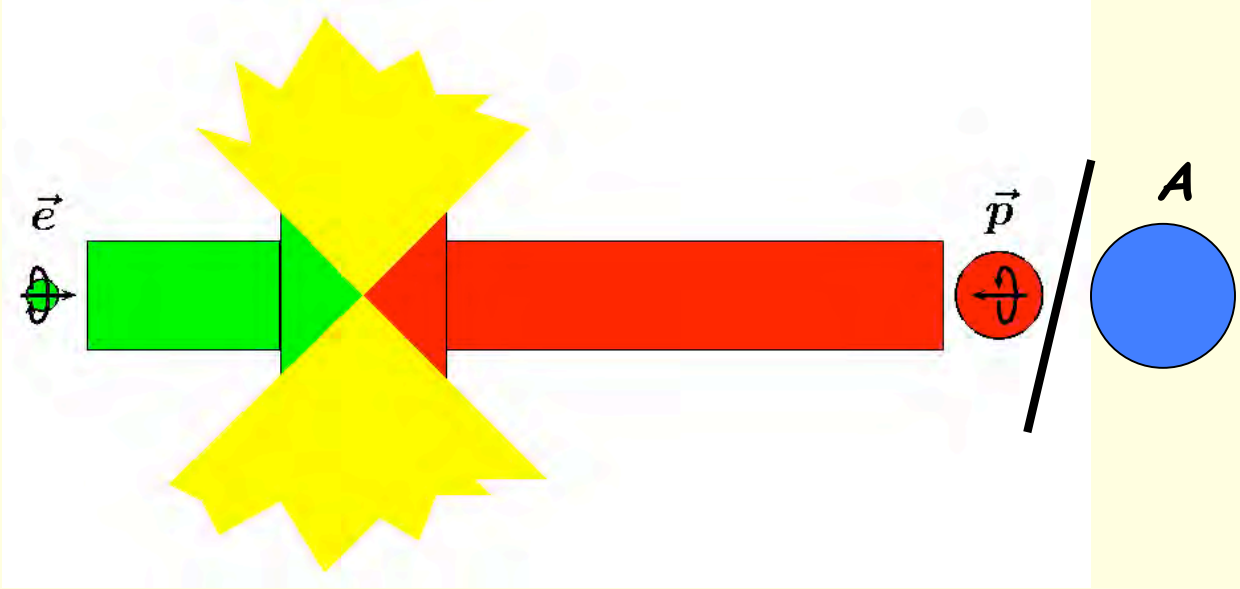
Physics & the Status of the Electron Ion Collider



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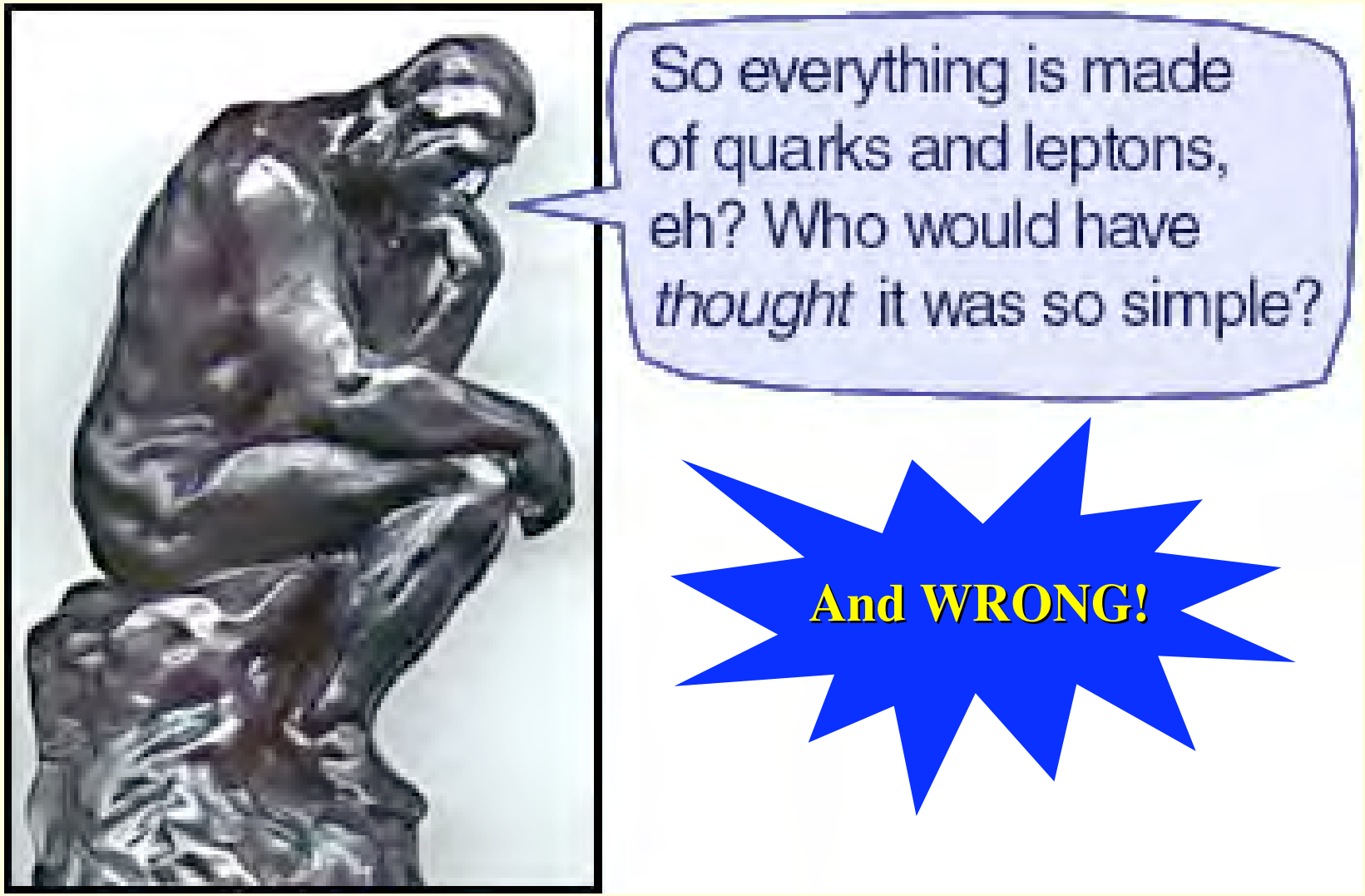
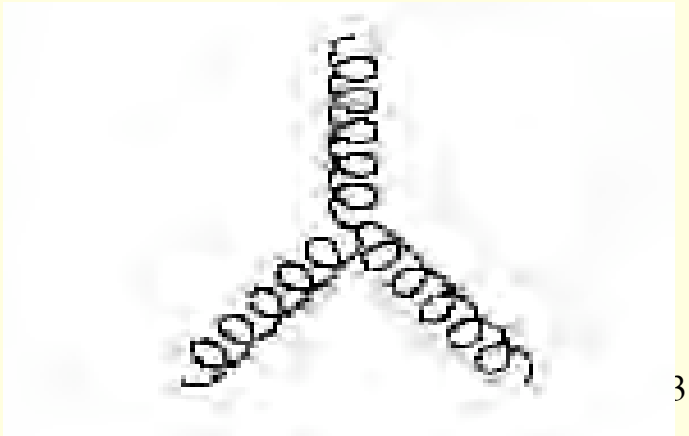

So everything is made of quarks and leptons, eh? Who would have *thought* it was so simple?
And WRONG!

WITHOUT GLUE THERE WOULD BE NO PROTONS, NO NEUTRONS, NO ATOMIC NUCLEI....

INTERACTIONS AMONGST GLUONS DETERMINE THE UNIQUE FEATURES OF STRONG INTERACTIONS!



Fundamental Questions in QCD

- How do gluons contribute to the structure of the nucleon?
- What role do the gluons play in determining the spin structure of the nucleon?
- What is the spatial distribution of the gluons and sea quarks in the nucleon?
- How do the gluons contribute to the structure of the nuclei?
- What are the properties of *high density* gluon matter?
- How do fast quarks and gluons interact when they traverse through nuclear matter?

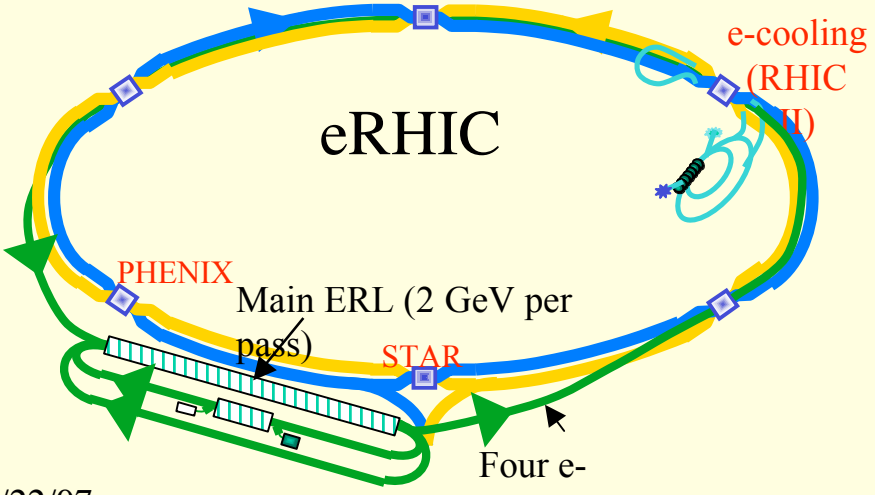
How do we get to the answers?

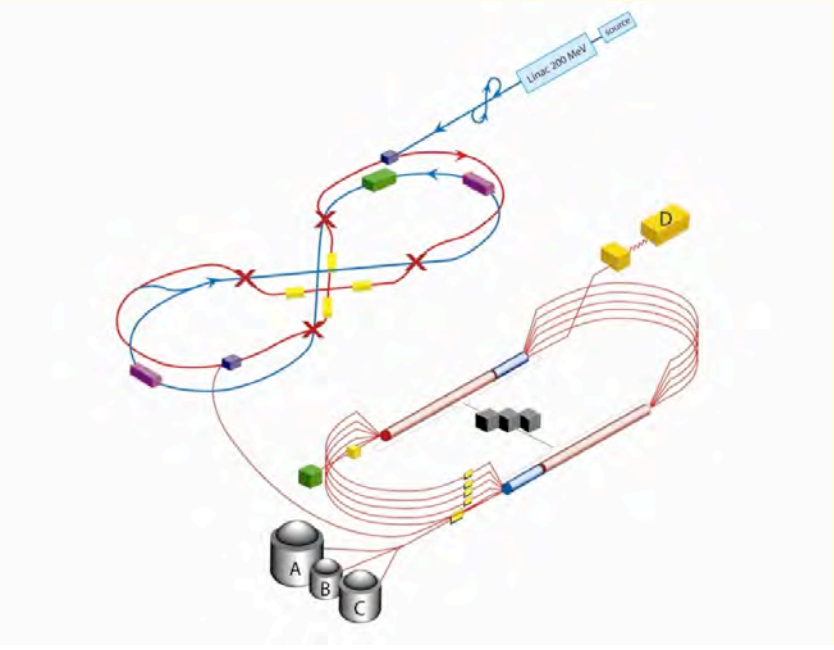
Precise imaging of the sea-quarks and gluons in the nucleon

Need to explore a new QCD frontier: of strong color fields in nuclei

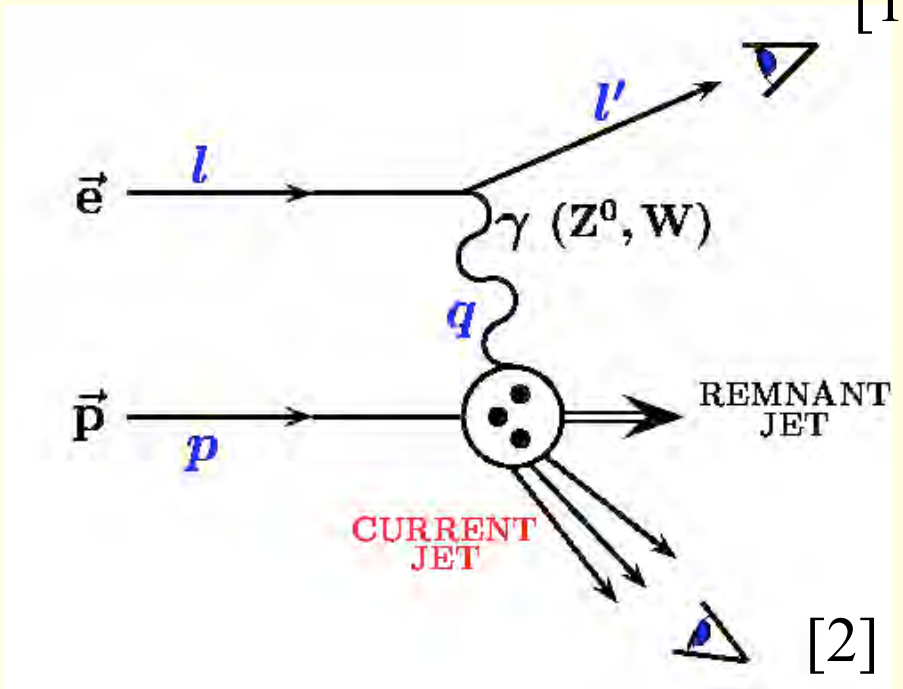
Electron Ion Collider

- Addition of a high energy polarized electron beam facility to the existing RHIC will drastically enhance our ability to study fundamental and universal aspects of QCD [**eRHIC**]
  - Alternatively, one could add a high energy hadron/nuclear beam facility at Jefferson Laboratory [**EL**ectron **I**on **C**ollider: **ELIC**]





Deep Inelastic Scattering



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

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

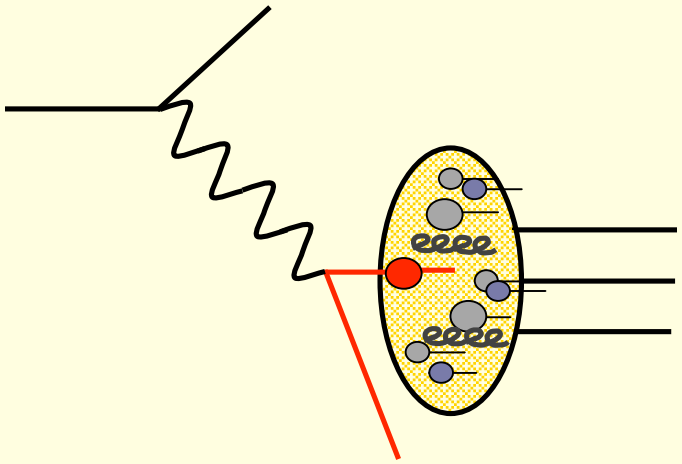
$$y = \frac{p \cdot q}{p \cdot l}$$

$$s = 4E_e E_p$$

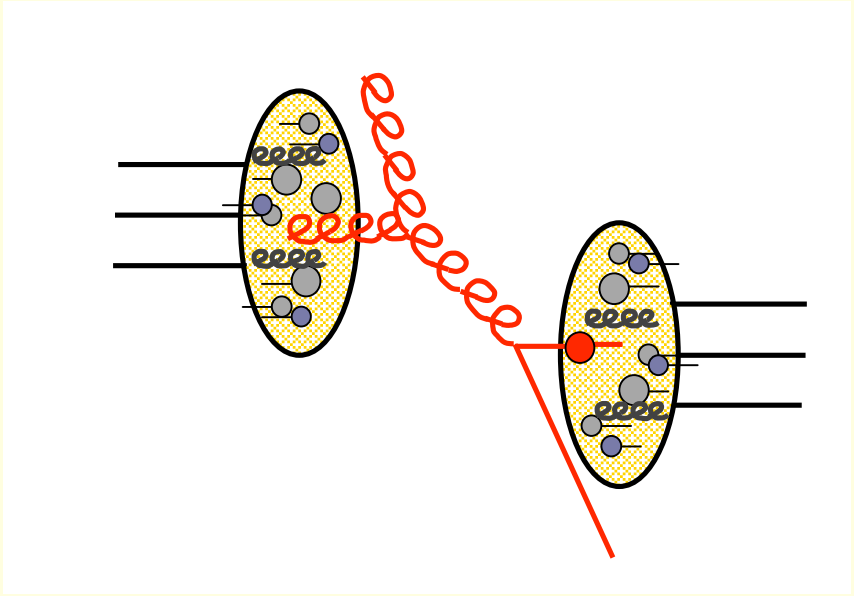
$$W = (q + p)^2$$

- Observe scattered electron [1] **inclusive** measurement : **< 2 fb^{-1}**
- Observe [1] + current jet [2] **semi-inclusive** measurement **4-5 fb^{-1}**
- Observe [1] + [2] + remnant jet [3] exclusive measurement **> 10 fb^{-1}**
- Luminosity requirements go up as we go from [1] --> [2] --> [3]
- **Exclusive measurements put demanding requirement on detectors, interaction region and their integration**

DIS

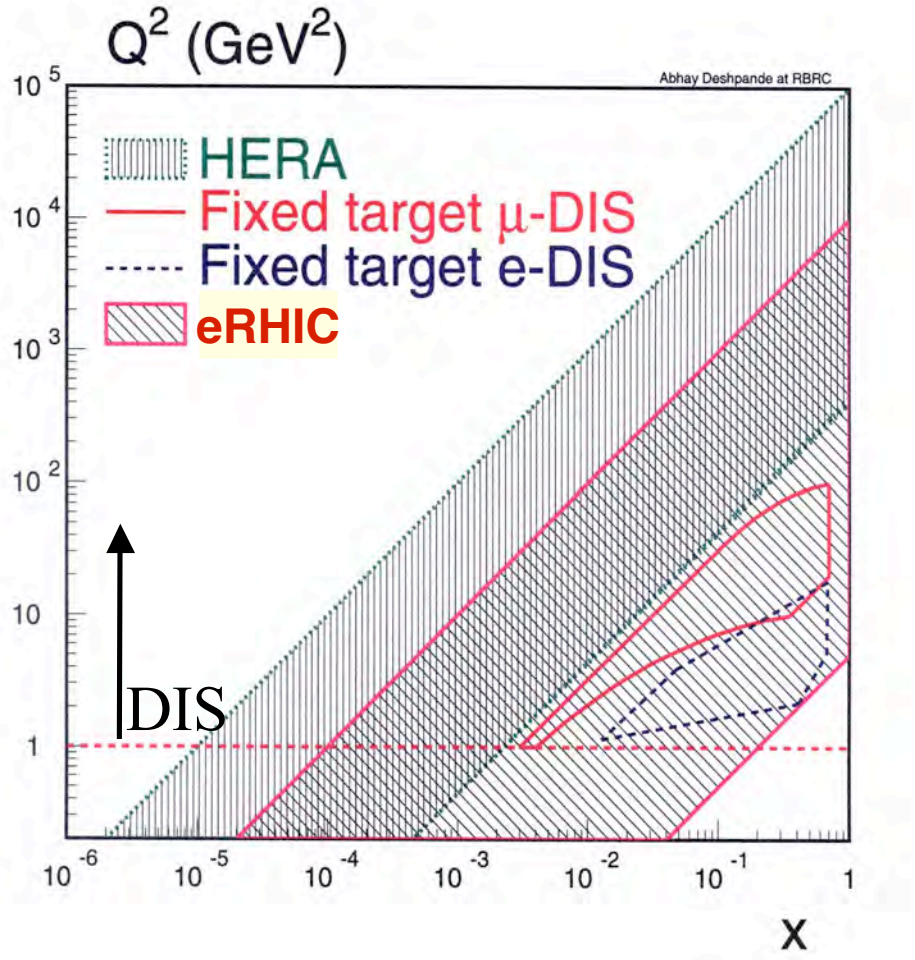


H-H



- DIS: precise kinematics is known event by event even for inclusive scattering
  - No ‘direct’ photon-gluon interaction
- H-H: no knowledge of event kinematics in inclusive scattering
  - Direct interactions between gluons and quarks IS the prime attractive feature…

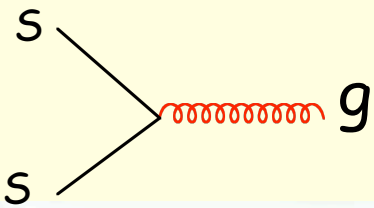
eRHIC vs. Other DIS Facilities



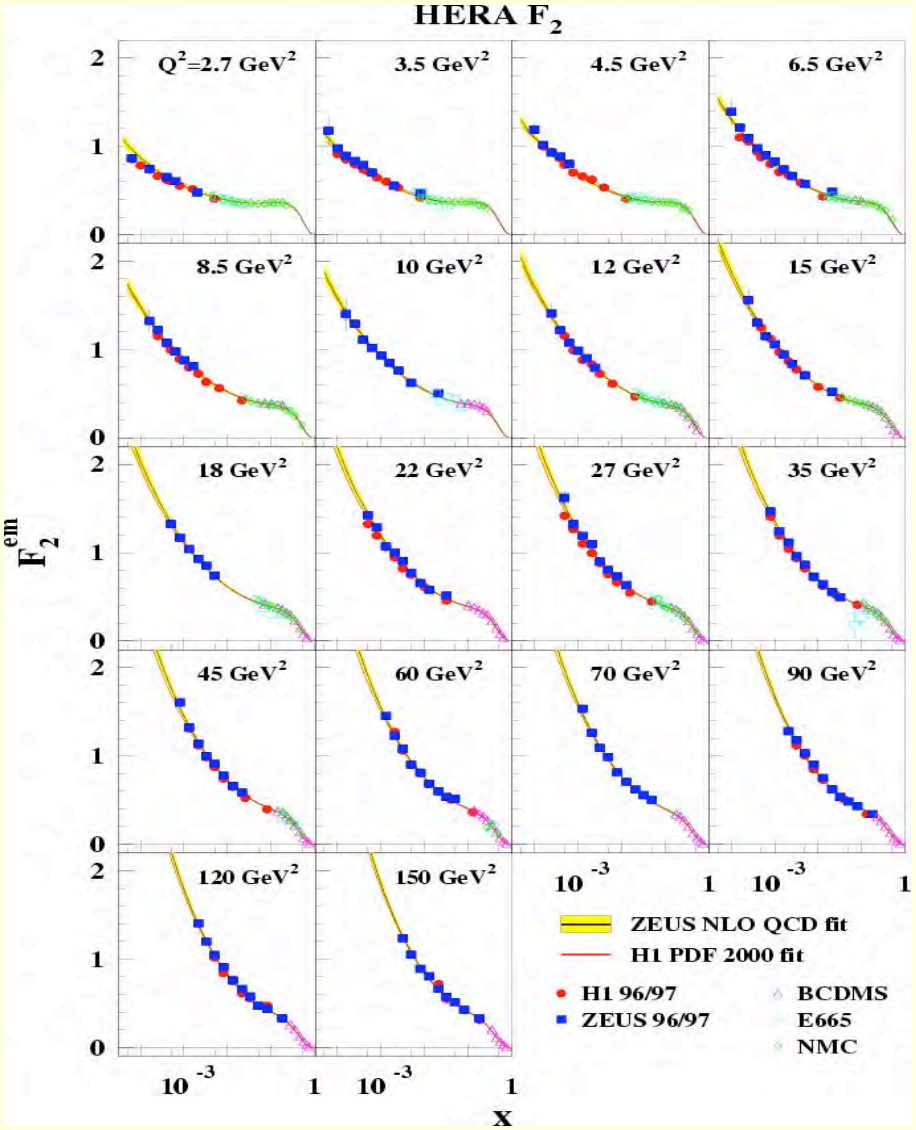
- **New kinematic region**
- E_e = 10 GeV (~5-20 GeV variable)
- E_p = 250 GeV (~50-250 GeV)
- E_A= 100 GeV
- **Sqrt[S_{ep}] = 30-100 GeV**
- Kinematic reach of eRHIC:
  - **$X = 10^{-4}$ --> 0.7 ($Q^2 > 1$ GeV^2)**
  - **$Q^2 = 0$ --> 10^4 GeV^2**
- **Polarization of e,p and light ion beams at least ~ 70% or better**
- **Heavy ions of ALL species at RHIC**
- Machine Luminosities envisioned
  - **L(ep) ~$10^{33\text{-}34}$ cm^{-2} sec^{-1}**
- **Luminosity GOAL: 50 fb^{-1} in 10 years**
  - **possible with 10^{33} cm^{-2} sec^{-1}**

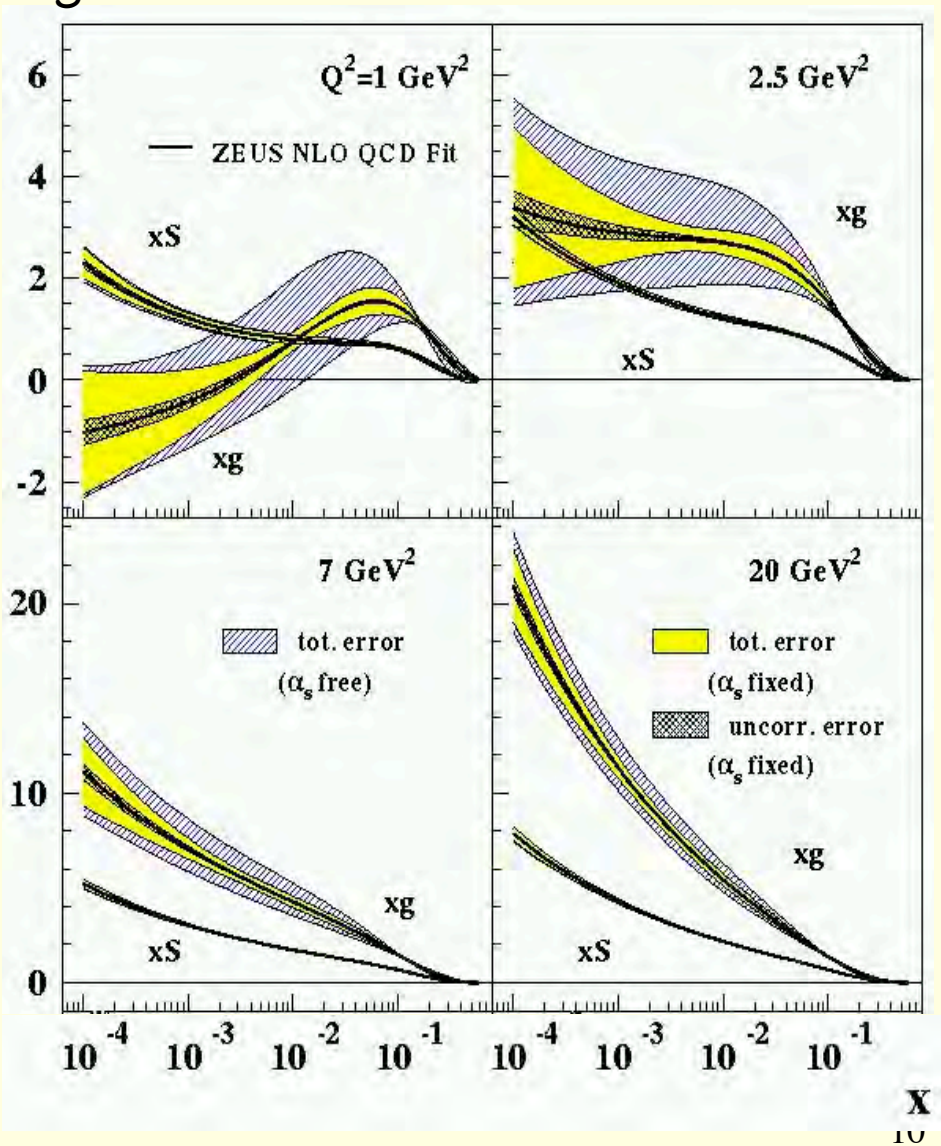
Nucleon Structure (including spin)

A low Q^2 puzzle ...



xS > xg ???





Is it really OK to use pQCD at such low Q^2 ?

It would be best if we can get to the gluon distribution by some other method. ---> Measurement of F_L

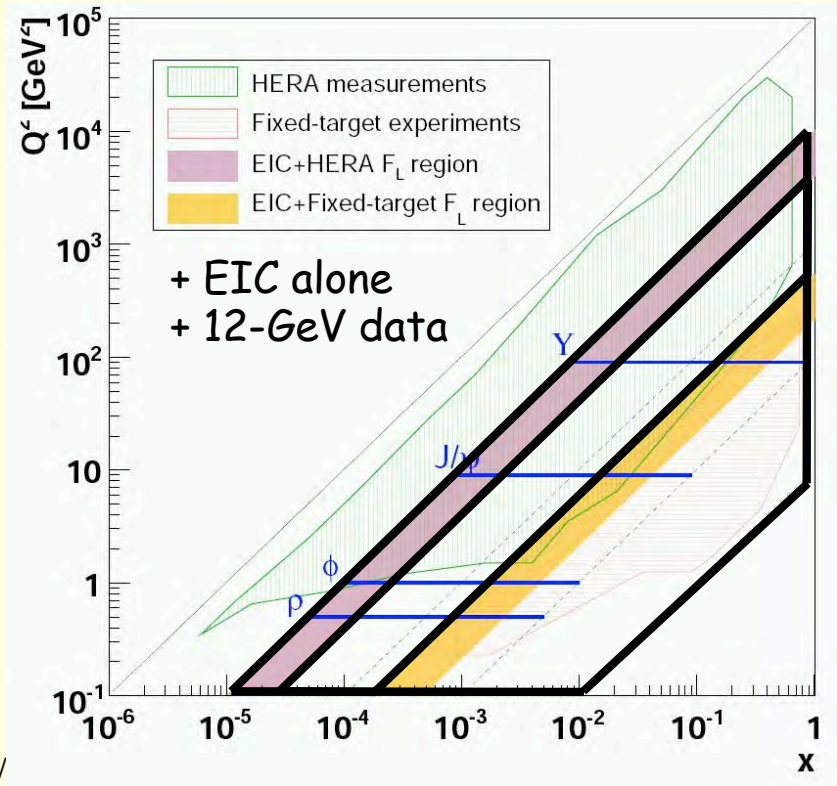
Deep Inelastic Scattering :

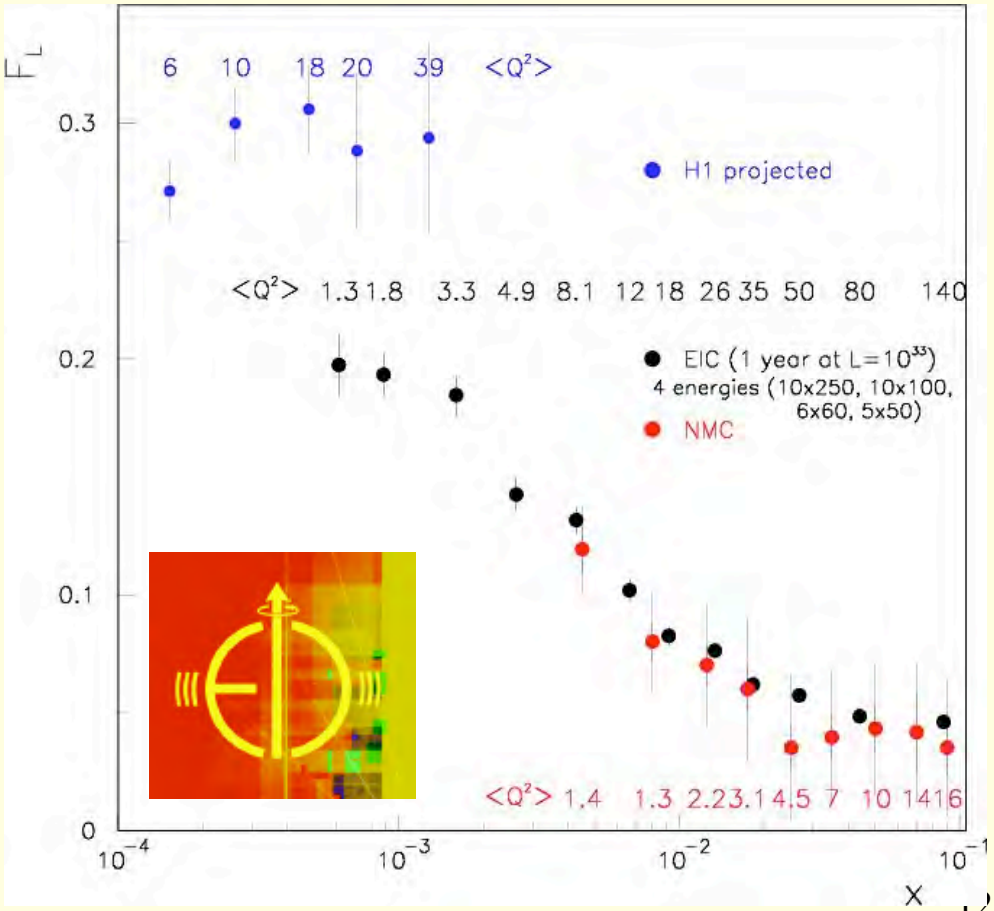
$$\frac{d^2\sigma^{ep\to eX}}{dxdQ^2} = \frac{4\pi\alpha_{e.m.}^2}{xQ^4}\left[\left(1-y+\frac{y^2}{2}\right)F_2(x,Q^2) - \frac{y^2}{2}F_L(x,Q^2)\right]$$

$$F_L \propto \frac{\alpha_s}{2\pi}\, x \int_x^1 \frac{d\xi}{\xi}\, \xi(1-\xi)\, g\left(\frac{x}{\xi}, Q^2\right) + \ldots$$

Longitudinal Structure Function F_L

- Requires energy variability of collider beam with minimal loss of luminosity
- Highly sensitive to effects of gluon, and an independent method to get to gluon distribution





(includes systematic uncertainties)

Physics with polarized beams at the EIC

- A comprehensive understanding of the nucleon spin structure:

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

  - Fixed target experiments ΔΣ…SLAC, CERN, DESY, Jlab
  - ΔG and L investigations starting… RHIC, Jlab, CERN
  - EIC: a precision device for these measurements

- …and precision tests and measurements…
  - Bjorken Spin Sum rule
  - Determination of strong interaction coupling $\alpha_s(Q^2)$

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 1-2% accuracy
- **Polarized gluon distribution function $\Delta G(x,Q^2)$*** **[1,2]**

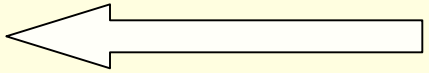
  -- at least three different experimental methods
- Precision measurement of $\alpha_S(Q2)$ from g_1 scaling violations [1]
- Spin structure of the photon from photo-production [2]
- Electroweak s. f. g_5 via virtual **$W^{+/-}$ production*** **(heavy quarks)** **[2]**
- Deeply Virtual Compton Scattering (DVCS), exclusive VM production

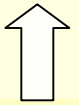
  >> Generalized Parton Distributions (GPDs) [3]
- **Transverse Spin Phenomena*** **[2,3]**
- Drell-Hearn-Gerasimov spin sum rule test at high ν [1]
- Flavor separation of PDFs through semi-inclusive DIS [2]
- Target/Current fragmentation studies [2,3]
- *… and many more ……*

***Also being pursued at RHIC Spin Now.**

[1] --> inclusive, [2]--> semi-inclusive

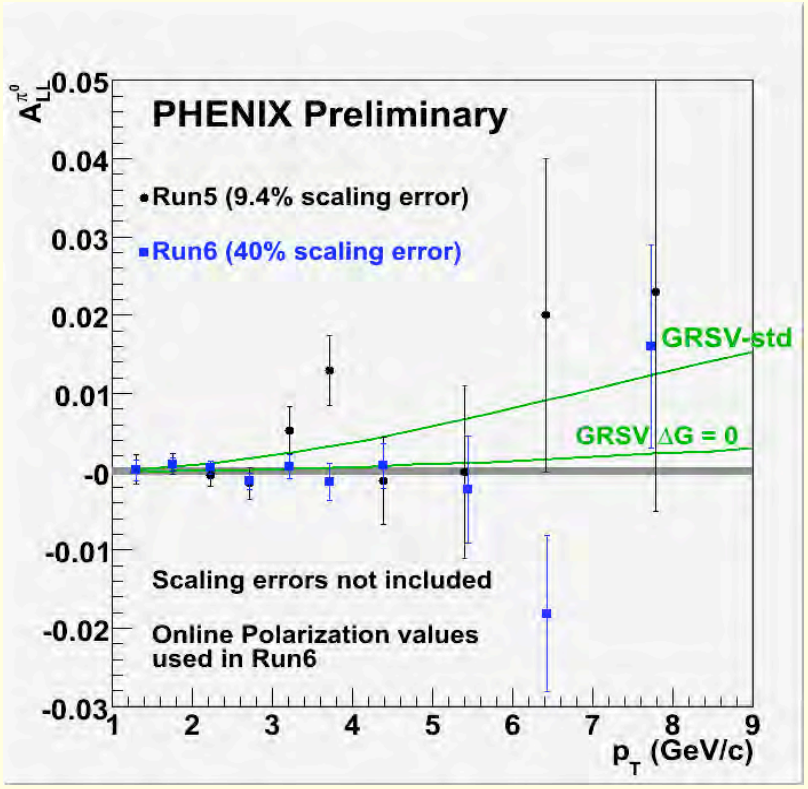
[3] --> exclusive measurements

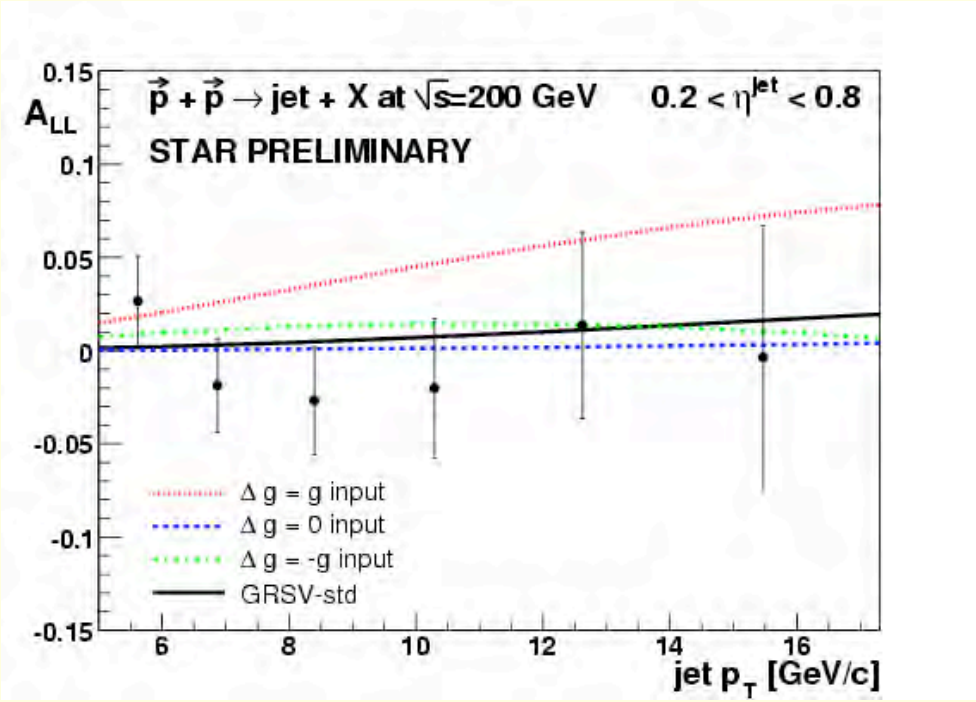




Luminosity Requirement

New Data from RHIC Spin:



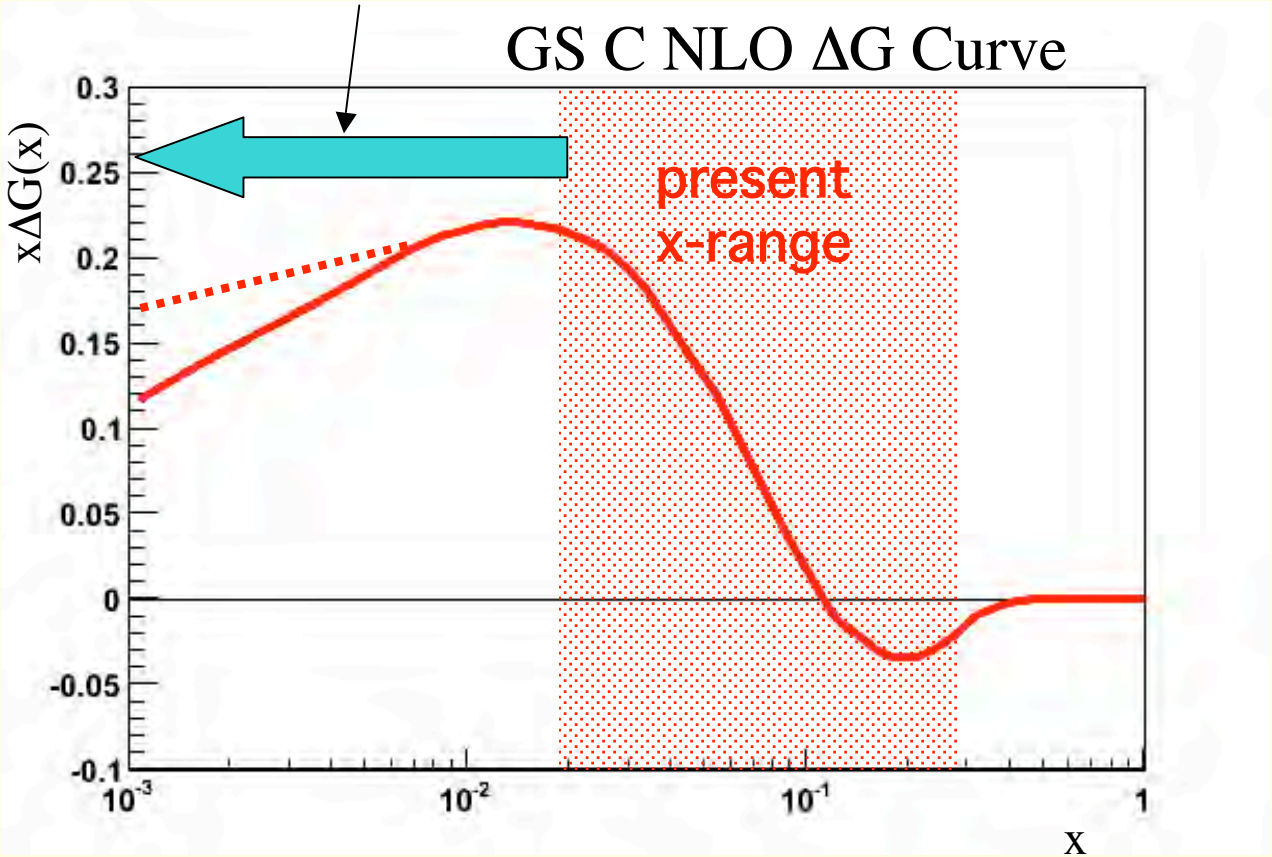


In the approximate x-range (0.02-0.3) covered by experiments, ΔG seems to be small

Focused direct and indirect ΔG measurements at low x with high precision are of *even* greater importance

RHIC x region slide....

Accessible with future detector upgrades and 500 GeV



However, a wider kinematical measurement still a better option…

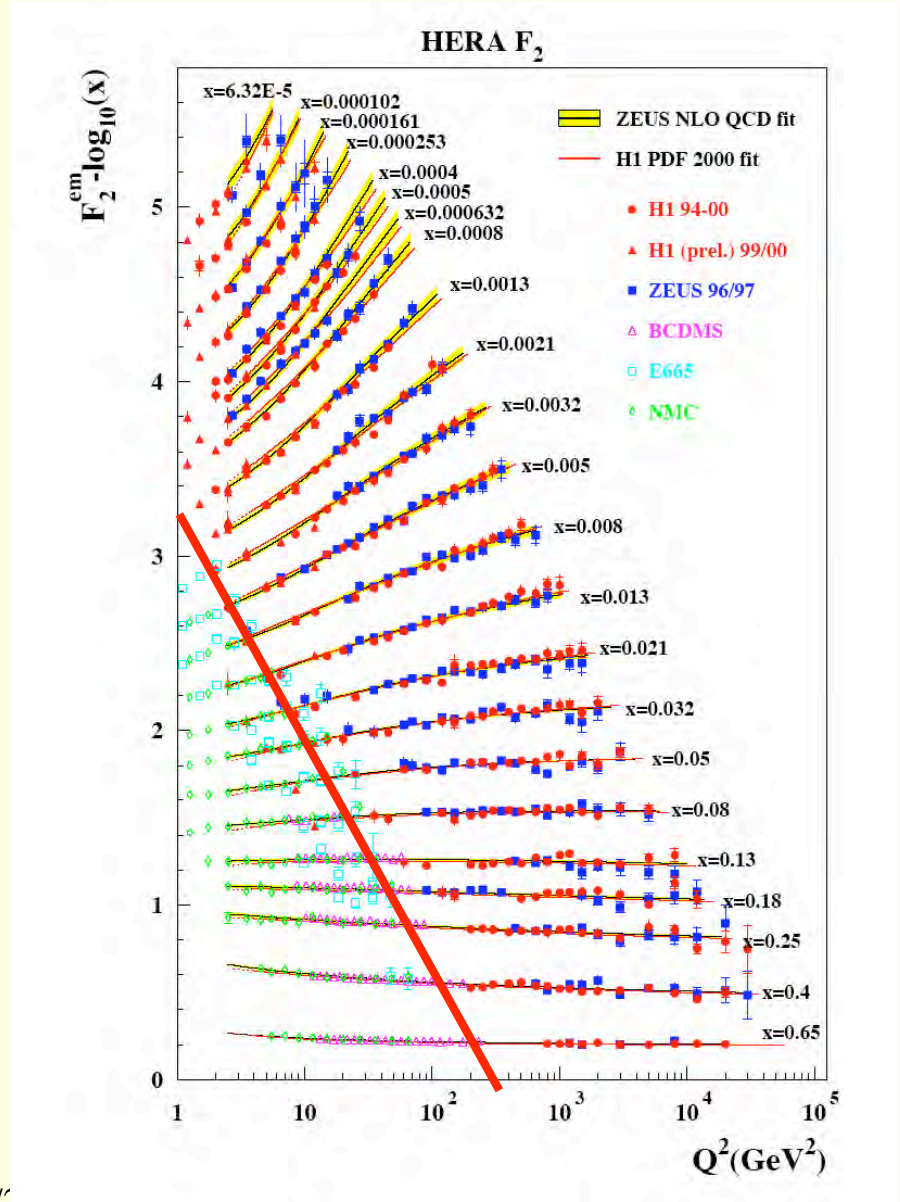
Inclusive Measurements
< 2 fb^{-1}

EM Calorimetry

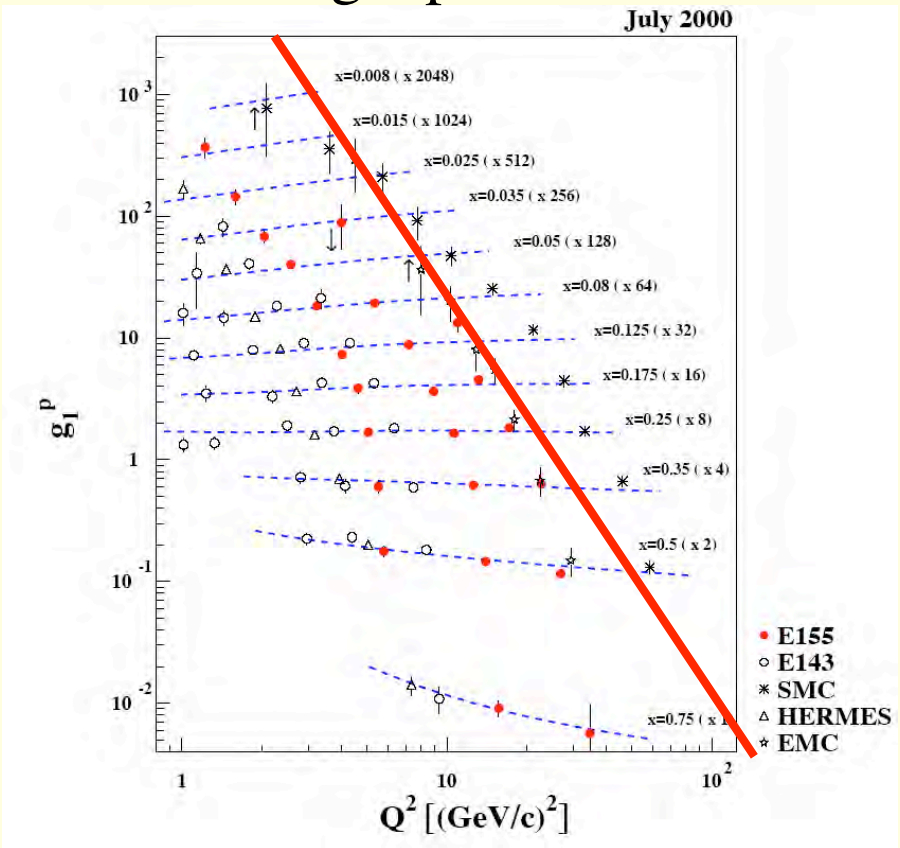
Tracking

Our Knowledge of Structure Functions

HERA un-polarizd DIS

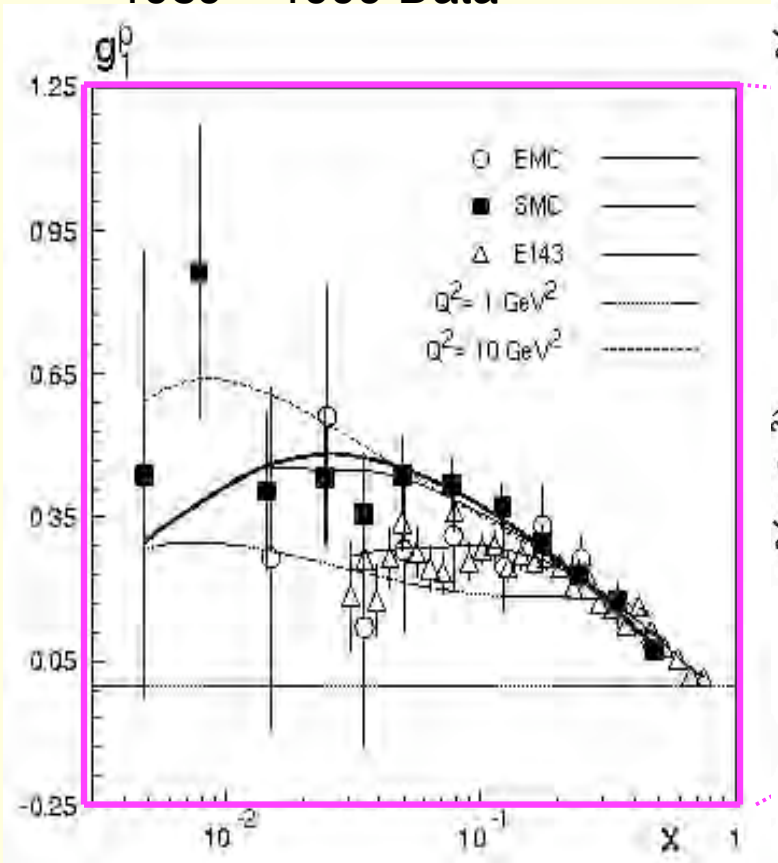


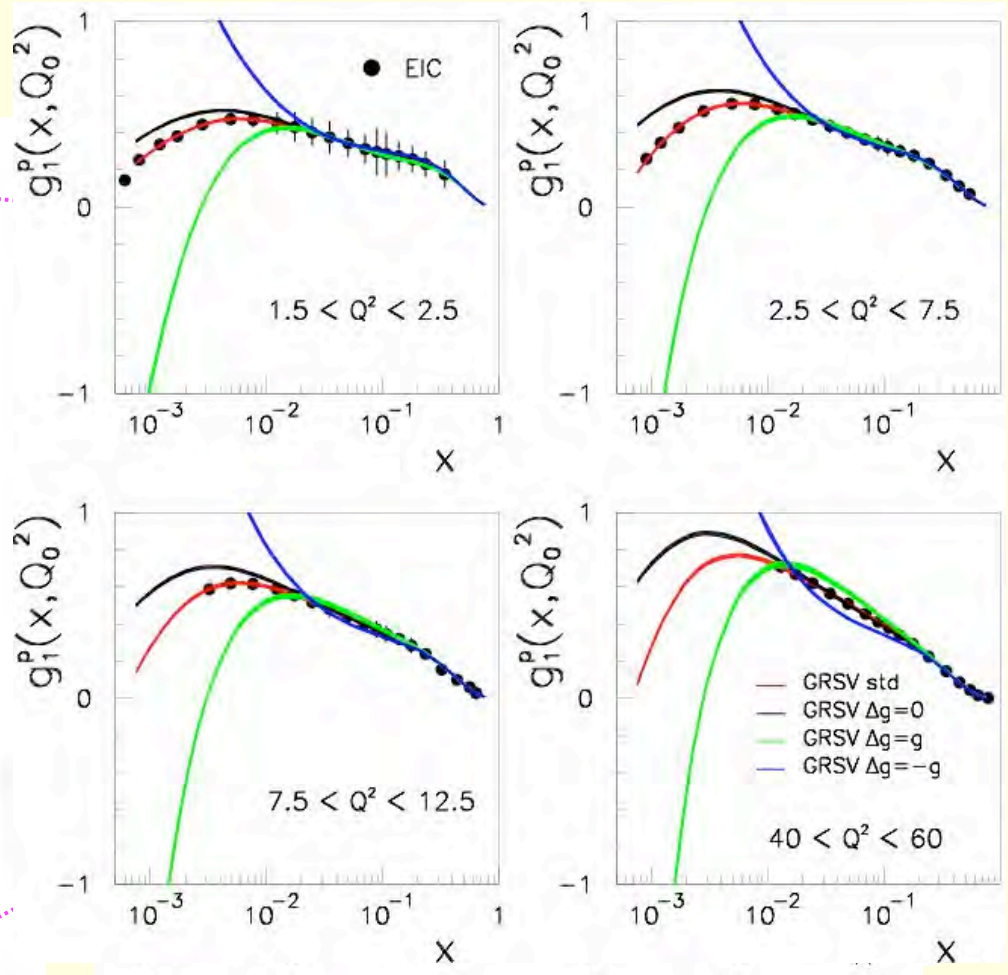
Fixed target polarized DIS



Spin Structure at Low x & ΔG

Fixed target experiments
1989 – 1999 Data

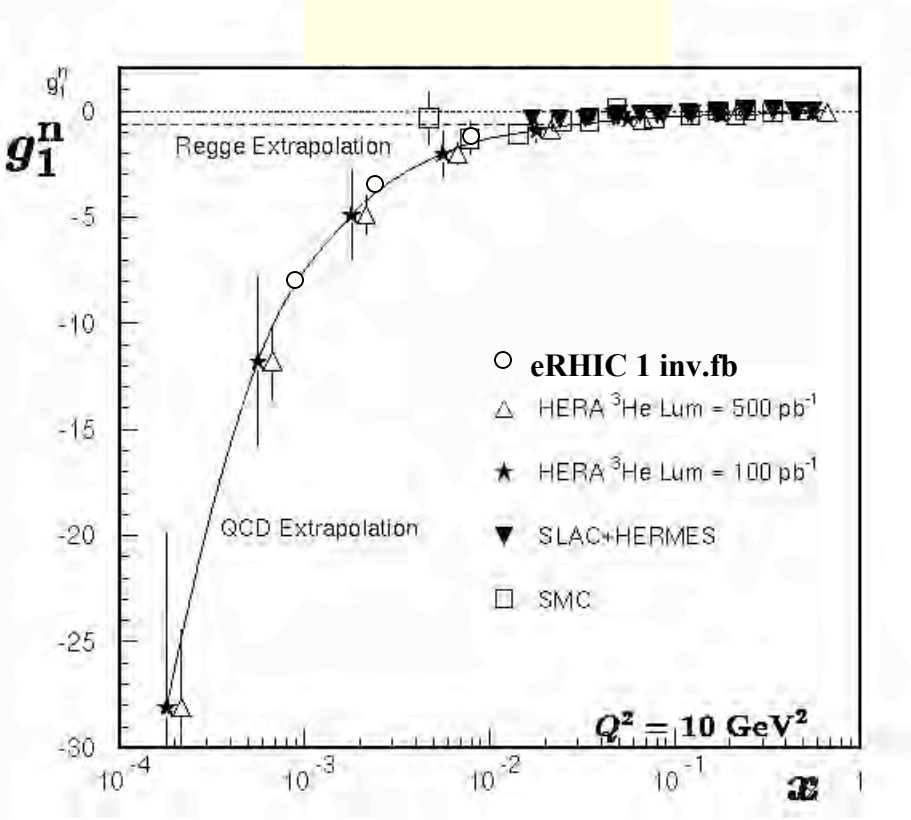




Studies included statistical error & detector smearing to confirm that asymmetries are measurable. No present or future approved experiment will be able to make this measurement

Beautiful program to complement and extend the RHIC Spin Program

Spin Structure of Neutron at Low x



- With polarized He
- ~ 2 weeks of data at EIC
- Compared with SMC & other projections
- **If combined with g1 of proton results in Bjorken sum rule test of better than 1-2% within a couple of months of running**

$$\Gamma_1^p - \Gamma_1^n = \frac{1}{6}\left|\frac{g_A}{g_V}\right| C_1^{NS}(Q^2)$$

Helium beams **can be stored & manipulated** in RHIC with **existing magnets**
Intense He beams & polarimetry need to be developed.
Both efforts need to start now!

Bj Sum Rule & Determination of α_s

$\alpha_s(M_Z)$ has been determined from Bj spin sum rule by many groups:

1. J. Ellis & M. Karliner, Phys. Lett. B341, 387 (1995)
2. G. Altarelli et al., Nucl. Phys. B496, 337 (1997)
3. B. Adeva et al. SMC Collaboration, Phys. Rev. D58 (1998) 112002
4. …….

Largest Uncertainties from low-x extrapolations!

$$\Gamma_1^p - \Gamma_1^n = \frac{1}{6}\left|\frac{g_A}{g_V}\right| C_1^{NS}(Q^2)$$

Particle Data Book (2002, 2004,2006), Extended version:

"Theoretically, this sum rule is better for determining α_s because perturbative QCD result is known to higher order (o(α_s^4)), and these terms are important at low Q^2…….. **Should data at lower x become available**, so that the low x extrapolation is more tightly constrained, the ***Bj sum rule method could give the best determination of α_s***"

Semi Inclusive Measurements

2-10 fb^{-1}

Good particle ID

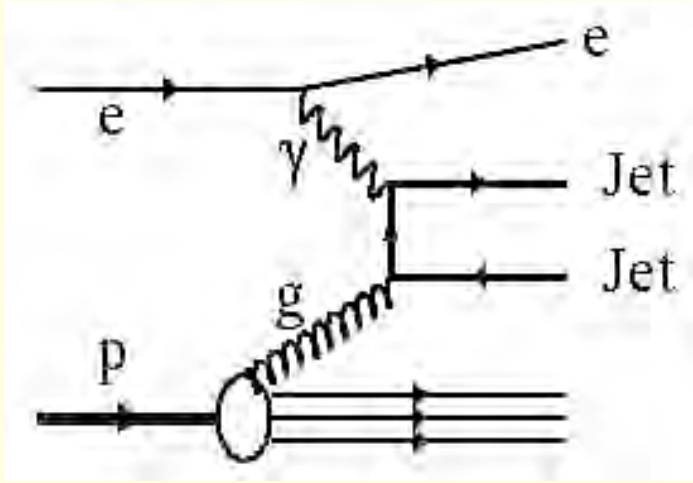
EM and HCAL

Tracking

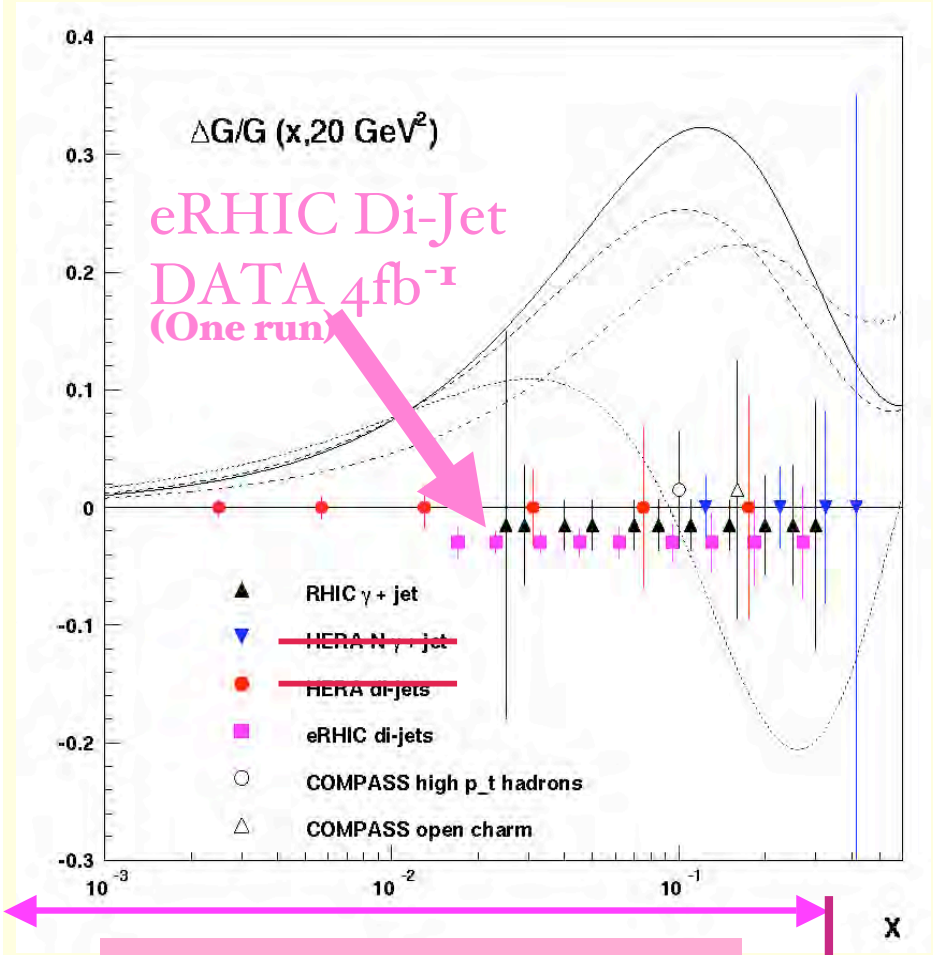
High Rate Environment

Other ways to get to the Polarized Gluon Distribution

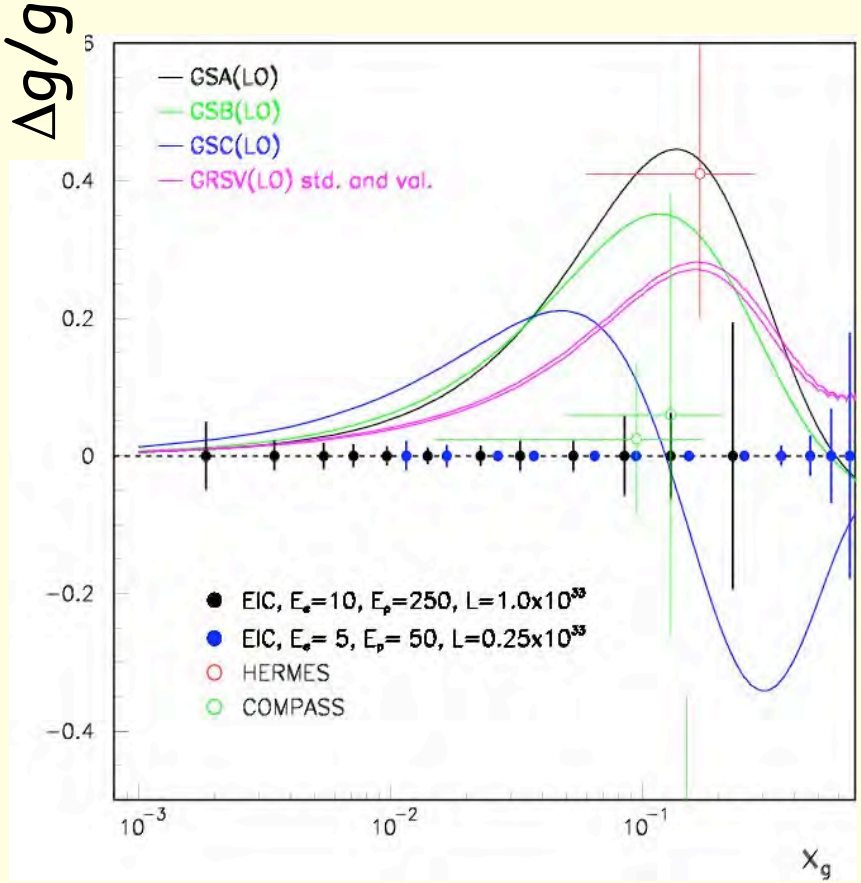
- While we expect scaling violations to be the best extractor of polarized gluon distribution over a wide range, it is important confirm / cross check with other methods…
- Semi-Inclusive Probes of polarized gluon distribution
  - All based on photon-gluon fusion reaction
  - Di-Jet, Di-hadron production, heavy quark (D^0 production)



ΔG from Di-Jets and Charm



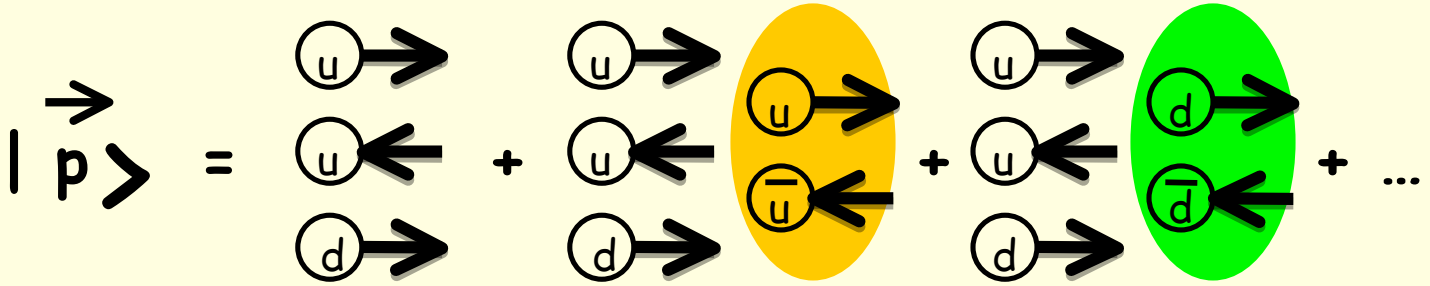
ΔG from scaling violations
$> x_{min} \sim 10^{-4}$ at eRHIC



Projected data on Δg/g with an EIC, via $\gamma + p \rightarrow D^0 + X$
$\hookrightarrow K^- + \pi^+$

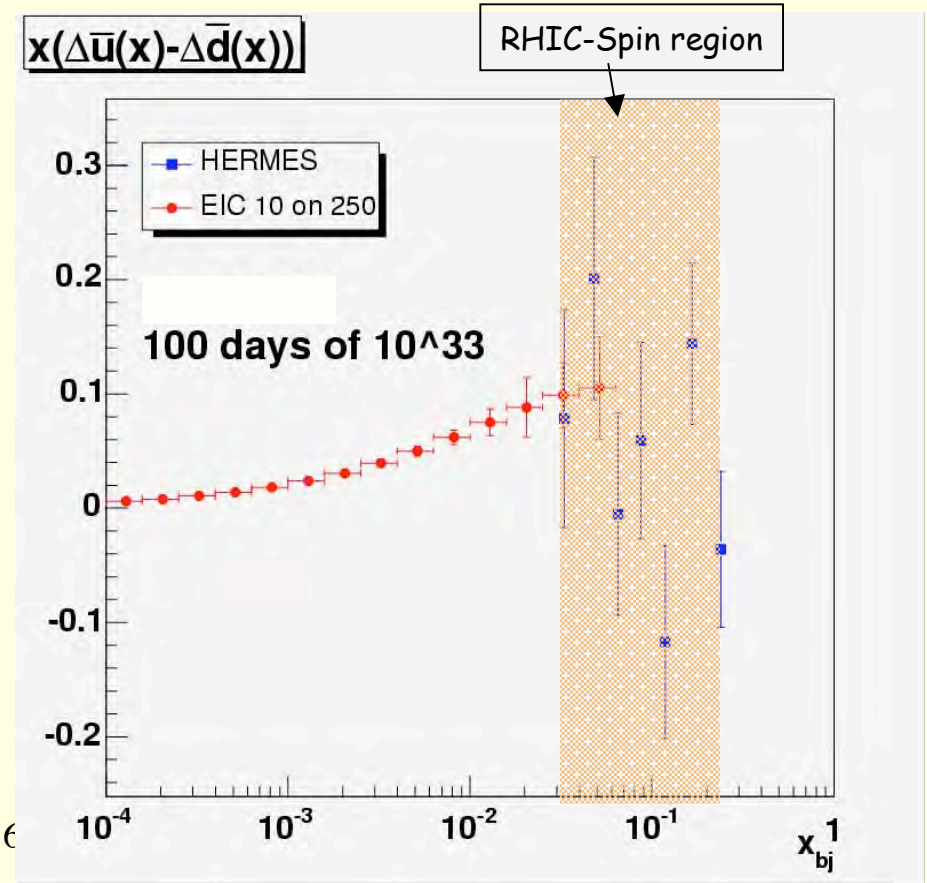
Precisely image the sea quarks

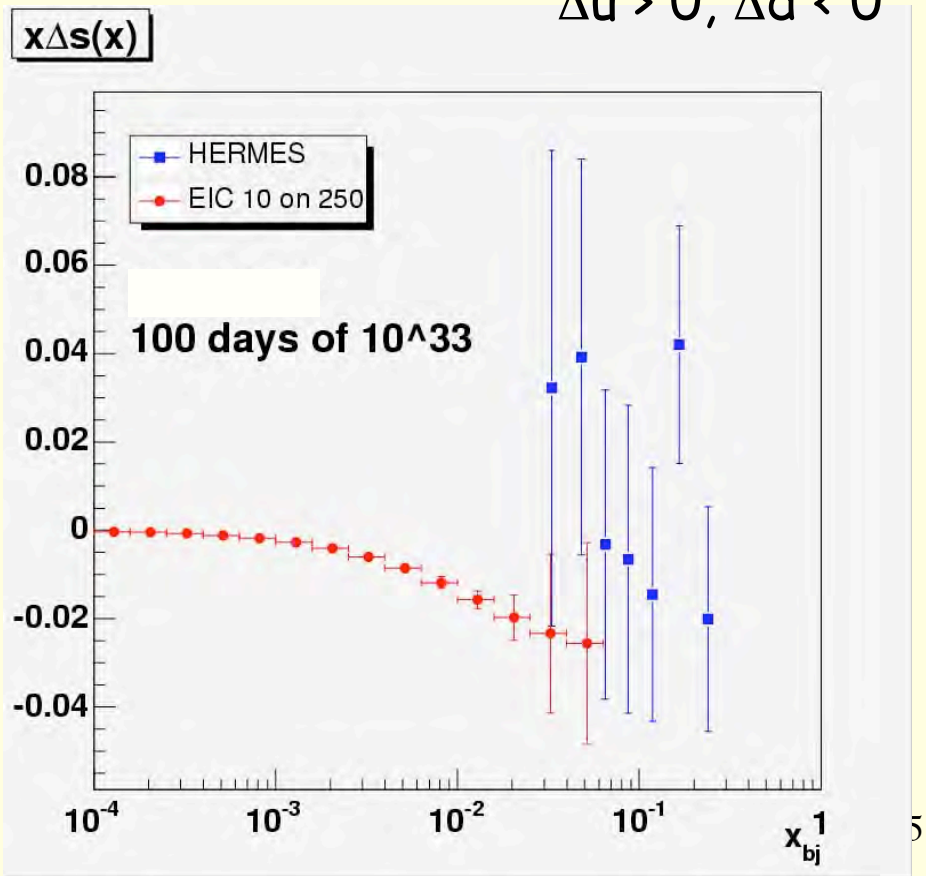
Spin-Flavor Decomposition of the Light Quark Sea



Many models _predict_

$\Delta u > 0, \Delta d < 0$





Exclusive DIS...

- $10\ fb^{-1}$

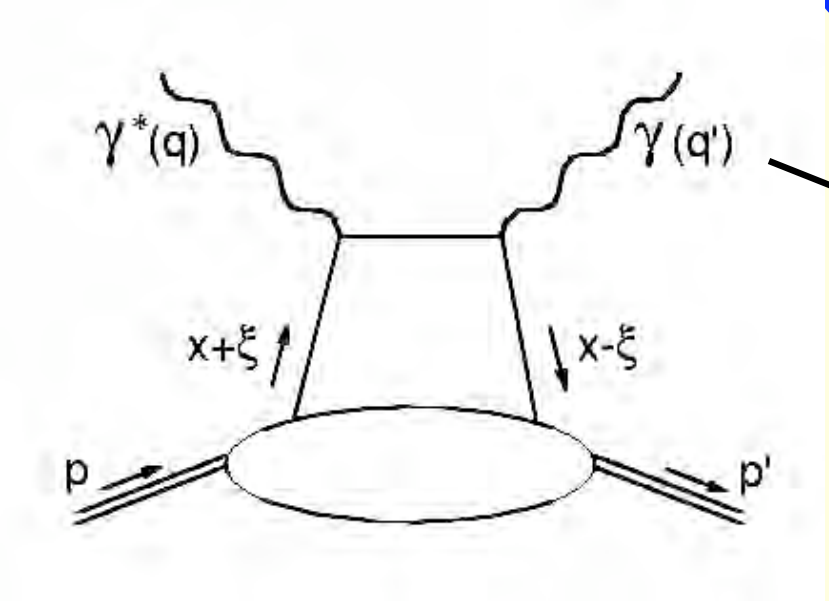
Excellent 4π detector

Particle ID

Calorimetry

High Rate Environment

DVCS/Vector Meson Productio: GPDs



- Hard Exclusive DIS process
- γ (default) but also **vector mesons** possible
- Remove a parton & put another back in!

- Claim: Possible access to skewed or off forward PDFs--> Generalized parton distributions?

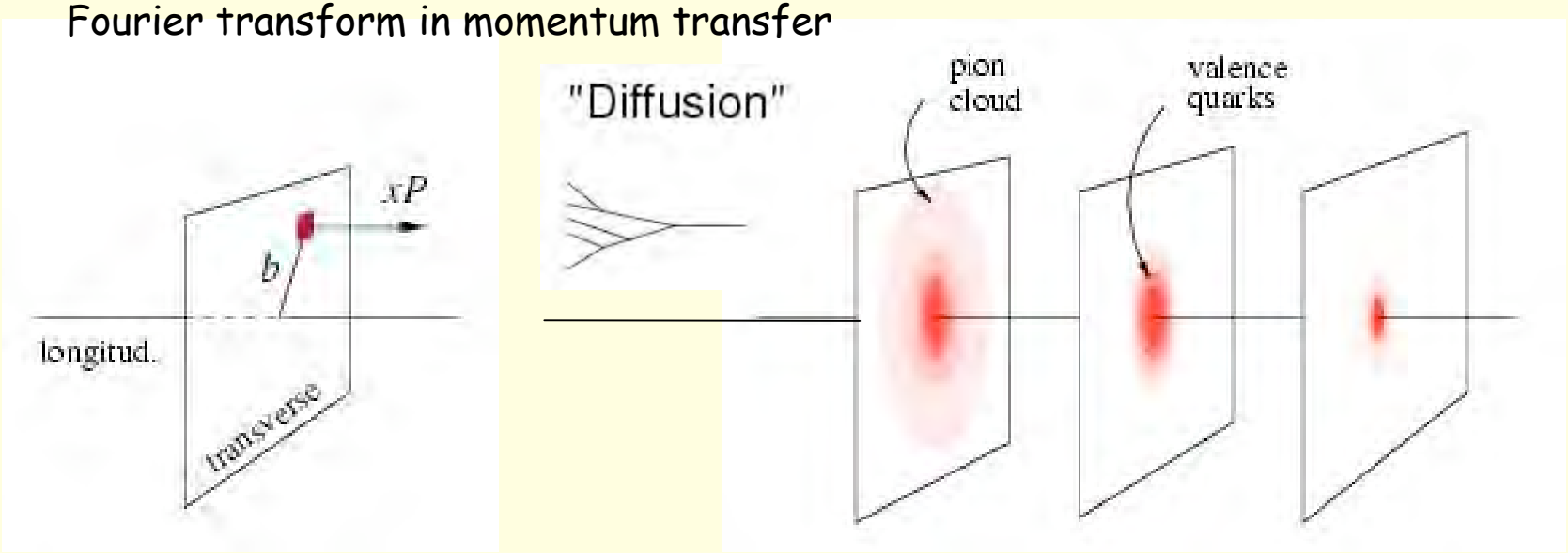
$$\int x dx [H(x,t,\xi)+E(x,t,\xi)] = 2J_{quark} = \Sigma + 2L_q$$

0 0 --> $-Q^2$

Experimental effort just beginning…To fully explore this physics beam Charge asymmetries need to be measured…

GPDs and Transverse Gluon Imaging

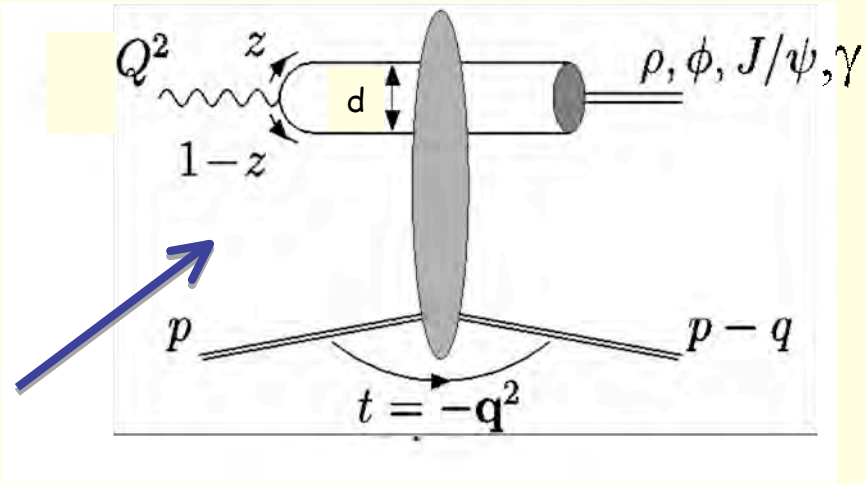
Fourier transform in momentum transfer

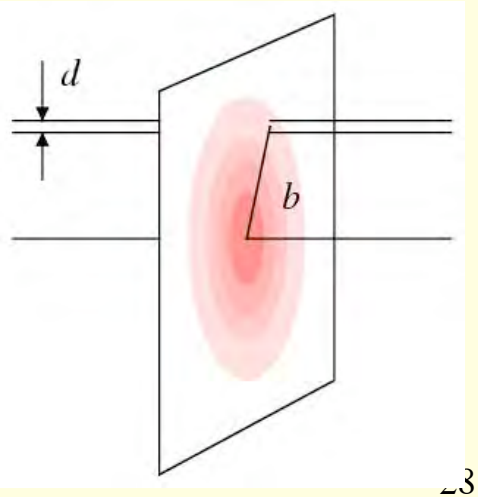


gives transverse size of quark (parton) with longitud. momentum fraction x

EIC:

1) x < 0.1: gluons!
2) $\xi \sim 0 \rightarrow$ the "take out" and "put back" gluons act coherently.





The glue in the nuclei

Physics with e-A collisions

Low luminosity requirements

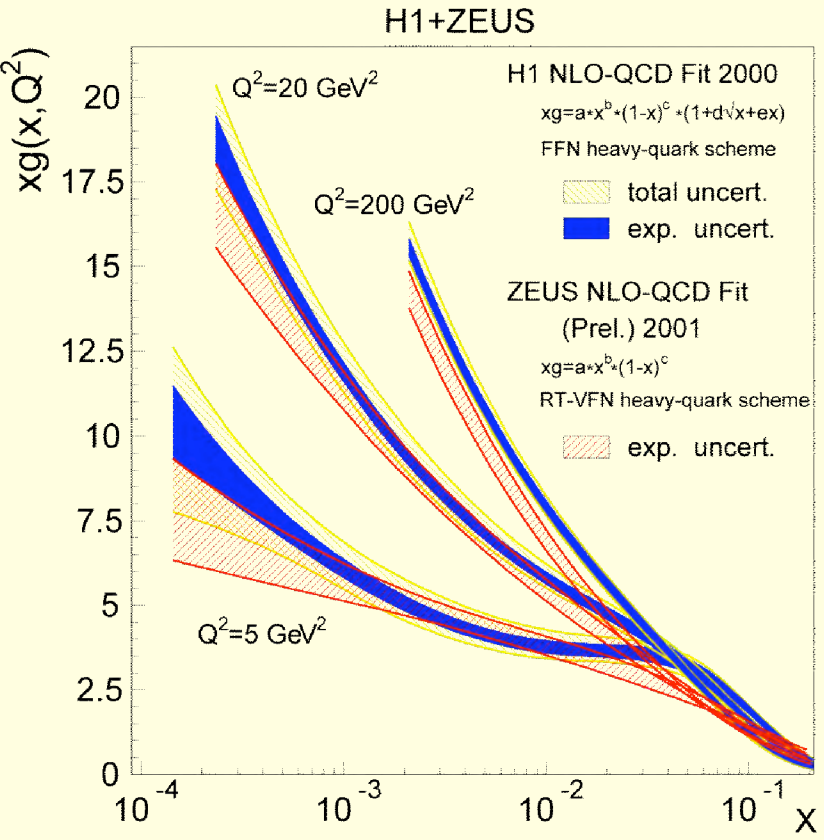
No polarization requirements… so far.

The High Energy Cross Section Problem...

Linear Evolution has a built in high energy "catastrophe"

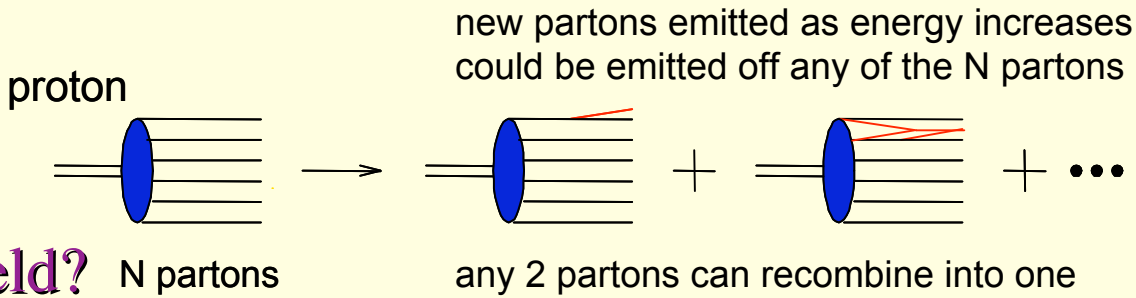
xG rapid rise for decreasing *x* and violation of (Froissart) unitary bound ⇒ **must saturate**

- What's the underlying dynamics?

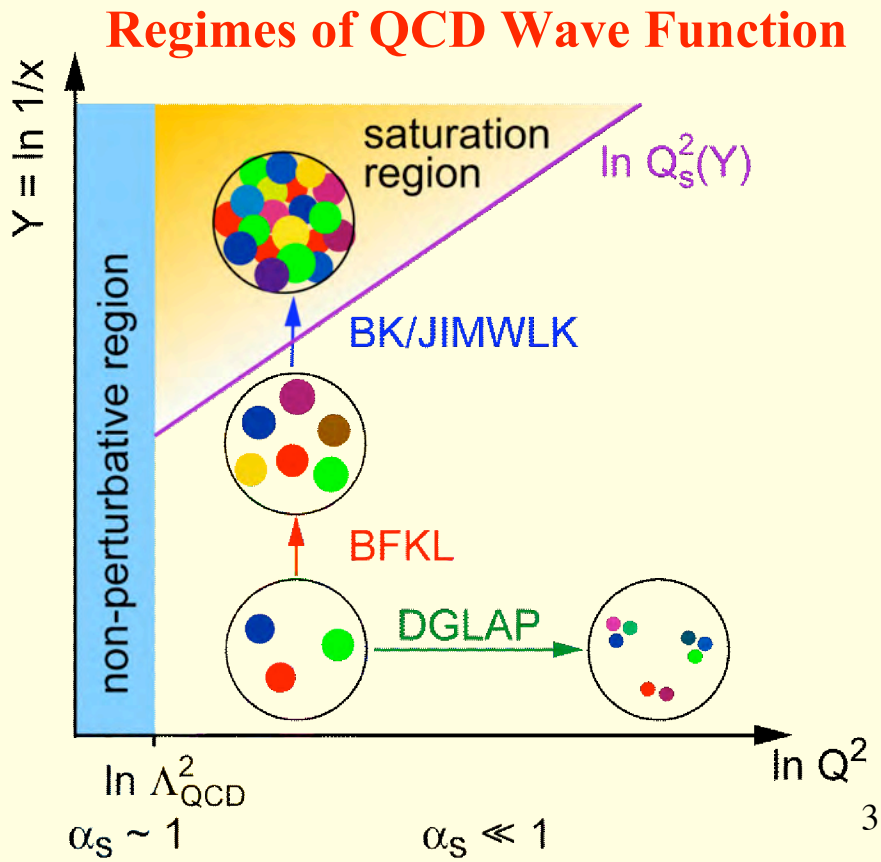


Non-Linear QCD - Saturation

- BFKL Evolution in x
  - linear
  - explosion of color field?



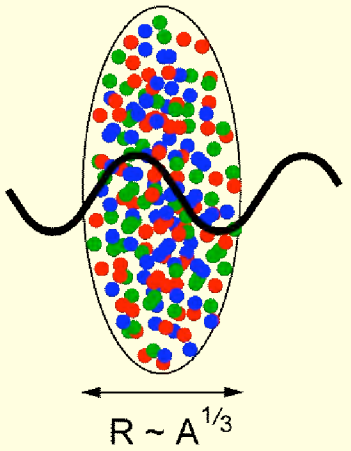
- New: BK/JIMWLK based models
  - introduce *non-linear* effects
  - ⇒ saturation
  - characterized by a scale $Q_s(x,A)$
  - arises naturally in the Color Glass Condensate (CGC) framework



e+A: Studying Non-Linear Effects

Scattering of electrons off nuclei:

- Probes interact over distances $L \sim (2m_N x)^{-1}$
- For $L > 2\,R_A \sim A^{1/3}$ probe cannot distinguish between nucleons in front or back of nucleon
- Probe interacts *coherently* with all nucleons



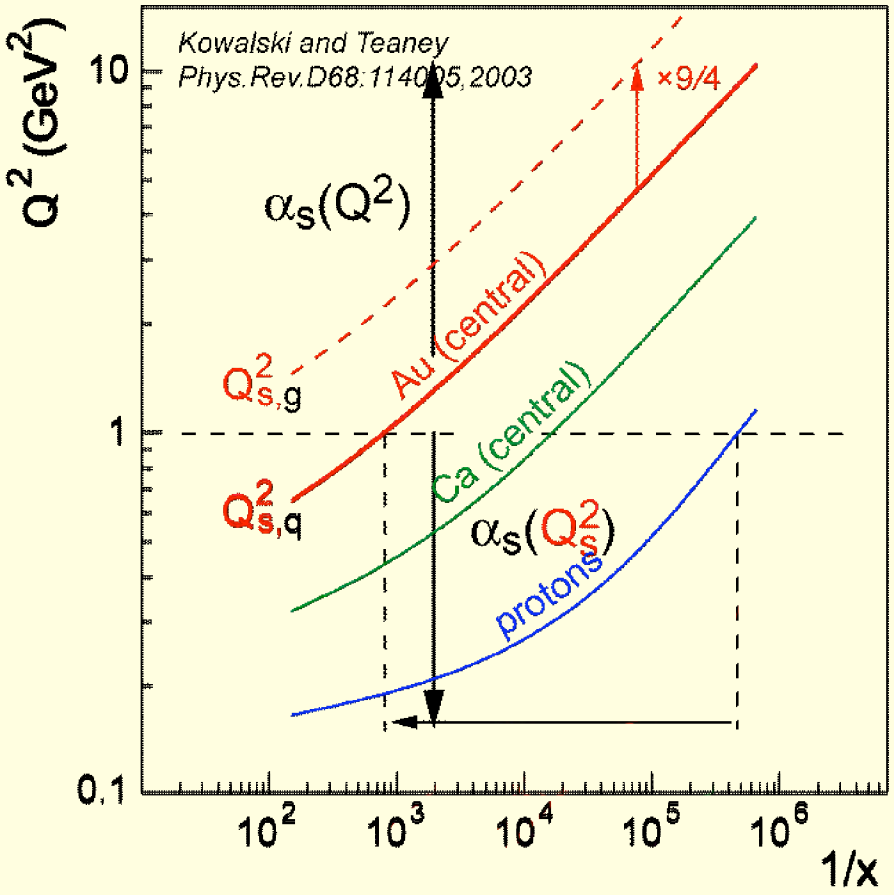
$$Q_s^2 \sim \frac{\alpha_s\, xG(x,Q_s^2)}{\pi R_A^2} \qquad \text{HERA}: \; xG \sim \frac{1}{x^{0.3}} \qquad \text{A dependence}: \; xG_A \sim A$$

Nuclear "Enhancement" Factor Pocket Formula:

$$(Q_s^A)^2 \approx cQ_0^2\left(\frac{A}{x}\right)^{1/3}$$

Enhancement of Q_S with A $\Rightarrow$ non-linear QCD regime reached at significantly lower energy in A than in proton

Nuclear "Enhancement" Factor



Note :

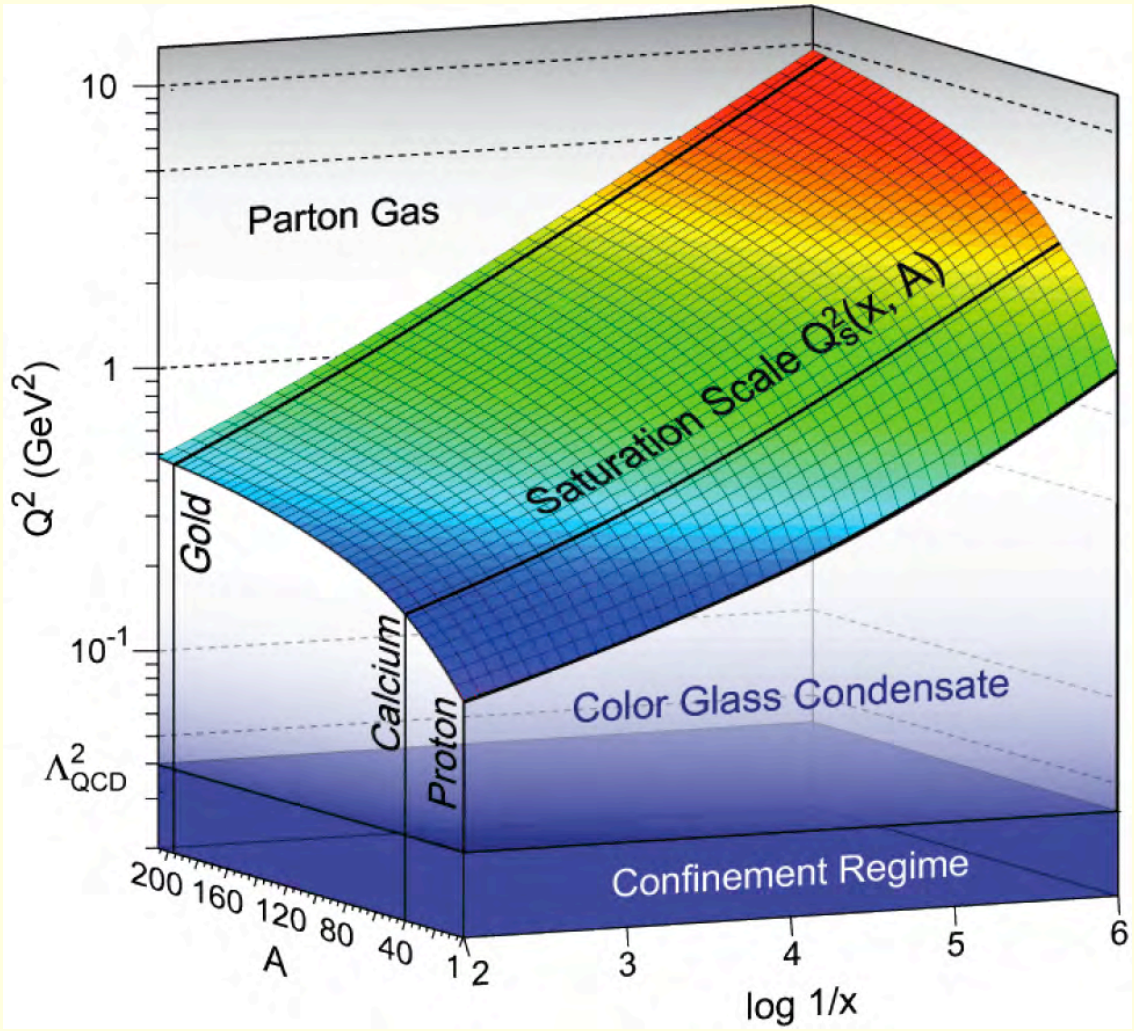
$$Q^2 > Q_s^2 \quad \Rightarrow \alpha_s = \alpha_s(Q^2)$$

$$Q^2 < Q_s^2 \quad \Rightarrow \alpha_s = \alpha_s(Q_s^2)$$

More sophisticated analyses ⇒ more detailed picture even exceeding the *Enhancement* from the pocket formula

(e.g. Armesto et al., PRL 94:022002, Kowalski, Teaney, PRD 68:114005)

A three dimensional view...



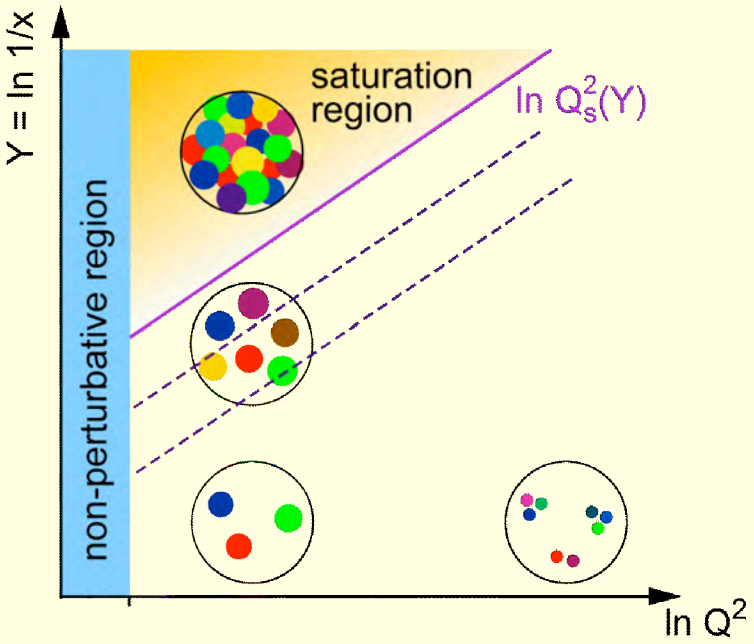
Fits to HERA data and nuclear NMC data in CGC model extrapolated to high energy.
Kowalski, Lappi & Venugopalan

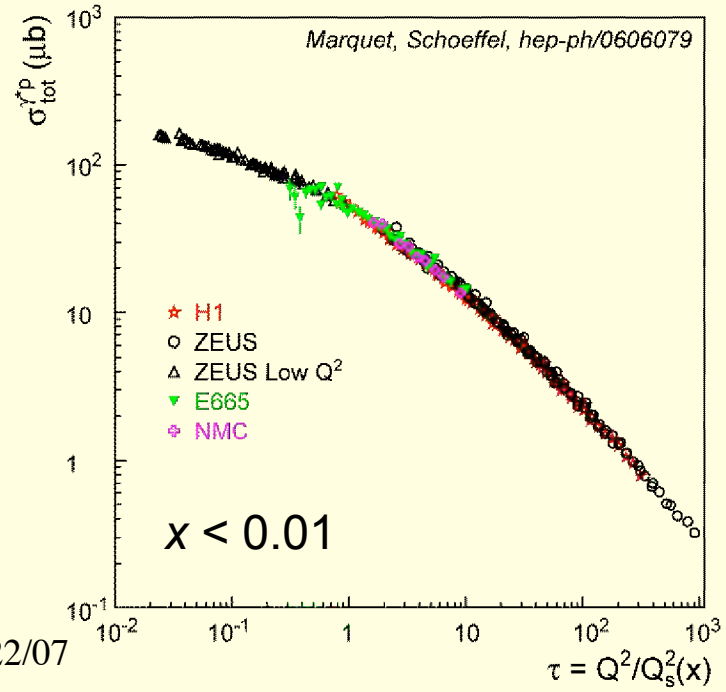
Plot by Ullrich & Lappi

Universality & Geometric Scaling

Crucial *consequence* of non-linear evolution towards saturation:

- Physics *invariant* along trajectories parallel to saturation regime (lines of constant gluon occupancy)
- Scale with $Q^2/Q^2_s(x)$ instead of x and Q^2 separately



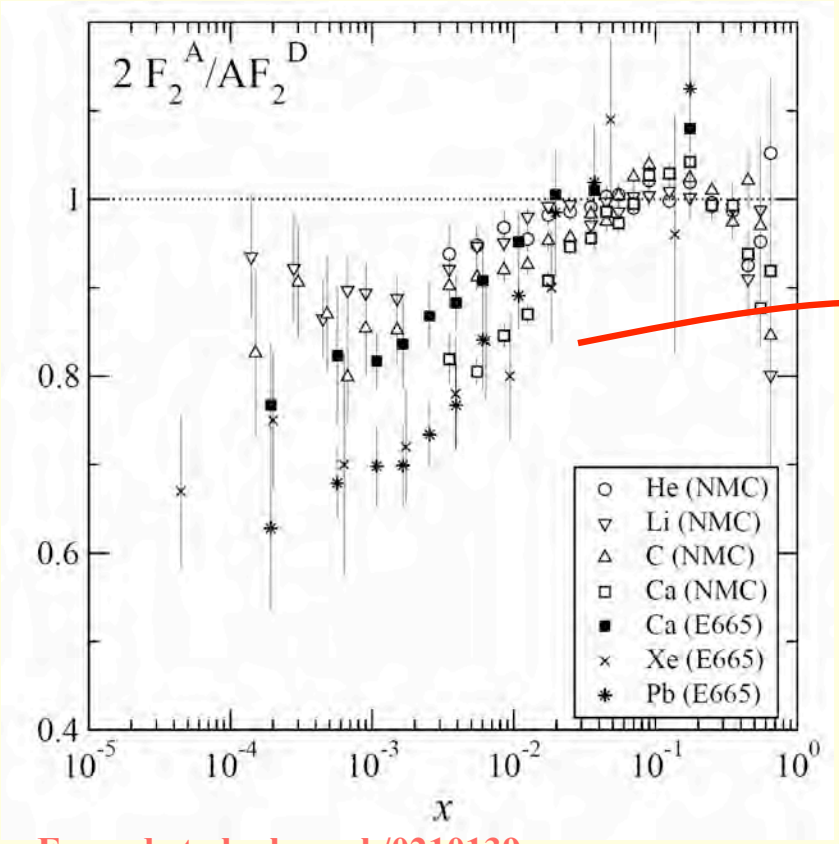


⇐ Geometric Scaling

- Consequence of saturation which manifests itself up to $k_T > Q_s$

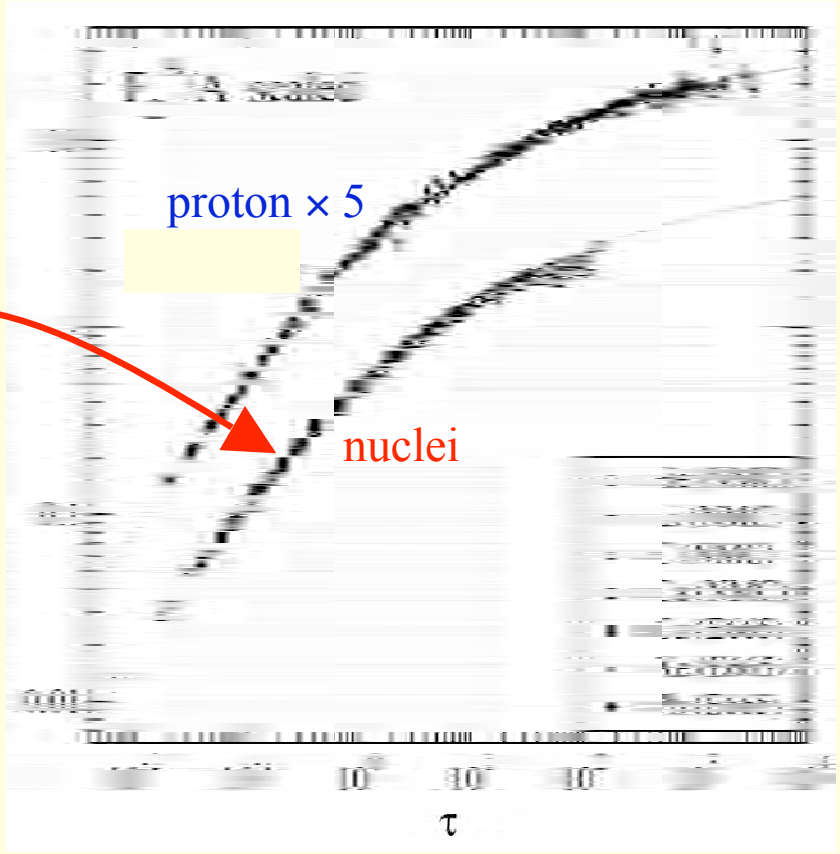
Q_s a Scale that Binds them All

Nuclear shadowing:



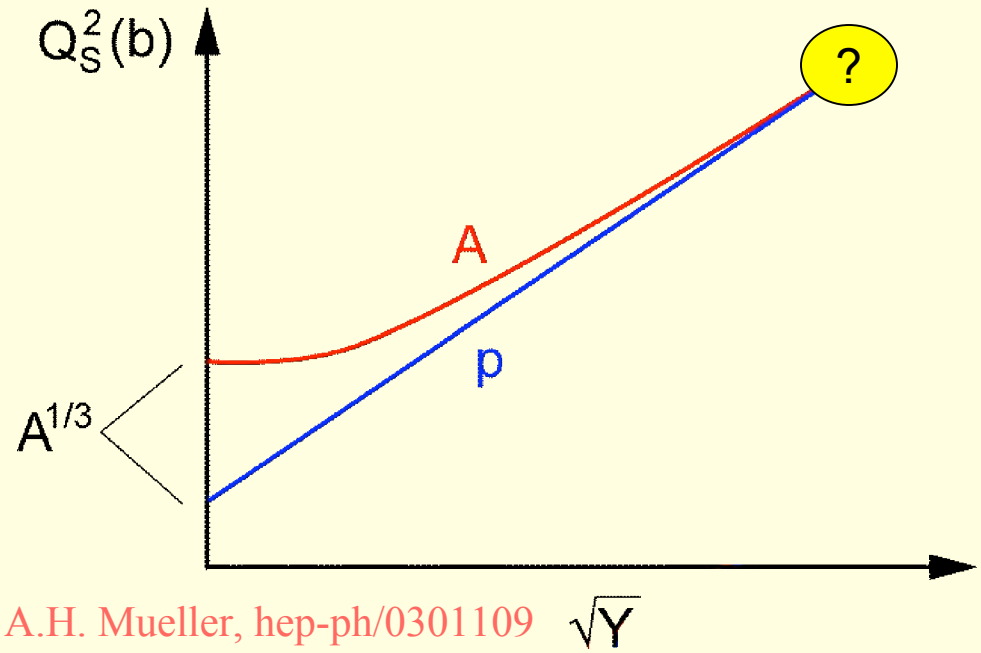
Freund et al., hep-ph/0210139

Geometrical scaling



Are hadron- and nuclei- wave function universal at low-x ?

A Truly Universal Regime ?



A.H. Mueller, hep-ph/0301109

Small *x* QCD evolution predicts:

- Q_S approaches universal behavior for ***all*** hadrons and nuclei

⇒ **Not only is the functional form f(Q_s) universal, but even Q_s becomes the same**

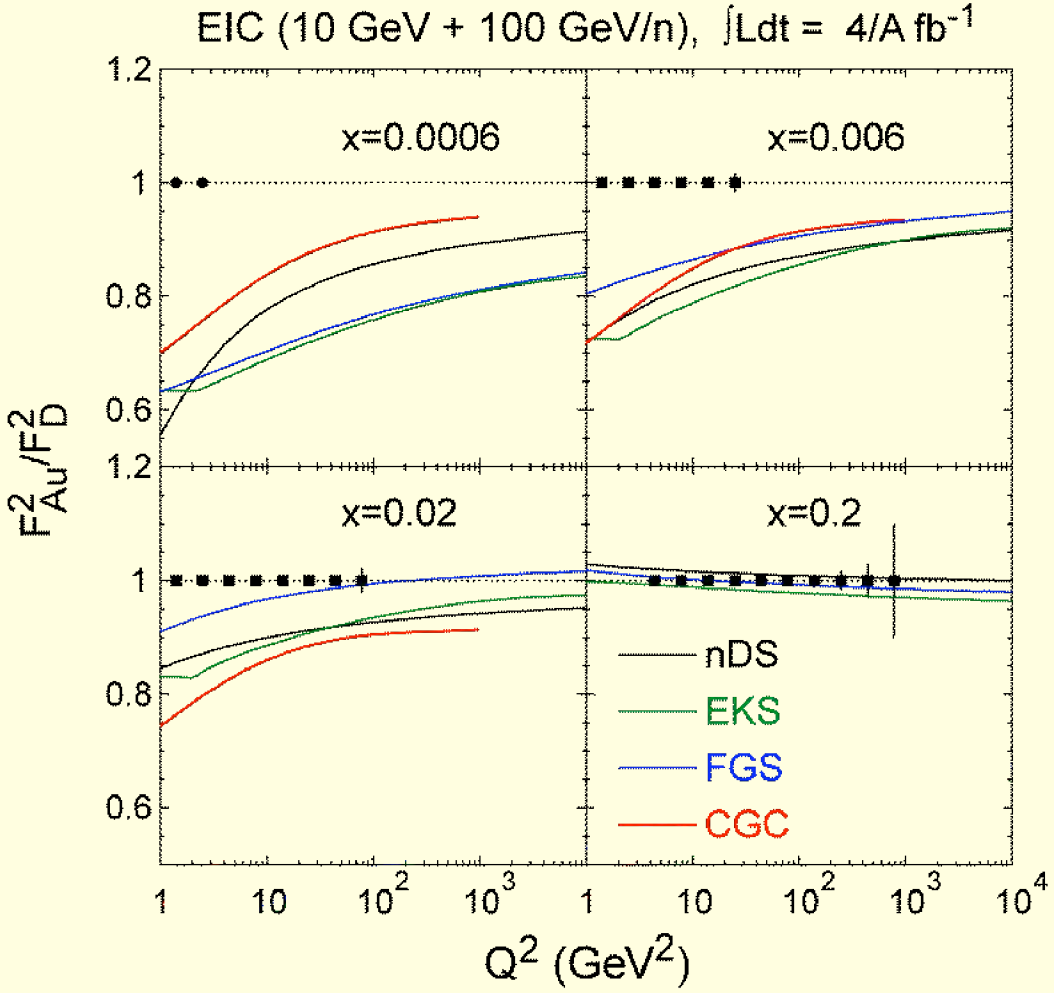
- Radical View:
  - **Nuclei and all hadrons have a component of their wave function with the *same* behavior**
  - **This is a conjecture! Needs to be tested**

What is the Momentum Distribution of Gluons?

Gluon distribution $G(x,Q^2)$

- Shown here:
  - Scaling violation in F_2: $\delta F_2/\delta \ln Q^2$
  - $F_L \sim \alpha_s\, G(x,Q^2)$
- Other Methods:
  - 2+1 jet rates (needs jet algorithm and modeling of hadronization for inelastic hadron final states)
  - inelastic vector meson production (e.g. J/ψ)
  - diffractive vector meson production ~ $[G(x,Q^2)]^2$

F_2 : Sea (Anti)Quarks Generated by Glue at Low x



F_2 will be one of the first measurements at EIC

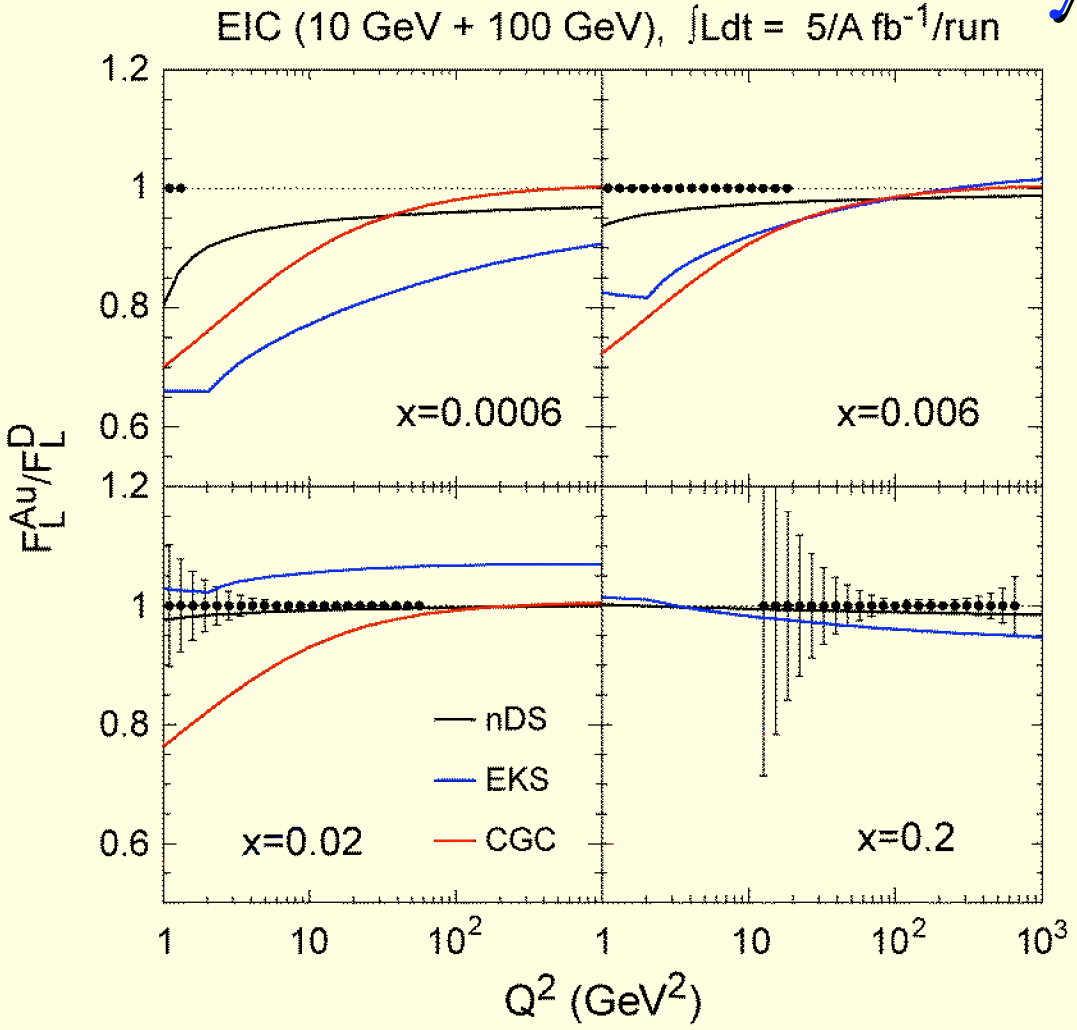
nDS, EKS, FGS:

pQCD based models with different amounts of shadowing

Syst. studies of $F_2(A,x,Q^2)$:
⇒ $G(x,Q^2)$ with precision
⇒ distinguish between models

$$\frac{d^2\sigma^{ep\to eX}}{dxdQ^2} = \frac{4\pi\alpha^2}{xQ^4}\left[\left(1-y+\frac{y^2}{2}\right)F_2(x,Q^2) - \frac{y^2}{2}F_L(x,Q^2)\right]$$

F_L at EIC: Measuring the Glue Directly



F_L requires √s scan

$Q^2/xs = y$

Here:

$\int Ldt$ = 5/A fb^{-1} (10+100) GeV

= 5/A fb^{-1} (10+50) GeV

= 2/A fb^{-1} (5+50) GeV

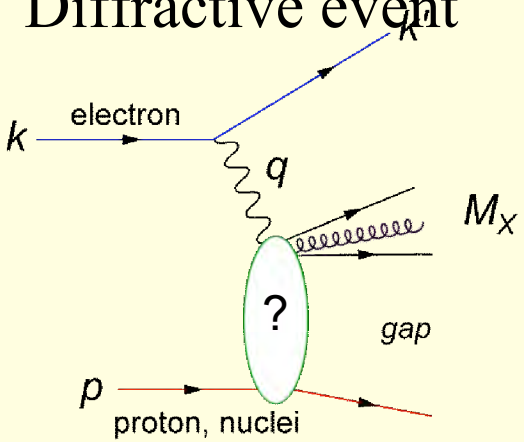
statistical error only

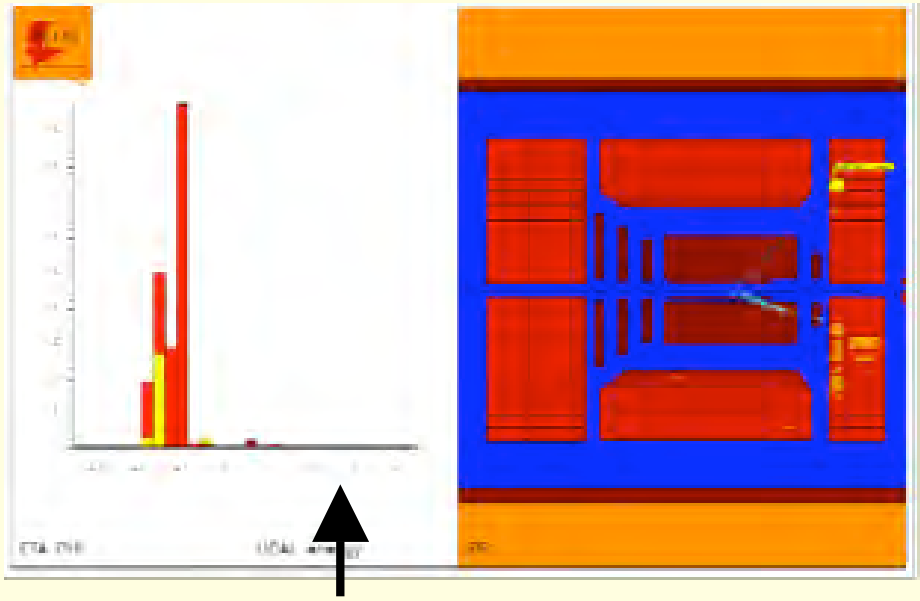
⇒ G(x,Q^2) with great precision

$$\frac{d^2\sigma^{ep\to eX}}{dxdQ^2} = \frac{4\pi\alpha^2}{xQ^4}\left[\left(1-y+\frac{y^2}{2}\right)F_2(x,Q^2) - \frac{y^2}{2}F_L(x,Q^2)\right]$$

Diffractive Physics in *e*+A

'Standard DIS event'
Diffractive event



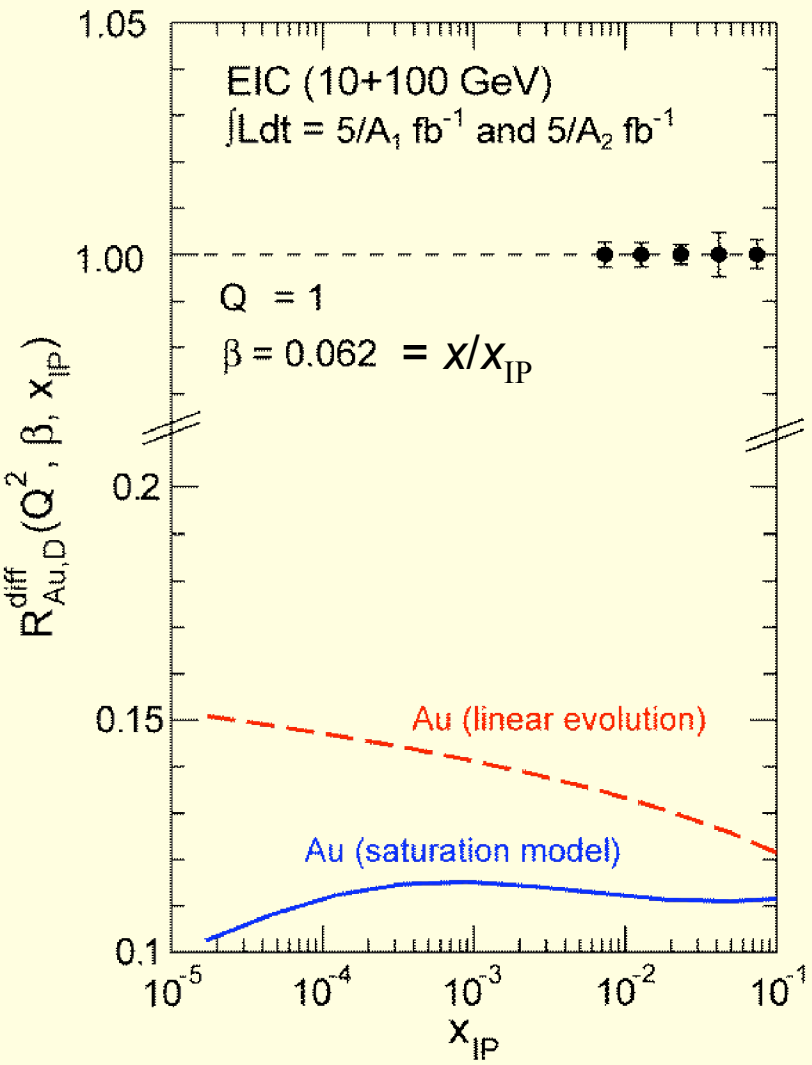


Detector activity in proton direction

7 TeV equivalent electron bombarding the proton …
but proton remains intact in 15% of cases …

- HERA/ep: 15% of all events are hard diffractive
- Diffractive cross-section $\sigma_{diff}/\sigma_{tot}$ in *e*+A ?
  - CGC Prediction: ~25-40%?

Diffractive Structure Function F_2^D at EIC



$$\frac{d^4\sigma^{eh\to eXh}}{dxdQ^2d\beta dt} = \frac{4\pi\alpha_{e.m.}^2}{\beta^2 Q^4}\left[\left(1-y+\frac{y^2}{2}\right)F_2^D - \frac{y^2}{2}F_L^D\right]$$

x_{IP} = momentum fraction of the pomeron w.r.t the hadron

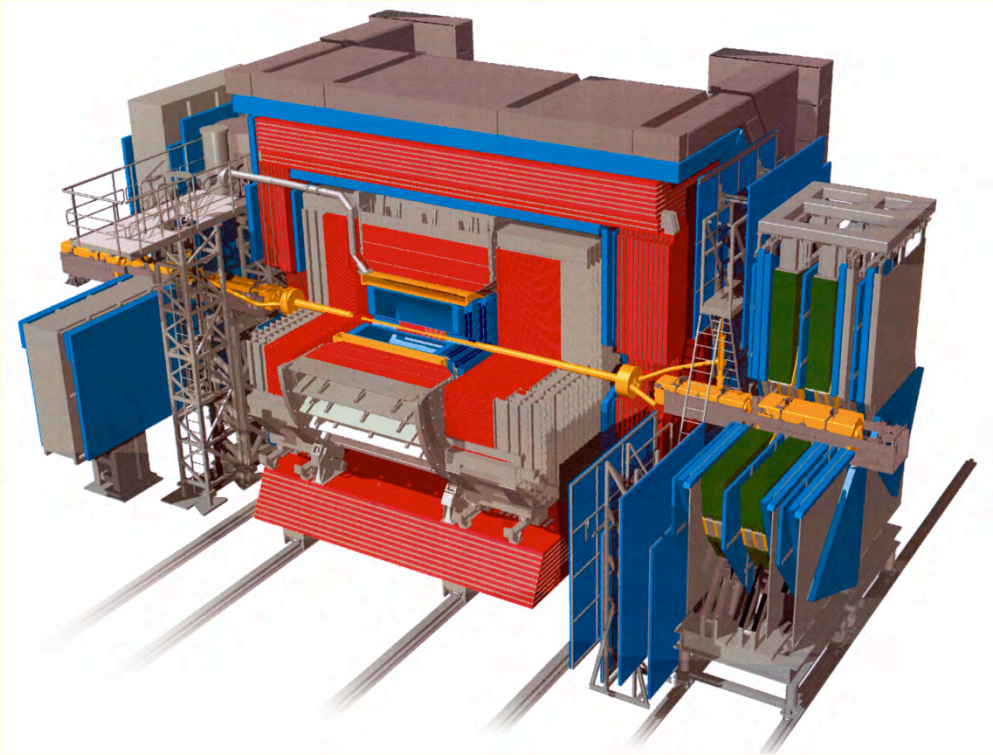
⇒ Distinguish between linear evolution and saturation models

⇒ Insight into the nature of pomeron

⇒ Search for exotic objects (Odderon)

Curves: Kugeratski, Goncalves, Navarra, EPJ C46, 413

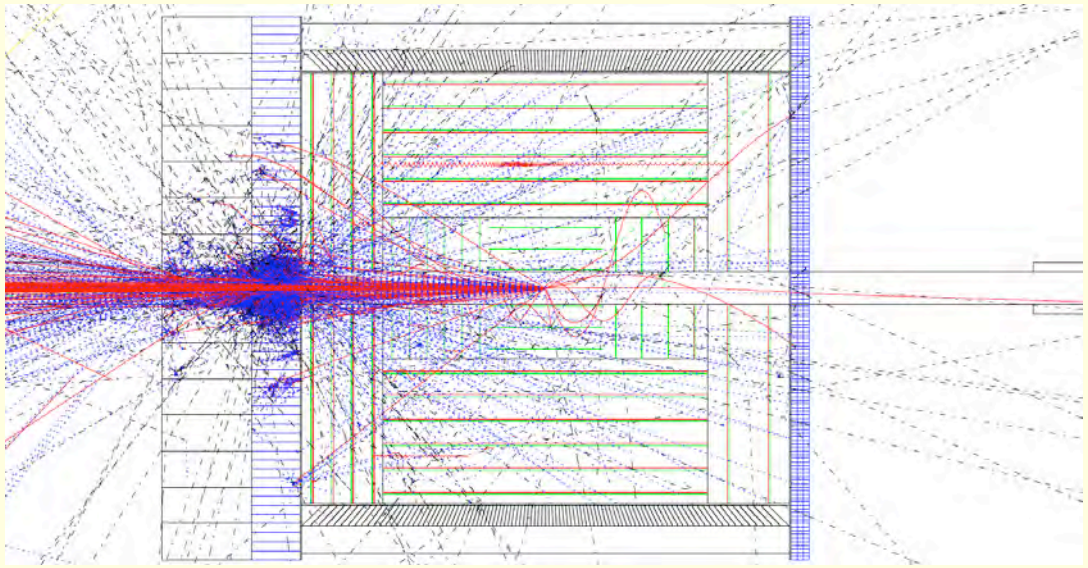
Detector design ideas .....



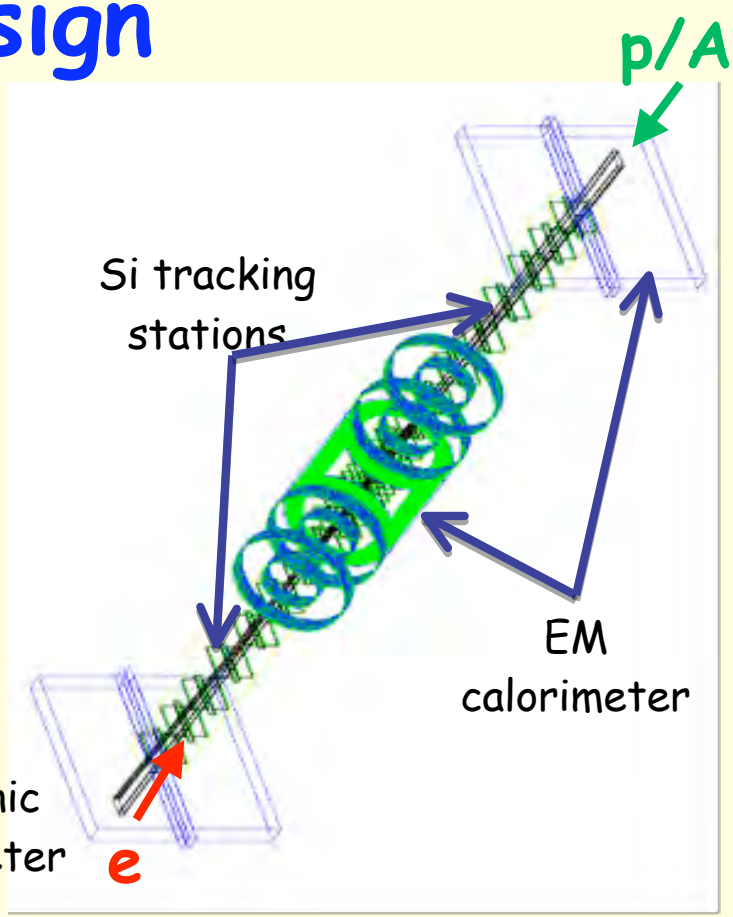
Main detector: learn from ZEUS (+ H1)

But: low-field region around central tracker
better particle identification
forward-angle detectors
auxiliary detectors for exclusive events
auxiliary detectors for normalization

Detector design



Main detector: Top view



Main detector:

Emphasize high-luminosity full physics program

Alternate detector:

Emphasize low-x, low-Q^2 diffractive physics ("HERA-III design", MPI-Munchen)

A few observations...

The case for the Electron Ion Collider has developed significantly since the early ideas were presented in 1999/2000.. This should continue.

My personal opinion is that we have a great chance to realize this facility now… and more probably here at BNL. *We* need to act decisively and aggressively.

The US QCD physics community supported the physics case this time in the NSAC long range planning process…. However, we need to find connections outside the QCD community and have their support if we are to realize this facility in the next Long Range Plan.

An Electron Ion Collider Collaboration/Working-Group is formed. A structure and set of responsibilities for various people are being discussed, among them detailed simulations of physics and detectors to as to prepare ourselves for detector R&D and design in the next few years.

The EIC Collaboration/Working Group

http://www.bnl.gov/eic & http://web.mit.edu/eicc

[17]C. Aidala, [28]E. Aschenauer, [10]J. Annand, [1]J. Arrington, [26]R. Averbeck, [3]M. Baker, [26]K. Boyle, [28]W. Brooks, [28]A. Bruell, [19]A. Caldwell, [28]J.P. Chen, [2]R. Choudhury, [10]E. Christy, [8]B. Cole, [4]D. De Florian, [3]R. Debbe, [26,24-1]A. Deshpande, [18]K. Dow, [26]A. Drees, [3]J. Dunlop, [2]D. Dutta, [7]F. Ellinghaus, [28]R. Ent, [18]R. Fatemi, [18]W. Franklin, [28]D. Gaskell, [16]G. Garvey, [12,24-1]M. Grosse-Perdekamp, [1]K. Hafidi, [18]D. Hasell, [26]T. Hemmick, [1]R. Holt, [8]E. Hughes, [22]C. Hyde-Wright, [5]G. Igo, [14]K. Imai, [10]D. Ireland, [26]B. Jacak, [15]P. Jacobs, [28]M. Jones, [10]R. Kaiser, [17]D. Kawall, [11]C. Keppel, [7]E. Kinney, [18]M. Kohl, [9]H. Kowalski, [17]K. Kumar, [2]V. Kumar, [21]G. Kyle, [13]J. Lajoie, [16]M. Leitch, [27]A. Levy, [27]J. Lichtenstadt, [10]K. Livingstone, [20]W. Lorenzon, [145]. Matis, [12]N. Makins, [6]G. Mallot, [18]M. Miller, [18]R. Milner, [2]A. Mohanty, [3]D. Morrison, [26]Y. Ning, [15]G. Odyniec, [13]C. Ogilvie, [2]L. Pant, [26]V. Pantuyev, [21]S. Pate, [26]P. Paul, [12]J.-C. Peng, [18]R. Redwine, [1]P. Reimer, [15]H.-G. Ritter, [10]G. Rosner, [25]A. Sandacz, [7]J. Seele, [12]R. Seidl, [10]B. Seitz, [2]P. Shukla, [15]E. Sichtermann, [18]F. Simon, [3]P. Sorensen, [3]P. Steinberg, [24]M. Stratmann, [22]M. Strikman, [18]B. Surrow, [18]E. Tsentalovich, [11]V. Tvaskis, [3]T. Ullrich, [3]R. Venugopalan, [3]W. Vogelsang, [28]C. Weiss, [15]H. Wieman,[15]N. Xu,[3]Z. Xu, [8]W. Zajc.

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95 Scientists, 28 Institutions, 9 countries

EIC Recommendation
NSAC LRP, May 4, 2007

We recommend the allocation of resources to develop accelerator and detector technology necessary to lay the foundation for a polarized Electron Ion Collider. The EIC would explore the new QCD frontier of strong color fields in nuclei and precisely image the gluons in the proton.

Without gluons there are no protons, no neutrons, and no atomic nuclei. Interactions among gluons determine the unique features of strong interactions. However, gluon properties in matter remain largely unexplored. Recent theoretical breakthroughs and experimental results suggest that both nucleons and nuclei when viewed at high energies appear as dense systems of gluons, creating the strongest fields in nature. The emerging science of this universal gluonic matter drives the development of a next generation high luminosity electron ion collider. Polarized beams in the EIC will give unprecedented access to the spatial and spin structure of gluons in the proton. The EIC embodies our vision for reaching the next QCD frontier. Realization of an EIC will require advancements in accelerator science and technology, detector R&D, and continued theoretical development.