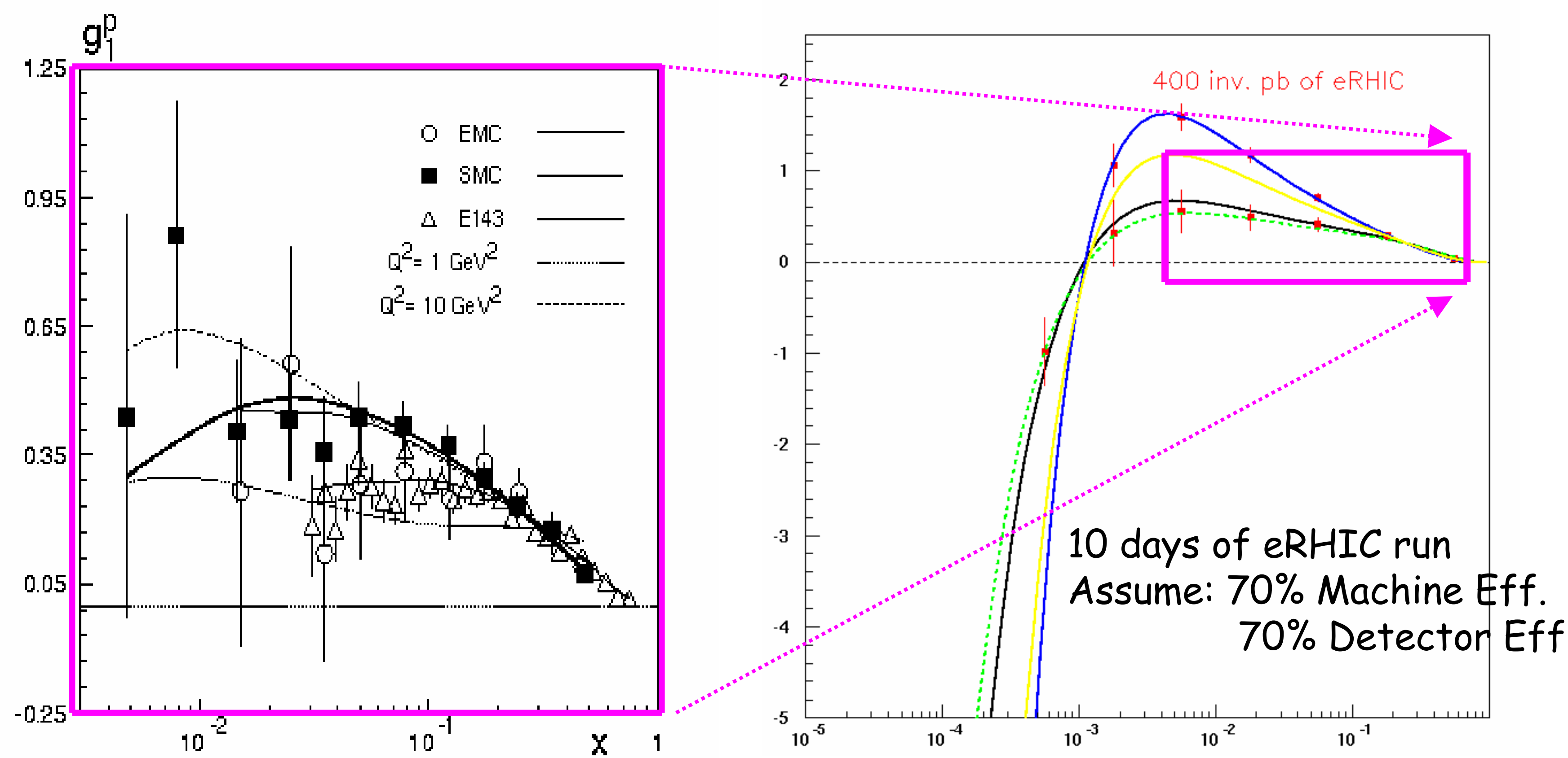
eRHIC is the first machine to allow access to all the contributions to the spin of the nucleon

- $g_1^p(x)$ pushed to much lower x
- ΔG accurately determined through several independent channels simultaneously
- Quark polns. accurately determined
- Transversity $\delta q(x)$ fully explored
- Access to DVCS process over a large range of x and Q^2 => possible determination of the contribution of orbital angular momentum $L_{q,g}$

g^p_1 at low x related to $\Delta G(x)$

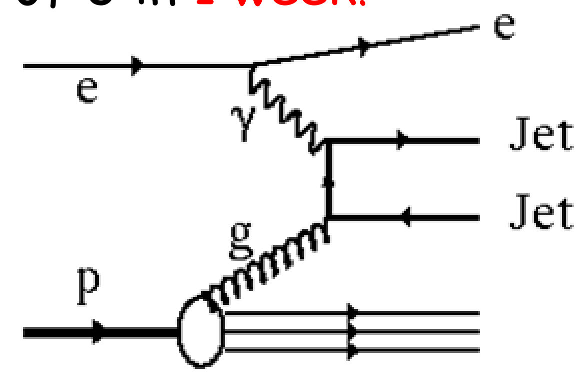
$x = 10^{-3} \rightarrow 0.7$
$Q^2 = 0 \rightarrow 10^3$ GeV
Fixed target experiments
1989 – 1999 Data

$x = 10^{-4} \rightarrow 0.7$
$Q^2 = 0 \rightarrow 10^4$ GeV
eRHIC 250 x 10 GeV
Lumi=85 inv. pb/day

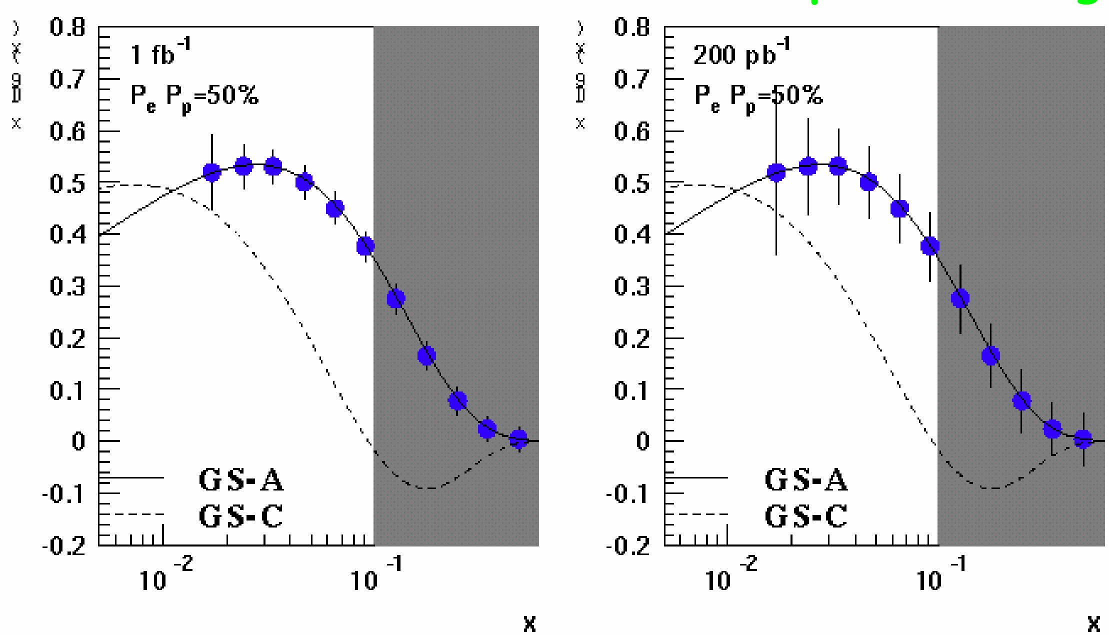


ΔG(x,Q²) at eRHIC

- Best determination from scaling violations of $g_1(x,Q^2)$
  - eRHIC will extend range in x and Q^2
  - improve existing measurements by a factor of 3 in 1 week!
- Direct measure via photon-gluon fusion
  - di-jets, high P_T hadrons
  - Successfully used at HERA
  - NLO calculations exist
  - Constrains shape in mid x region



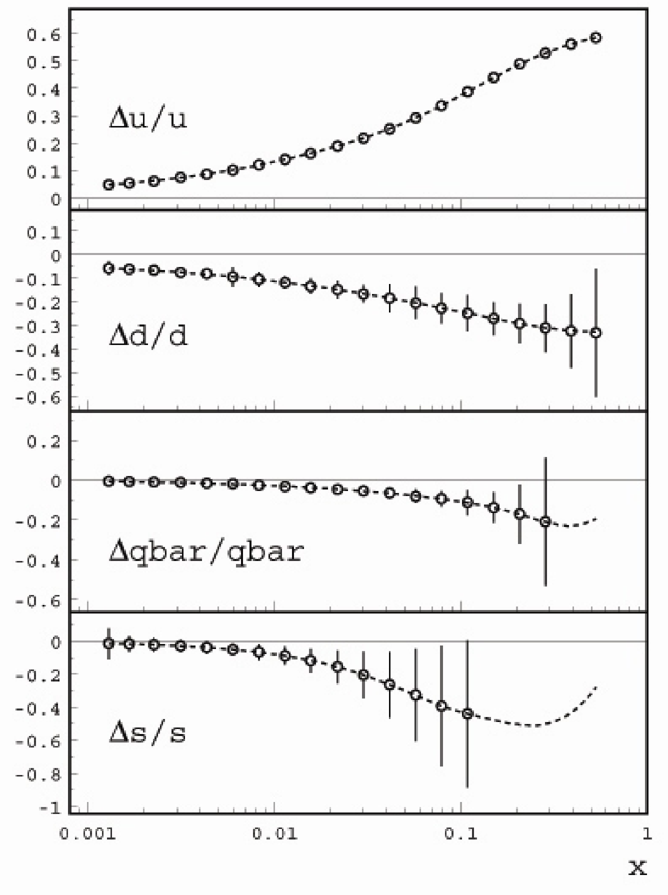
A.De Roeck, A.Deshpande, V.Hughes, J.Lichtenstadt, G. Radel

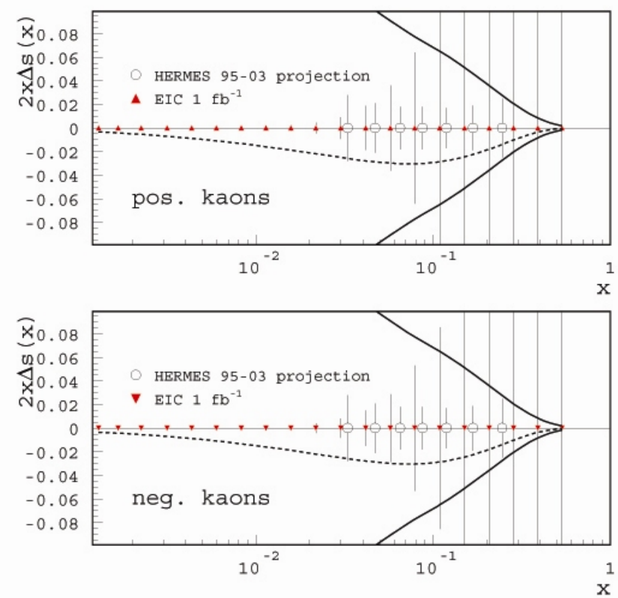


1 fb^{-1} in 2 weeks at eRHIC

Scaling violation data plus di-jet analysis will yield total uncertainty 5-10% after 1 year

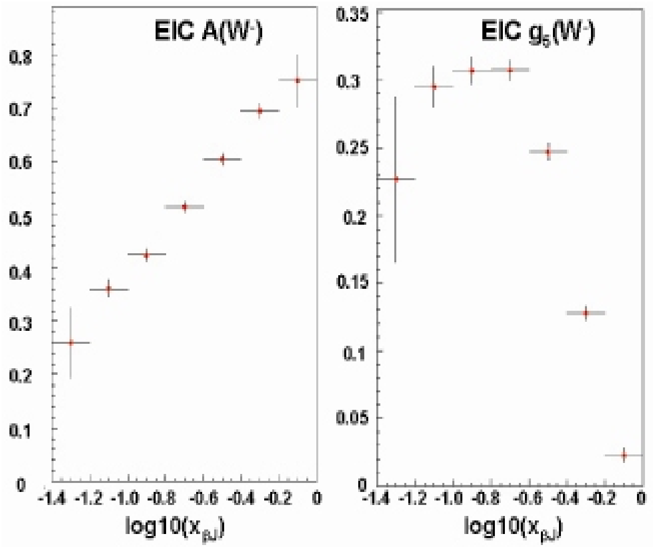
eRHIC determination of polarized quarks and anti-quarks





E. Kinney and U.Stösslein

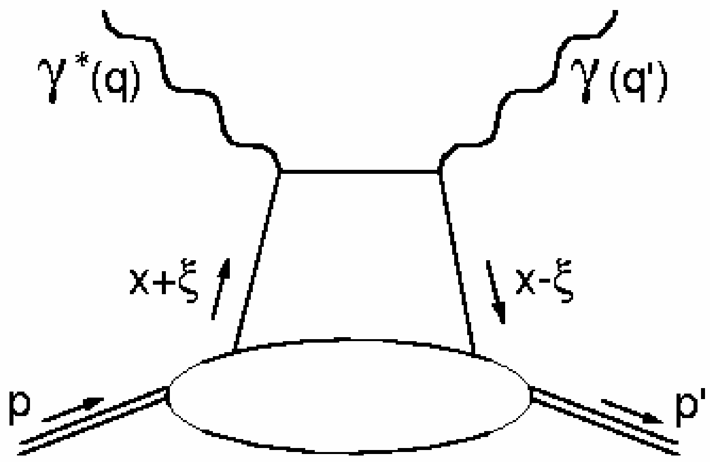
Parity violating lepton scattering



- requires a positron beam
- determines new combinations of Δu, Δd, Δs etc.
- analog sum rule to Bjorken

A. Deshpande

DVCS - Vector Meson Production



- Hard exclusive process
- Photon or vector meson out
- Possible access to skewed or off-forward PDF's
- Access to quark orbital angular momentum
- Theoretical debate continues

$$\int x dx \left[H(x,t,\xi) + E(x,t,\xi)\right] = 2J_q = \Sigma + 2L_q$$

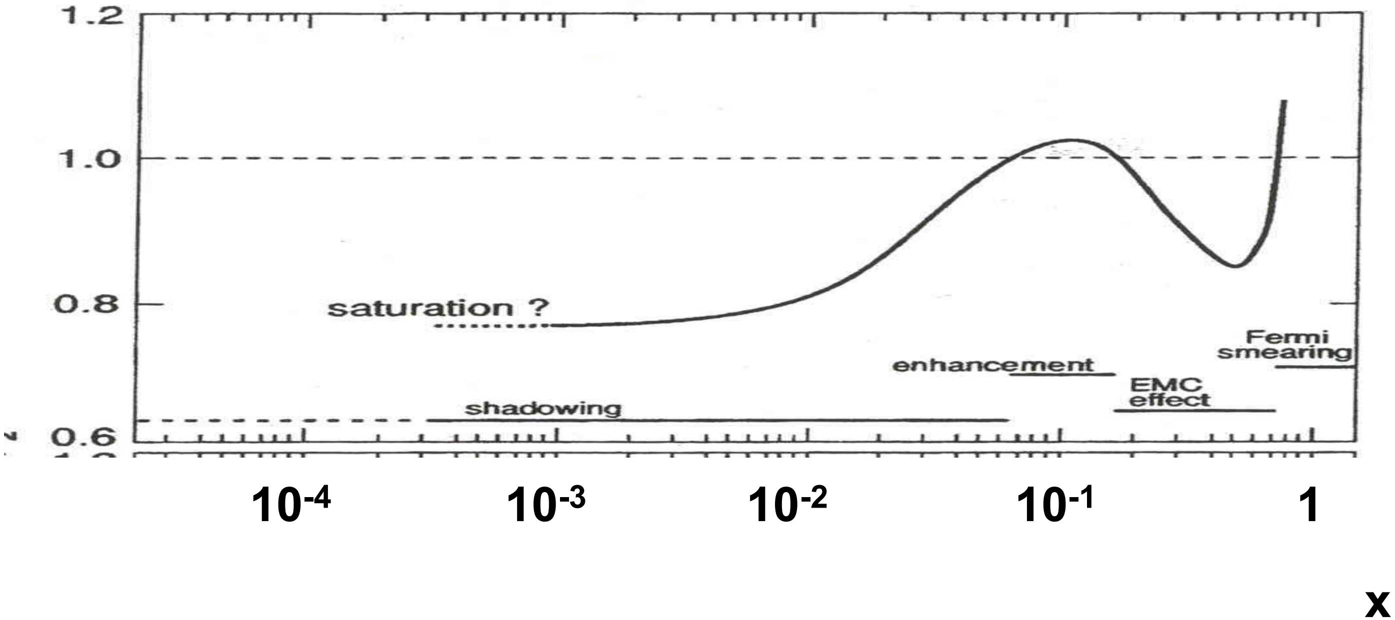
X. Ji

eRHIC will measure the DVCS process over a large range of x and Q^2

Quarks and gluons in Nuclei

- EMC effect: quark momenta are modified compared to the free nucleon

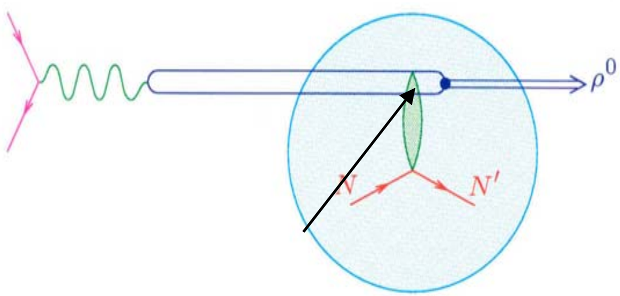
F_2^A/F_2^D



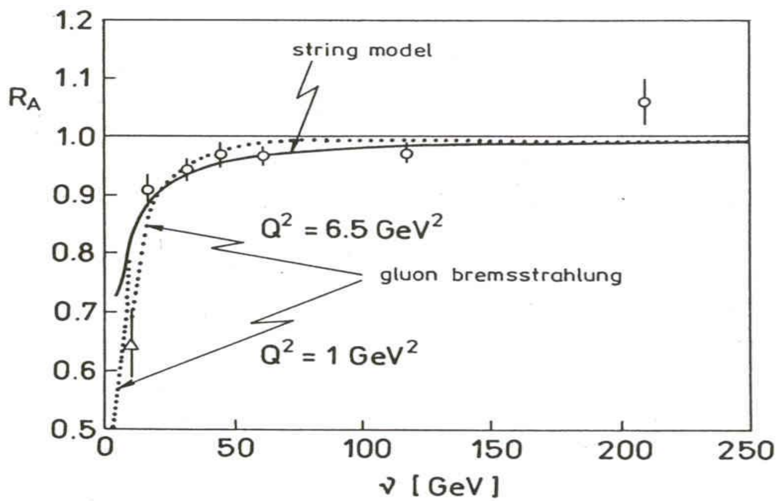
- Gluons in nuclei: almost no experimental information
  - shadowing
  - saturation
  - initial conditions for perfect liquid
- Fast partons traversing nuclei - hadronization

Quarks in the Nucleus

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!)

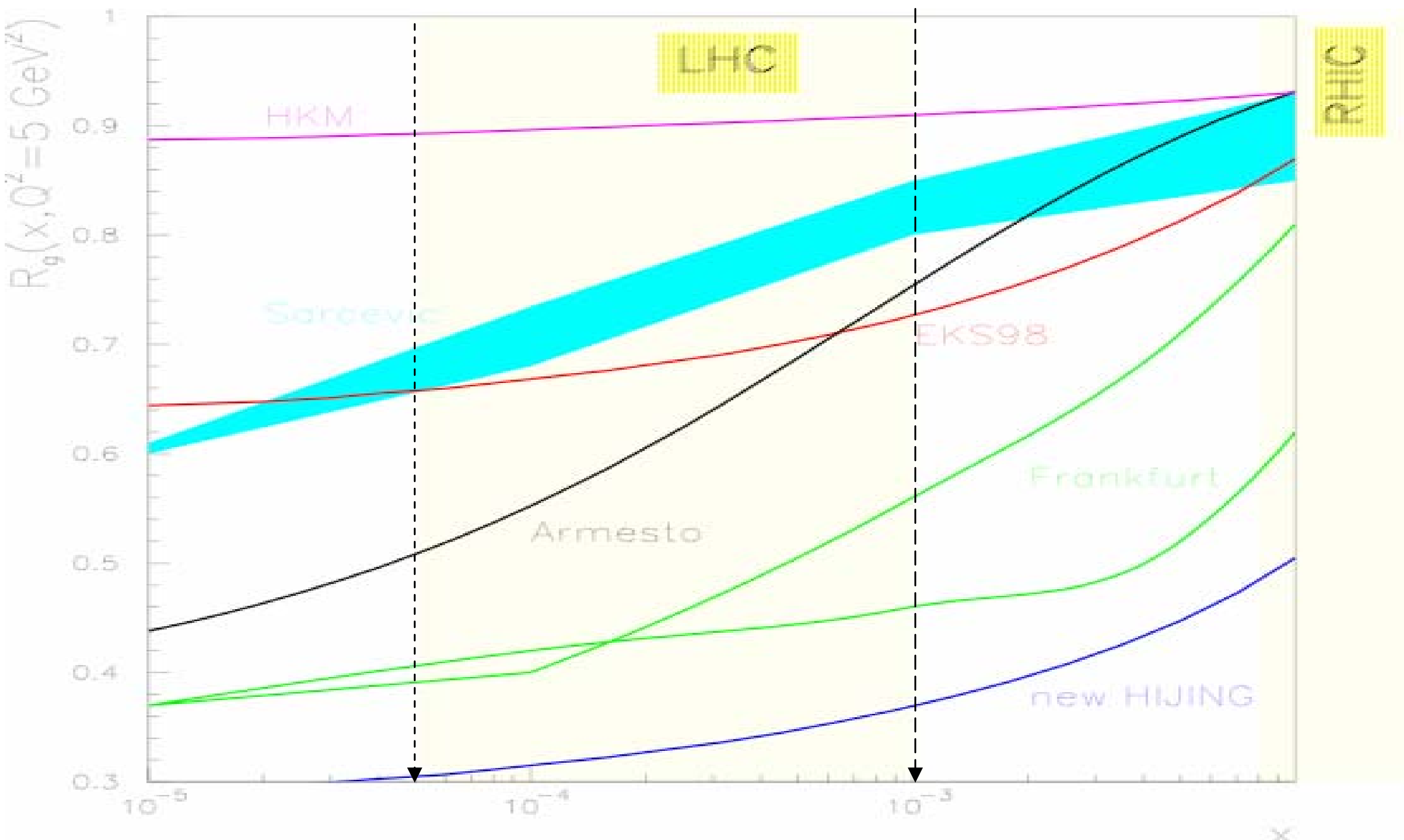


Space-Time Structure of Photon



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

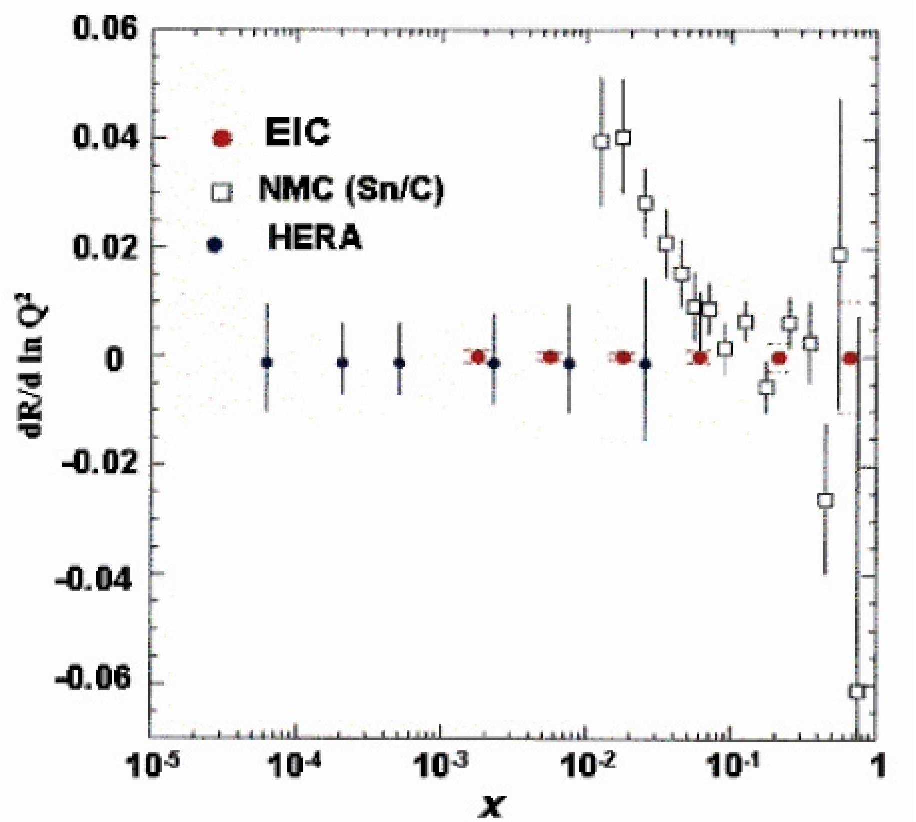
Ratio of Gluon densities in Lead to Proton at $Q^2 = 5\ (GeV/c)^2$



Factor 3 uncertainty in glue => factor 9 uncertainty in semi-hard HI-parton cross-sections at LHC !

R. Venugopalan

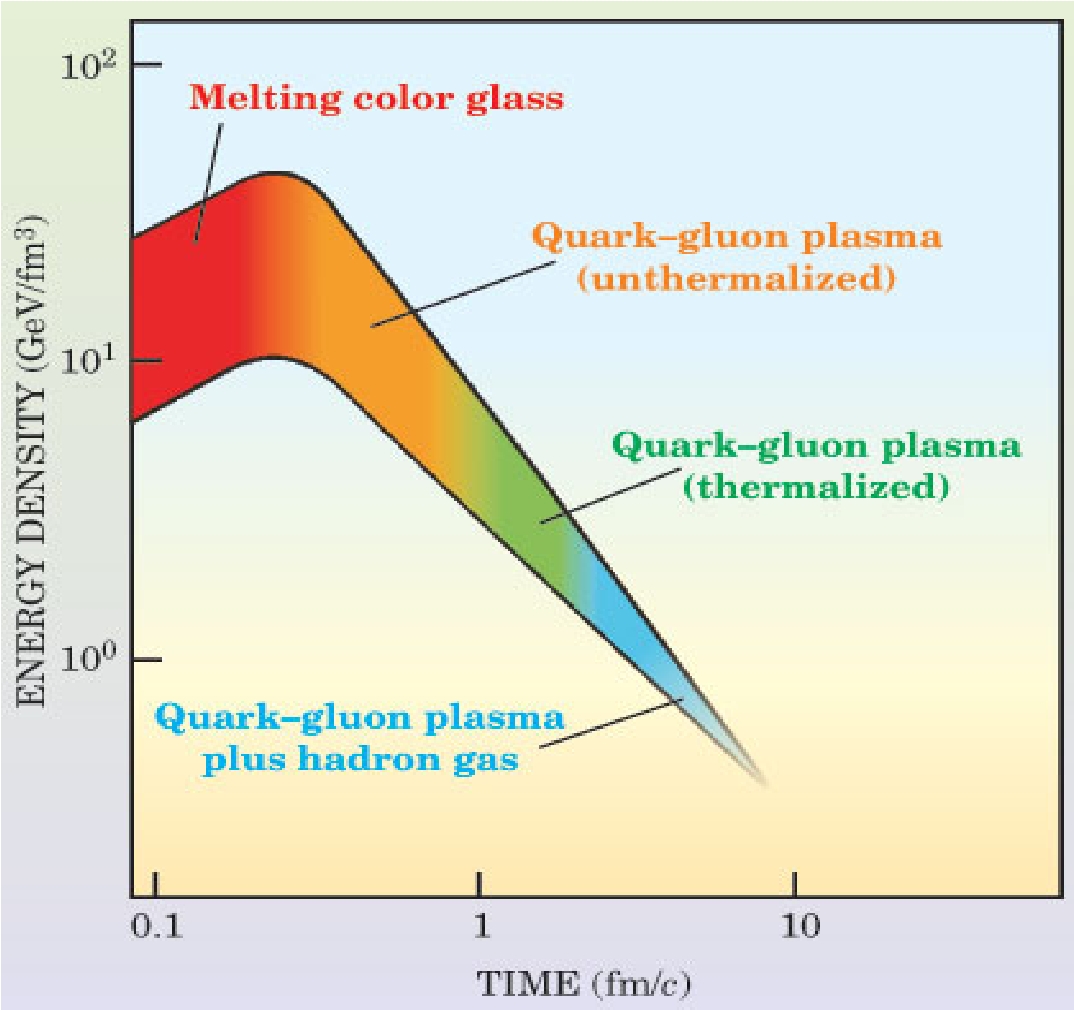
eRHIC projections for nuclear quark distributions



1 pb^{-1}

T. Sloan

Initial conditions for the perfect liquid/QGP



McLerran, Ludlam; Physics Today

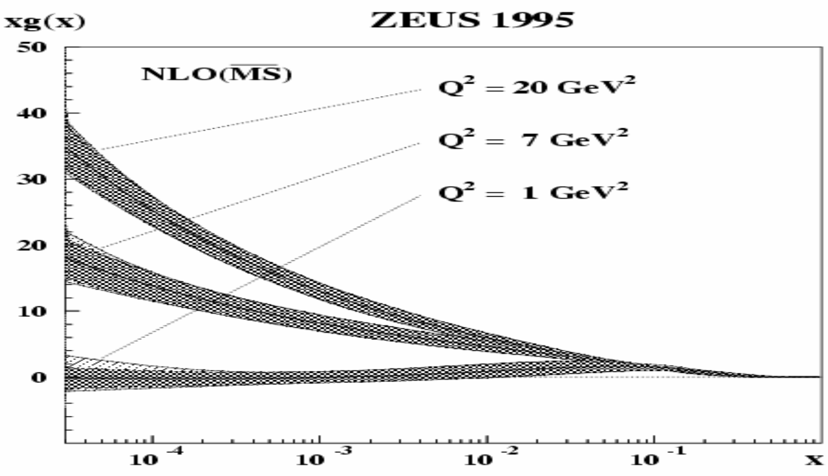
Using Nuclei to Increase the Gluon Density

- Parton density at low x rises as $\frac{1}{x^{\delta}}$
- Unitarity ⇒ saturation at some Q_s^2
- In a nucleus, there is a large enhancement of the parton densities / unit area compared to a nucleon

$$\frac{G_A/\pi R_A^2}{G_N/\pi r_N^2} \approx A^{1/3}\frac{G_A}{A G_N} \approx A^{1/3}$$

$$\approx 6 \quad \text{for} \quad A = 200$$

$$x_{ep}\left(Q_s^2\right) = \frac{X_{eA}\left(Q_s^2\right)}{\left(\frac{4}{3}A^{1/3}\right)^{1/\delta}}$$



Example:

Q^2=4 (GeV/c)^2

δ< 0.3

A = 200

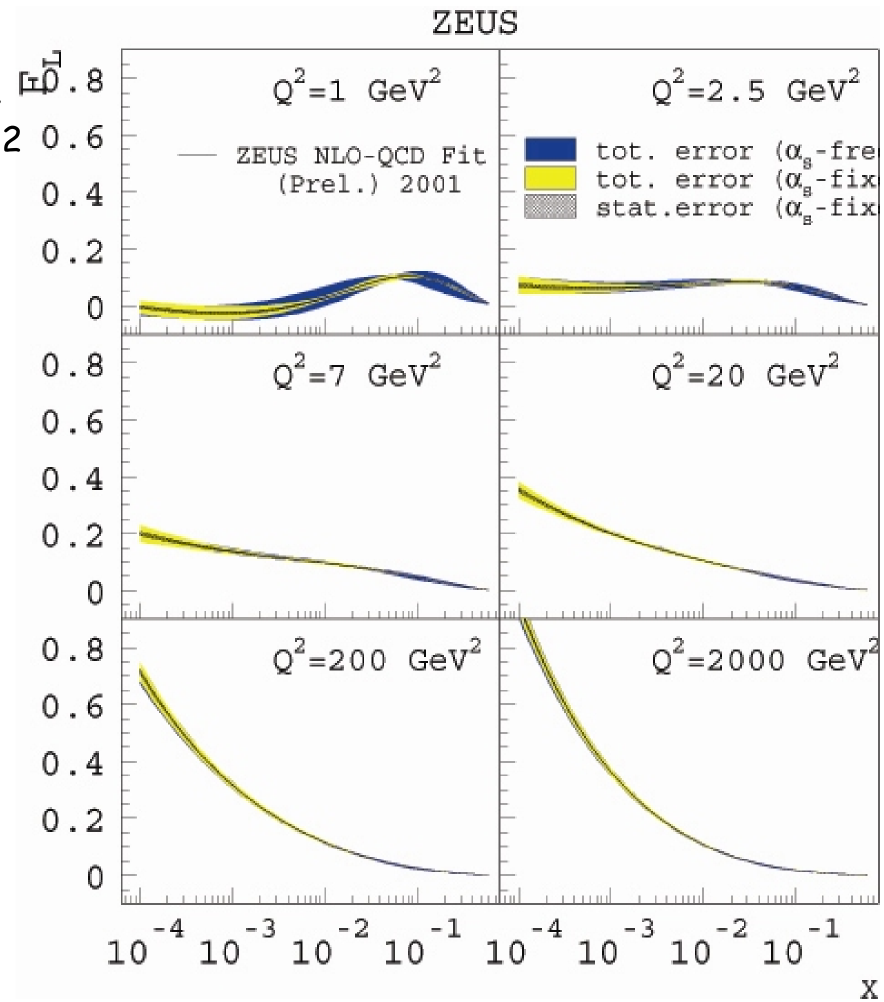
$X_{ep}=10^{-6}$ for $X_{eA} = 10^{-3}$

eA at eRHIC ≈ same parton density as ep at LHC energies!

Longitudinal structure function F_L

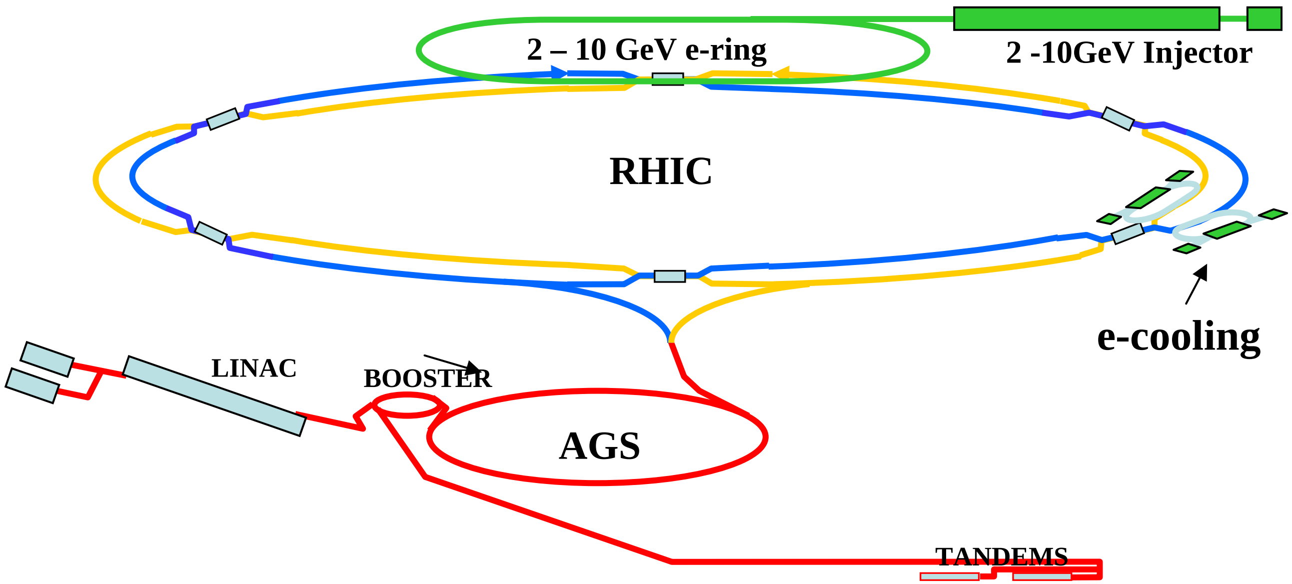
- Extracted from scaling violations of F_2
- Experimentally can be determined directly
- Highly sensitive to effects of gluon
- With precise enough F_2 and F_L one can extract the coefficient λ of the saturation scale
- Logarithmic derivatives of F_2 and F_L with Q will be sensitive to *CGC*

Hopefully, a first measurement at HERA before June 2007



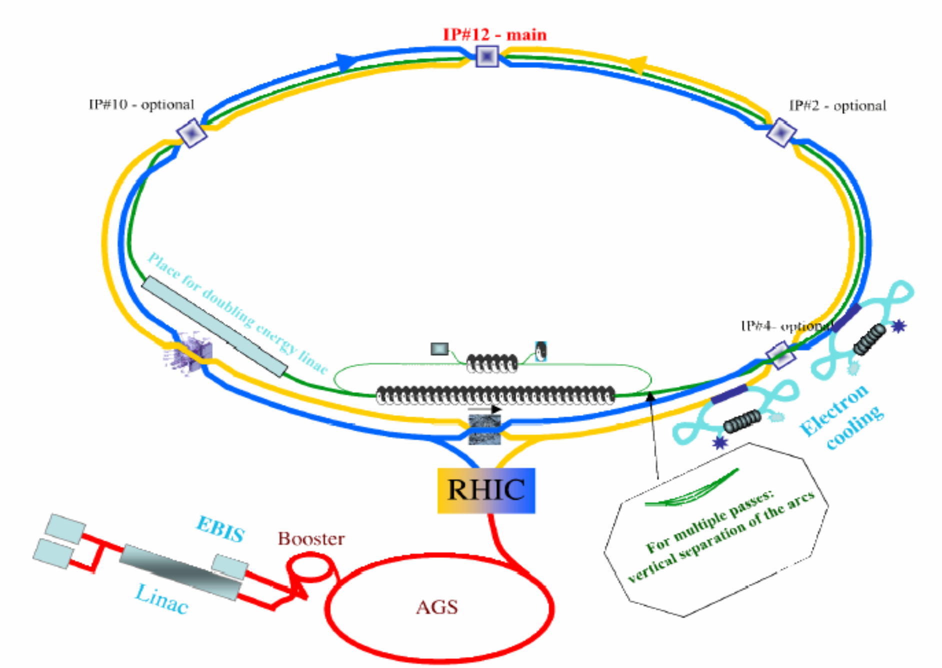
eRHIC ring-ring design

- Collisions at 12 o'clock interaction region
- 10 GeV, 0.5 A e-ring with 1/3 of RHIC circumference
- Inject at full energy 5 – 10 GeV
- Existing RHIC interaction region allows for typical asymmetric detector (similar to HERA or PEP II detectors)



eRHIC: linac-ring concept

- Two possible designs are presented in the ZDR
- Electron beam is transported to collision point(s) directly from superconducting energy recovery linac (ERL)
- Features:
  - Higher luminosity (~ X 5) possible
  - Rapid reversal of electron polarization
  - Machine elements free region approx. ±5m
  - Simpler IR region design: Round beams possible
  - Multiple interaction regions
  - No positrons



eRHIC cost: ~ $ 600 million
eRHIC technically driven schedule: ~ 10 years

https://www.bnl.gov/qcdfp

- Long Range Planning Exercise for Nuclear Physics planned to start in the U.S. in Fall 2006
- Goal: identification of EIC as a major priority for new construction
- Strong European participation very welcome.
- QCD: Future Perspectives Workshop at BNL in July
  RHIC+ RHIC/spin+RHIC II + eRHIC + JLab@12GeV + HERA + LHeC + ...
- Exciting program evolving......

Summary

- A high luminosity lepton-ion collider (EIC) offers a very exciting future for the study of the fundamental structure of matter.
- Polarized $e^{\pm}$ probes in collider geometry will offer unprecedented access to the sea quarks and gluons of the nucleon and atomic nuclei.
- eRHIC appears to be a very attractive means to realize it in a cost-effective and timely way.
- It is essential that the community of physicists working to realize the future of the QCD lab at BNL work together and with the broader QCD community to make EIC a reality in about a decade.

Please come to the July meeting at BNL!