Inclusive and Semi-inclusive DIS at eRHIC

Ed Kinney, University of Colorado

- Introduction
- Basics of Deep Inelastic Lepton Scattering
- Why use a collider?
- Quark/Gluon Structure of the Proton
- Meson Structure Functions
- Hadronization
- Quark Structure in Nuclei
- Extreme Partonic Matter
- Sermonette

What do we know about quarks and gluons in the nucleon?

- Three valence quarks plus virtual sea of quark-antiquark pairs
- Mass of quarks is small relative to nucleon mass
    - ✓ Large kinetic and "potential" energies
- Distribution of quarks and gluons in "momentum" variable x
- Quarks and Gluons carry roughly half the momentum
- Quarks spins make up only 30% of the proton spin

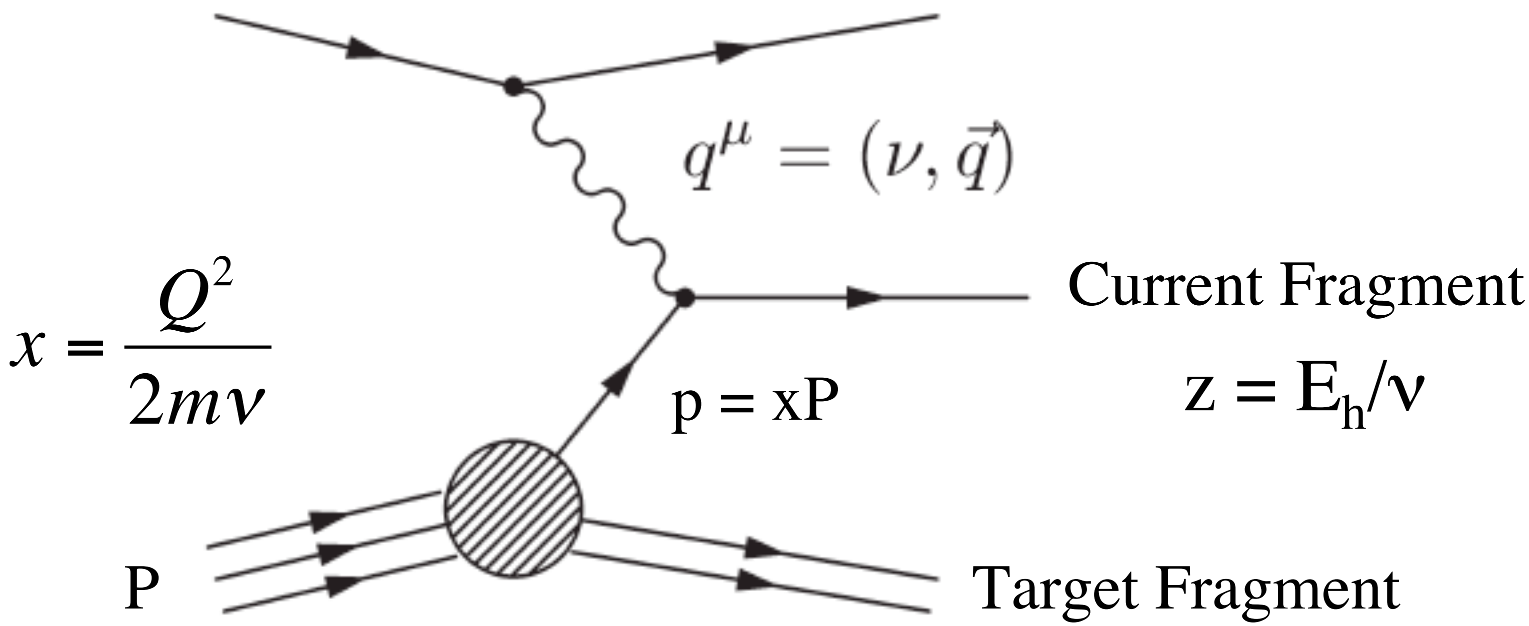
What should we know?
(an incomplete list!)

- Precise knowledge of distributions at large momentum
- Spatial distribution of quarks and gluons
- Distributions of strange and charm quarks
- Precise polarized distributions
- The role of orbital angular momentum in spin

And what happens in the nucleus?

- What is the effect of the nucleus on nucleon structure?
- What is the quark/gluon dynamics “inside” the nuclear force?
- Can we use the nucleus to learn about QCD?

Scattering from quarks in a nucleon (or nucleus):



Hadronic Final State Invariant $W^2 = (q + P)^2$

Note that this is easier than in hadron-hadron collisions because the probe and its interaction are simple, distinct, and well understood.

If we detect the scattered electron and measure its momentum vector, then we know the direction/energy of the virtual photon, and also something about the polarization of the virtual photon, even with unpolarized electrons.

This is at a cost of a relatively weak interaction which is not sensitive to the glue.

- At sufficiently large W^2 and Q^2, one finds that the cross section for deep inelastic scattering becomes simple:

$$\frac{d^2\sigma}{dx dQ^2} = \frac{2\pi\alpha_{em}^2}{Q^4}\left[(1+(1-y)^2)F_2(x,Q^2) - y^2 F_L(x,Q^2)\right]$$

Where I have ignored PV processes and there is no polarization

$$y = \nu / E$$

$$F_L = F_2 - 2xF_1$$

In the simple quark-parton model

$$F_2(x,Q^2) = \sum_{f=u,d,s,c,b,t} e_f^2 \left(xq_f(x,Q^2) + x\overline{q}_f(x,Q^2) \right)$$

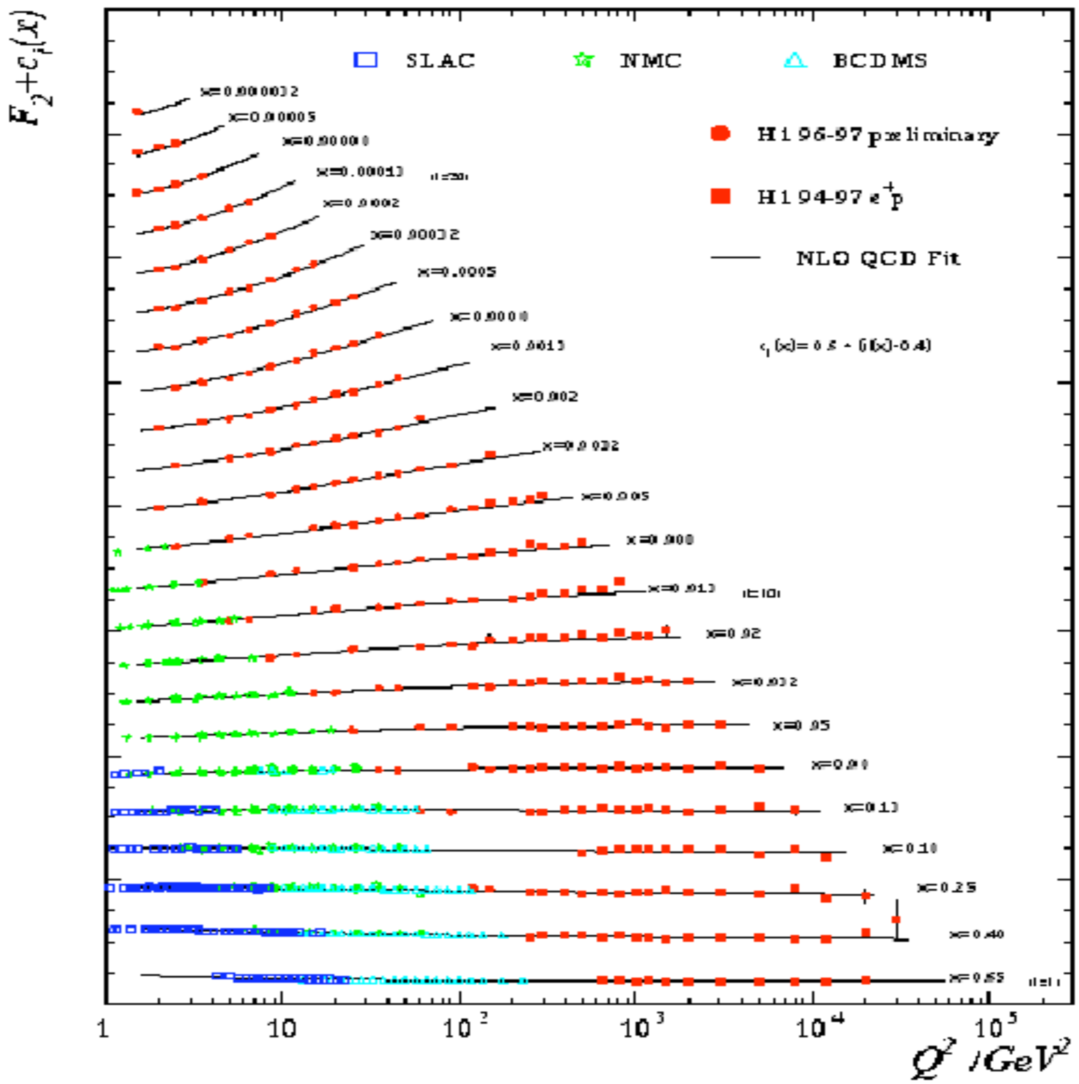
$$F_1(x,Q^2) = \frac{1}{2} \sum_{f=u,d,s,c,b,t} e_f^2 \left(q_f(x,Q^2) + \overline{q}_f(x,Q^2) \right)$$

$$= \frac{1}{2x} F_2(x,Q^2)$$

$$F_L = 0$$

- Inclusive DIS cross sections are mostly F_2
- F_L is hard to measure, but worth it, because it tells us about deviation from the simple model, and in fact turns out to be gluonic in nature

Data from Inclusive Charged Lepton DIS



- Deep inelastic scattering data combined with constraints from sum rules allow these flavor separated functions to be separated.

- Note that the separation into flavors (including antiquarks) relies heavily on neutrino DIS; photons sum over all charges squared!

- Different types of reactions are used:

    - Inclusive DIS: only the scattered lepton is detected
    - Semi-inclusive DIS: in addition to the scattered lepton one or two high energy (high z) hadrons are detected in coincidence
    - Exclusive: “know” all final state particles and momenta

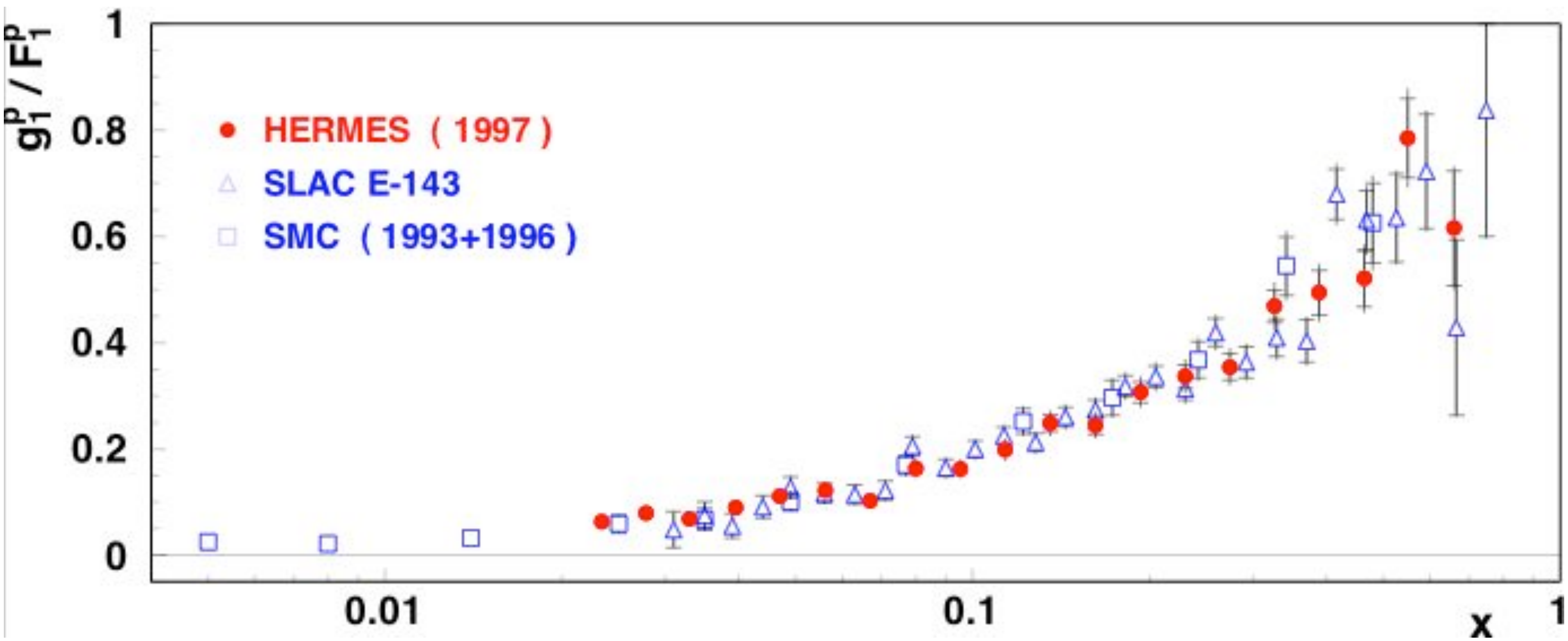
If beam and target are longitudinally polarized, then one can determine the polarized structure functions Δq_f which describe the difference between the structure function of quarks aligned with the proton spin and that of the quarks anti-aligned:

$$\frac{d^2\sigma^{\uparrow\downarrow}}{dxdQ^2} - \frac{d^2\sigma^{\uparrow\uparrow}}{dxdQ^2} \propto \frac{1}{2}\sum_f e_f^2\left(\Delta q_f(x,Q^2) + \Delta\overline{q}_f(x,Q^2)\right) = g_1(x,Q^2)$$

Usually, the actual quantity measured is an asymmetry, rather than the absolute polarized cross sections. After removing the effects from the fact that the photons are not perfectly polarized along the lepton beam direction, one determines the photon asymmetry A_1:

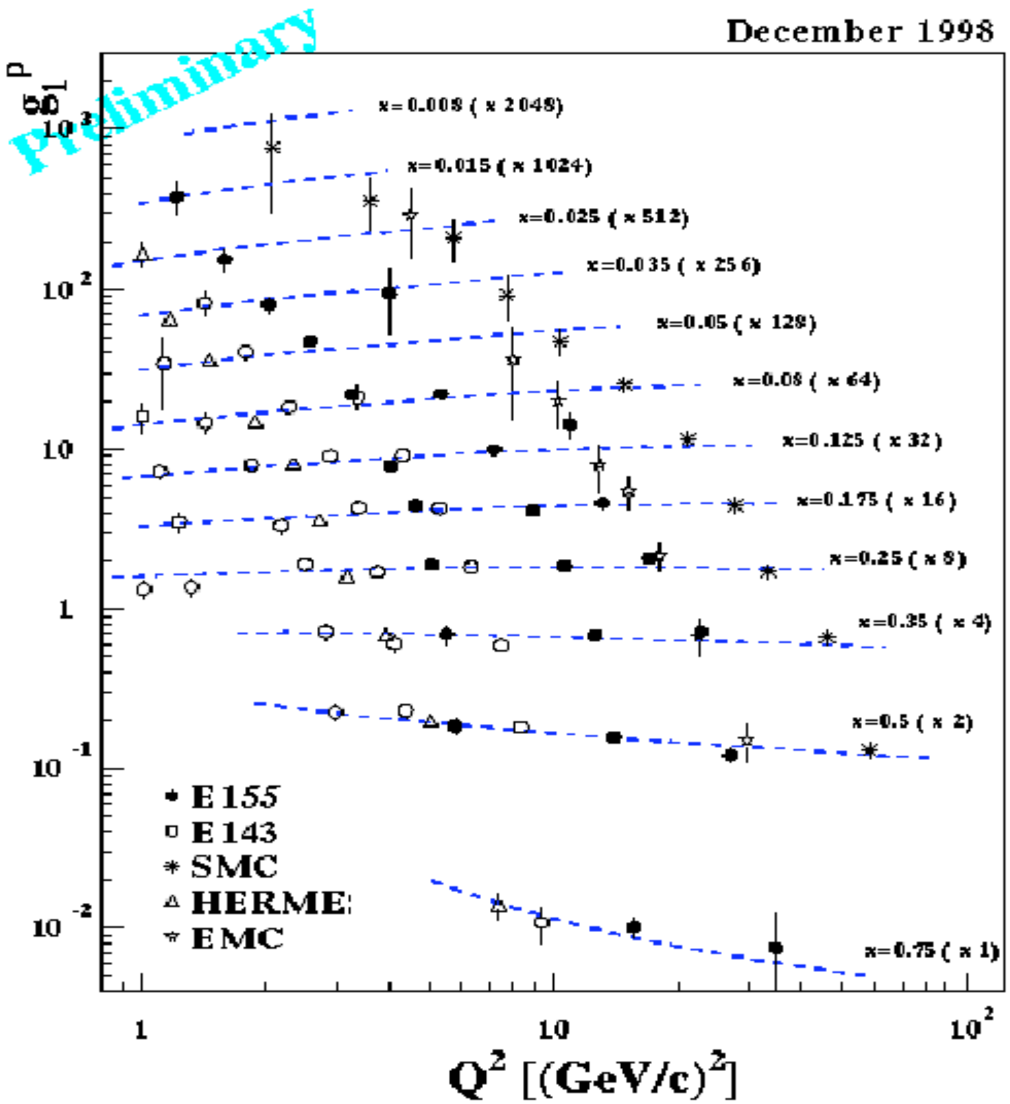
$$A_1(x) \propto \frac{\sum_f e_f^2 \Delta q_f(x)}{\sum_{f'} e_{f'}^2 q_{f'}(x)}$$

Inclusive A_1 Measurements



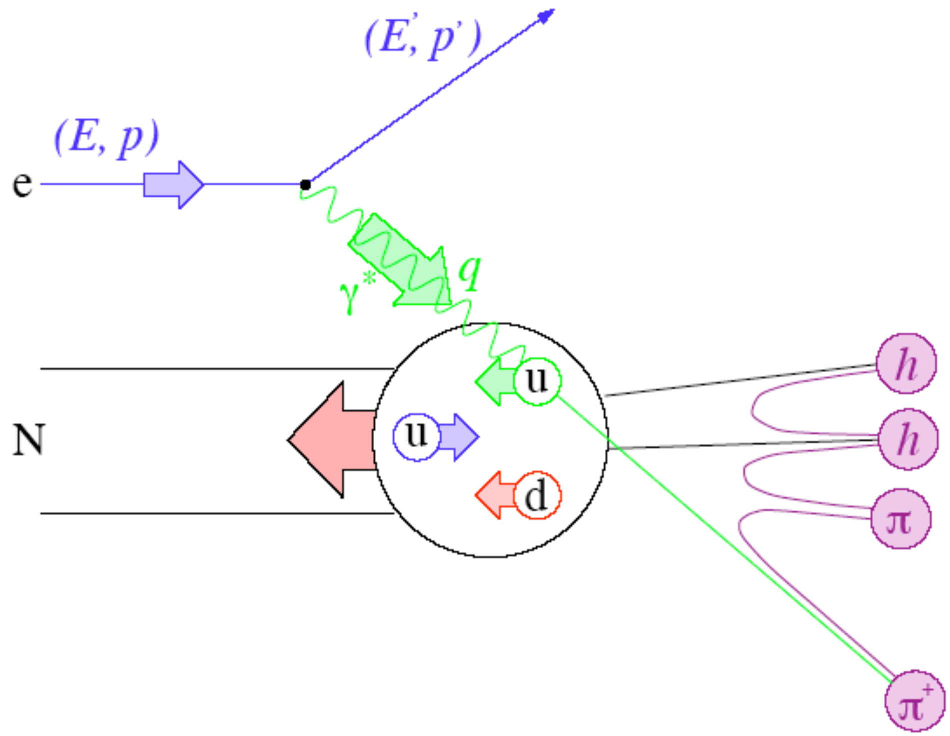
$$A_1 \approx \frac{g_1}{F_1}$$

Data from inclusive polarized charged lepton experiments:



Semi-inclusive DIS

In the polarized case, the only direct method available to separate the quark flavors (until a neutrino factory is built) is semi-inclusive DIS.



• Again, at sufficiently large W^2 and Q^2, one finds that the cross section for deep inelastic scattering becomes simple:

$$\frac{d^2\sigma}{dx\,dQ^2\,dz} \propto \sum_f e_f^2 q_f(x) D_f^h(z)$$

Where $q_f(x)$ is the quark structure function for flavor f

and $D^h{}_f(z)$ is the fragmentation function for hadron type h from quark flavor f

If beam and target are longitudinally polarized, then one can determine the polarized structure functions Δq_f which describe the difference between the structure function of quarks aligned with the proton spin and that of the quarks anti-aligned:

$$\frac{d^2\sigma^{\uparrow\downarrow}}{dxdQ^2dz} - \frac{d^2\sigma^{\uparrow\uparrow}}{dxdQ^2dz} \propto \sum_f e_f^2 \Delta q_f(x) D_f^h(z)$$

Note: We've ignored possible spin dependence in D

• The hadron type detected in the final state "tags" the flavor of the quark which was struck. This is only statistically true for hadrons at high *z*

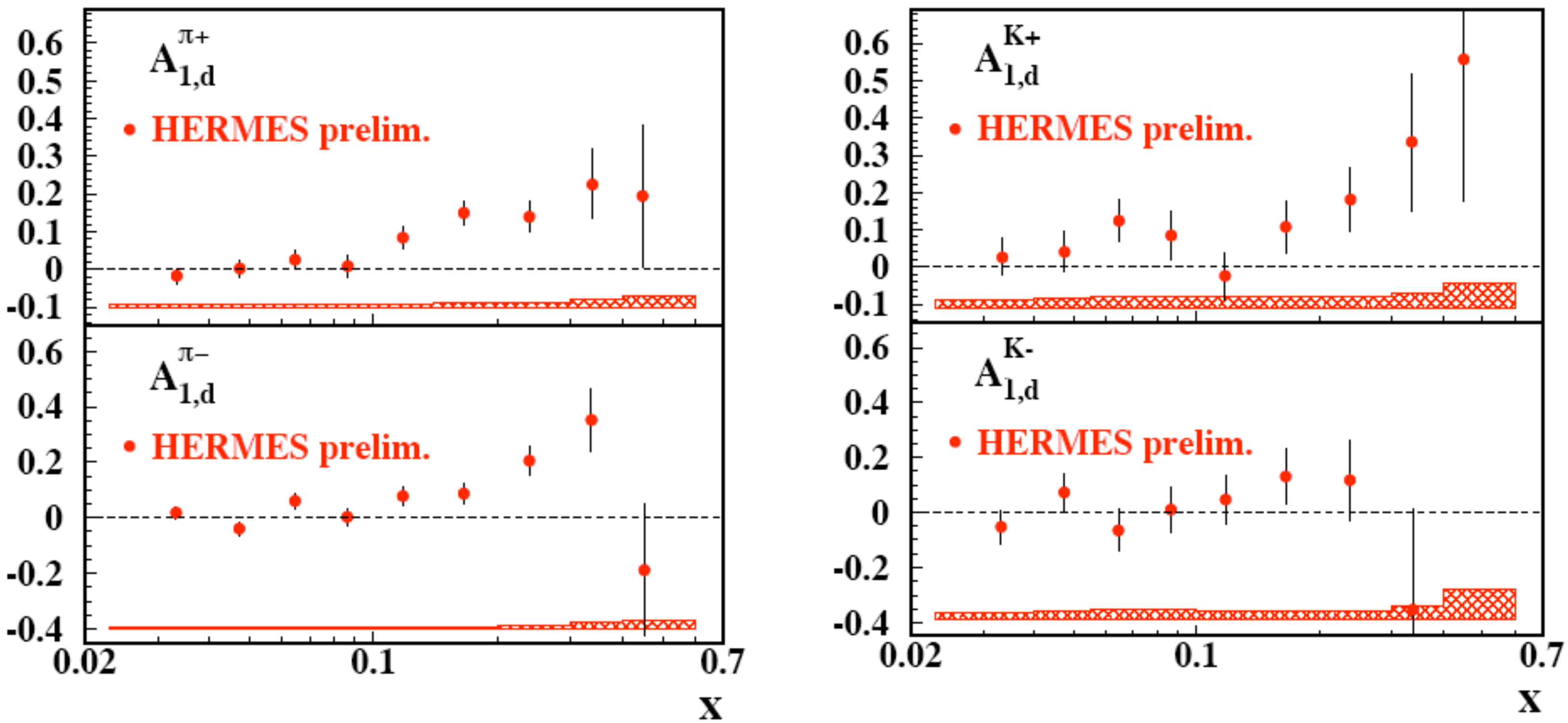
• Also recall that the cross section goes as the quark charge squared, thus *up* quarks get increased by a factor of 4

-> This is known as *u*-quark dominance

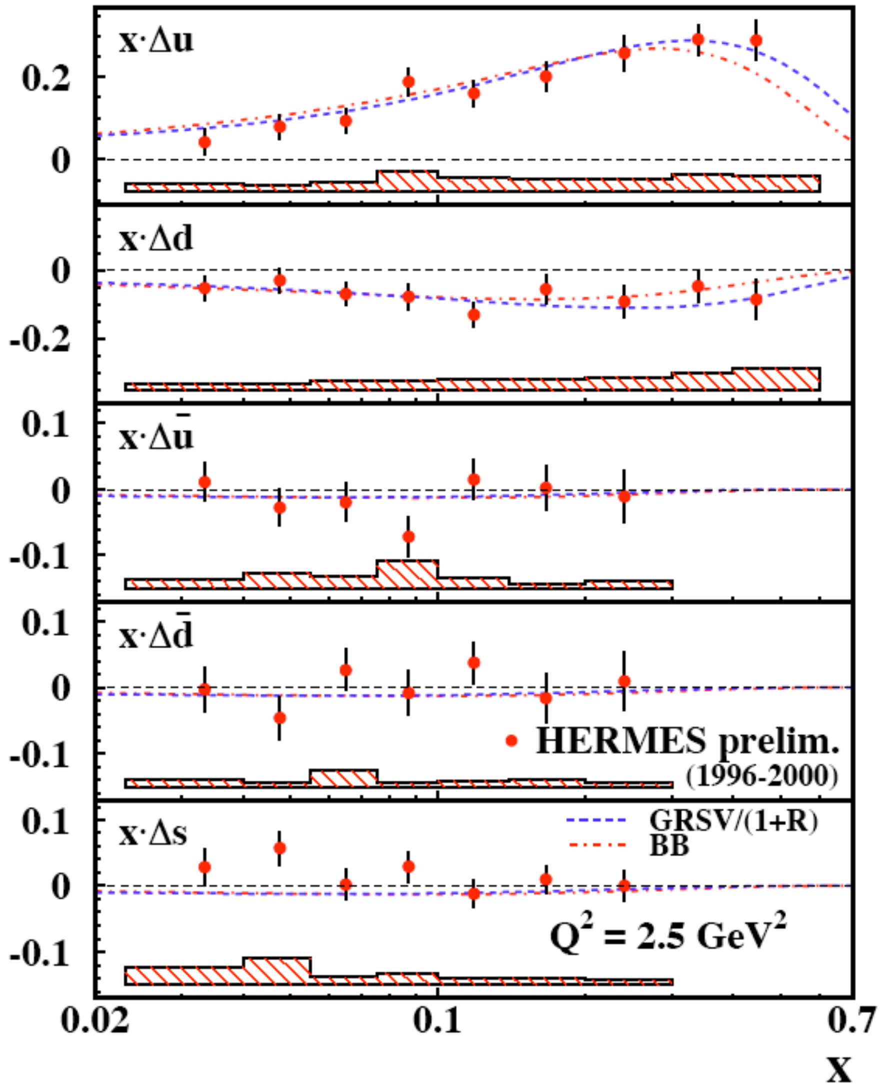
• Using as many identified hadrons as possible (pions and kaons), one can perform a global fit using the semi-inclusive asymmetries A^h_1:

$$A_1^h(x) \propto \frac{\sum_f e_f^2 \Delta q_f(x) D_f^h(z)}{\sum_{f'} e_{f'}^2 q_{f'}(x) D_{f'}^h(z)}$$

Semi-inclusive results from the HERMES Experiment



Spin-flavor decomposition from HERMES



Isoscalar extraction - formalism

In LO double-spin asymmetries are given by

$$A_{\parallel}^{(h)} = \frac{N_{(h)}^{\leftleftarrows} L^{\rightrightarrows} - N_{(h)}^{\rightrightarrows} L^{\leftleftarrows}}{N_{(h)}^{\leftleftarrows} L_P^{\rightrightarrows} + N_{(h)}^{\rightrightarrows} L_P^{\leftleftarrows}} \rightarrow A_1^K = \frac{\sigma_{1/2}^K - \sigma_{3/2}^K}{\sigma_{1/2}^K + \sigma_{3/2}^K} = \frac{\sum_q e_q^2 \, \Delta q(x,Q^2) \, D_q^K(z,Q^2)}{\sum_{q'} e_{q'}^2 \, q'(x,Q^2) \, D_{q'}^K(z,Q^2)} \, .$$

Inserting pdf's and fragmentation functions a simple matrix relation results

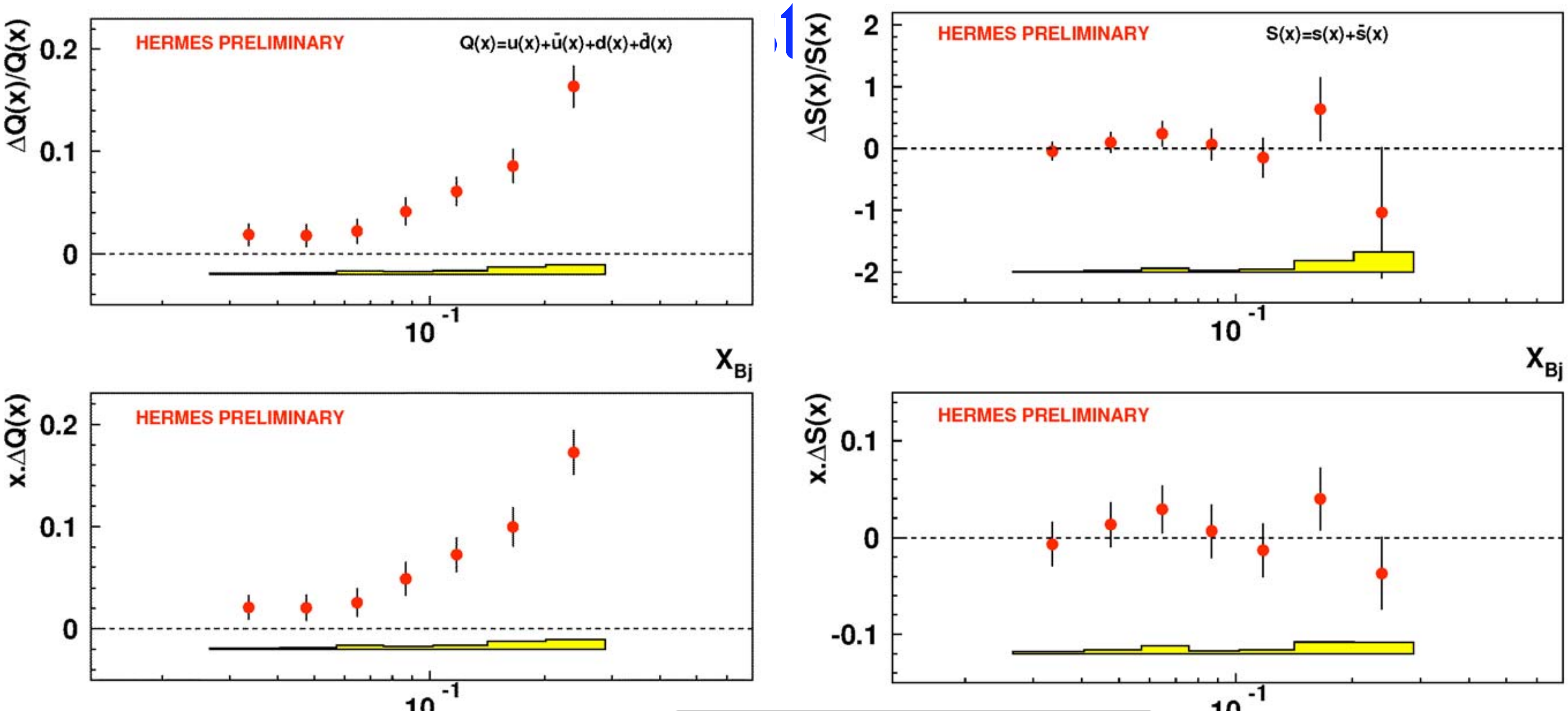
$$\begin{pmatrix} A_d(x) \\ \\ A_d^K(x) \end{pmatrix} = C_R \begin{pmatrix} P_q(x) & P_S(x) \\ \\ P_q^K(x) & P_S^K(x) \end{pmatrix} \begin{pmatrix} \Delta Q(x)/Q(x) \\ \\ \Delta S(x)/S(x) \end{pmatrix} .$$

where $Q(x) \equiv u(x) + \overline{u}(x) + d(x) + \overline{d}(x)$ and $S(x) \equiv s(x) + \overline{s}(x)$ and

$$P_Q(x) = \frac{5Q(x)}{5Q(x) + 2S(x)}, \quad P_S(x) = \frac{2S(x)}{5Q(x) + 2S(x)}$$

$$P_Q^K(x) = \frac{Q(x) \int \mathcal{D}_{non-str}^K dz}{Q(x) \int \mathcal{D}_{non-str}^K dz + S(x) \int \mathcal{D}_{str}^K dz}, P_S^K(x) = \frac{S(x) \int \mathcal{D}_{str}^K dz}{Q(x) \int \mathcal{D}_{non-str}^K dz + S(x) \int \mathcal{D}_{str}^K dz}$$

Quark polarizations and helicity



$.02 < x_{bj} < 1$

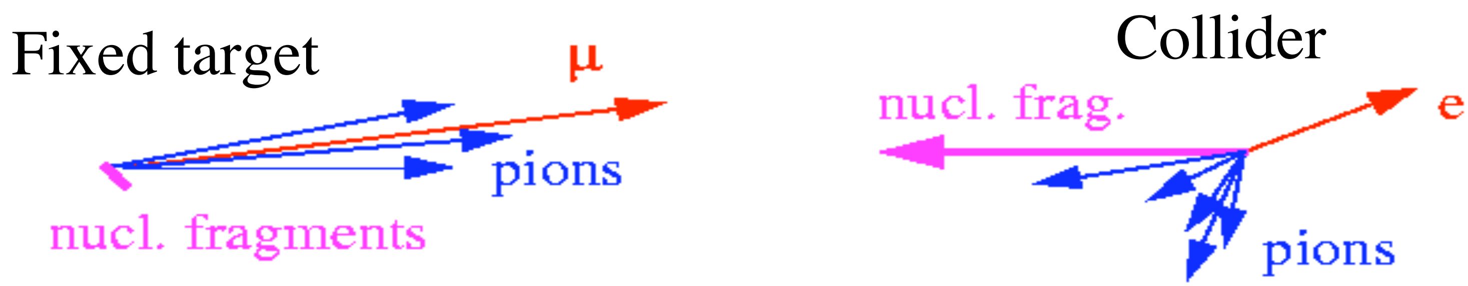
	First moments
ΔQ	$0.286 \pm 0.026 \pm 0.011$
ΔS	$0.006 \pm 0.029 \pm 0.007$

- COMPASS already has a large higher Q^2 semi-inclusive data sample, expect more precise results

- Parity violating electron scattering and low-energy neutrino reactions are constraining integrals of distributions

- Jefferson Lab is now leading the world in measuring structure functions at large x

Why Collider In Future?



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- Collider geometry--> distinct advantages (HERA Experience)
- Higher Center of Mass energies reachable
- Better angular resolution between beam and target fragments
  – Better separation of electromagnetic probe
  – Recognition of rapidity gap events (diffractive physics at HERA)
  – Better measurement of nuclear fragments

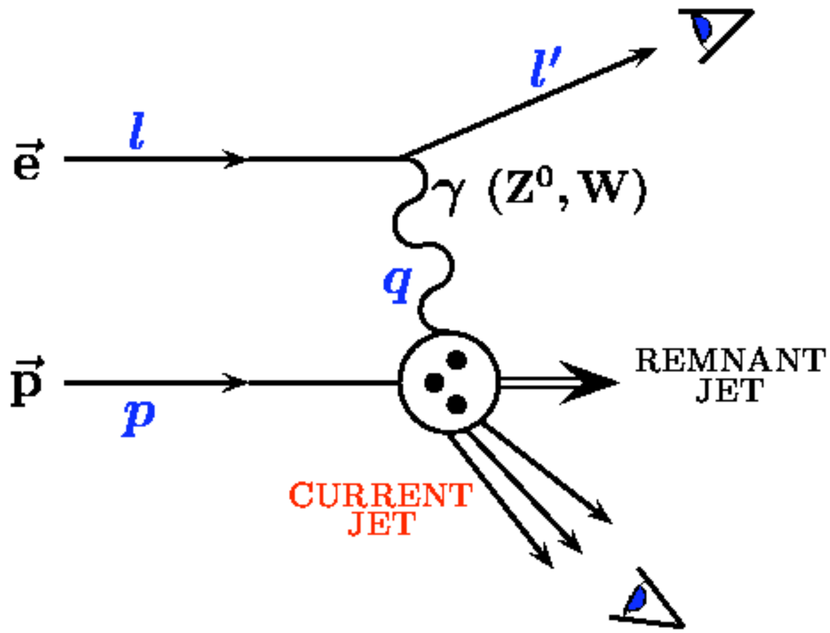
Basic Characteristics for the Electron-Ion Collider

- Electron Energy 5-10 GeV
- Proton Energy 50-300 GeV
- Polarized Electrons(positrons) and Protons, ^{3}He
- ep Luminosities of 10^{33}-10^{34}/cm^2/s
- Unpolarized ion beams d - Au
- e-ion luminosities of 10^{31}-10^{32} /cm^2/s

Two design efforts at present:

eRHIC at BNL and ELIC at Jefferson Lab

Collider Kinematics



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

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

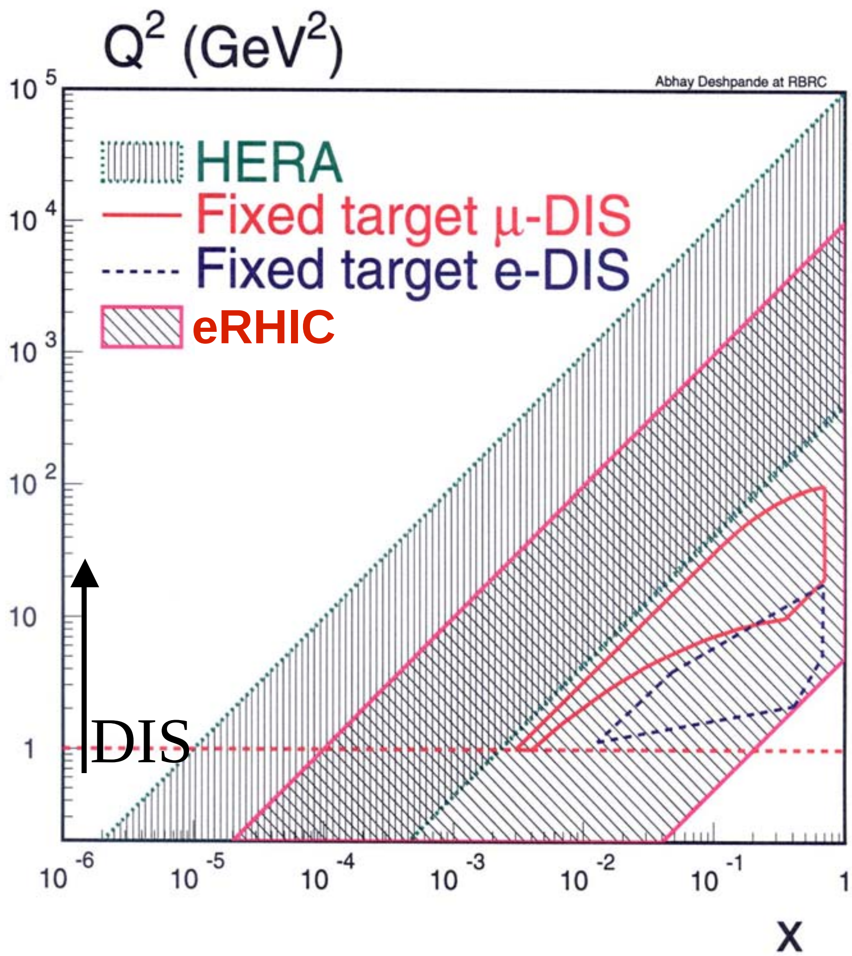
$$y = \frac{p \cdot q}{p \cdot l}$$

$$s = 4E_e E_p$$

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

$$z = \frac{p_h \cdot p}{q \cdot p}$$

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) ~$10^{33\text{-}34}$ cm^{-2} sec^{-1}**
  - **L(eA) ~$10^{31\text{-}32}$ cm^{-2} sec^{-1} N^{-1}**

A.Deshpande. & V. W. Hughes

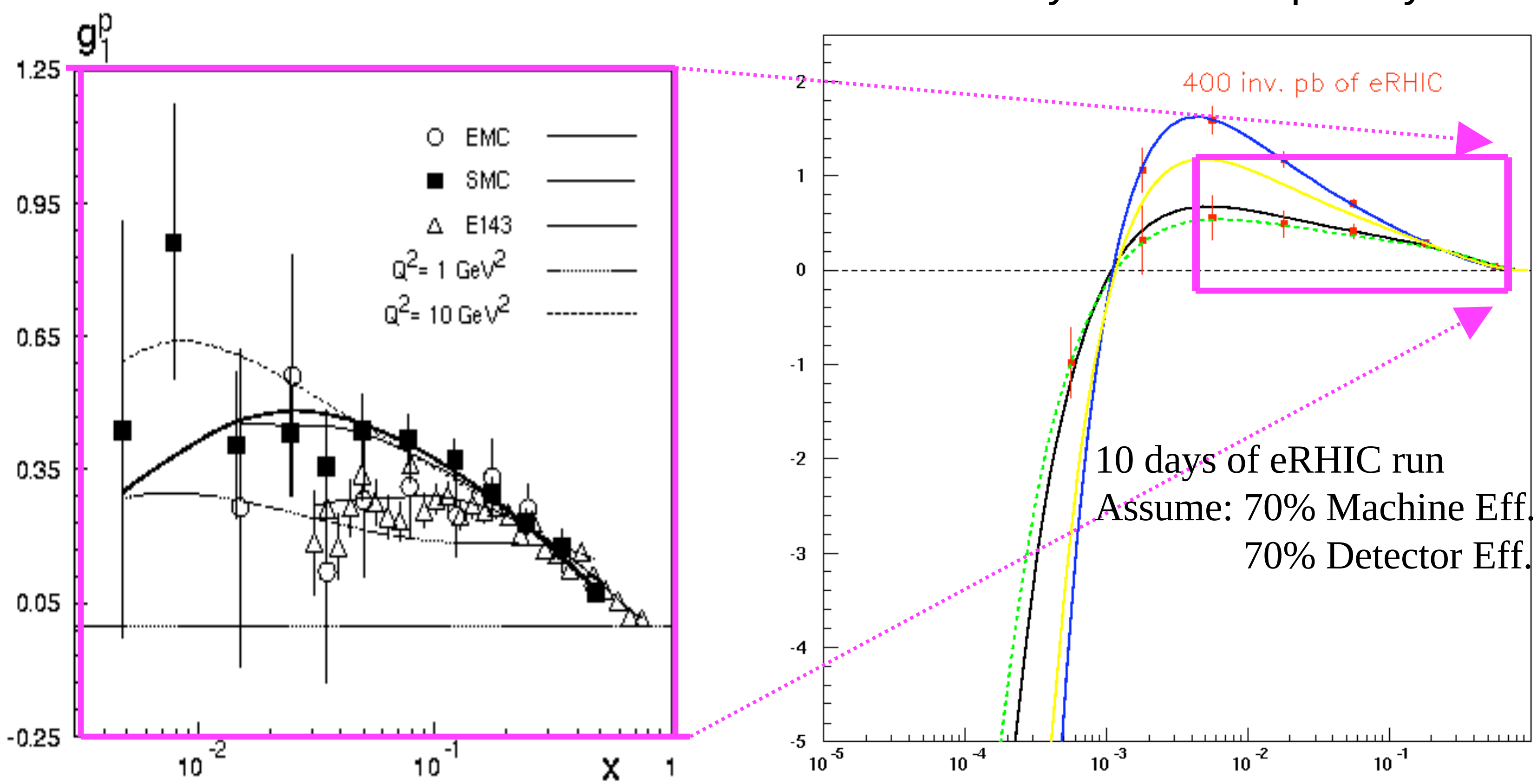
Proton Structure from Inclusive Polarized Scattering at low x

Fixed target experiments

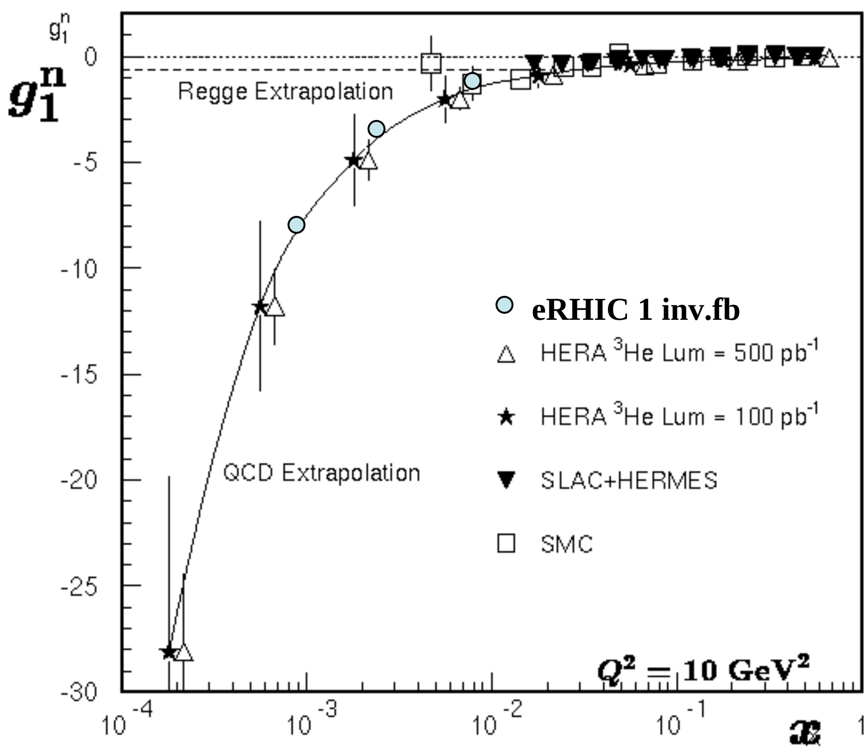
1989 – 1999 Data

eRHIC 250 x 10 GeV

Luminosity = ~85 inv. pb/day



Spin Structure of Neutron at Low x

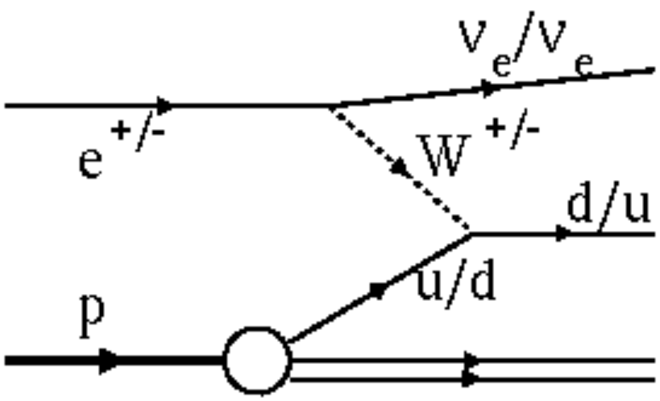


- With polarized He
- ~ 2 weeks of data at EIC
- Compared with SMC(past) & possible HERA data
- **If combined with g1 of proton results in Bjorken sum rule test of better than 1-2% within a couple of months of running**

Parity Violating Structure Function g_5

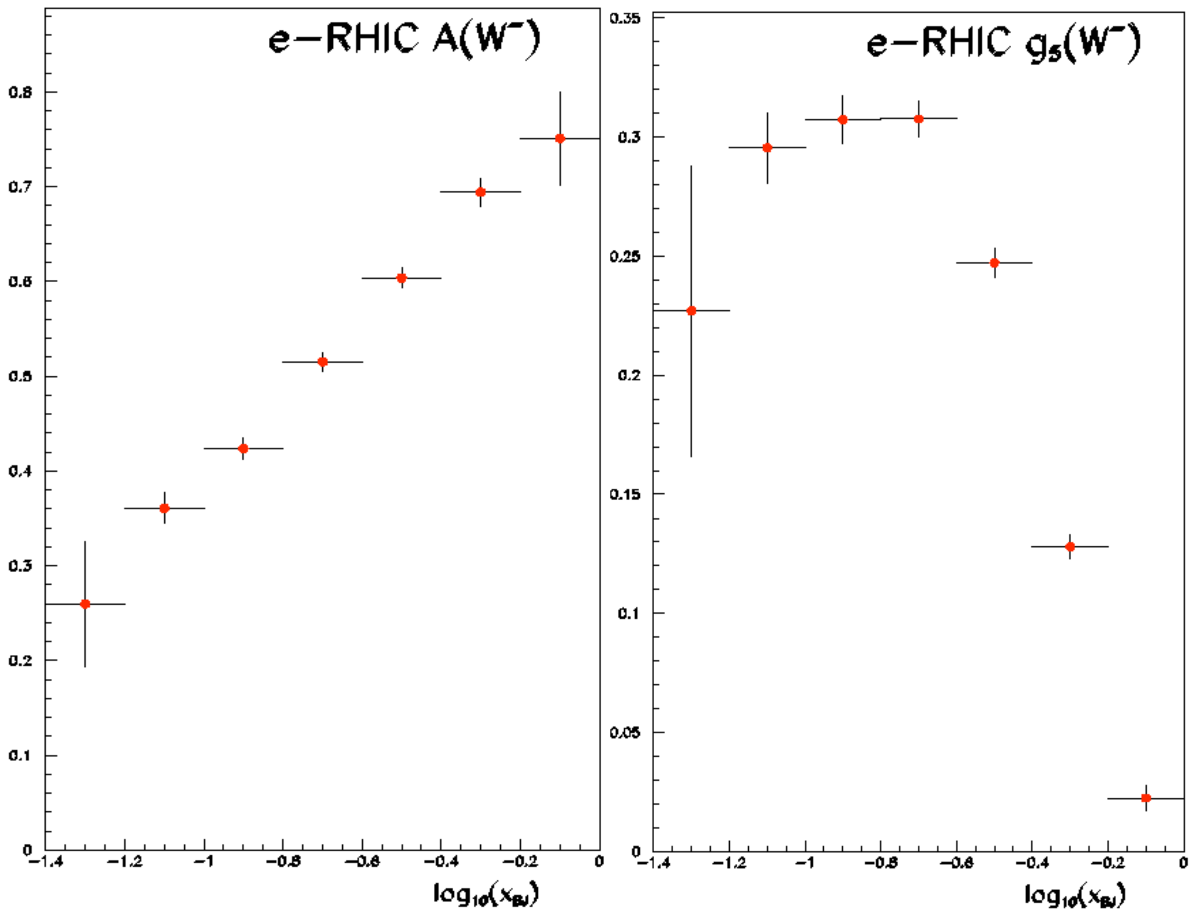
$$g_5^{W-} = \Delta u + \Delta c - \Delta\bar{d} - \Delta\bar{s}$$

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



- 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

Measurement Accuracy PV g_5 at eRHIC



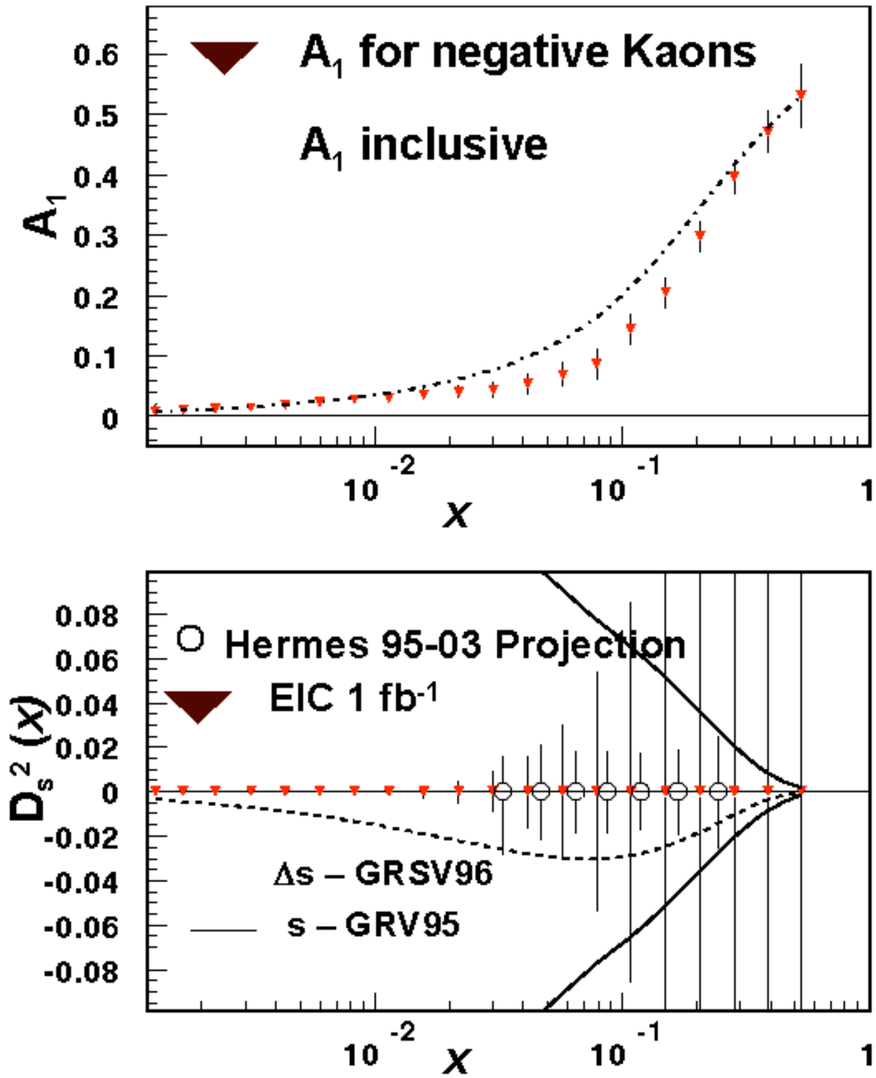
Assumes:

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

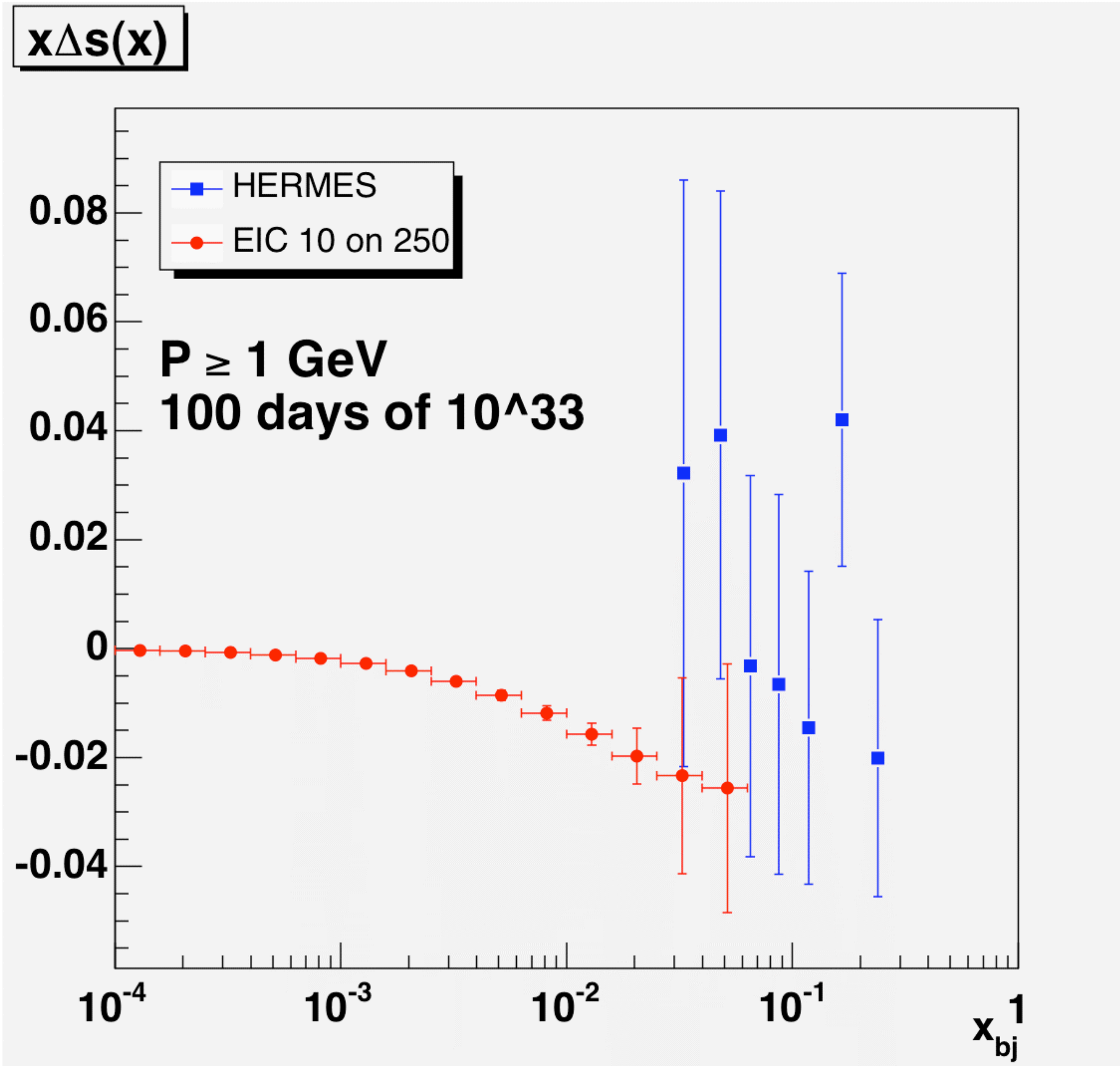
Strange Quark Distributions at eRHIC



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

- *5 GeV on 50 GeV*

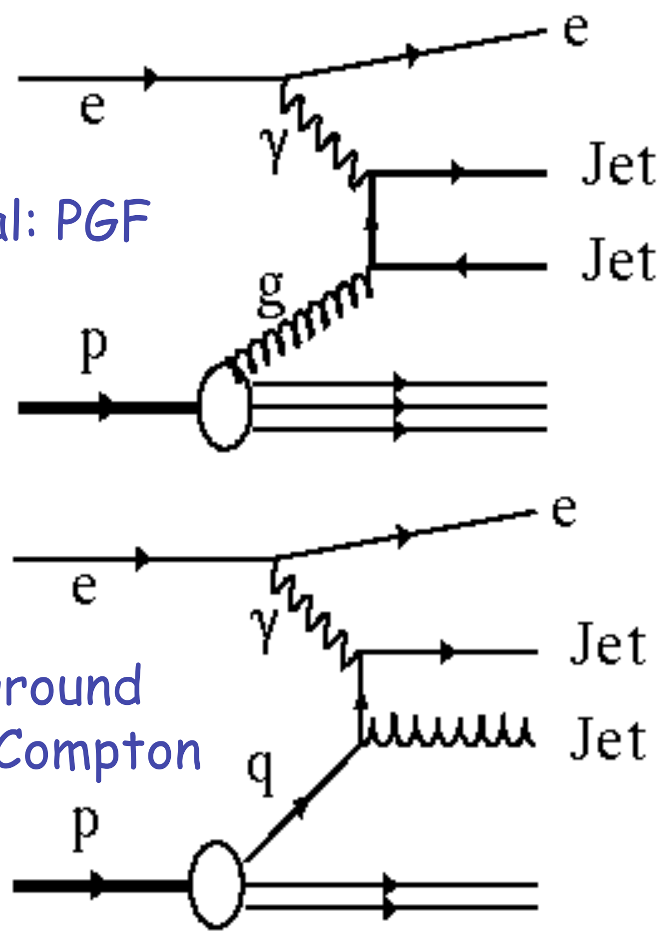
- Upper Left: statistical errors for kaon related asymmetries shown with A_1 inclusive
- Left: Accuracy of strange quark distribution function measurements possible with eRHIC and HERMES (2003-05) and some theoretical curves on expectations.


xΔs(x)
HERMES
EIC 10 on 250
P ≥ 1 GeV
100 days of 10^33
0.08
0.06
0.04
0.02
0
-0.02
-0.04
10^-4
10^-3
10^-2
10^-1
1
x_bj

Photon Gluon Fusion at EIC

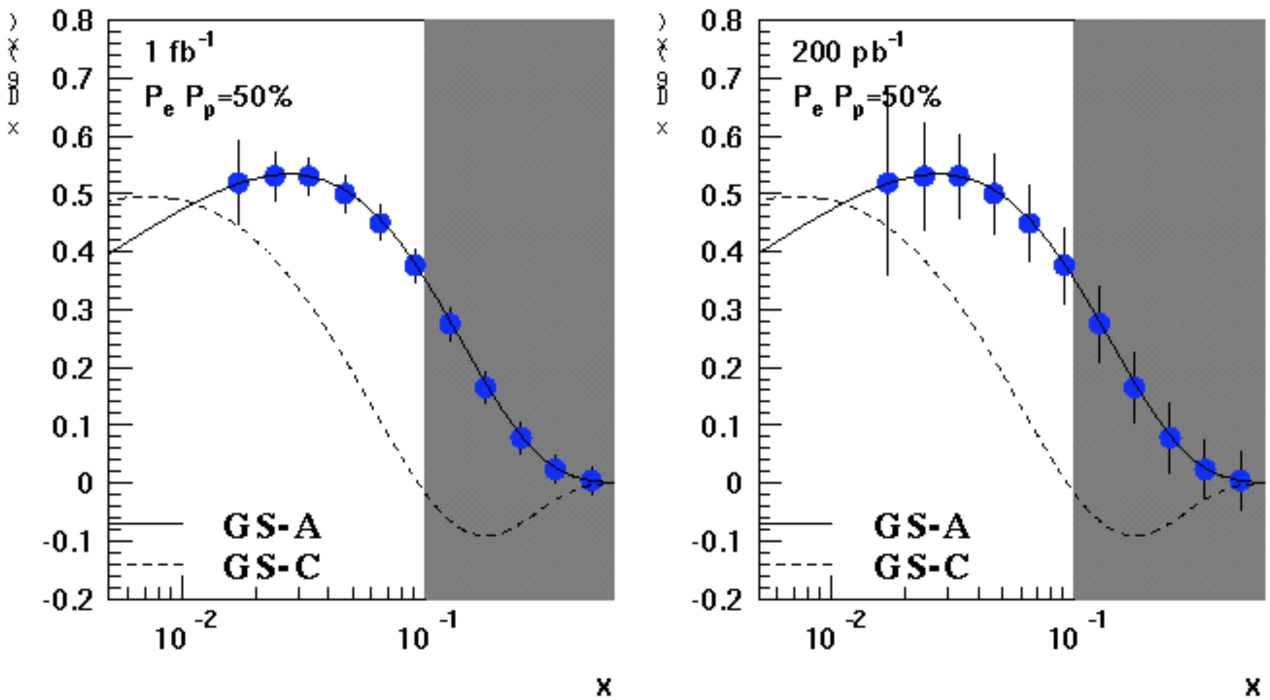
Signal: PGF

Background
QCD Compton



- "Direct" determination of ΔG
  - -> Di-Jet events: (2+1)-jet events
  - -> High pT hadrons
- Need high Sqrt(s)
  - -> 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

Di-Jet events at eRHIC: Analysis at NLO

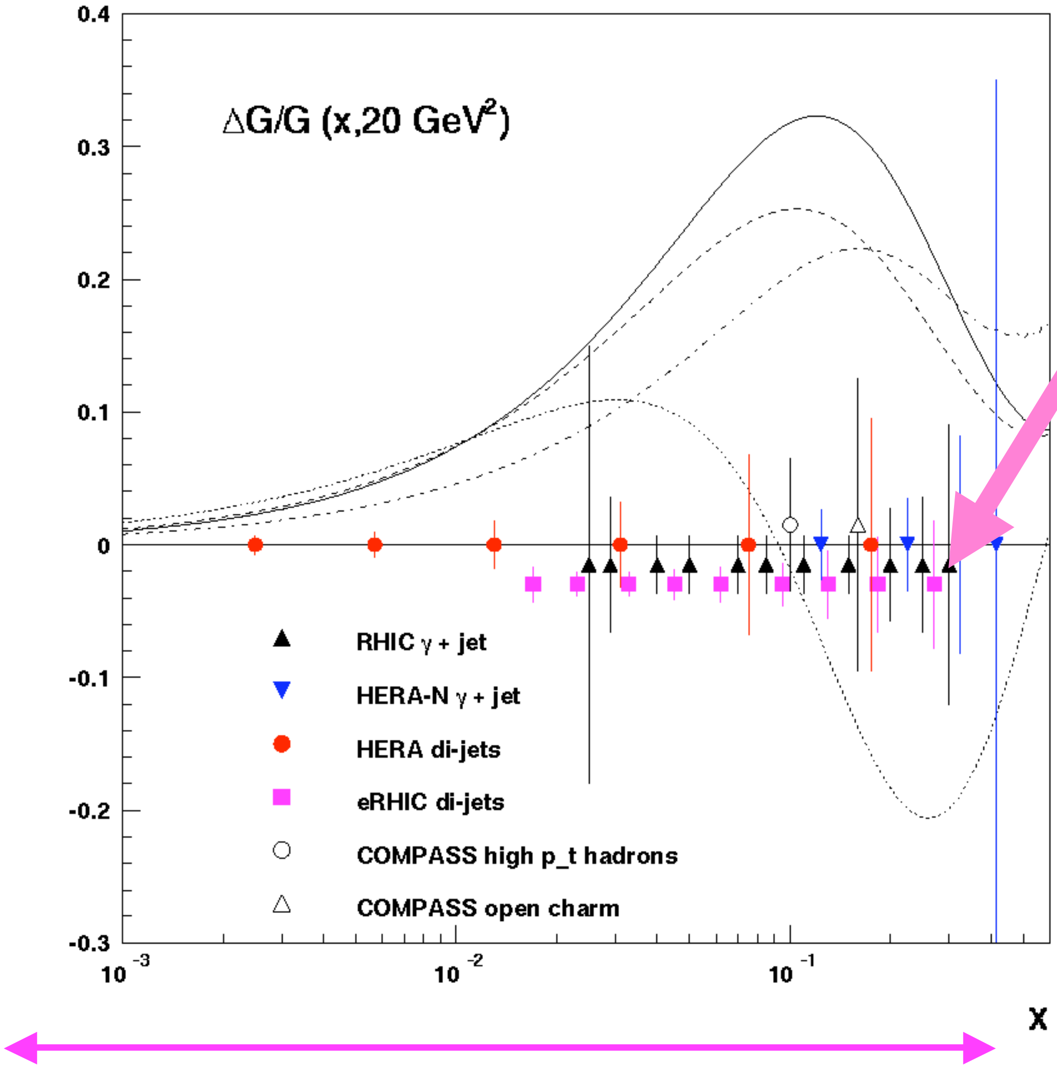


- Stat. Accuracy for two luminosities
- Detector smearing effects considered
- NLO analysis

- 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 program

G. Radel, A. De Roeck
Abhay Deshpande

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



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

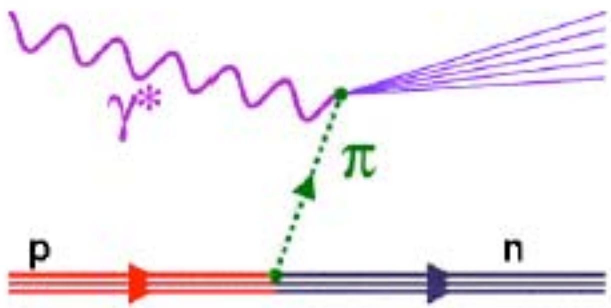
- Good precision
- Clean measurement in x range 0.01< x < 0.3
- Constrains shape of ΔG(x)
- Polarization in HERA much more difficult than RHIC.

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

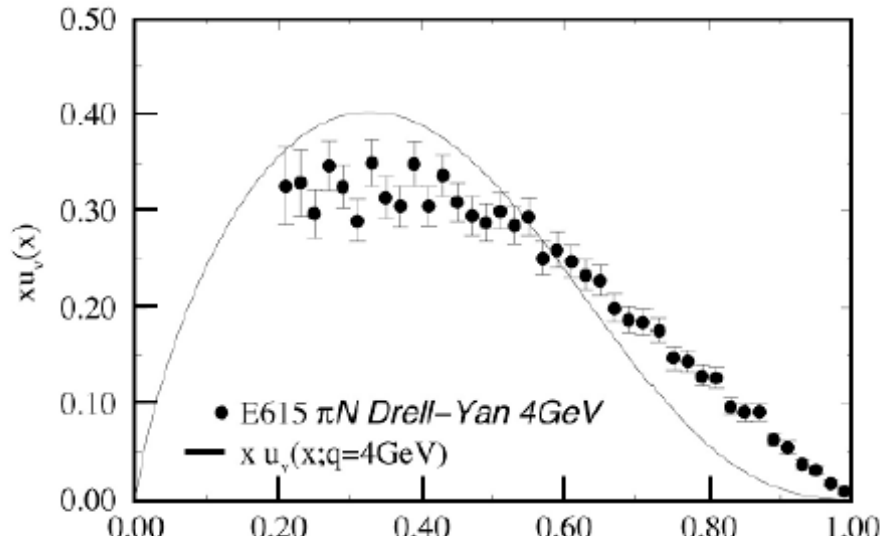
R. Holt

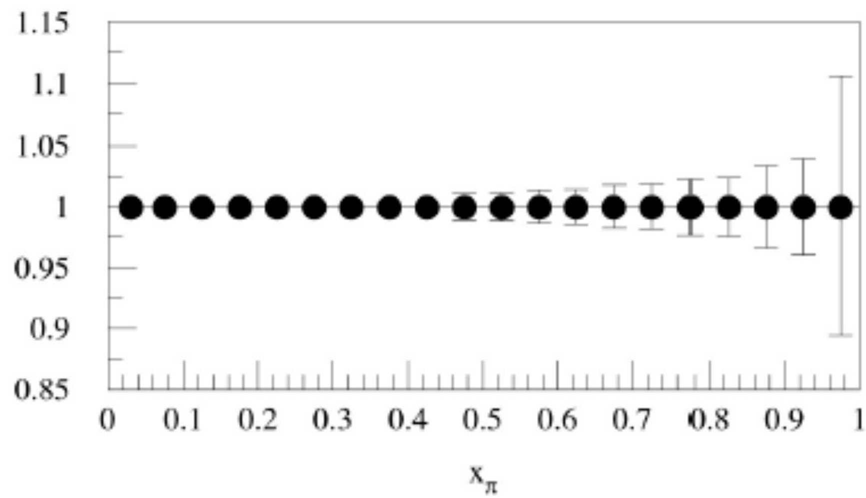
Quark Distribution in the Pion Cloud

Sullivan Process



5 GeV e- on 25 GeV p



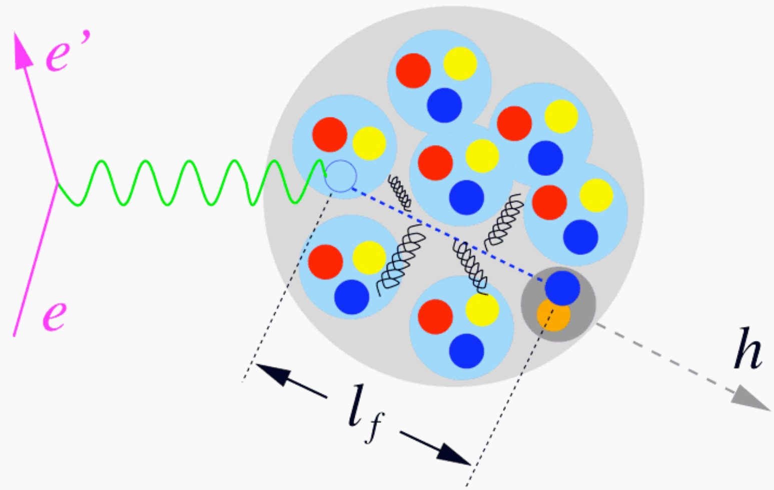


Hadronization:
The Dynamics of Confinement

- How does a fast colored quark or gluon turn into a group of hadrons?
- How are baryons formed?
- Are their correlations among the hadrons we can exploit?
- Can we use Lambda hyperons to study quark spin?
- Can we use the nucleus as a laboratory to study energy loss of quarks through nuclear matter?

-> Needs moderate CM energy and 4π detector!

Hadron Electro-Production in Nuclei



- Hadron production from nuclei can be influenced by

  → Pre–hadronized quark interactions with extra nucleons in nucleus
  → Produced hadron interactions with spectator nucleons

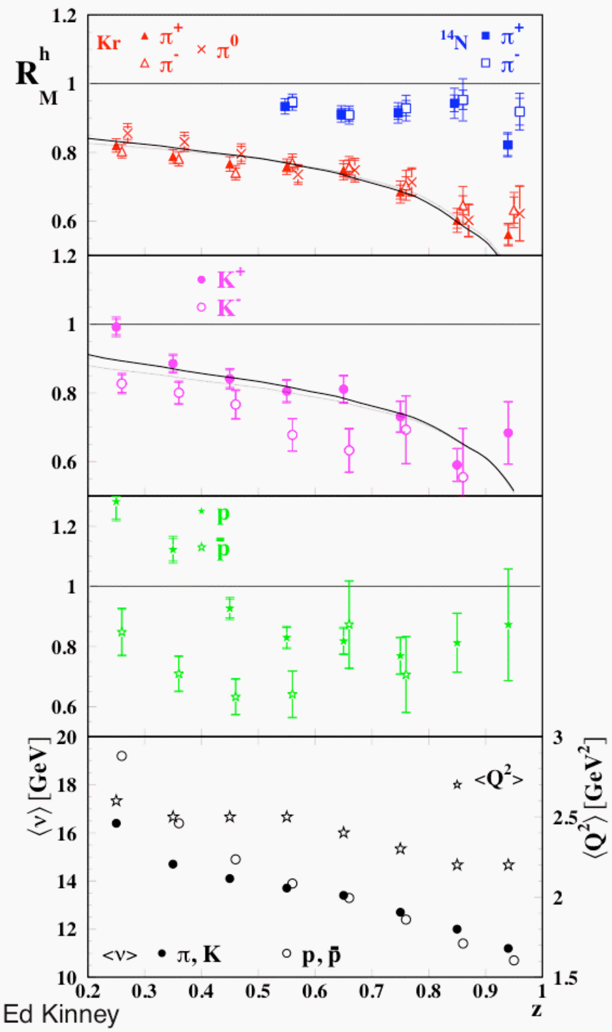
- $\tau_f = l_f/c$, hadron formation time will affect which dominates

Definition of Attenuation Ratio

$$R_A(z,\nu) = \frac{\left(\frac{1}{\sigma}\frac{d\sigma}{dz d\nu}\right)_A}{\left(\frac{1}{\sigma}\frac{d\sigma}{dz d\nu}\right)_D} = \frac{\left(\frac{1}{N_e}\frac{dN_h}{dz d\nu}\right)_A}{\left(\frac{1}{N_e}\frac{dN_h}{dz d\nu}\right)_D}$$

where $$\frac{1}{N_e}\frac{dN_h}{dz d\nu} \approx \frac{\sum_f e_f^2 q_f(x) D_f^h(z)}{\sum_f e_f^2 q_f(x)}$$

Hadron Type Dependence: ν Dependence



- RICH allows separation of hadron species (^{84}Kr only)
- Protons are less attenuated than pions and kaons → longer formation time?

$\sigma_{\pi^{\pm}} \approx 25$ mb

$\sigma_{K^{+}} \approx 17$ mb $\quad \sigma_{K^{-}} \approx 23$ mb

$\sigma_{p} \approx 40$ mb $\quad \sigma_{\bar{p}} \approx 60$ mb

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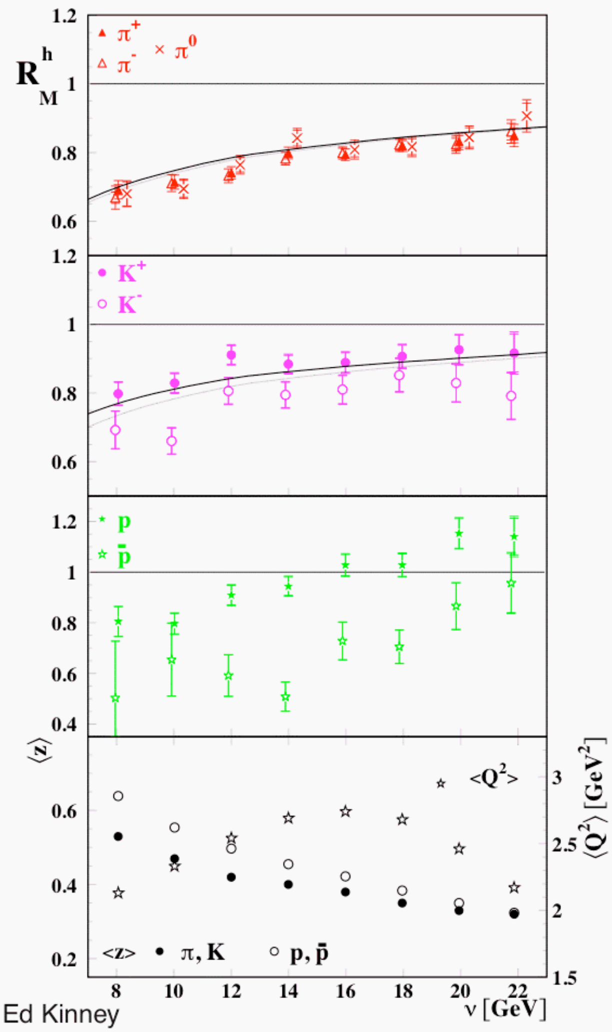
Hadron Type Dependence: z Dependence



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- At large momentum $\sigma_{\bar{p}} \approx 1.5\ \sigma_p$
- Momentum range = 4–15 GeV
- At lower momenta anti–proton annihilation becomes more significant $\rightarrow$ may explain difference between proton and anti–proton attenuation

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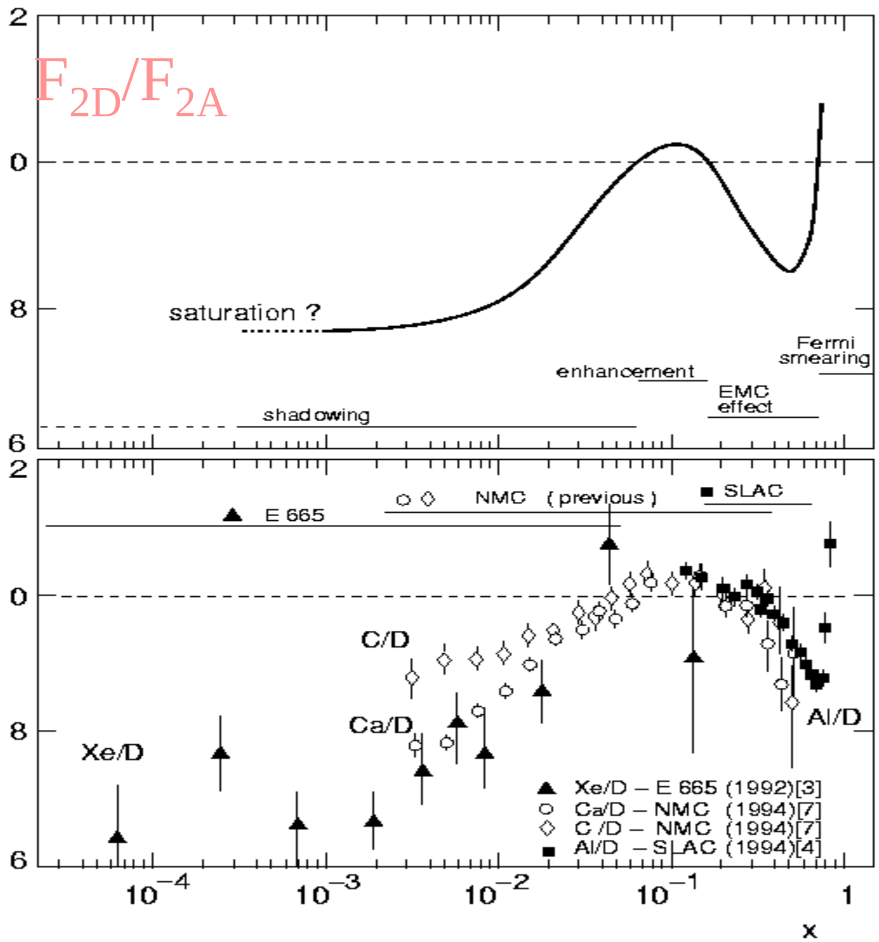
DIS inside the Nucleus



Regions of:

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

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

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

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)

And still more physics…

- Precision measurement of $\alpha_S(Q2)$ from g_1 scaling violations
- Polarized structure function of the photon from photo-production
- Transversity (See A. Bruell's talk next)
- Drell-Hearn-Gerasimov spin sum rule test at high ν
- Target fragmentation studies
- …

Why don't Northerners (yankees) and Southerners (crackers) work well together?

Basic Phenomenon: Northerners speak quickly
Southerners speak slowly

Northern belief: People who speak slowly are stupid

Southern belief: People who speak quickly are dishonest

Northerners think Southerners are stupid

Southerners think Northerners are dishonest

Why is there tension between "discovery" and "precision" physicists?

Basic Phenomenon:
"Discoveries" are often hard to understand in detail
"Precise studies" test detailed understanding

"discovery" belief: "precision" lost in unimportant details

"precision" belief: "discovery" is sloppy work

Discovery thinks precision is dull
Northerners think Southerners are stupid

Precision thinks Discovery is careless
Southerners think Northerners are dishonest

Lessons from Tycho Brahe (1546-1601)

Lifelong commitment to *precision* study of astronomy (before telescopes!)

Motivated by "wrong" theory; died before seeing first comprehensive phenomenalogical analysis

BUT…

Became famous for *discovering* a new star

Used fame to build first "National Laboratory" in Denmark, with 5% of the GNP of Denmark(!)

Hired Johannes Kepler

Outlook

Many of these studies are still with ideal detectors; we have just begun to optimize real detectors!

Only a small group working on these at present; more people would be very welcome!

Thanks and apologies to all EIC workers who I have borrowed from!

http://www.bnl.gov/eic IS a working website