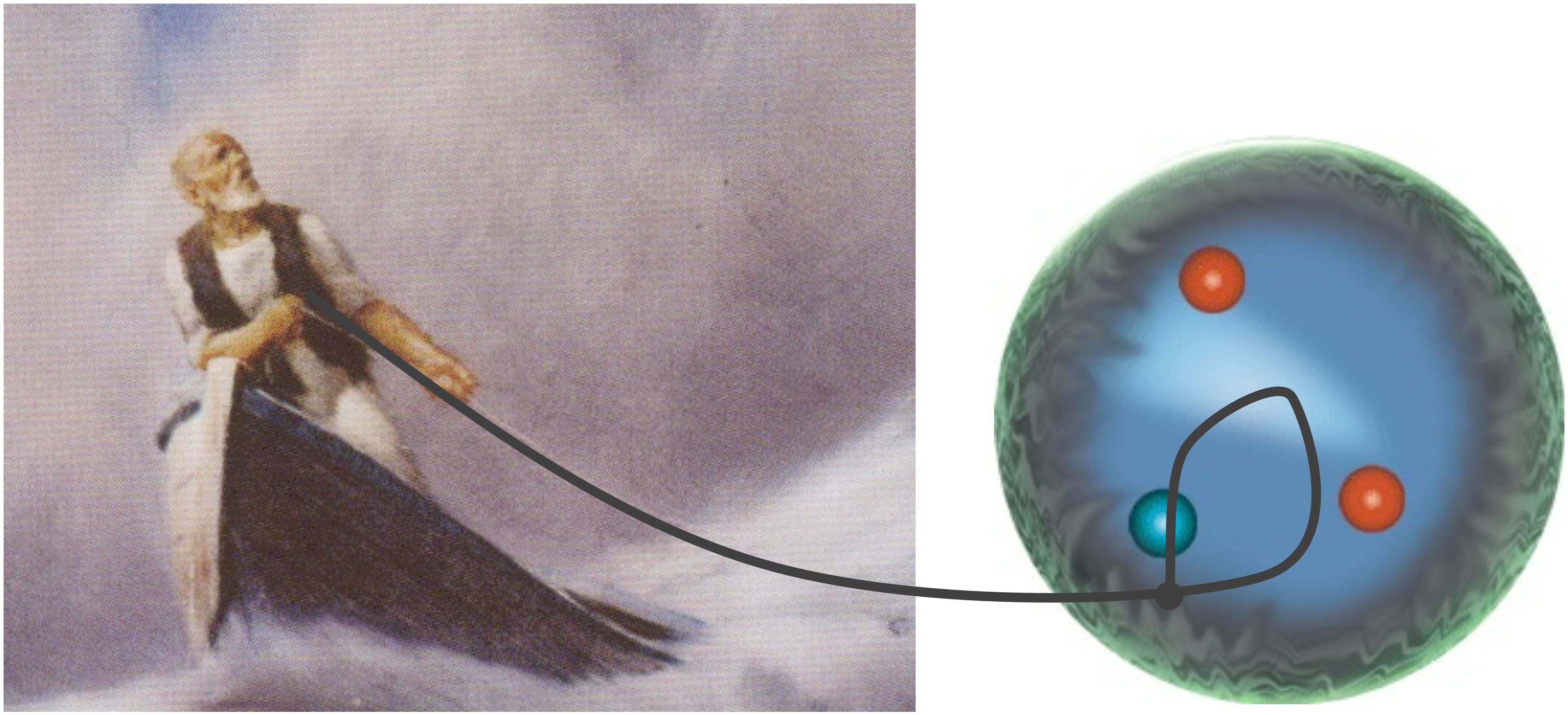
Argonne NATIONAL LABORATORY

The Sea of the Proton and Nuclei



Donald Geesaman

HUGS Summer School

8 June 2021

U.S. DEPARTMENT OF ENERGY

References and Credits

Many of the slides I am using are stolen from my colleagues Paul Reimer and Arun Tadepalli.

Proton Sea References

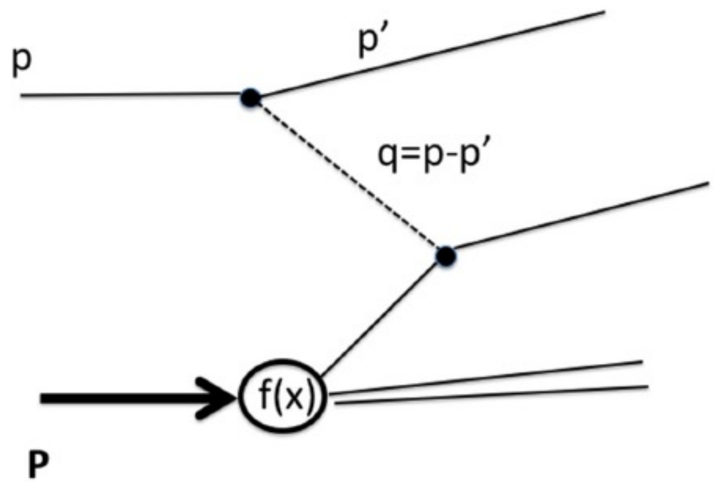
- Chang & Peng, Flavor structure of the nucleon sea. Prog. Part. Nucl. Phys. **79**, 95–135 (2014).
- Geesaman & Reimer, The sea of quarks and antiquarks in the nucleon. Rep., Prog. Phys. **82**, 046301 (2019)
- Dove et al., Nature **590,** 561 (2021)

The Sea in a Nucleus References

- Hen et al., Rev. Mod. Phys. **89**, 045002 (2017)
- Kulagin and Petti, Phys. Rev. C **90**, 045204 (2014)

Heuristic Parton Model - What are you measuring: The Distribution of Quarks

- Only single point parton currents contribute – No Q^2 dependence of form factor
- Parton mass is negligible
- No interference between different partons
- Final state interactions can be neglected



$$P_\mu = (P, k_t, \sqrt{P^2 + m^2})$$

$$xP_\mu = (xP, 0, \sqrt{(xP)^2 + m_q^2})$$

$$0 \sim m_q^2 = (xP_\mu + q_\mu)^2 = (x^2 m_q^2 + q_\mu q^\mu + 2xP_\mu q^\mu)$$

$$Q^2 = -q_\mu q^\mu \quad P_\mu q^\mu = m\nu \ \ in\ rest\ frame$$

$$x = \frac{Q^2}{2m\nu}$$

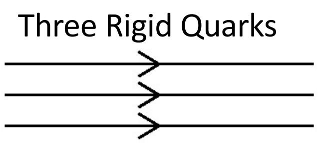
$$F_2 = \sum e_i^2 x q_i(x, Q^2)$$

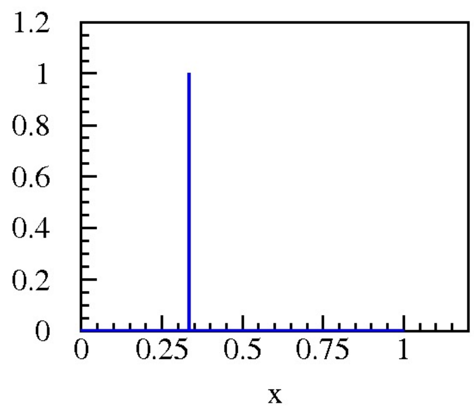
$$\frac{d^2\sigma}{dxdQ^2} = \frac{4\pi\alpha^2}{xQ^2}\left[(1-y)F_2(x,Q^2) - xy^2 F_1(x,Q^2)\right]$$

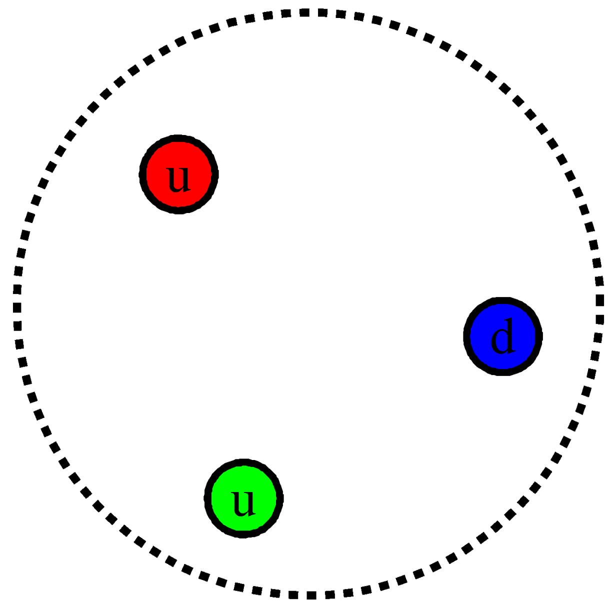
$$F_L = F_2 - 2xF_1 \qquad R = \sigma_L / \sigma_T = F_L / (2xF_1)$$

From Constituent Quarks to Partonic Quarks

- Constituent Quark/Bag Model motivated valence approach
  - Use valence-like (primordial) quark distributions at some very low scale, Q^2, perhaps a few hundred MeV







From Constituent Quarks to Partonic Quarks

- Constituent Quark/Bag Model motivated valence approach
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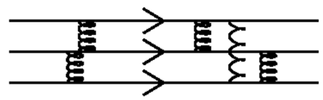
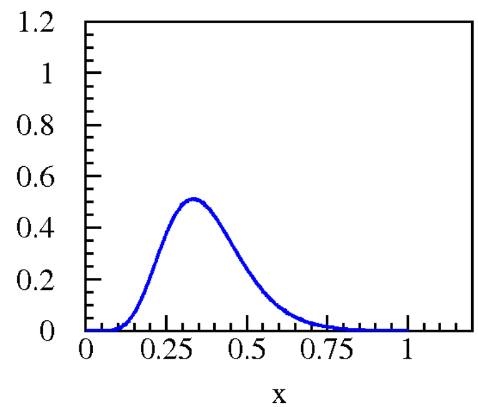
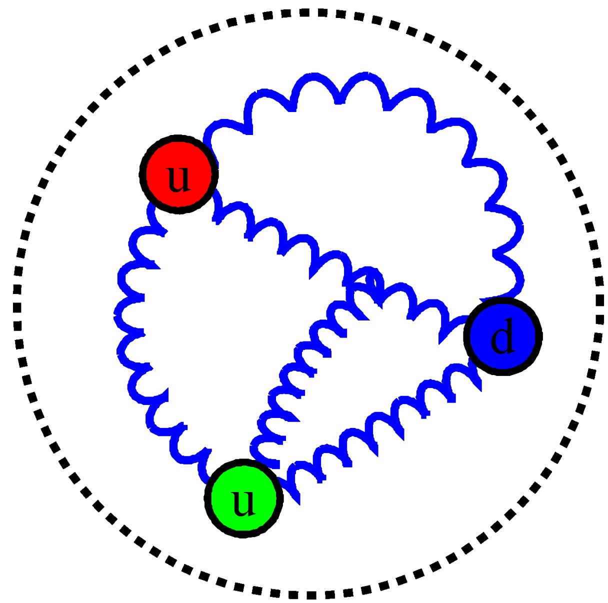
Three interacting Quarks







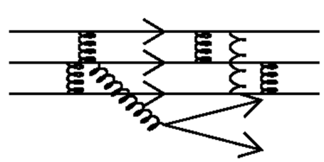
From Constituent Quarks to Partonic Quarks

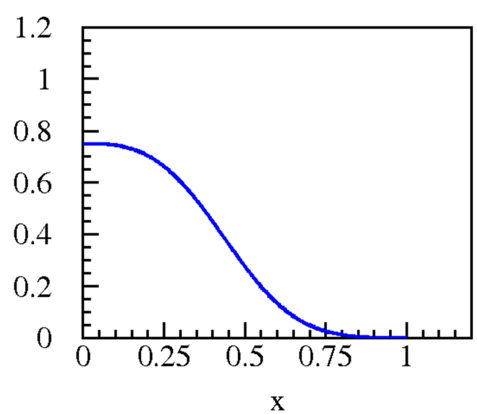
- Constituent Quark/Bag Model motivated valence approach
  - Use valence-like (primordial) quark distributions at some very low scale, Q^2, perhaps a few hundred MeV
  - Radiatively generate sea and glue. Gluck, R
    Vogt, ZPC 53, 127 (1992)

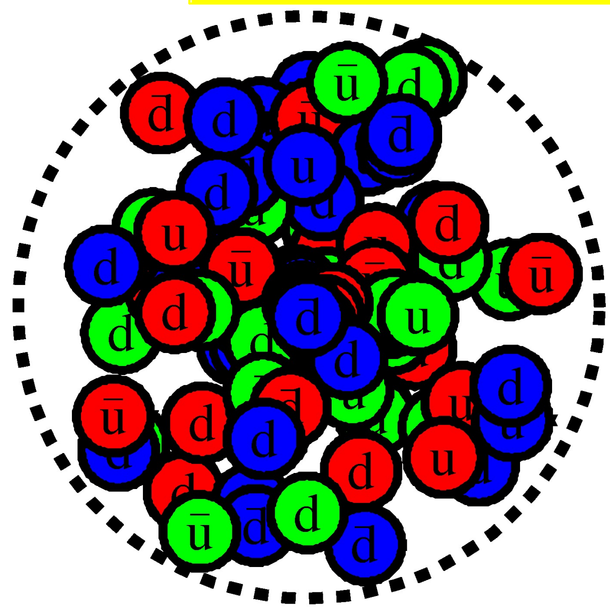
What does valence mean?

$\int_0^1 [u(x) - \bar{u}(x)]\,dx = 2$

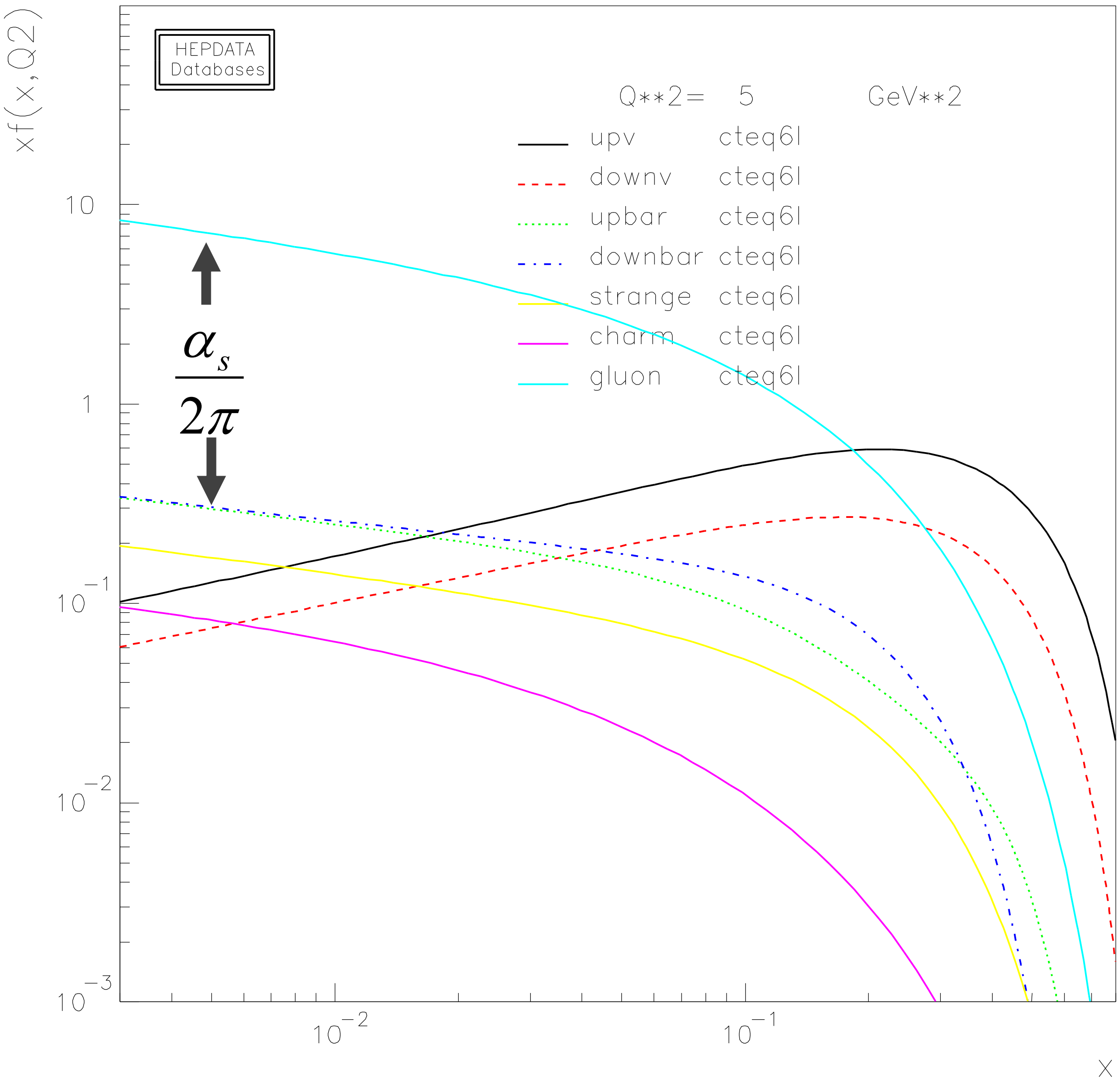
$\int_0^1 [d(x) - \bar{d}(x)]\,dx = 1$







Partonic content of the Proton: The valence quarks and glue get all the respect.

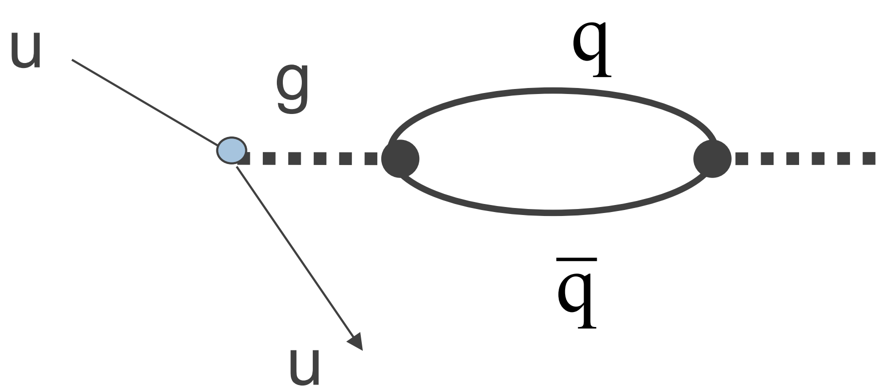


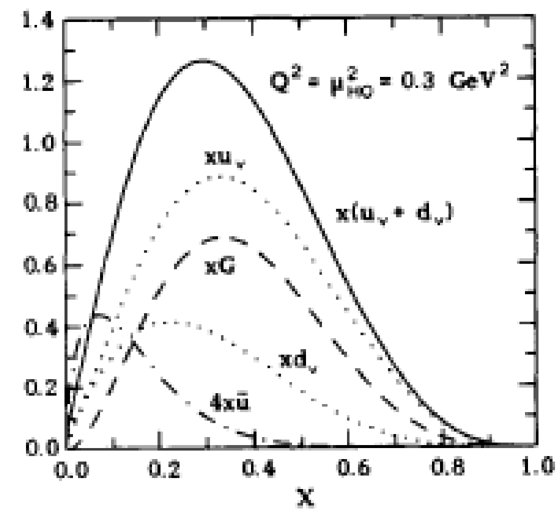
- Valence quarks determine the charge and flavor of hadrons
- Seem to explain the magnetic moments.
- We thought, until 1990, that the valence quarks carried the spin
- New accelerators, like the JLAB 12 GeV upgrade, get built to study high x quarks
- The glue dominates hadron structure at low x
- Accelerators like HERA are built and new accelerators like the electron-ion collider are planned to study the glue. With high luminosity they also probe high x valence structure at high Q2.

Maybe the sea quarks will go away!

Motivated by desire to link to constituent quark or bag models, the hope was that as some low scale, Q, of a few hundred MeV/c, valence-like quark distributions plus glue would describe the nucleon, and the sea could be radiatively generated.

Gluck, Godbole, and Reya (Z. Phys. C, 66 (1989)





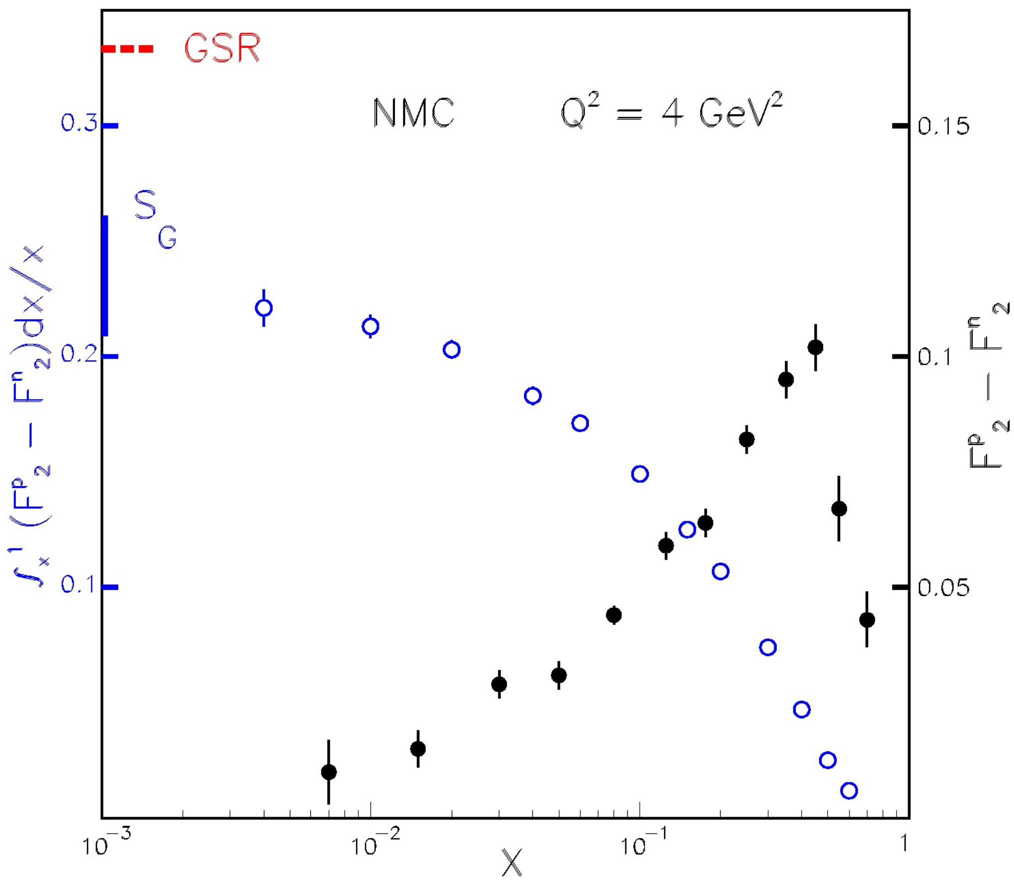
Then it was found that the sea was not flavor symmetric. –**NMC** (PRL **66,** 2712 (1991)

It was then realized that some valence-like sea was needed.
GRV, ZPC53, 127(92)

Light Antiquark Flavor Asymmetry: Brief History

Gottfried Sum

$$\int_0^1 [F_2^p(x) - F_2^n(x)]\frac{dx}{x} = \frac{1}{3} + \frac{2}{3}\int_0^1 [\bar{u}(x) - \bar{d}(x)]dx$$



NMC: Arneodo et al. PRD **50**, R1 (1994)

$$\int_0^1 [\ldots] = 0.235 \pm 0.026$$

How to look closer at the sea?

- Inclusive Deep Inelastic Scattering
  - Compare neutral current (e,e') and neutrino scattering

Are the nuclear effects the same?

- Semi-inclusive DIS
  - $\sigma(x,h,z) \approx \sigma_{\gamma q} \sum_i q_i(x,Q^2) D_i^h(z)$ where D is the fragmentation function for a quark to produce a hadron h with a fraction of the total momentum of the quark.
  - A special case in neutrino scattering is charm production leading to multi-muon events
    $\nu + s \rightarrow \mu^- + c \text{ and then } c \rightarrow \mu^+ + \upsilon_\mu + s$
    $\bar{\upsilon} + \bar{s} \rightarrow \mu^+ + \bar{c} \text{ and then } \bar{c} \rightarrow \mu^- + \bar{\upsilon} + \bar{s}$

- Vector boson production in hadron-induced reactions
  - γ, W^+, W^-, Z

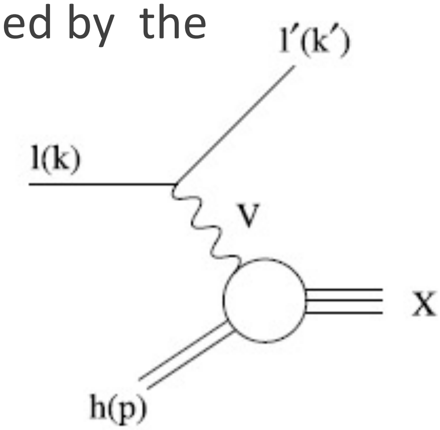
Most of the information on the sea came from deep-inelastic lepton scattering, especially charged current neutrino experiments

$Q^2 = (k-k')^2 = \text{mass}^2$ of the virtual boson

$x = Q^2/(2m\nu)$ is the fractional momentum nucleon carried by the parton

$\nu = E_{beam} - E_{scattered}$ $y = \nu / E_{beam}$

$$\frac{d\sigma}{dx} = \sum_i \sigma_{l-q_i} \otimes f_i(x)$$



muon and electron scattering~ $2x(4/9[u+c+\bar{u}+\bar{c}]+1/9[d+s+\bar{d}+\bar{s}])$

ν charge current scattering ~ $2x[d+s+(1-y)^2(\bar{u}+\bar{c})]$

anti-ν c. c. scattering~ $2x[u+c+(1-y)^2(\bar{d}+\bar{s}))]$

parity violating ν scattering, F_3~ $2x(d+s-\bar{u}-\bar{c})$

parity violating anti-ν scattering~ $2x(u+c-\bar{d}-\bar{s})$

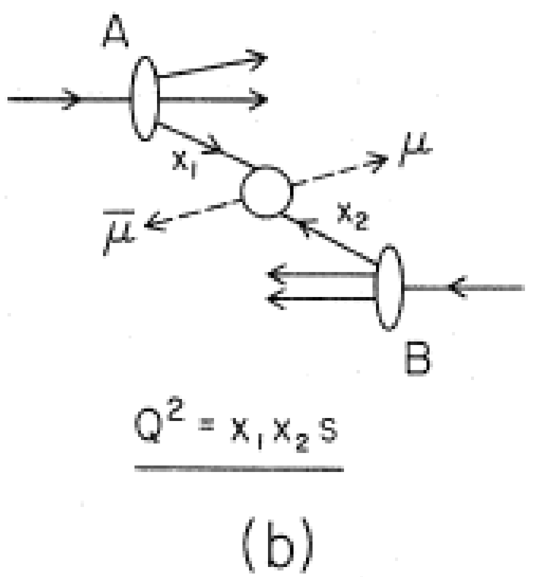
The high statistics ν experiments are all done on nuclear targets

We need a probe with direct sensitivity to the sea quarks. Drell and Yan identified such a mechanism

VOLUME 25, NUMBER 5 PHYSICAL REVIEW LETTERS 3 AUGUST 1970

MASSIVE LEPTON-PAIR PRODUCTION IN HADRON-HADRON COLLISIONS AT HIGH ENERGIES*

Sidney D. Drell and Tung-Mow Yan
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305
(Received 25 May 1970)



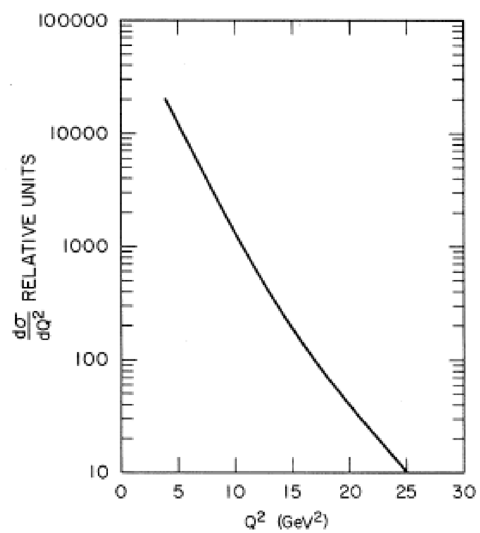
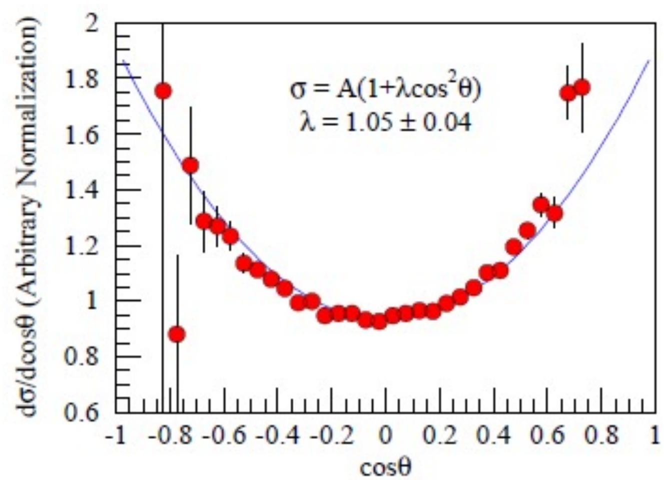
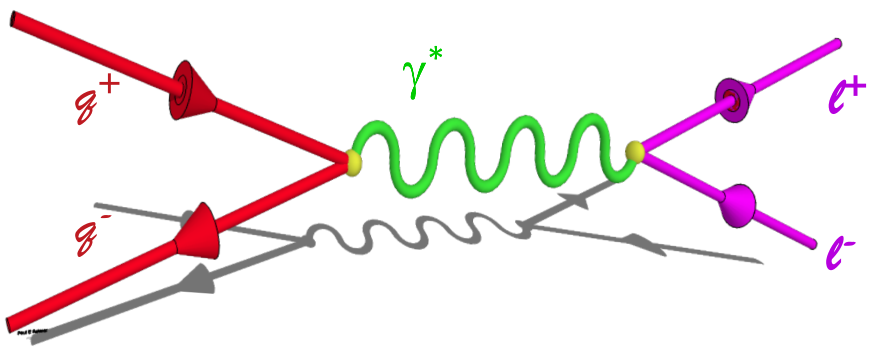


FIG. 2. $d\sigma/dQ^2$ computed from Eq. (10) assuming identical parton and antiparton momentum distributi[c]
and with relative normalization.

Also predicted $\lambda(1+\cos^2\theta)$ angular distributions



Drell-Yan Cross Section—Sensitivity to Sea Quarks



I will tend to use x_1 and x_b
Interchangably as well as x_2 and x_t

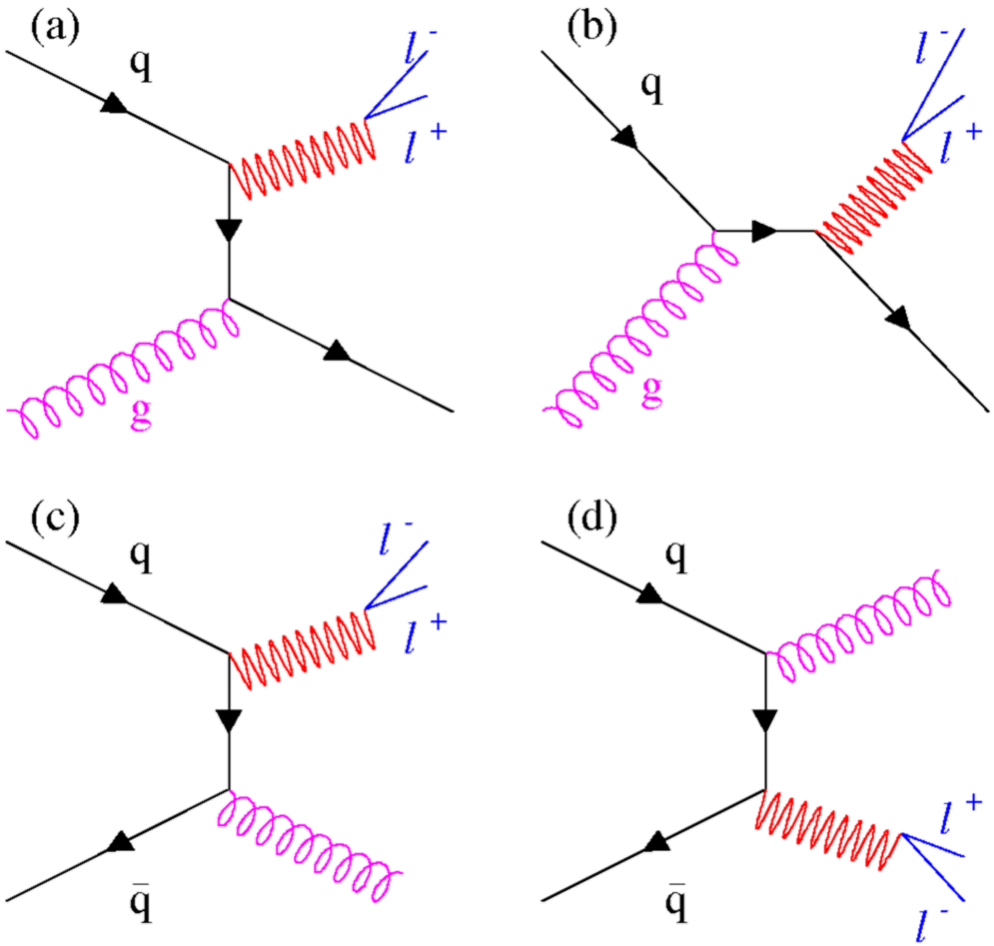
Cross Section

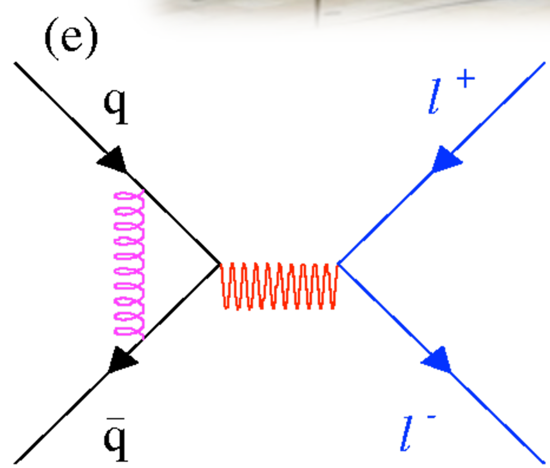
- Point-like scattering of spin-1/2 particles
- Convolution of beam and target parton distributions

$$\frac{d^2\sigma}{dx_\mathrm{b}dx_\mathrm{t}} = \frac{4\pi\alpha^2}{x_\mathrm{b}x_\mathrm{t}s} \sum_{q\in\{u,d,s,\dots\}} e_q^2 \left[\bar{q}_\mathrm{t}(x_\mathrm{t})q_\mathrm{b}(x_\mathrm{b}) + \bar{q}_\mathrm{b}(x_\mathrm{b})q_\mathrm{t}(x_\mathrm{t})\right]$$

Bodwin proved the Factorization Theorem for this process!

Next-to-Leading Order in α_s





These effects are significant (factor of ~2 due to definition of pdf to make DIS simple), but to a good approximation cancel out in the ratio. They are included in the analysis.

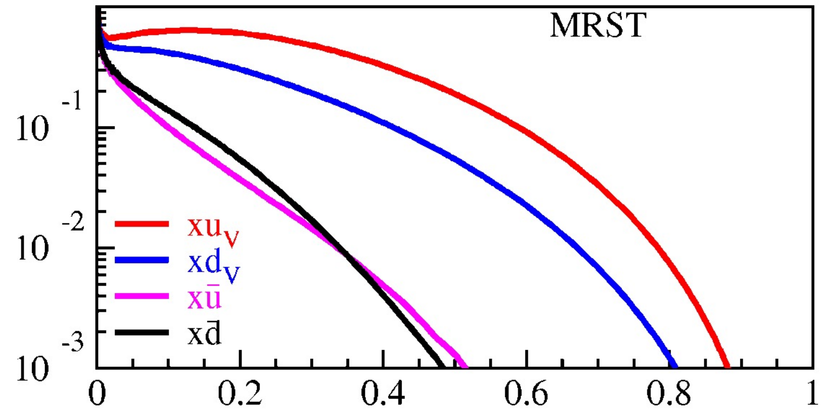
Extracting $\bar{d}(x)/\bar{u}(x)$

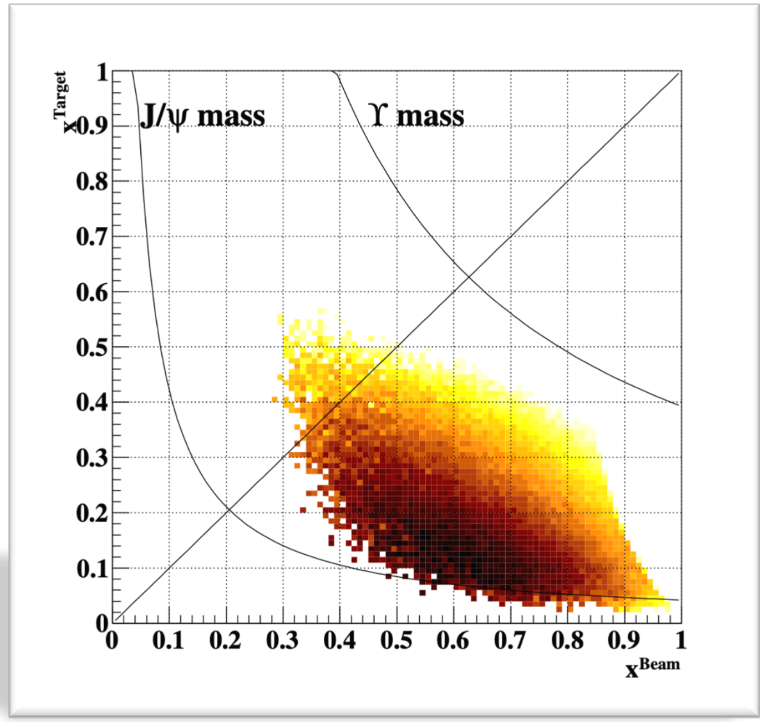
With a proton beam at high x_b 4/9 u(x) ~ 8*1/9 d(x) and with x1>x2, this is primarily sensitive to $\bar{u}_t$

Assume charge symmetry (implicit in most PDF fits) ($u_p = d_n$ *and* $\bar{u}_p = \bar{d}_n$ …)

Assume nuclear effects in deuterium are small (estimated to be a few percent in this kinematic range) $\sigma_d \cong \sigma_p + \sigma_n$

$$\frac{\sigma^{\mathrm{pd}}}{2\sigma^{\mathrm{pp}}} = \frac{1}{2}\left[1 + \frac{\bar{d}(x)}{\bar{u}(x)}\right]$$

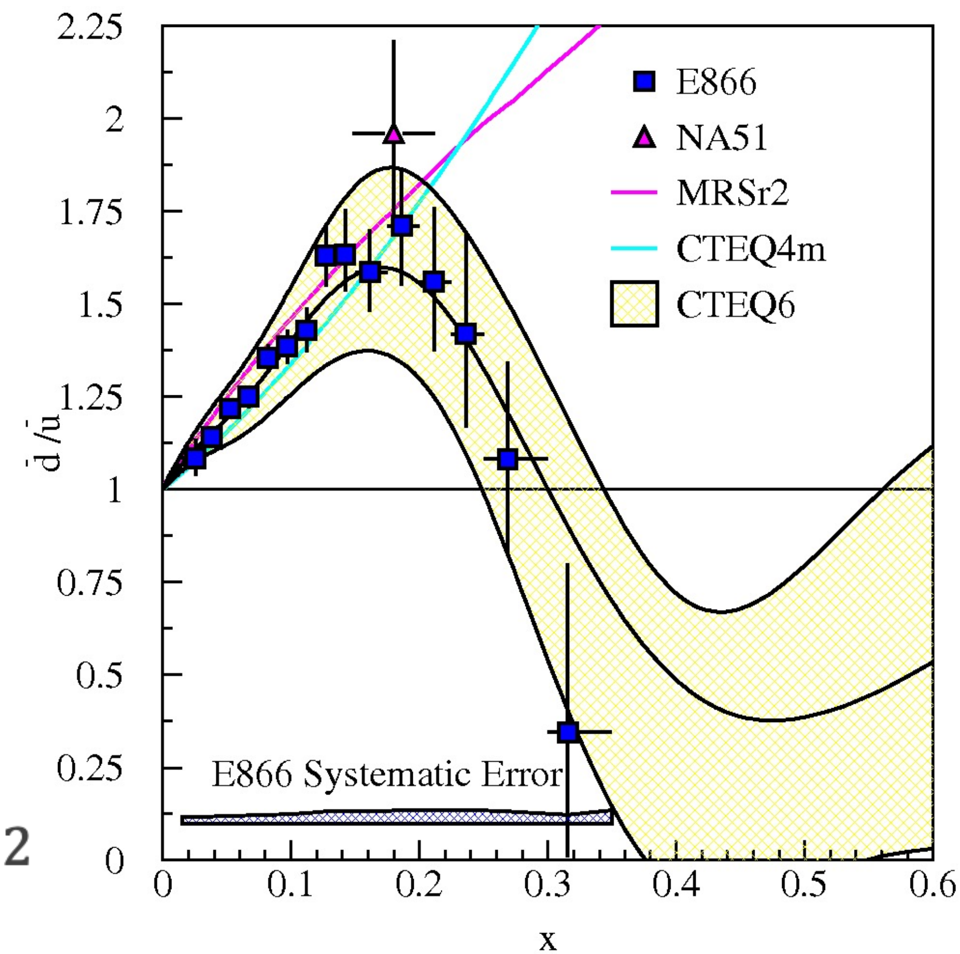




NA51 and NuSea Drell-Yan Results

- Naïve Assumption:
  $\bar{d}(x) = \bar{u}(x)$
- NMC (Gottfried Sum Rule)
  $$\int_0^1 [\bar{d}(x) - \bar{u}(x)]dx \neq 0$$
- CERN NA51 (Drell-Yan):
  $\bar{d}(0.18) \approx 2\times\bar{u}(0.18)$
- Fermilab E866/NuSea:
  $\bar{d}(x)/\bar{u}(x)$ for $0.015 \leq x \leq 0.035$

$$\int_0^1 [\bar{d}(x) - \bar{u}(x)dx = 0.118 \pm 0.012$$



This proton is never just 3 quarks at any scale!

Main message from this talk!

Why? It must be a non-perturbative mechanism!

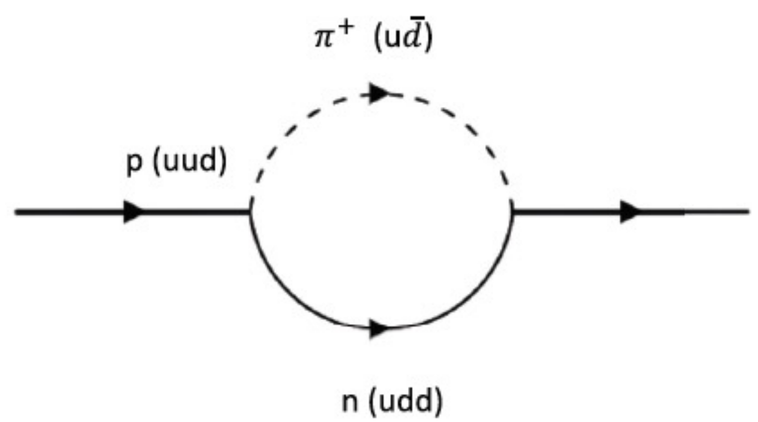
- Perturbative QCD cannot predict such a large effect.

- Pauli Blocking. With more u than d quarks in a proton, naively there are 4 spin-color allowed states for u$\bar{u}$ and 5 allowed states for d$\bar{d}$.
  This is subject to lots of debate: Field and Feynman PRD 15, 2560 (1977)
  Steffans and Thomas PRC 55, 900 (1997)

Why do we not have to consider this
In QCD evolution?

- This is related to statistical models (Bourrely and Soffer NPA 941, 307 (2015) and detailed balance models (Zhang and Zhang PRD 82, 074021 (2010)). There are three ways a $|uudu\bar{u}>$ can transition to a |uudg> but only two ways a |uudd$\bar{d}$>can transition to a |uudg>.

- Meson-baryon Models

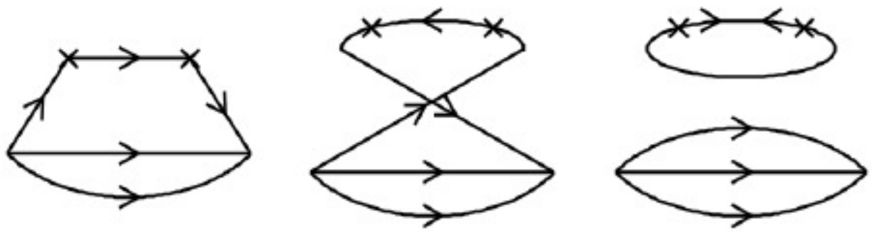


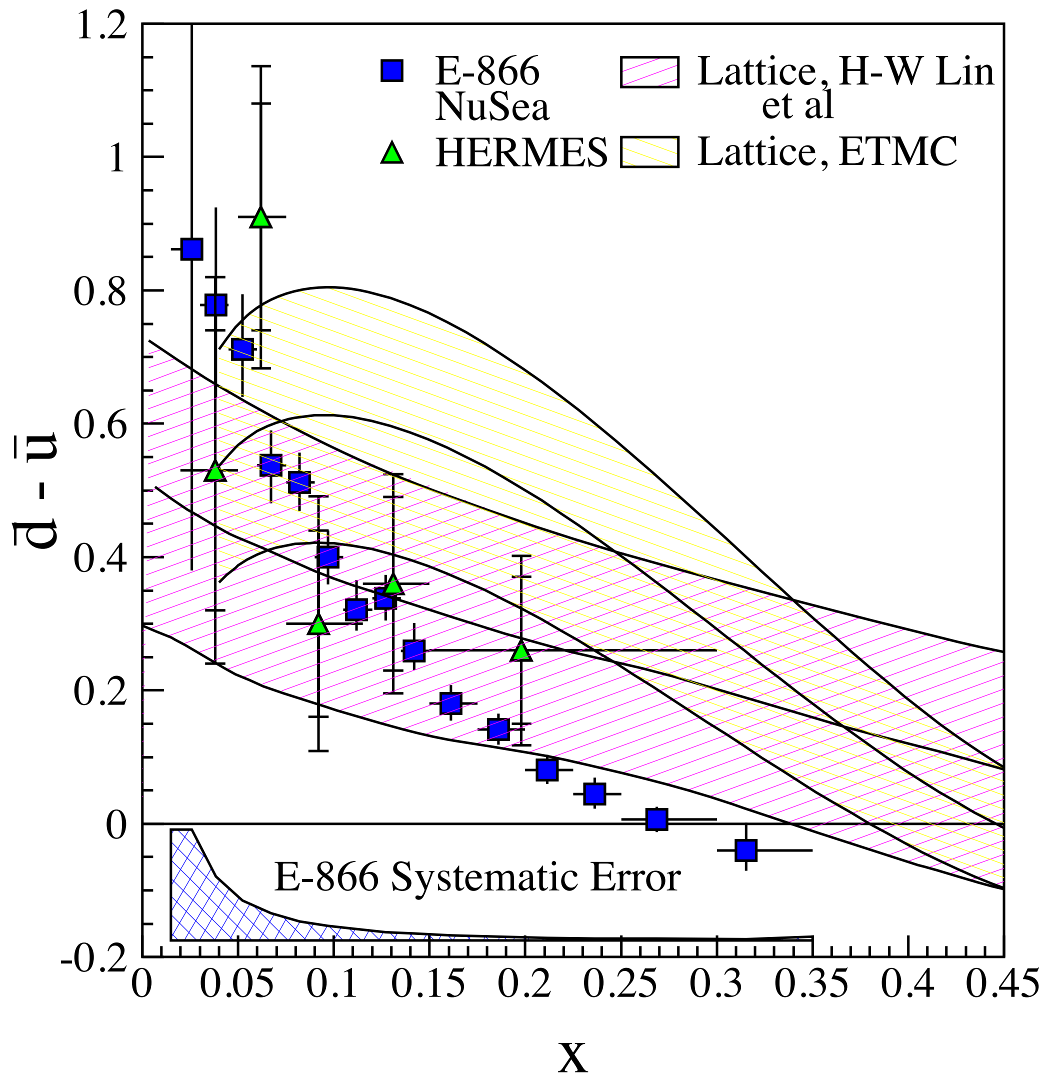
- Chiral quarks models and instantons

- Lattice QCD

How is the Sea Created?

- Lattice weighs in!!





Of course the pion cloud is an old idea.

- 1972 Sullivan
- 1980 Chiral/Cloudy Bag Model
  Pions have to be included to preserve chiral symmetry in bag or bag-like models

- 1983 Thomas used the calculated pionic content and measured DIS to conclude that the fraction of the momentum of the nucleon carried by pions was 5+/-1.5% and was consistent with a bag radius of 0.87 +/-0.10 fm.

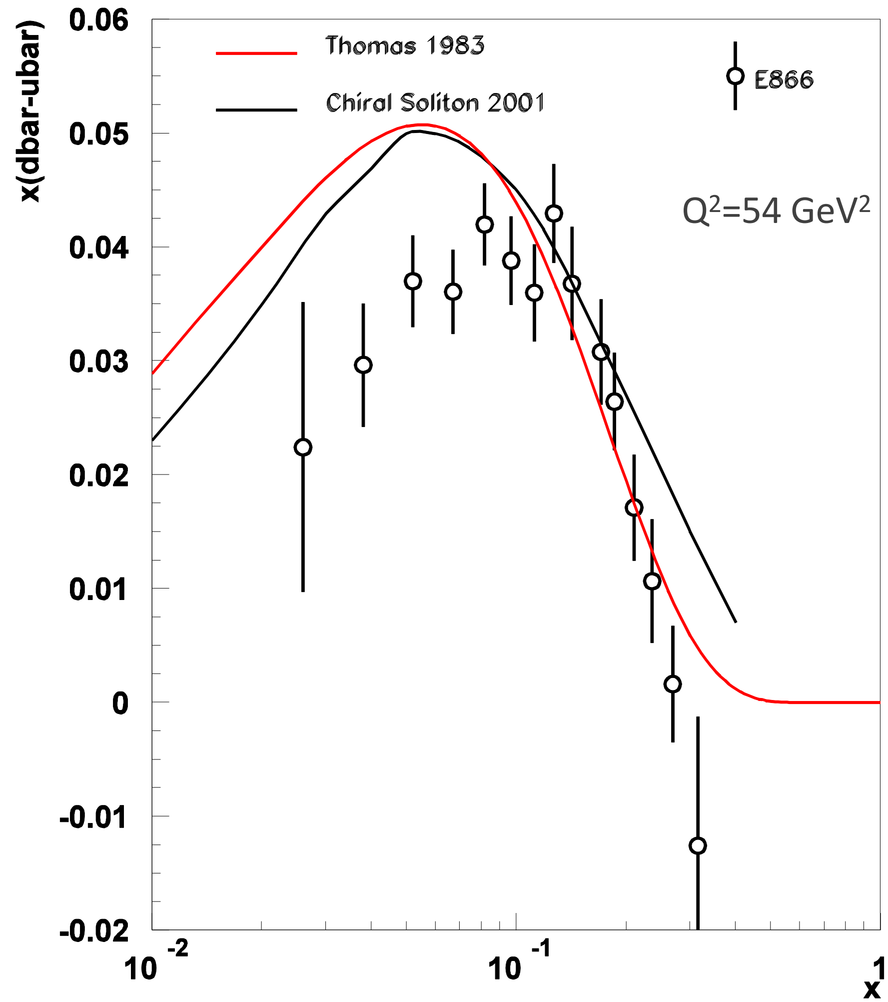
Even today this is not such a bad representation of

$$x(\bar{d}-\bar{u})$$

The problem is it also predicts the ratio

$$\bar{d}/\bar{u}=5$$

as x goes to 1 from the charged and neutral pion Clebsch-Gordan coefficients



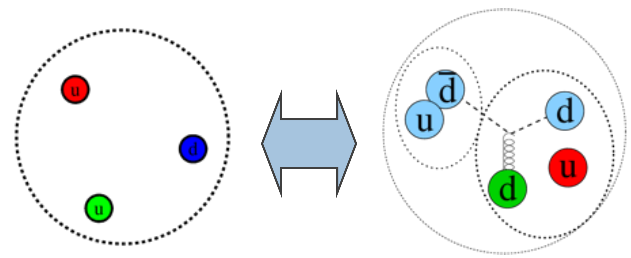
Adding Deltas and isoscalar sigma and omega can bring ratio down to ~1.5 but isoscalar terms are uncomfortably large .
Chiral model predicts ratio of 11/7 at high x

Non-perturbative Models: Pion Cloud

- Meson Cloud in the nucleon Sullivan process in DIS

$$|p\rangle = (1 - \sum a_i)|p_0\rangle + a_{|N\pi\rangle}|N\pi\rangle + a_{|\Delta\pi\rangle}|\Delta\pi\rangle + a_{|\Lambda K\rangle}|\Lambda K\rangle + \cdots$$

- In its simplest form, Clebsch-Gordon Coefficients and πN, $\pi\Lambda$ couplings

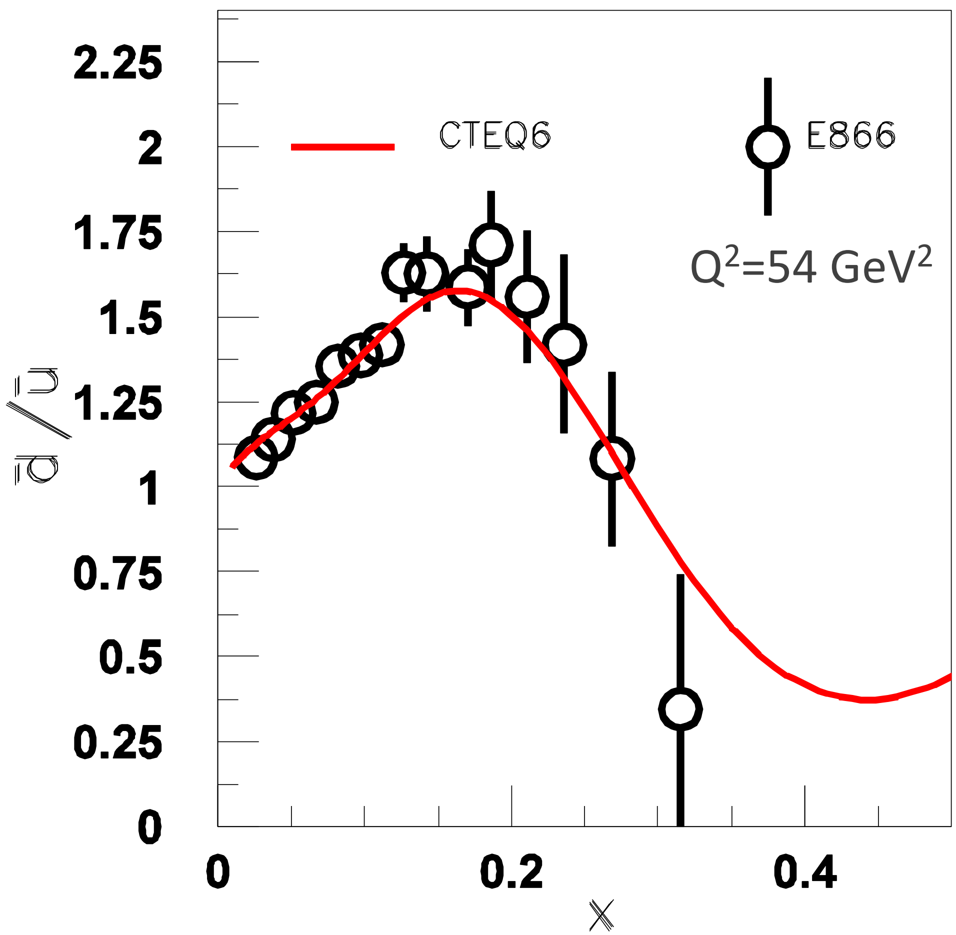


$$a_{|N\pi\rangle}: \quad |N\pi\rangle = \begin{cases} |p, \pi^0\rangle & \frac{u\bar{u}+d\bar{d}}{2} & -\sqrt{\frac{1}{3}} \\ |n, \pi^+\rangle & u\bar{d} & \sqrt{\frac{2}{3}} \end{cases}$$

$$a_{|\Delta\pi\rangle}: \quad |\Delta\pi\rangle = \begin{cases} |\Delta^{++}, \pi^-\rangle & d\bar{u} & \sqrt{\frac{1}{2}} \\ |\Delta^+, \pi^0\rangle & \frac{u\bar{u}+d\bar{d}}{2} & -\sqrt{\frac{1}{3}} \\ |\Delta^0, \pi^+\rangle & u\bar{d} & \sqrt{\frac{1}{6}} \end{cases}$$

Predicts $\bar{d} > \bar{u}$ unless Δ^{++} *dominates, possible at extremely high x*.
Example modern calculation: Alberg and Miller PRC 100, 035205 (2019)

The ratio at high x is one discriminator between models.

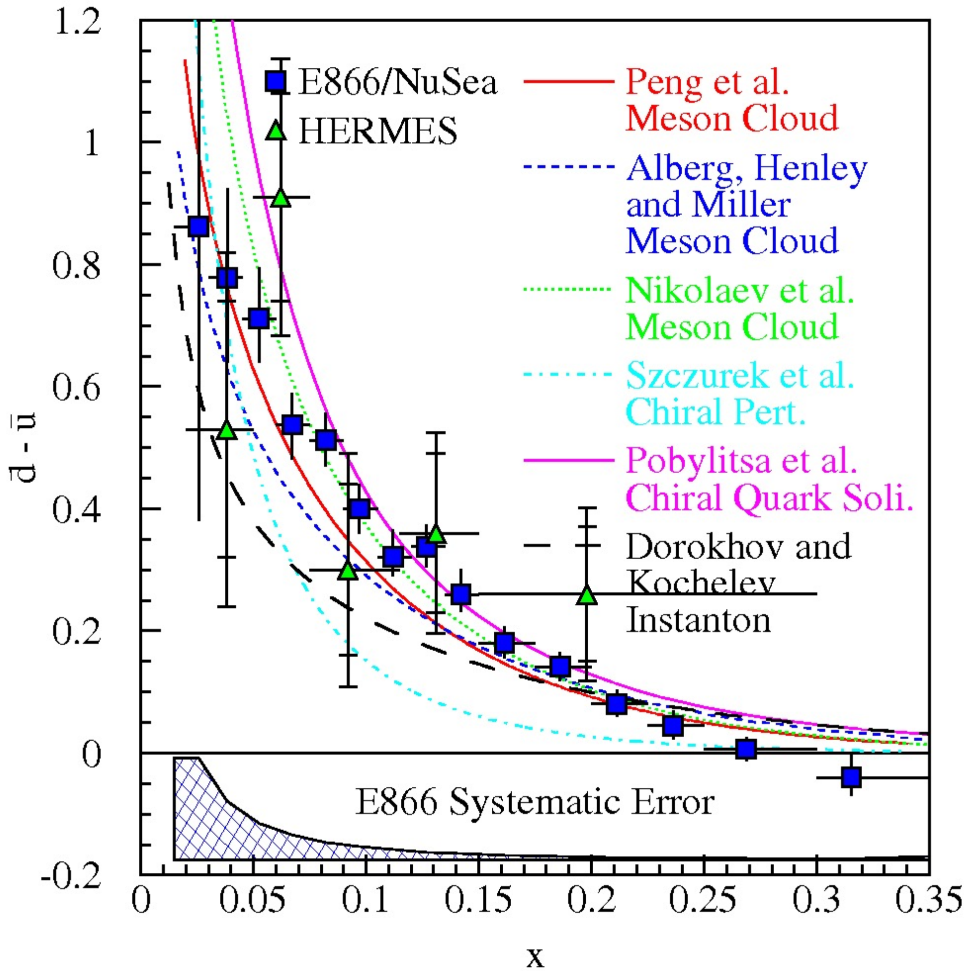


5 in pion model
4 in Instanton model
1.6 in chiral soliton model
1.4 in statistical model

No model naturally predicts a ratio less than 1.0

This emphasizes a region where the absolute value of the antiquarks is small relative to valence quarks.

Models vs dbar-ubar.



A key seems to be the spin carried by the non-singlet anti-quarks

E866 $$\int_0^1 \left[\bar{d}(x) - \bar{u}(x)\right] dx = 0.118 \pm 0.012$$

Pion content – flavor non-singlet anti-quarks carry 0 net spin.
Pions do affect the spin carried by the quarks through their interaction with the remnant baryon.

Statistical Model - Bourelly and Soffer

$$(\Delta\bar{d} - \Delta\bar{u}) = -(\bar{d} - \bar{u})$$

Instanton

$$(\Delta\bar{d} - \Delta\bar{u}) = -[5/3](\bar{d} - \bar{u})$$

Chiral quark-Soliton - Dresslar et al. EPJC18, 719 (2001) gives similar result.

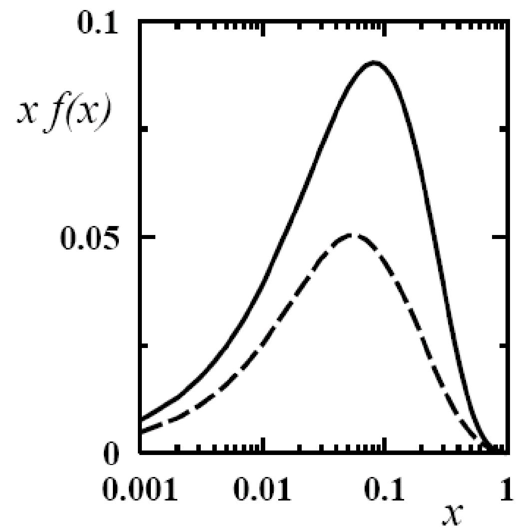


Figure 1: The polarized and unpolarized antiquark flavor asymmetries obtained in model calculations in the large–N_c limit (chiral quark–soliton model), evolved (LO) from the low normalization point of $\mu^2 = (600\,\mathrm{MeV})^2$ to a scale of $\mu^2 = (5\,\mathrm{GeV})^2$. Dashed line: Unpolarized flavor asymmetry, $x[\bar{d}(x) - \bar{u}(x)]$, see Ref.[5]. Solid line: Polarized flavor asymmetry, $x[\Delta\bar{u}(x) - \Delta\bar{d}(x)] \equiv x\Delta_3(x)$, see Refs.[4, 7].

Current data from HERMES and Compass.
SIDIS from JLab will shed light on this.

What do the data tell us ?

- E866 - PR D64, 052002 (2001) Q^2=54 GeV^2

$$\int_0^1 \left[\bar{d}(x) - \bar{u}(x)\right] dx = 0.118 \pm 0.012$$

- HERMES - PR D71, 012003 (2005)

$$\int_{0.023}^{0.3} (\Delta\bar{d} - \Delta\bar{u}) dx = -0.048 \pm 0.057 \pm .028$$

- COMPASS- PLB 693, 227 (2010) Q^2=3 GeV^2

$$\int_{0.004}^{0.3} (\Delta\bar{d} - \Delta\bar{u}) dx = -0.06 \pm 0.04 \pm .02$$

- de Florian et al - PRD 80, 034030 (2009) Q^2=10 GeV^2

$$\int_0^1 (\Delta\bar{d} - \Delta\bar{u}) dx = -0.117 \pm 0.036$$

- JAM PRL 119 132001 (2017)

$$\int_0^1 (\Delta\bar{d} - \Delta\bar{u}) dx = -0.05 \pm 0.08$$

To be compared with
0, -1 or -5/3 * flavor asymmetry

3 σ from zero
2 σ from .197=Chiral soliton

JLAB 12 GeV

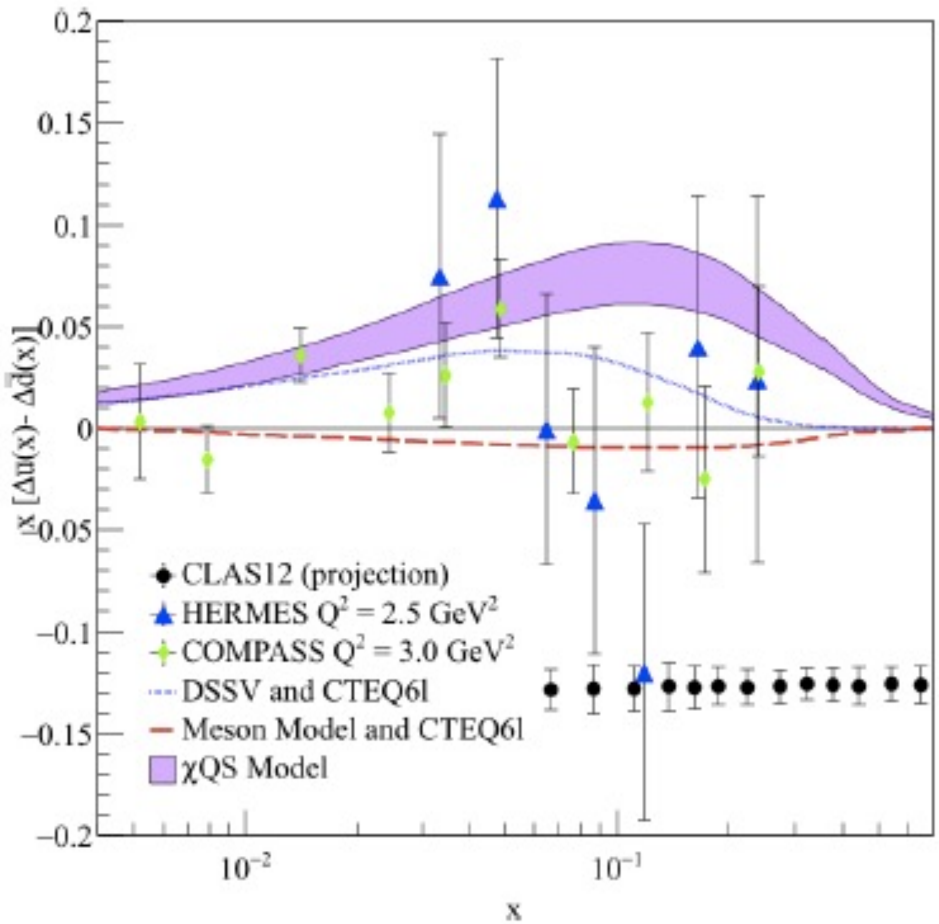
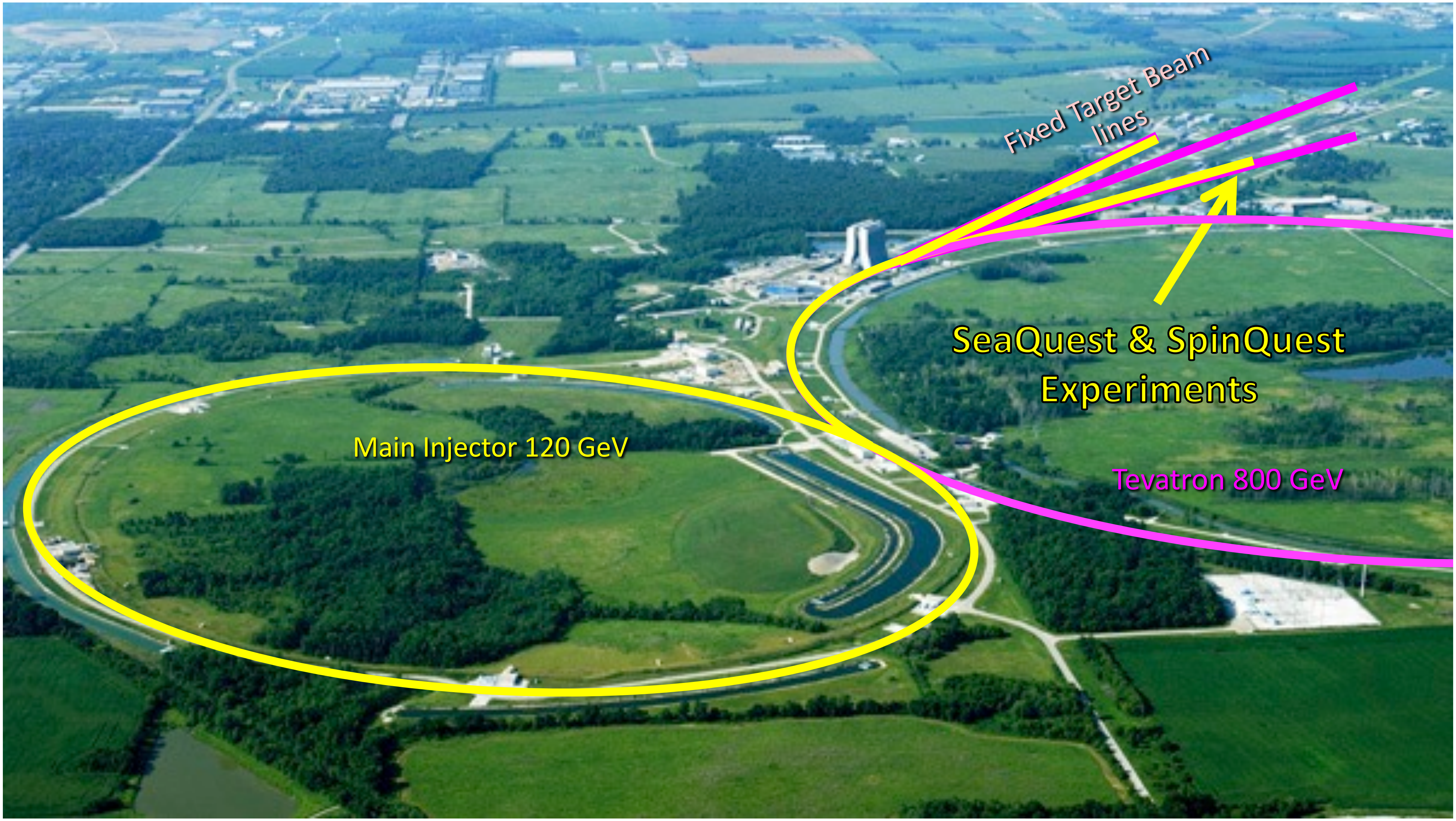
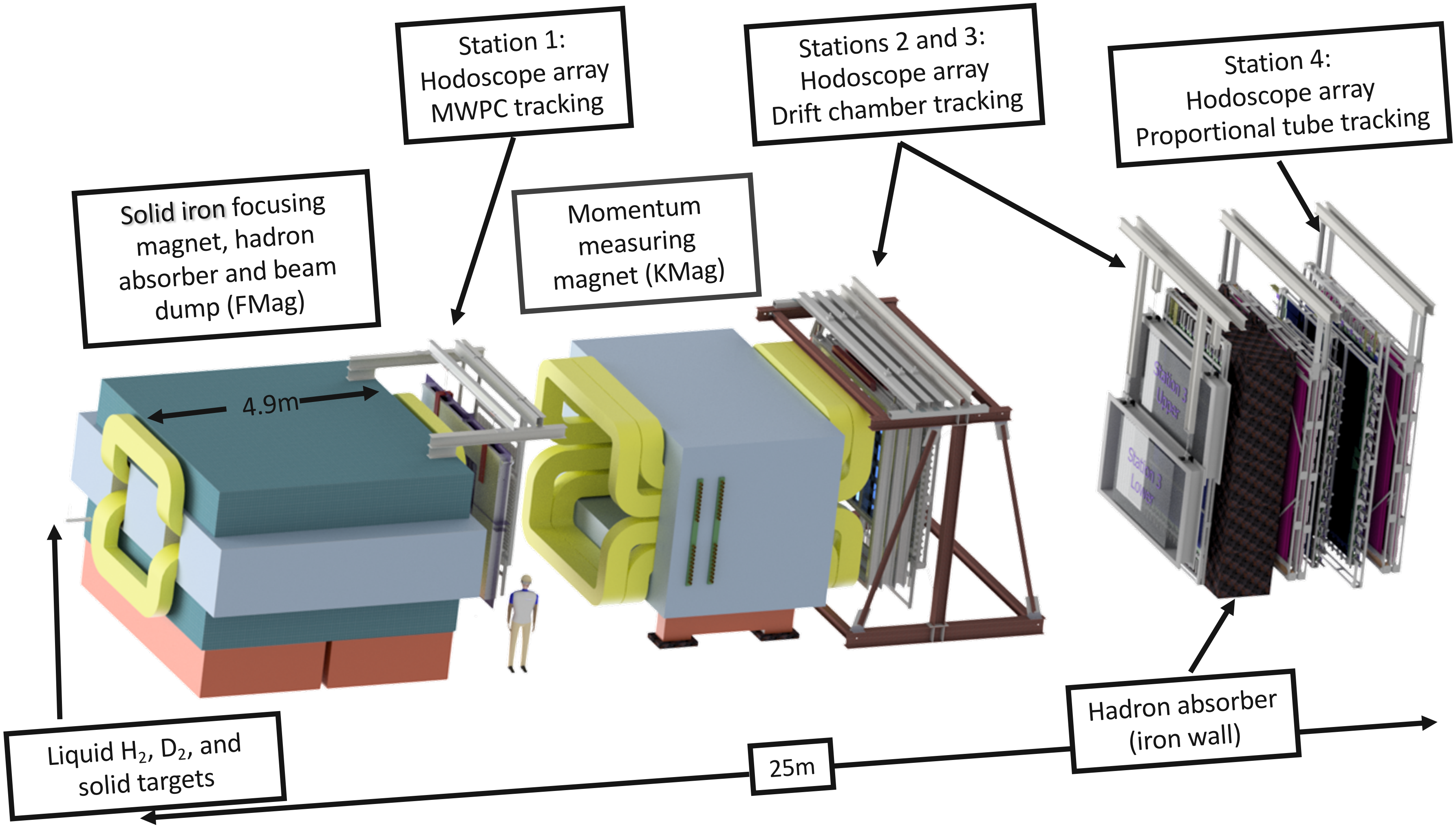


Figure 14. Projected JLAB uncertainties for a semi-inclusive DIS measurement of $x(\Delta\bar{u} - \Delta\bar{d})$ compared to HERMES [52] and COMPASS [53] data, an early global fit [54], another chiral quark soliton [121] model and another meson cloud model [99]. Adapted from [116] with permission.

Hafidi et al, Studies of parton Distributions in semiinclusive DIS

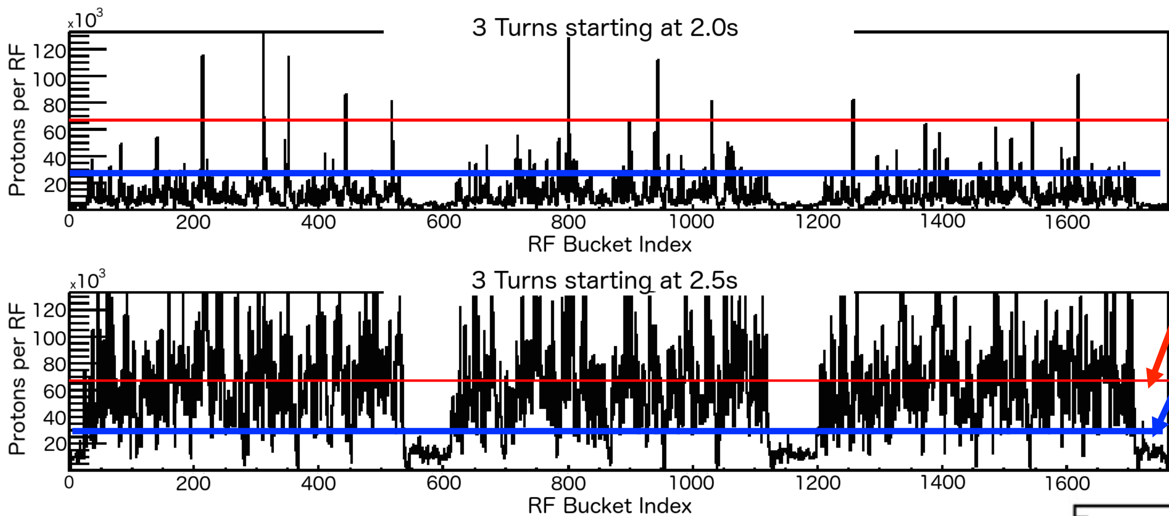
We want to confirm the fall off at higher x
SeaQuest Experiment at FNAL





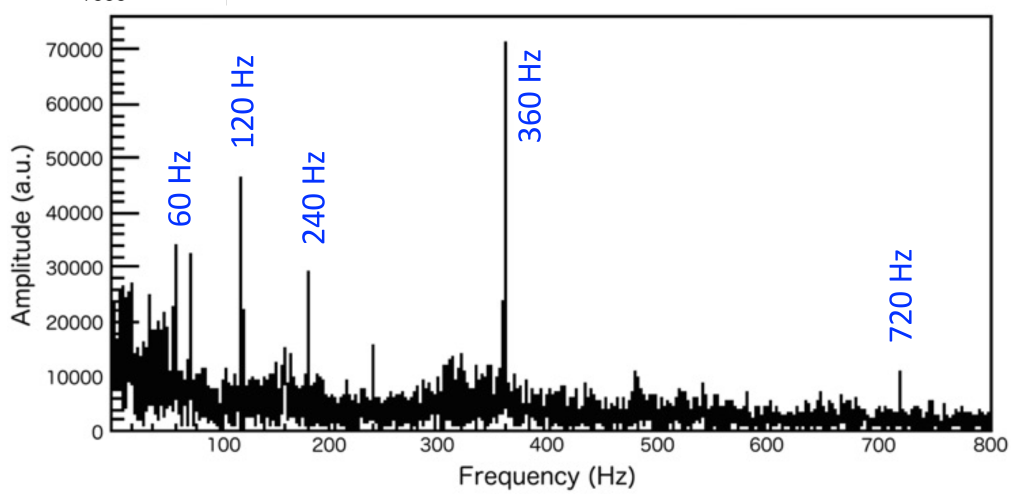
$$\frac{d^2\sigma}{dx_{\mathrm{b}}dx_{\mathrm{t}}} = \frac{4\pi\alpha^2}{x_{\mathrm{b}}x_{\mathrm{t}}s} \sum_{q\in\{u,d,s,\dots\}} e_q^2 \left[\bar{q}_{\mathrm{t}}(x_{\mathrm{t}})q_{\mathrm{b}}(x_{\mathrm{b}}) + \bar{q}_{\mathrm{b}}(x_{\mathrm{b}})q_{\mathrm{t}}(x_{\mathrm{t}})\right]$$

Randomly Chosen Beam Intensity Profile



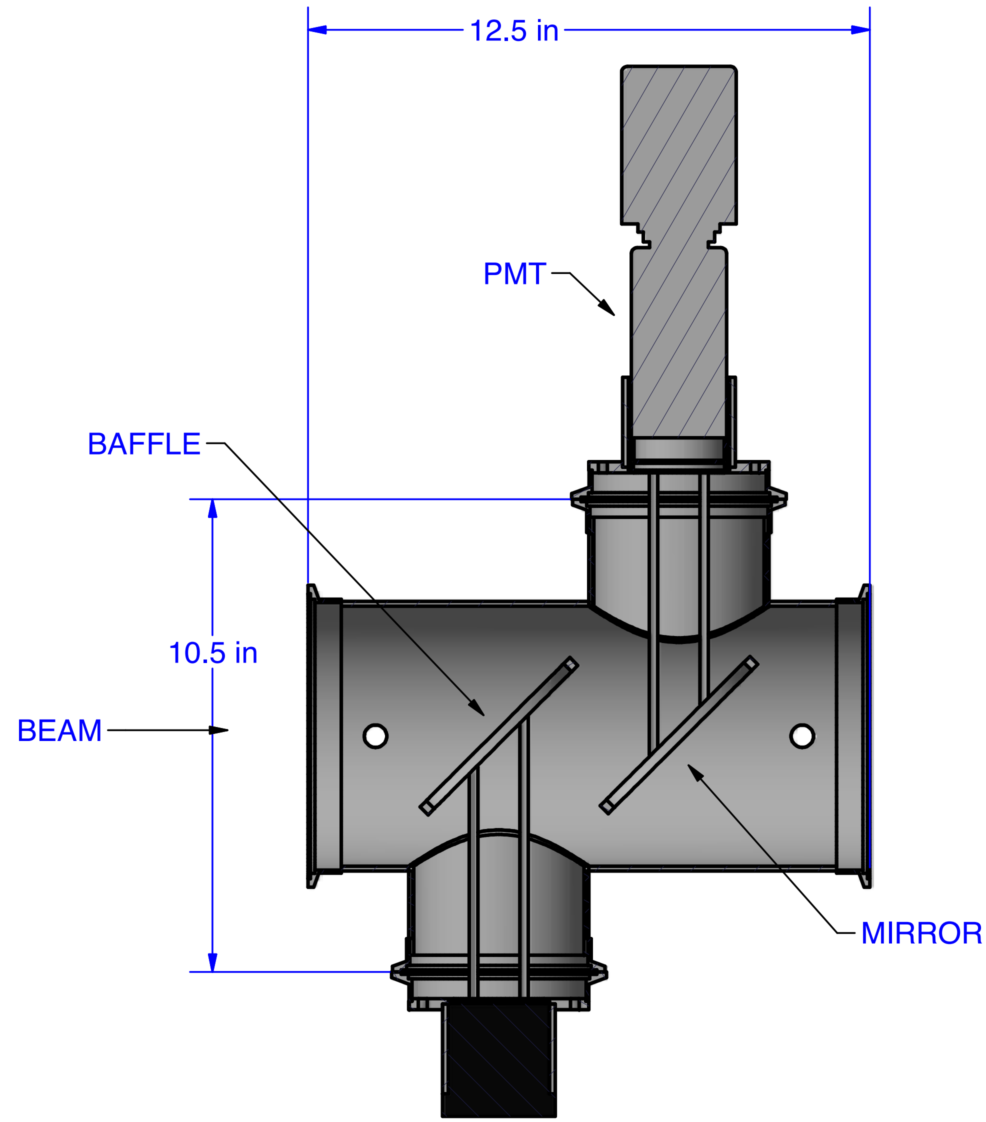
- **Each bin is 19 ns**
- Veto Level
- Even beam distribution

Fourier Transform



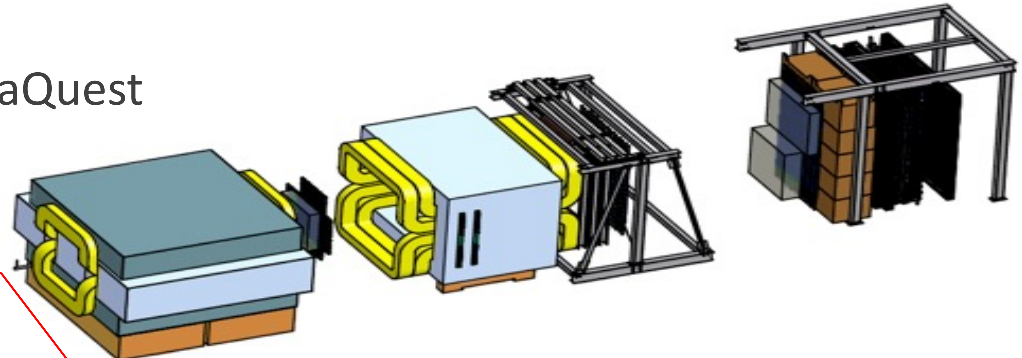
Beam Cherenkov

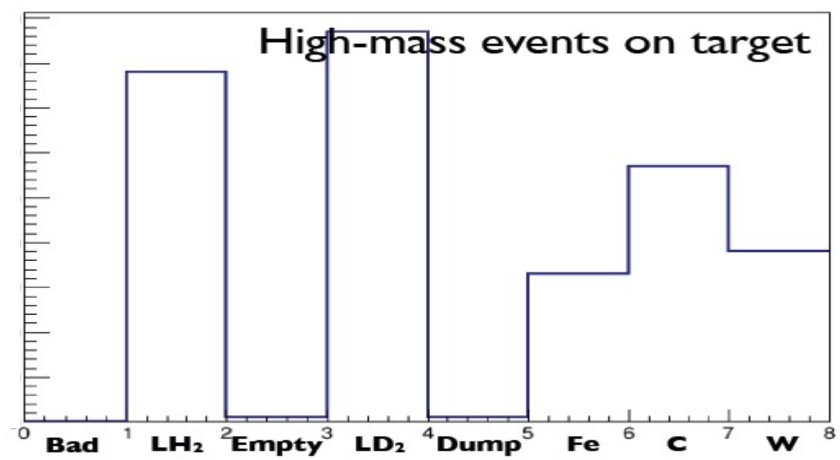
- <16 ns time resolution
- Approx. 30 to $3{\times}10^{16}$ protons/RF cycle
- Calibrated every minute against beam line SEM



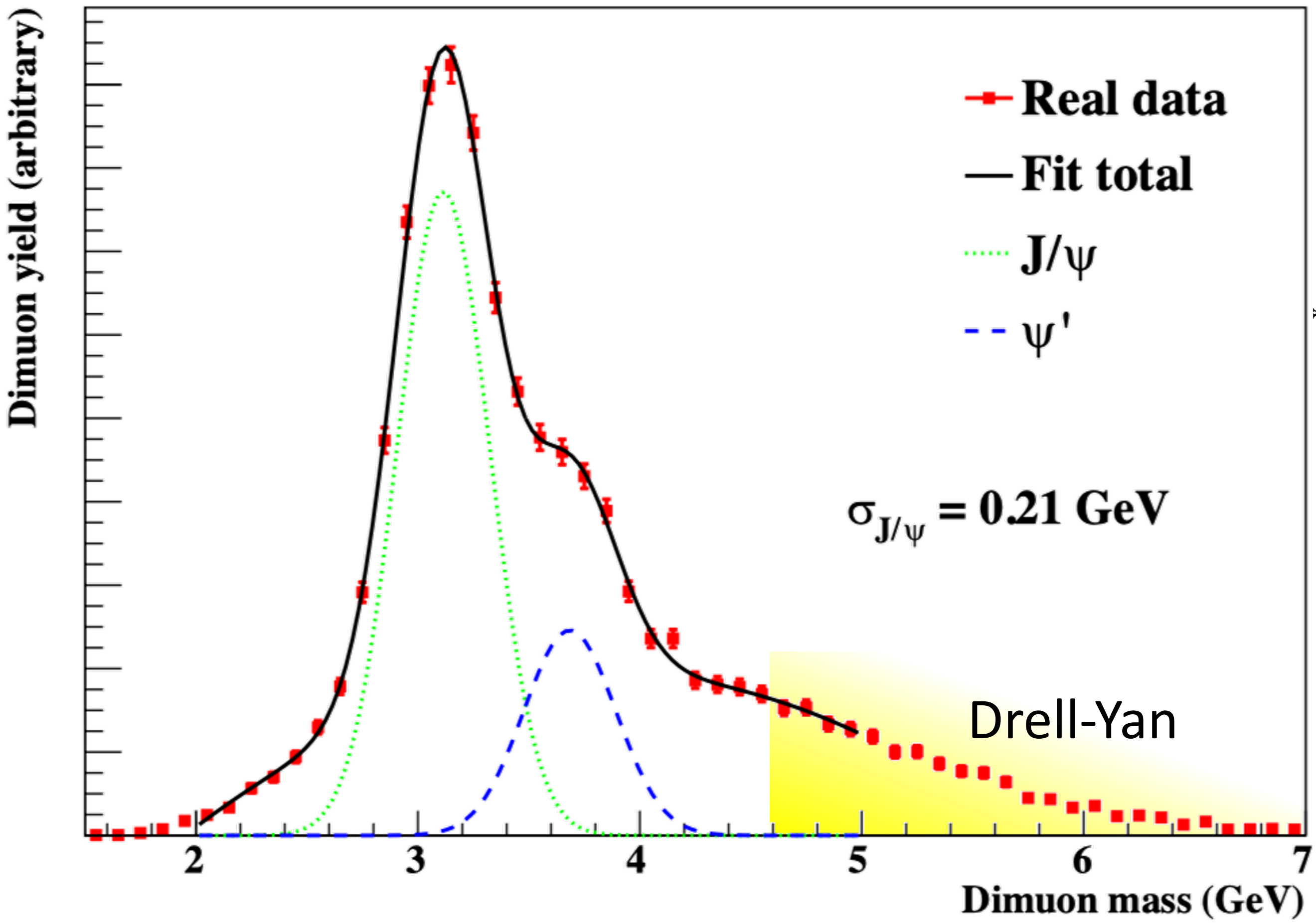
Do We Reconstruct Events When there are Events?

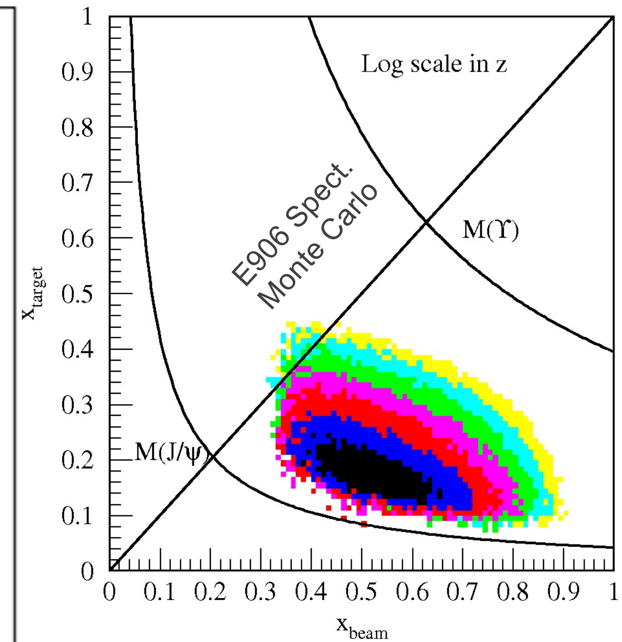
- Entire beam interacts upstream of first SeaQuest Spectrometer tracking chamber
- Spatial resolution poor along beam axis
- Resolve target vs beam dump





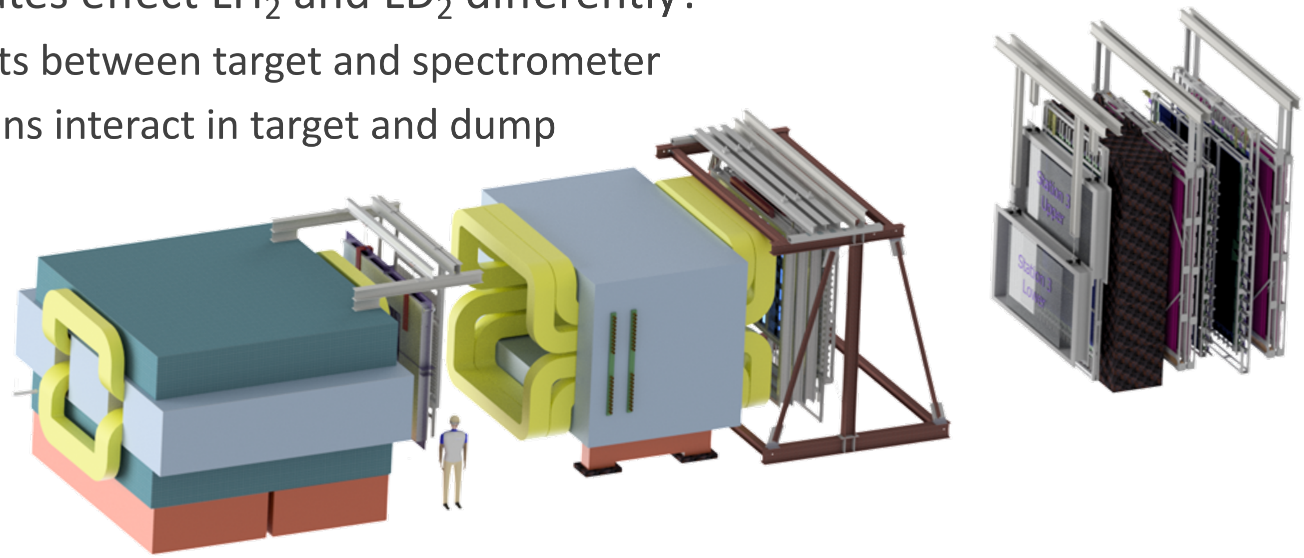
E906 Mass Spectrum





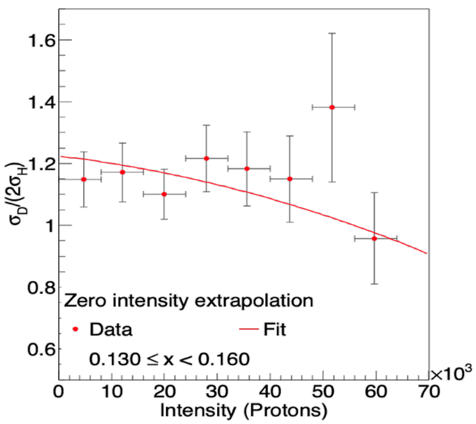
Rate Dependent Effects

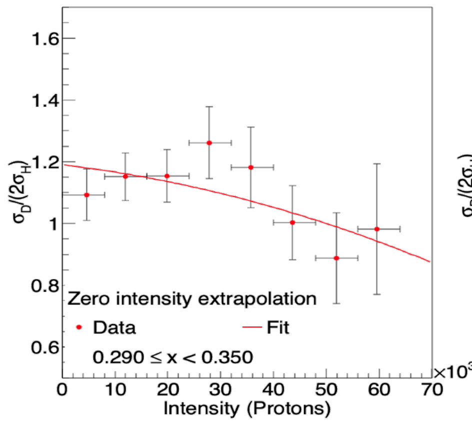
- We were expecting these effects and had handled them in E866/NuSea
- Overall question: Do the rates effect LH_2 and LD_2 differently?
  - 1^{st} order, all beam interacts between target and spectrometer
  - 2^{nd} order, different fractions interact in target and dump

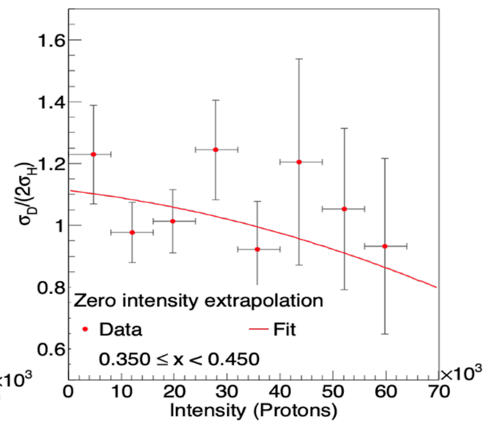


- Primary problem:
  - Background from two uncorrelated muons
  - Different distribution from target and dump

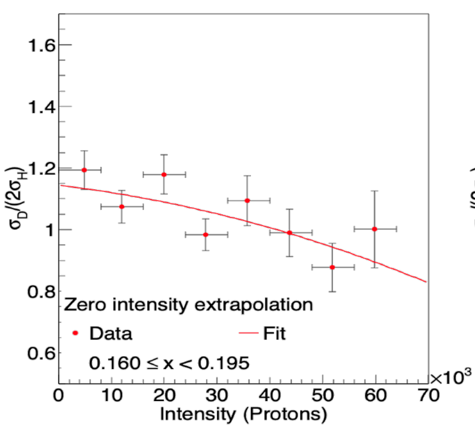
Intensity Extrapolation

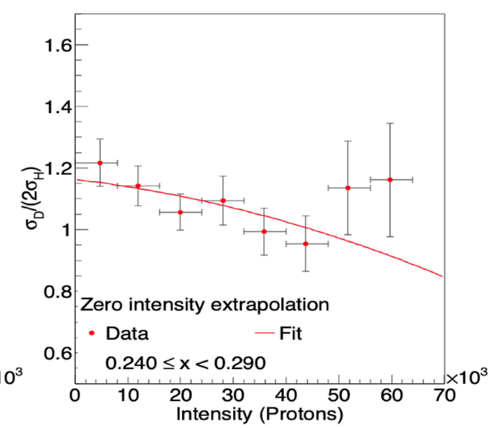


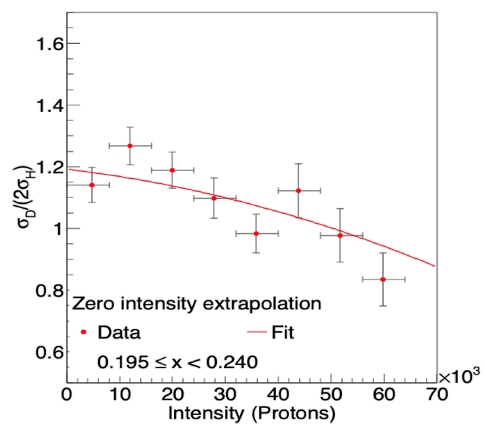




$$\frac{Y_D(x_t, I)}{2Y_H(x_t, I)} = R_{x_t} + a\,I + b\,I^2$$



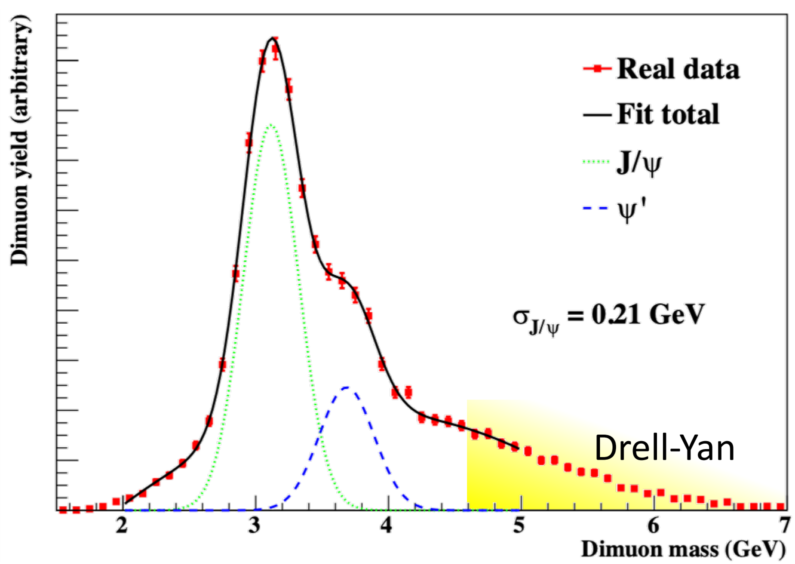


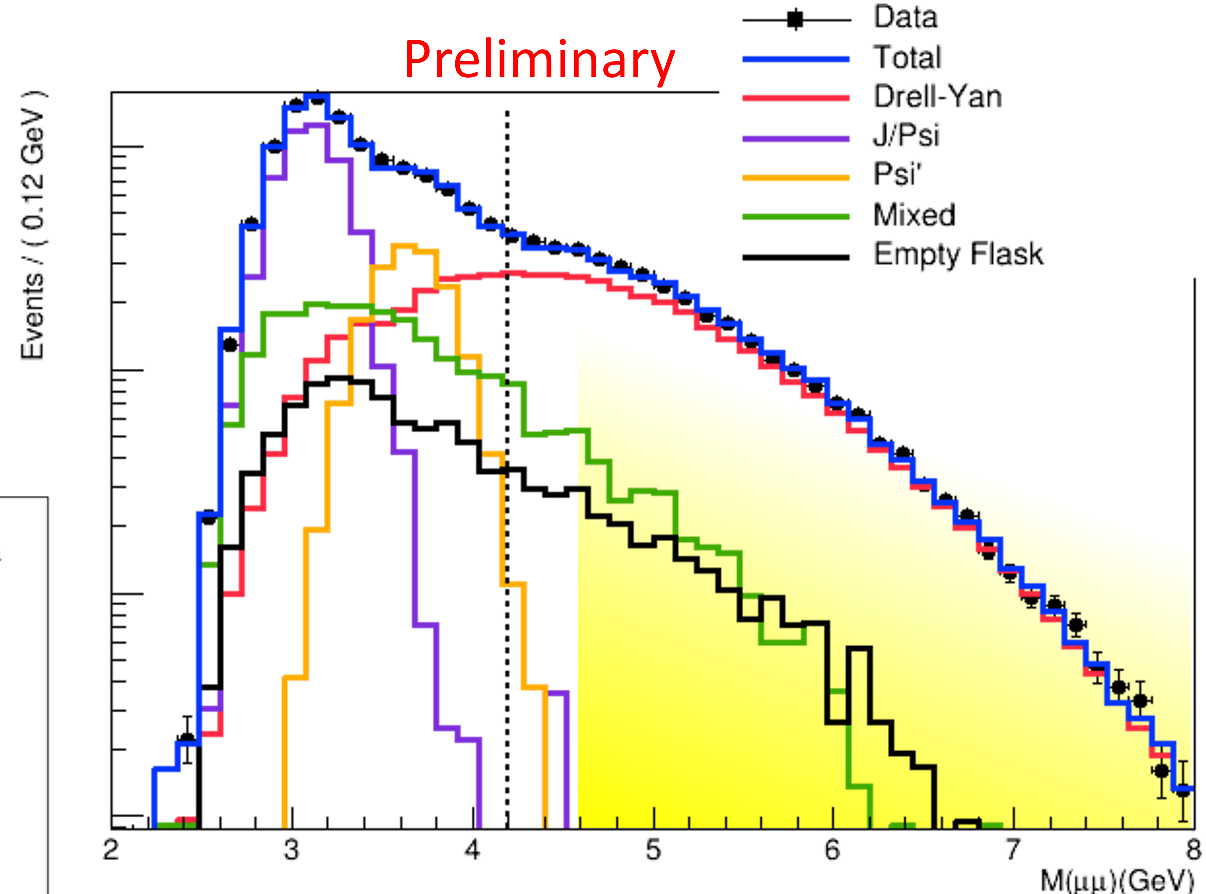


Intensity = 0 intercept from simultaneous fits gives ${}^{\sigma_d}/_{2\sigma_p}$ for different x_T bins

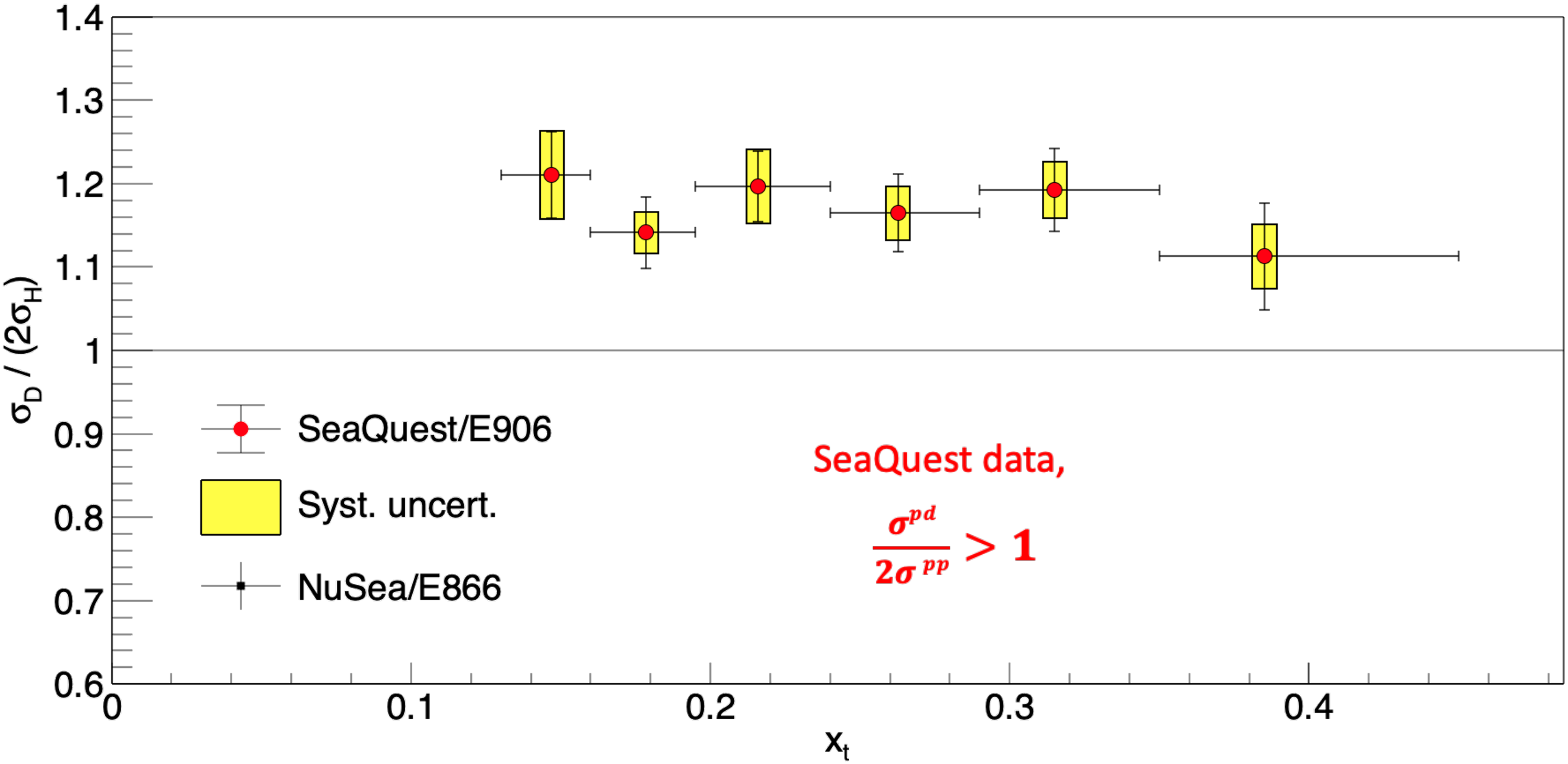
Cross Check of Rate Dependence

- Multi-component mass fit
- Combinatorial background "mixed" and reconstruction efficiency





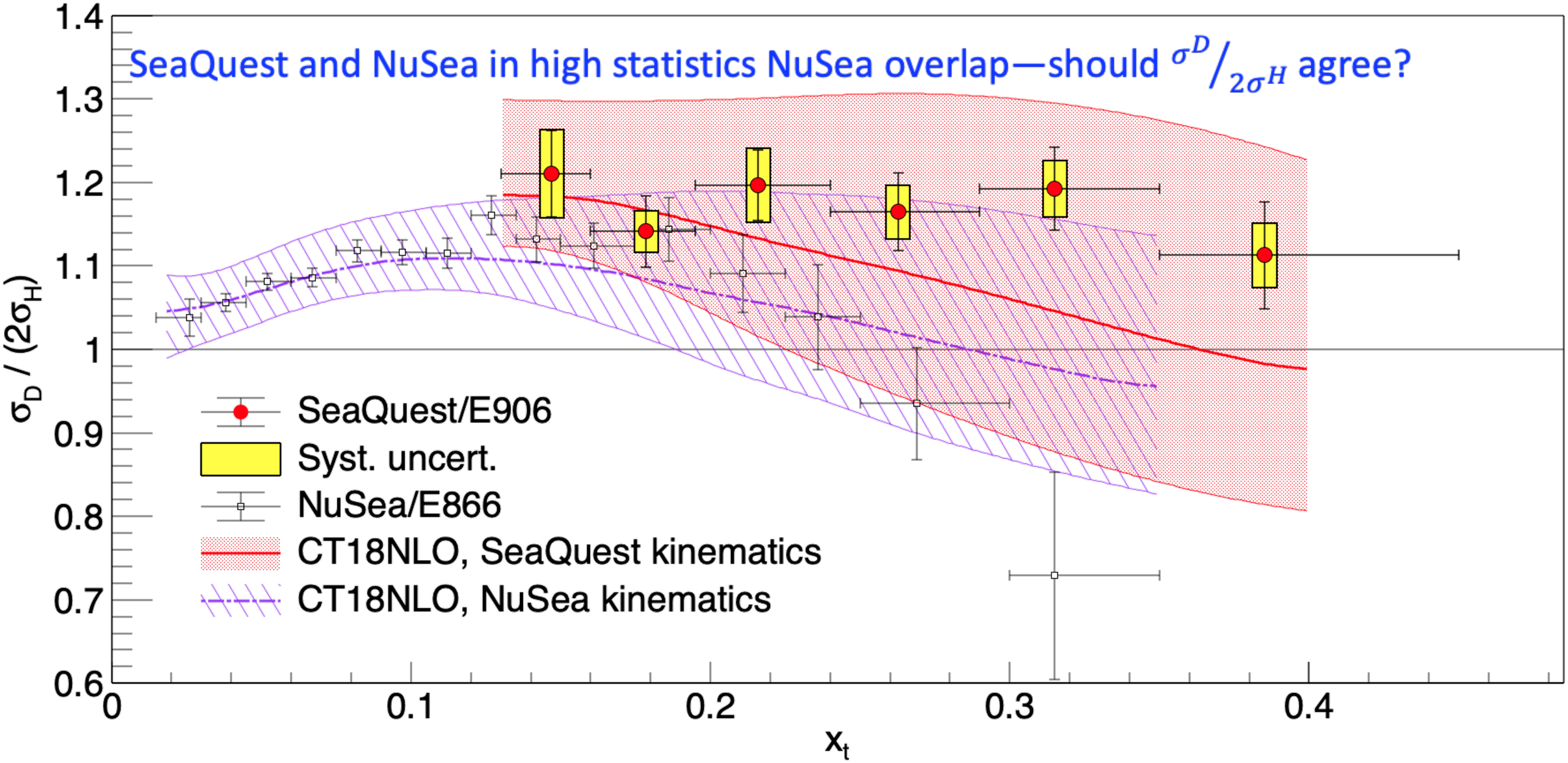
SeaQuest



SeaQuest data,

$$\frac{\sigma^{pd}}{2\sigma^{pp}} > 1$$

SeaQuest and E866



SeaQuest's $\bar{d}/\bar{u}$ Extraction

$$\frac{\sigma^D}{2\,\sigma^H} = \frac{1}{2}\left[1 + \frac{\bar{d}}{\bar{u}}\right]$$

- **Correct way to extract quark distributions is within the context of a global fit.**

What we did instead:

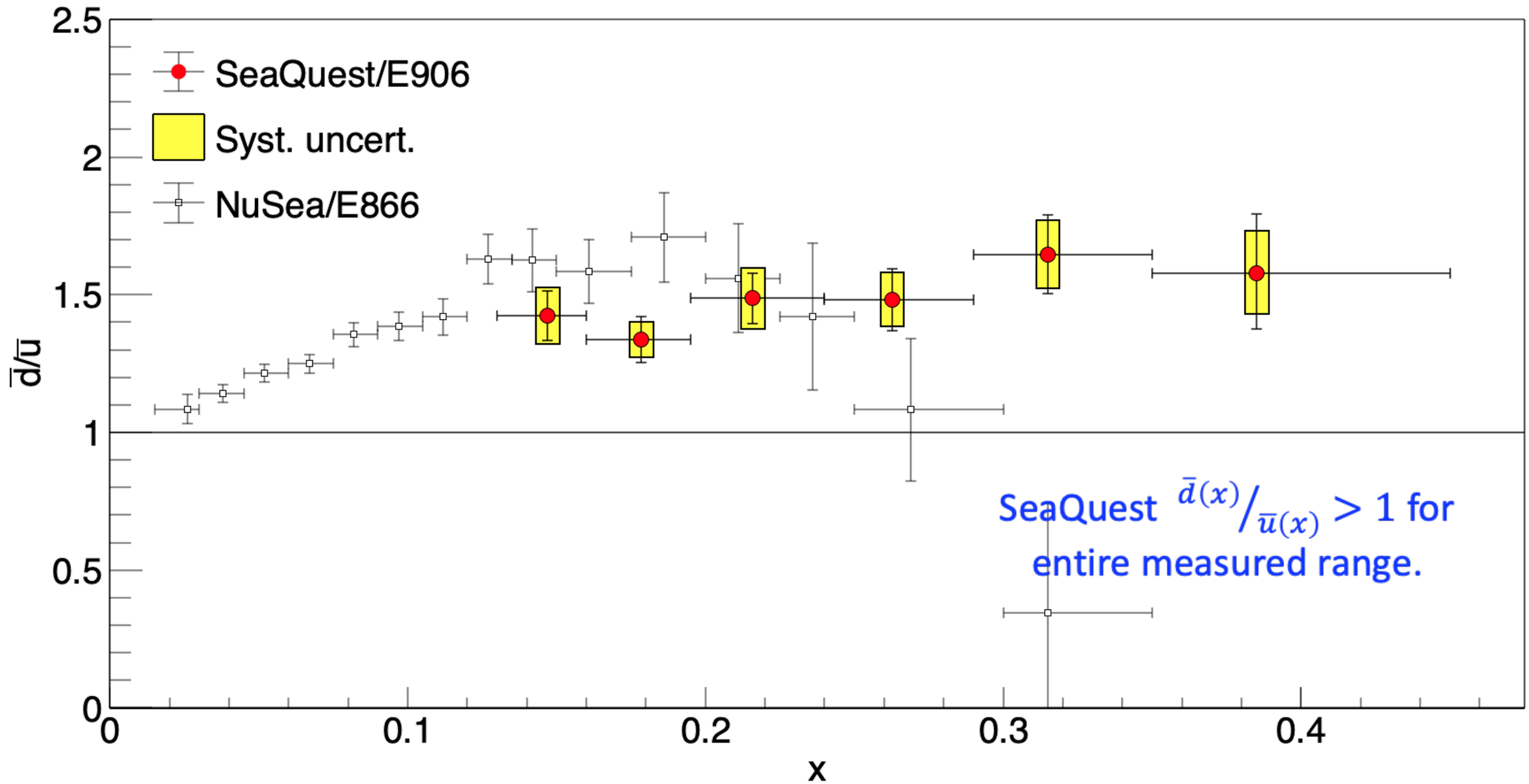
- Assume the current global fits are omnipotent except for $\bar{d}/\bar{u}$
- Compute

$$\frac{\sigma^D}{2\sigma^H} = \frac{\iint \frac{d\sigma^D_{NLO}}{dx_1 dx_2} dx_1\, dx_2}{2\iint \frac{d\sigma^H_{NLO}}{dx_1 dx_2} dx_1\, dx_2} \text{ with } \bar{d}/\bar{u}\,\big]_i$$

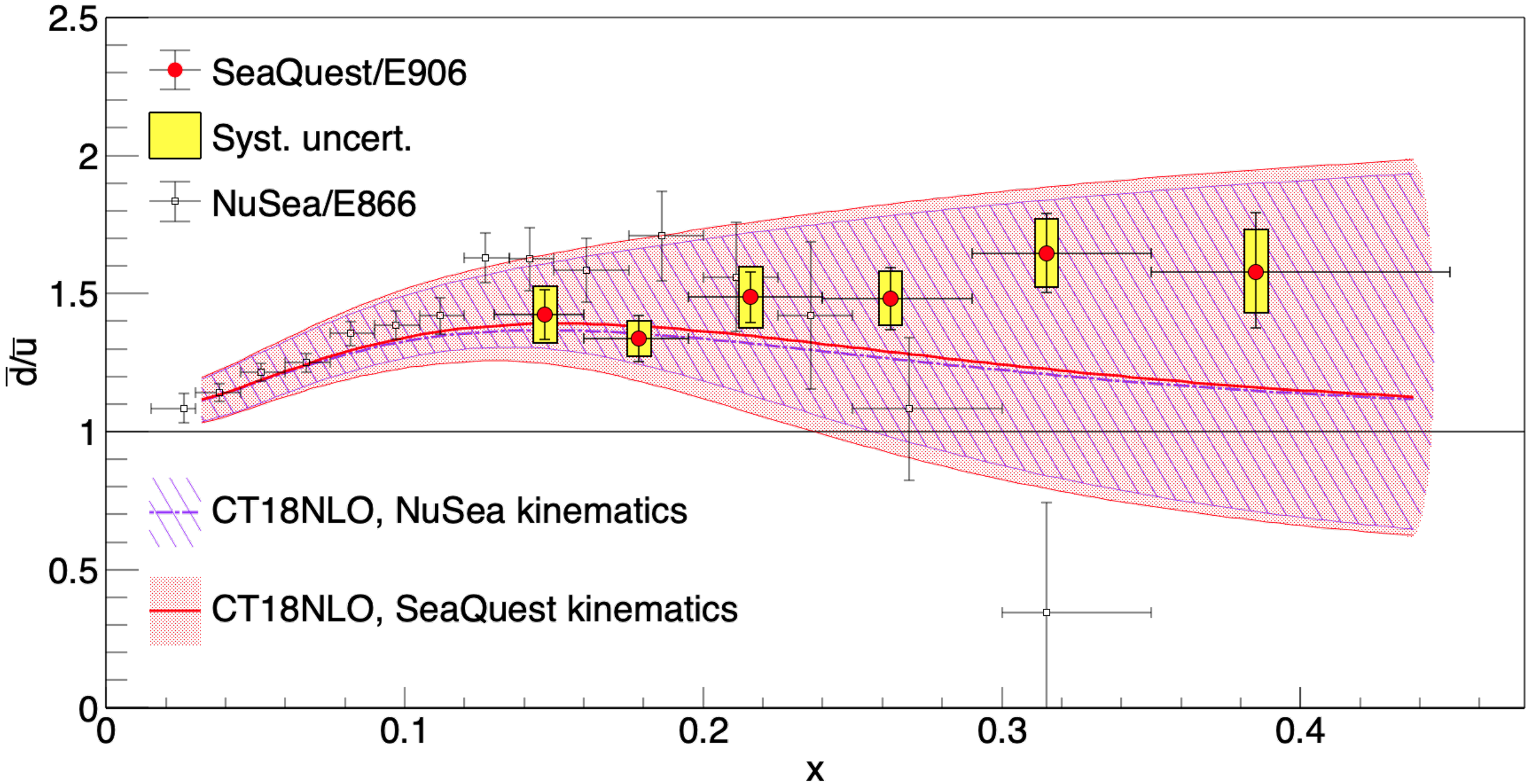
and the integrals are over the experimental acceptance

- Compare with measured $\frac{\sigma^D}{2\sigma^H}$, and iterate on $\bar{d}/\bar{u}\,\big]_{i+1}$

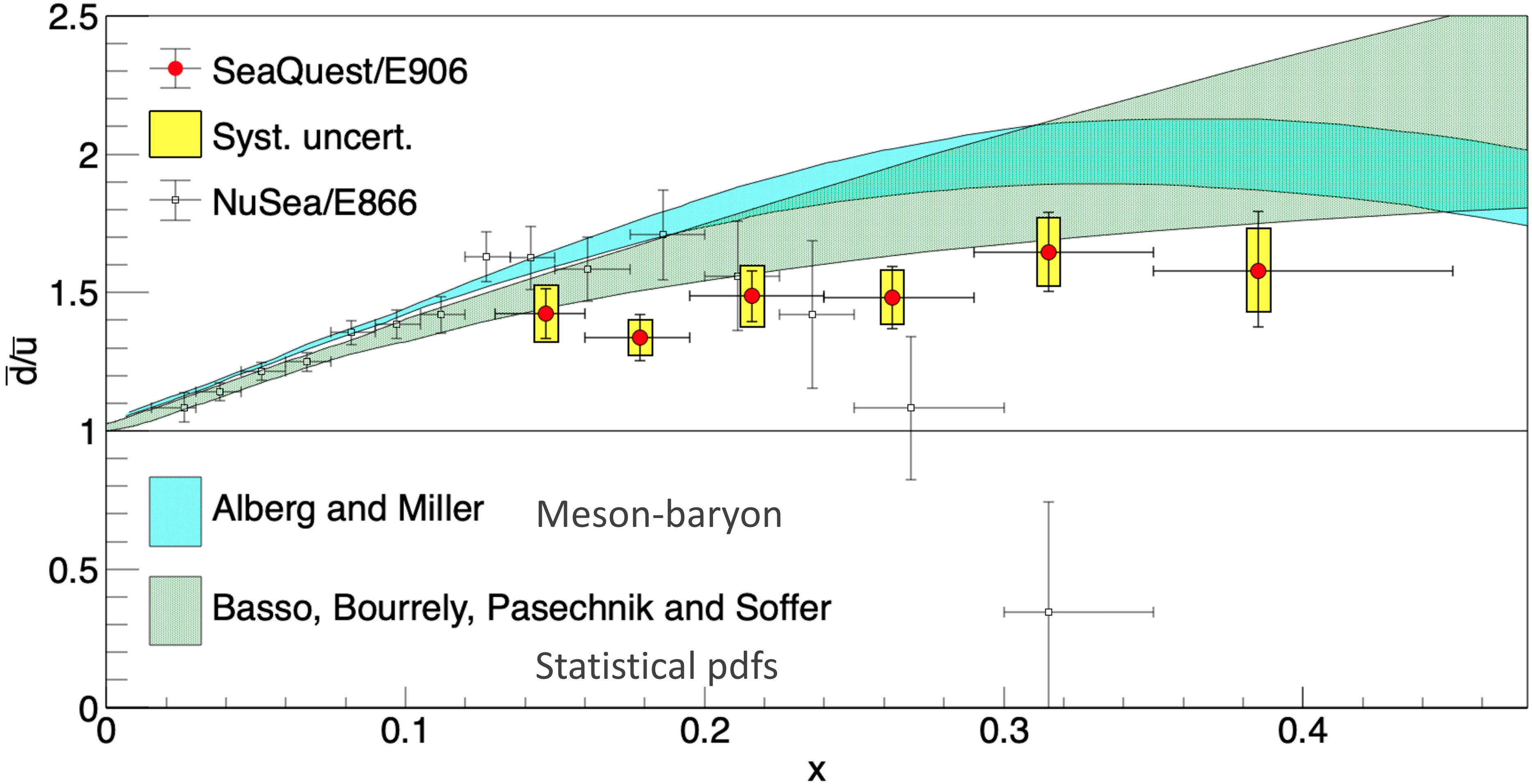
SeaQuest and E866



SeaQuest compared with Global Fits

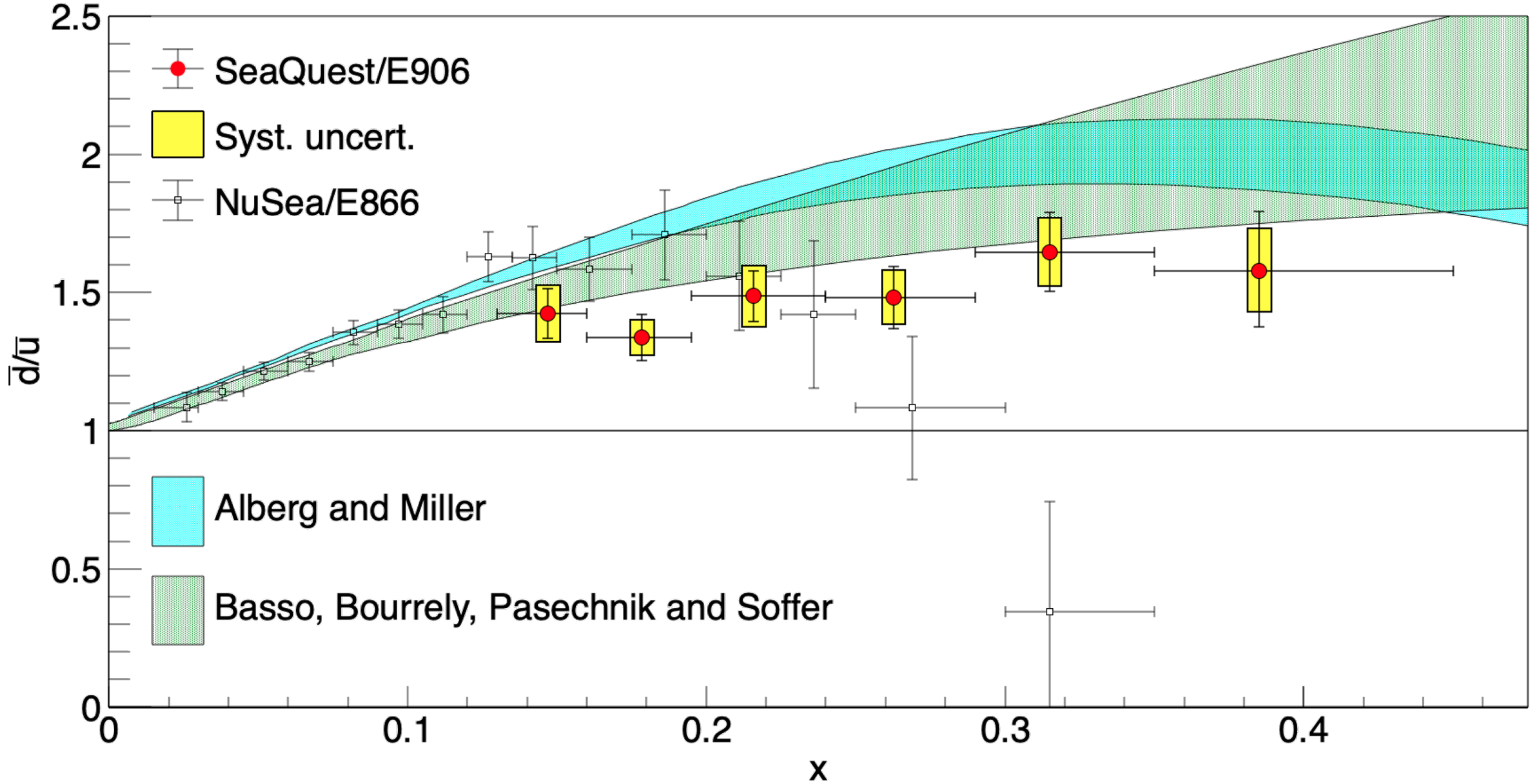


SeaQuest compared with Models



This has impact on searches for new W' and Z' particles at the LHC. For pp collisions, Nusea data favored $u\bar{u}$ *production of* Z'. Seaquest favors $u\bar{d}$ production of W'.

The ratio at high x is one discriminator between models.



5 in simplest pion model, ~1.9 in Alberg and Miller
4 in Instanton model
1.6 in chiral soliton model
~1.9 in statistical model

Media

Quanta magazine

QUANTUM PHYSICS

Decades-Long Quest Reveals Details of the Proton's Inner Antimatter

27

Twenty years ago, physicists set out to investigate a mysterious asymmetry in the proton's interior. Their results, published today, show how antimatter helps stabilize every atom's core.

reddit

Posted by u/m3prx 18 days ago

487

The asymmetry of antimatter in the proton

nature.com/articl...

30 Comments Share Save Hide

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WIRED

Le Monde

SCIENCE & MÉDECINE

Le proton, cette particule essentielle et mal définie de la matière

PHYSIQUE - Le constituant principal du noyau des atomes se révèle être un sac de nœuds complexe, qui échappe encore à l'entendement

NEWS RELEASE 24-FEB-2021

Nature's funhouse mirror: understanding asymmetry in the proton

DOE/ARGONNE NATIONAL LABORATORY

NATURE PODCAST · 24 FEBRUARY 2021

The quark of the matter: what's really inside a proton?

EurekAlert! AAAS

ScienceNews

INDEPENDENT JOURNALISM SINCE 1921

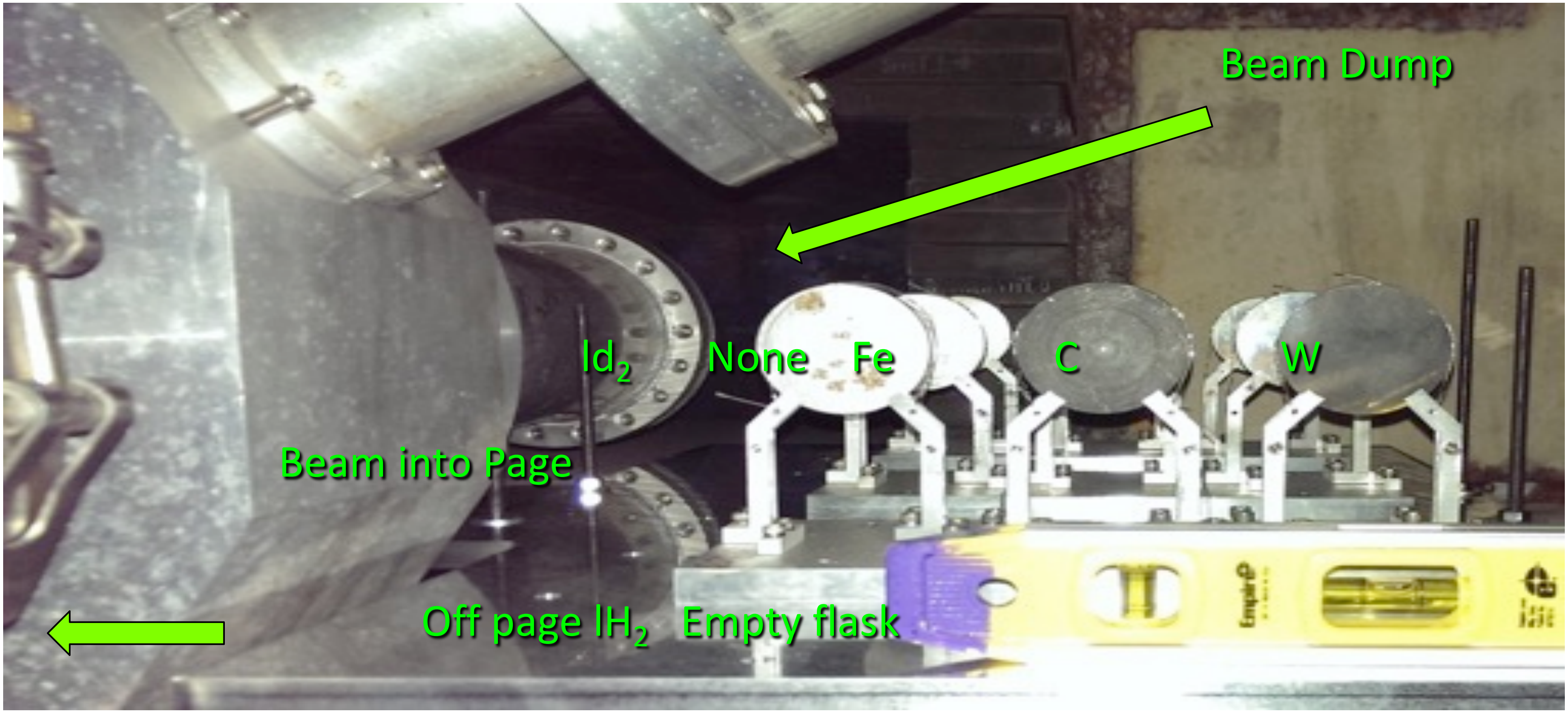
NEWS PARTICLE PHYSICS

Protons' antimatter is even more lopsided than we thought

In the sloshing sea of particles within a proton, down antiquarks outnumber up antiquarks

Google News

What about the Solid Targets?



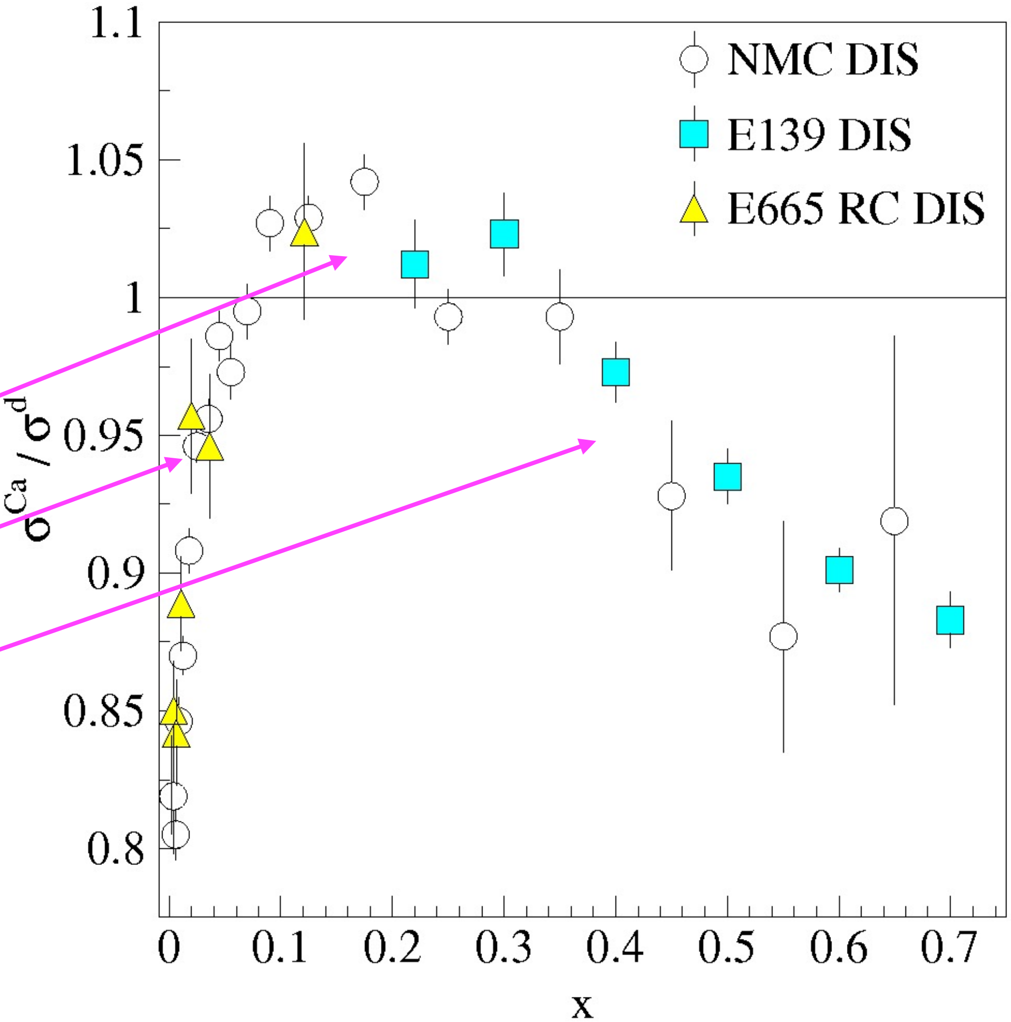
EMC Effect in Anti Quarks?

- DIS results establish nuclear dependence of quark distributions.
- There were some expectations of large antiquark effects

Anti-Shadowing

Shadowing

EMC Effect



So in the "EMC" region, with the ratio less than 1, the momentum carried by the quarks in a proton in a nucleus is less that in free space. Two alternatives leap to mind.

- **Change in hadron structure**

- F_2^A/F_2^D looks like d $\ln F_2$/d ln Q^2
- Q^2 rescaling
- Factorization scale changes in nucleus
- Scale of nucleon changes – nucleon swells in the nucleus so lower average quark momentum
- No clear evidence at hadron level in (e,e'p) knockout reactions

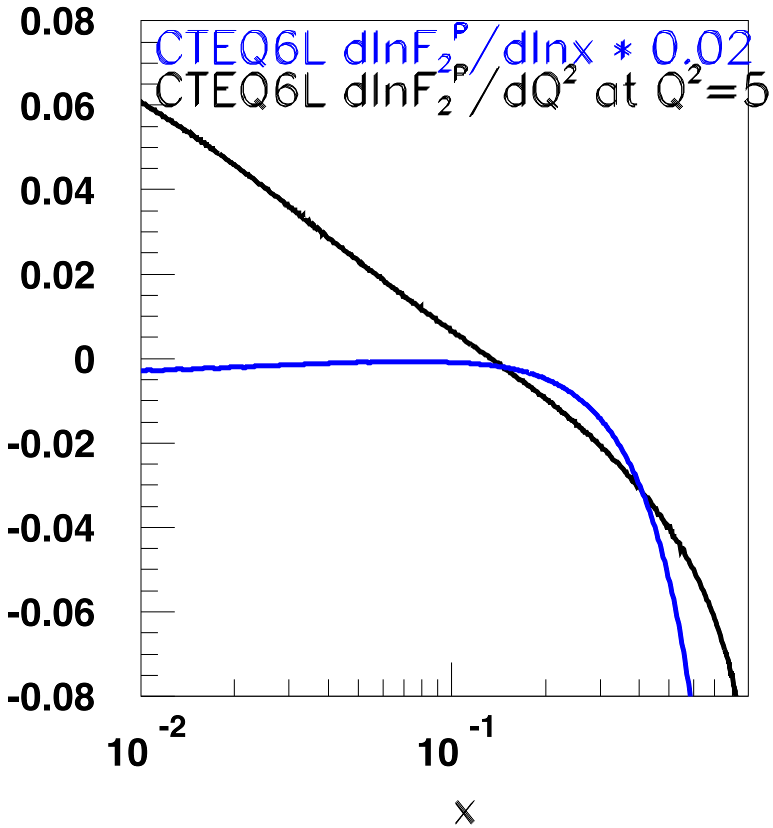
- Percolation of quarks between nucleons

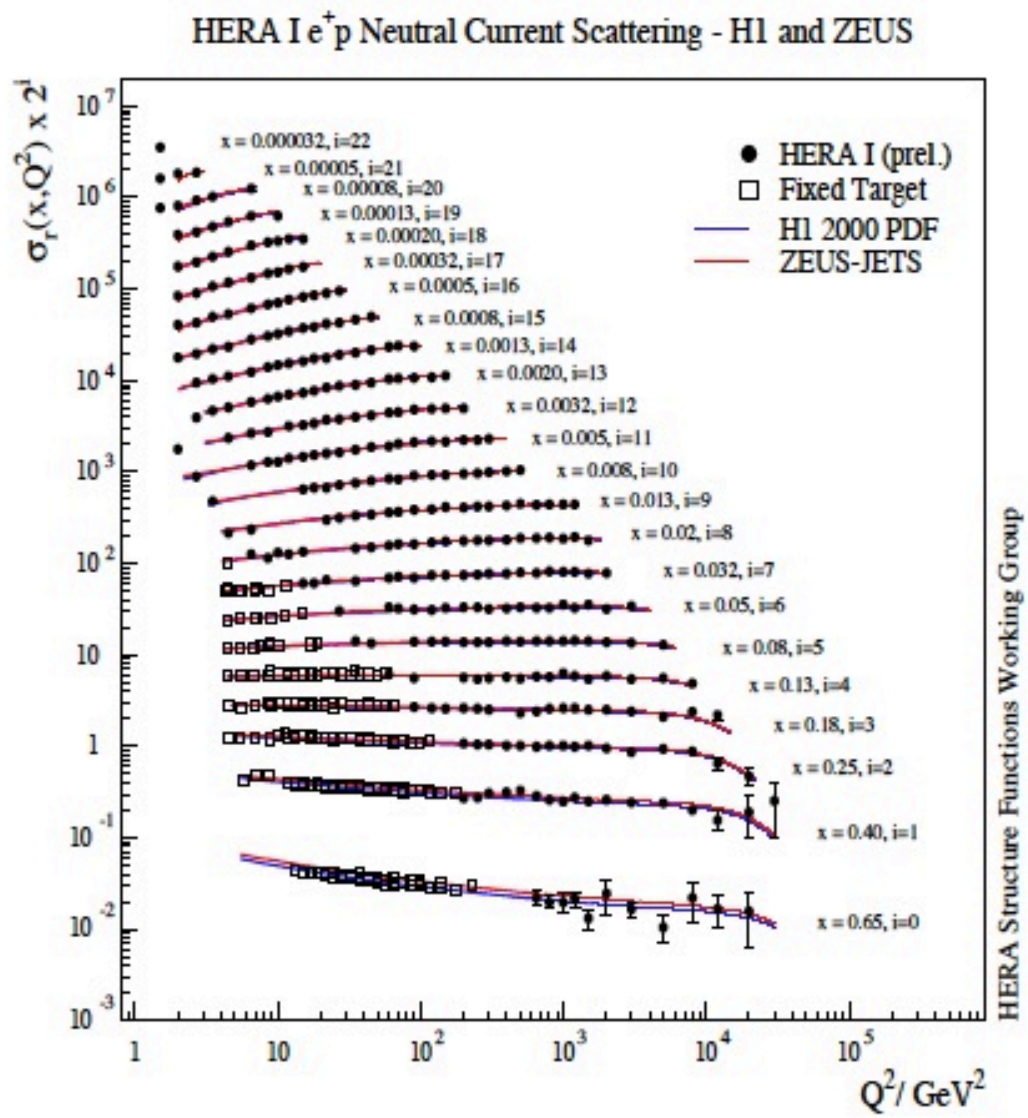
- **Many body effects causes distribution of proton momenta to change**
- F_2^A/F_2^D looks like $F_2^D(x/.95)/F_2^D(x)$
- X rescaling

$$q_A = \int \frac{dy}{y} f^A(y) q_N(\frac{x}{y}) + \int \frac{dy}{y} f_x^A(y) q_x(x/y)$$

- If $f^{A(y)}$ peaks at 0.95 – explains EMC effect
- Is there other stuff in the nucleus to carry momentum – momentum conservation is important –
- mesons – but where are the antiquarks, Antishadowing from mesons
- Virtual photons. F&S.
- 6 quark clusters

We know that QCD describes well the Q^2 Dependence through DGLAP





Perhaps the fraction of momentum carried by the glue changes?

NMC results. Fraction of the momentum carried by quarks changes ~-2+/-1%   Z. Phys. C. 51, 387 (91)

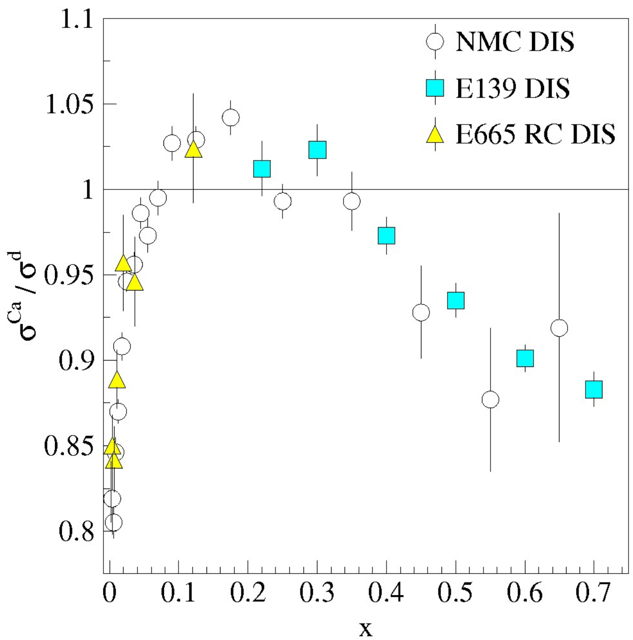
	X range	Momentum sum	Stat.	Sys
D	0.-1	0.148		
Ca-D	.0035-0.78	-.0035	.0006	.0014

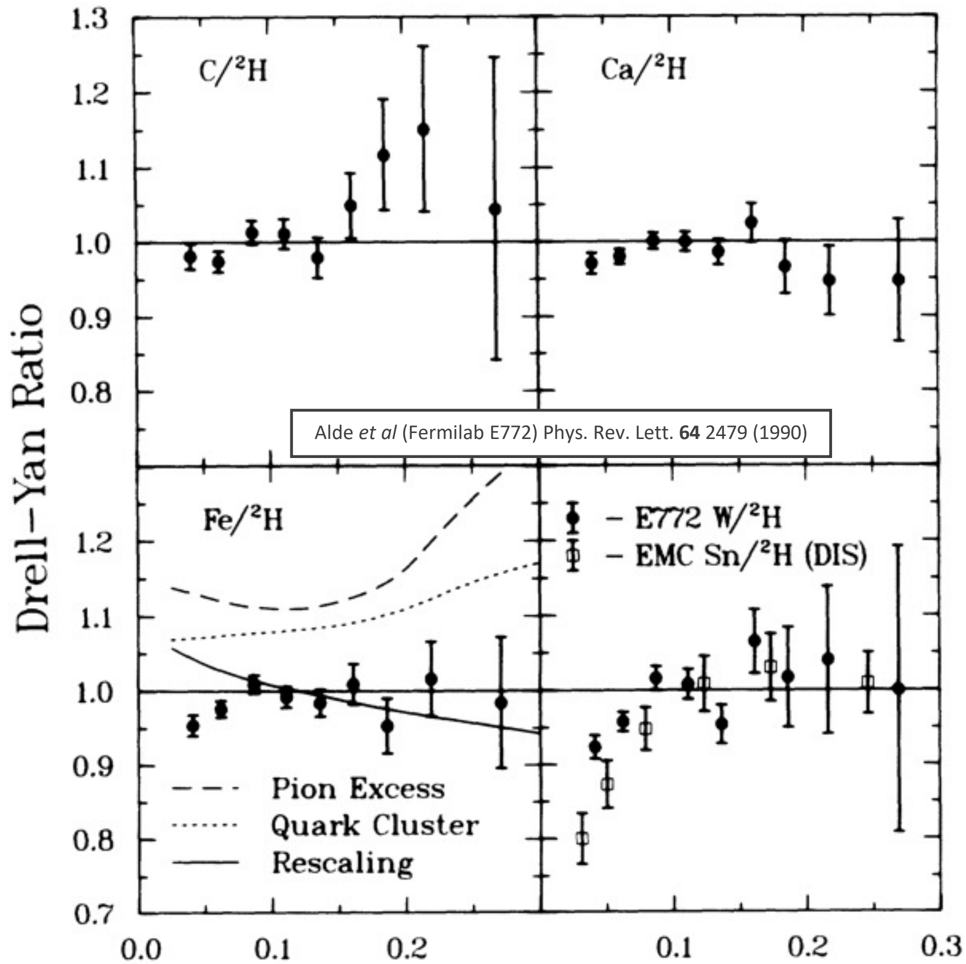
If the structure of the nucleon changes, or if off-shell effects are important, why should the fraction of momentum carried by the glue stay the same?

EMC Effect With Anti-Quarks?

Alde et al. E772 Collaboration. Phys. Rev. Lett. 64:2479 (1990)

- DIS results establish nuclear dependence of quark distributions.
- **No dramatic effects were seen in proton induced Drell-Yan at 800 GeV**





A successful picture must not just describe a narrow x region. One comprehensive approach that tries to do that is the papers of Kulagin and Petti. [NPA765,126(6) .. PRC82,054614(2010)]

$$F_2^A = F_2^{IA} + \delta_\pi F_2^A + \delta_{coh} F_2^A$$

F_2^{IA} contains scattering from bound nucleons

Nuclear spectral function

Off shell nucleon structure functions

$$F_2^{\mathrm{LT}}(x, Q^2, p^2) = F_2^{\mathrm{LT}}(x, Q^2)(1 + \delta f_2(x, Q^2)v),$$
$$\delta f_2 = \partial \ln F_2^{\mathrm{LT}} / \partial \ln p^2,$$

$v=(p^2/M^2-1)$

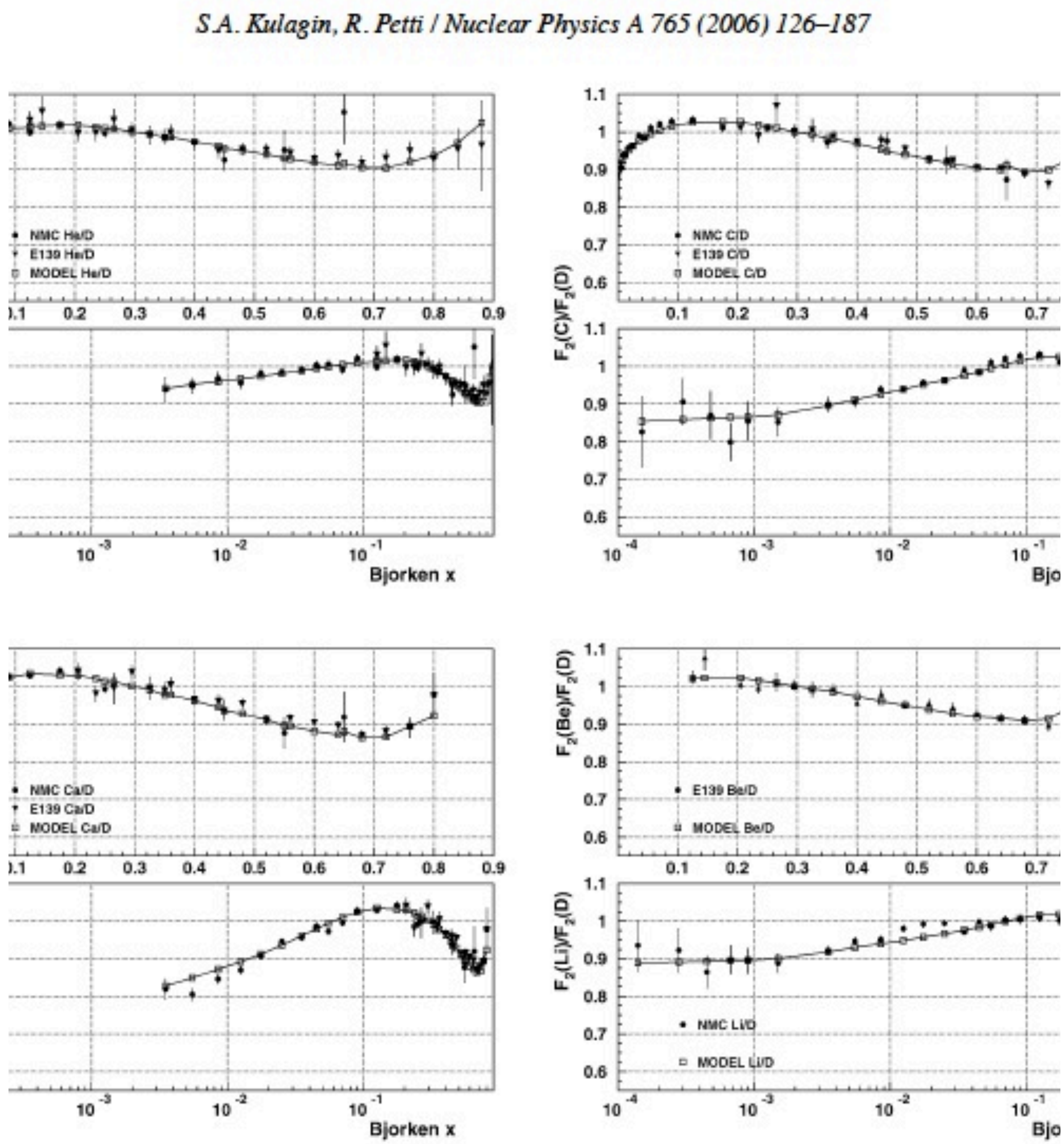
As used it is hard to separate this prescription from binding corrections. It is extracted from fits to heavy nuclei.

$\delta_\pi F_2$ contains the interaction with nuclear meson field and conserves momentum at hadron level.

$\delta_{coh} F_2^A$ is the coherent interaction of the intermediate virtual vector boson calculated in a generalized (to fix Q^2 dependence) vector dominance model.

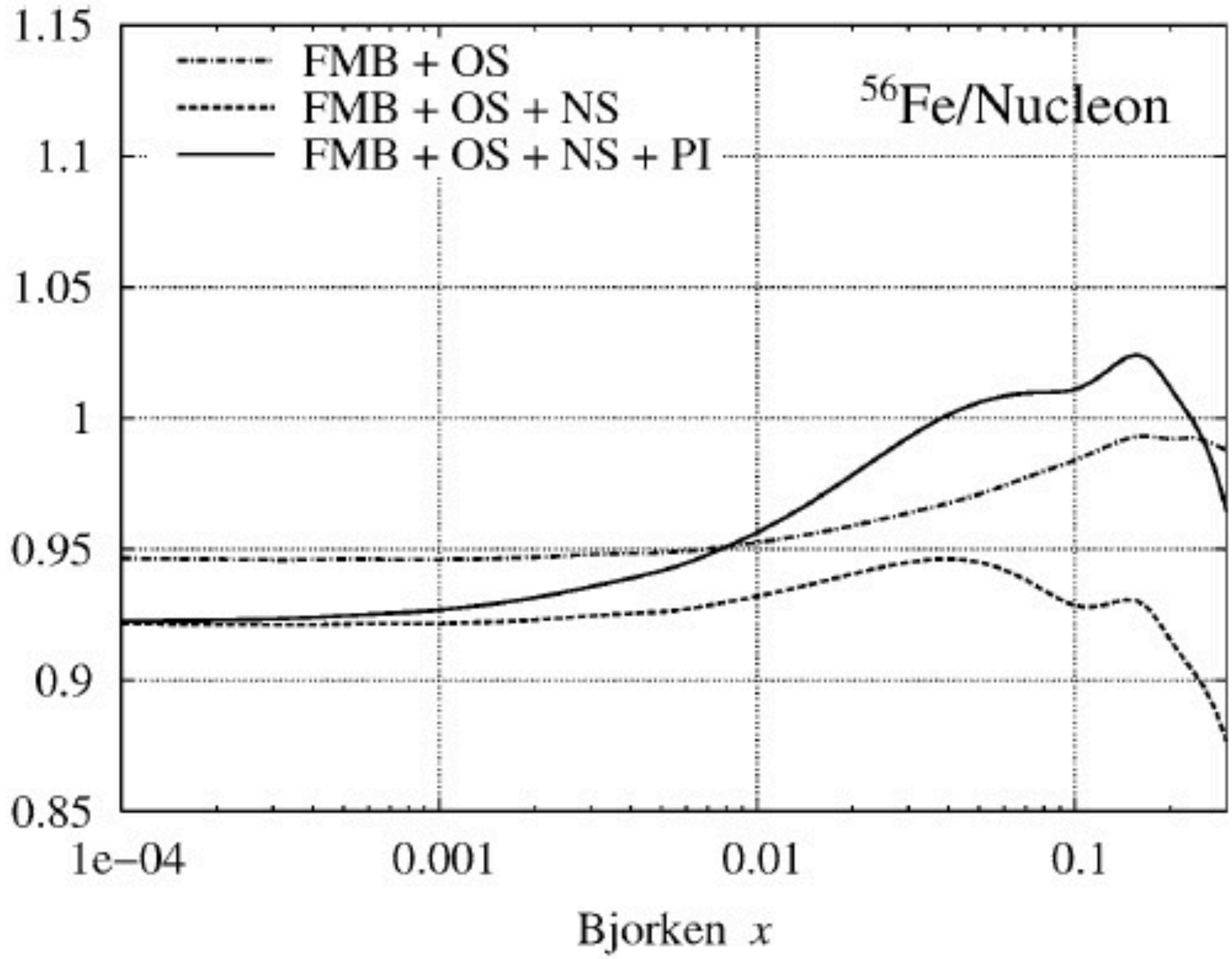
Fundamentally there is little "QCD" in this. Only the off-shell effects and the implementation of the generalized vector dominance model distinguish it from a hadronic description of nuclear parton distributions.

This works extremely well!



It reproduces little sea quark effect for 0.04<x<.2

$qbar_A/qbar_D$

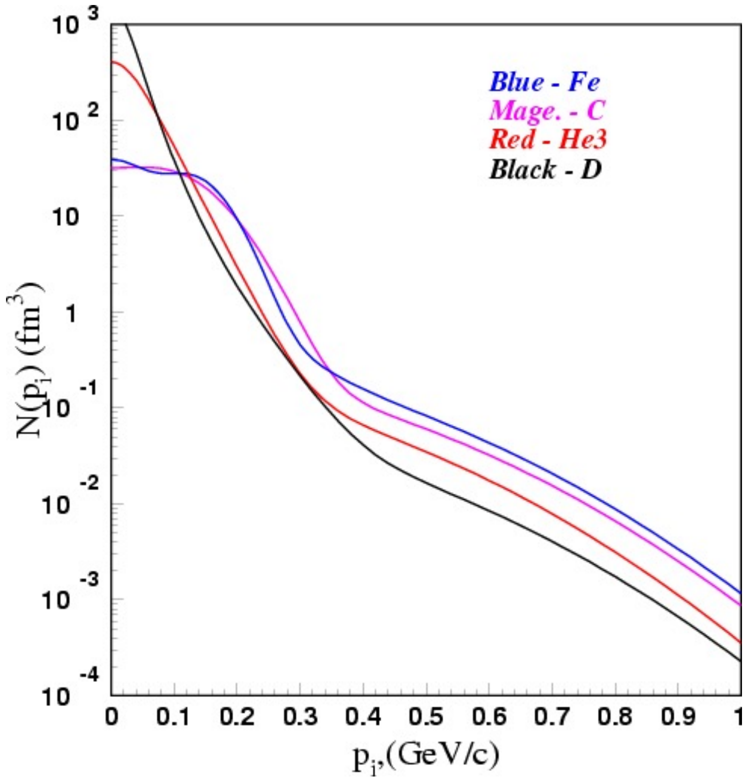


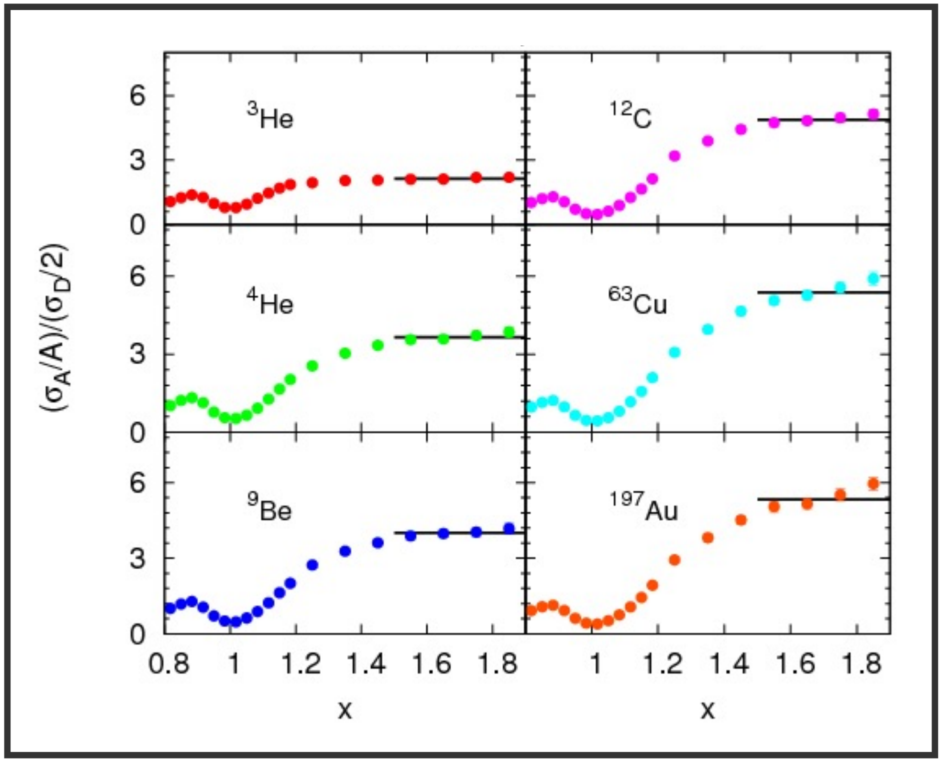
Short-range structure in nuclei

- **Inclusive scattering from nuclei at x>1** [JLab E02-019]

– **Goal is to understand *high-momentum components* and map out strength, isospin dependence of *Short-Range Correlations* (SRCs) in nuclei**

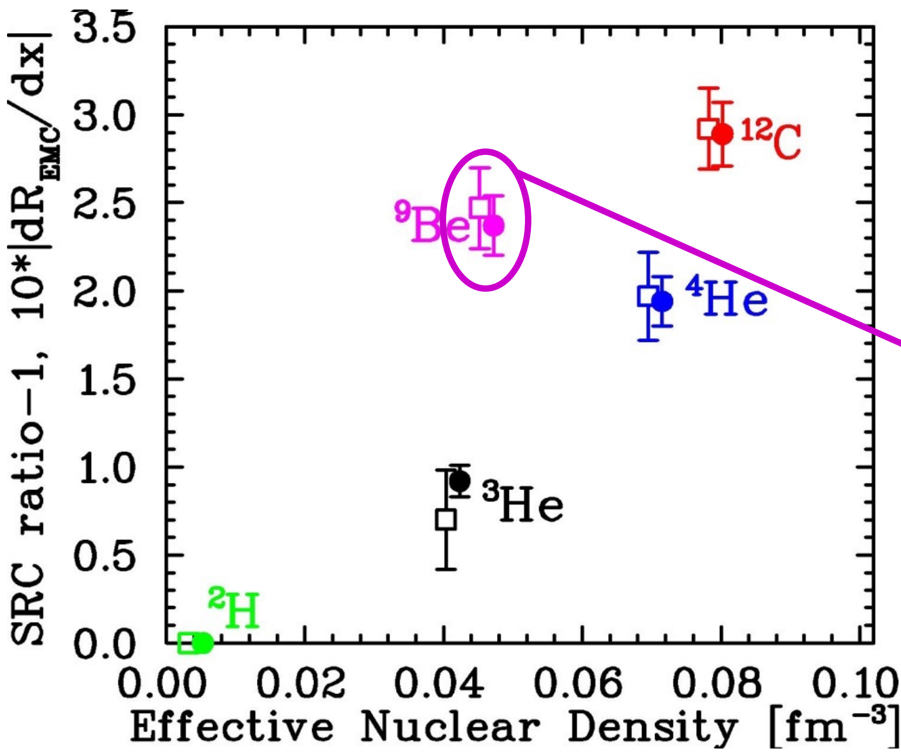
  - Important part of nuclear structure: ~15% of nucleons, 60% of kinetic energy for ^{4}He
  - Relevant to neutron star structure, N-N potential, medium modification in sub-threshold hadron production, neutrino scattering/oscillation experiments, etc…





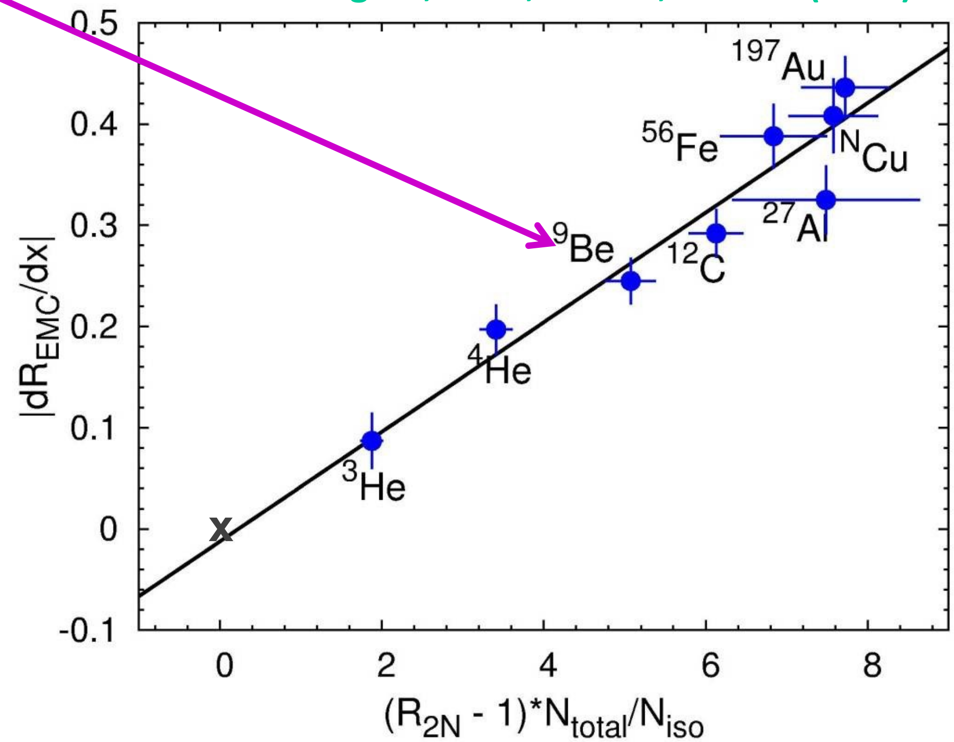
N. Fomin, *et al.*, PRL108 (2012) 092052

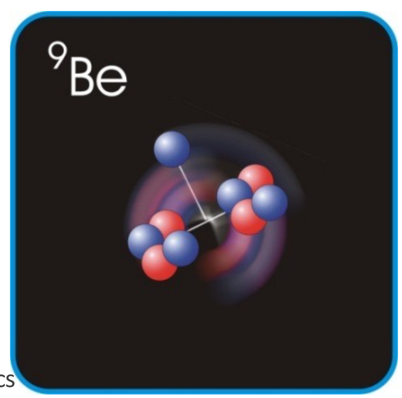
Correlation between SRCs and EMC effect



N. Fomin, *et al.*, PRL 108, 092052 (2012)
J. Seely, *et al.*, PRL103, 202301 (2009)

L. Weinstein, *et al.*, PRL 106, 052301 (2011)
J. Arrington, *et al.*, PRC 86, 065204 (2012)





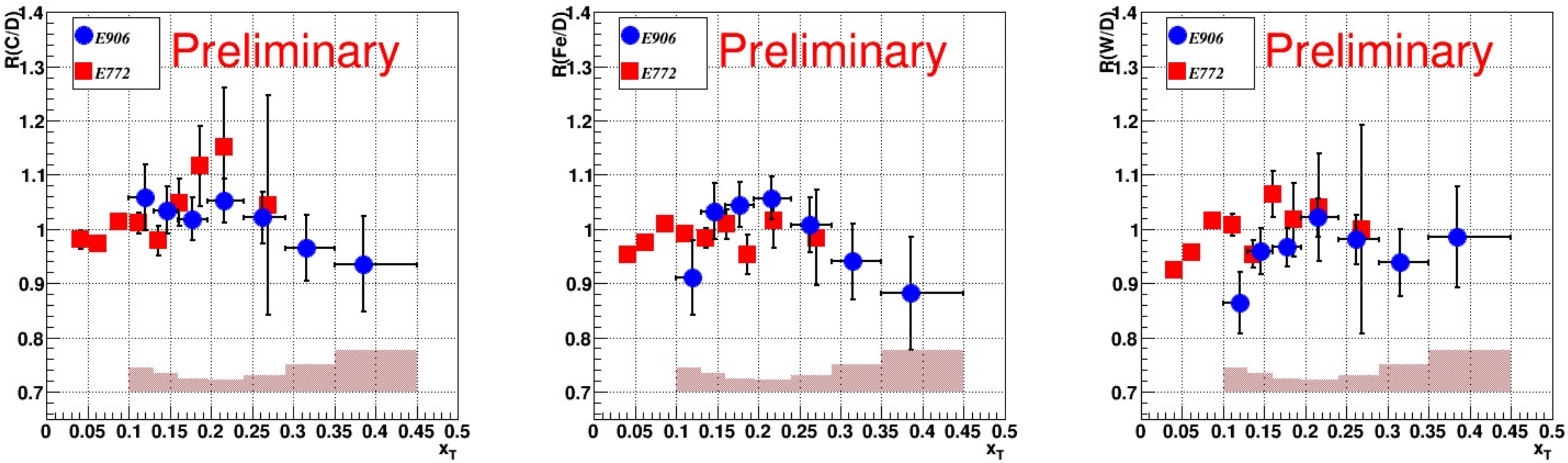
Significant overlap of ^{9}Be and (2 alpha + neutron) Wiringa/Pieper – ANL theory – GFMC calculation

GFMC also used to obtain average nuclear density

What does this mean for the sea quarks?

- Since sea distributions fall faster with x than valence distributions, x rescaling predicts a larger EMC effect for sea that is counterbalanced by the additional sea quarks from the nuclear meson field.
- Off-shell effects for anti-quarks and valance quarks do not have to be the same.
- More short-range correlations implies more kinetic energy in nucleons and therefore larger spectral corrections.
- Many models have not seriously faced the consequences for the sea quarks.

SeaQuest Preliminary Nuclear Dependence

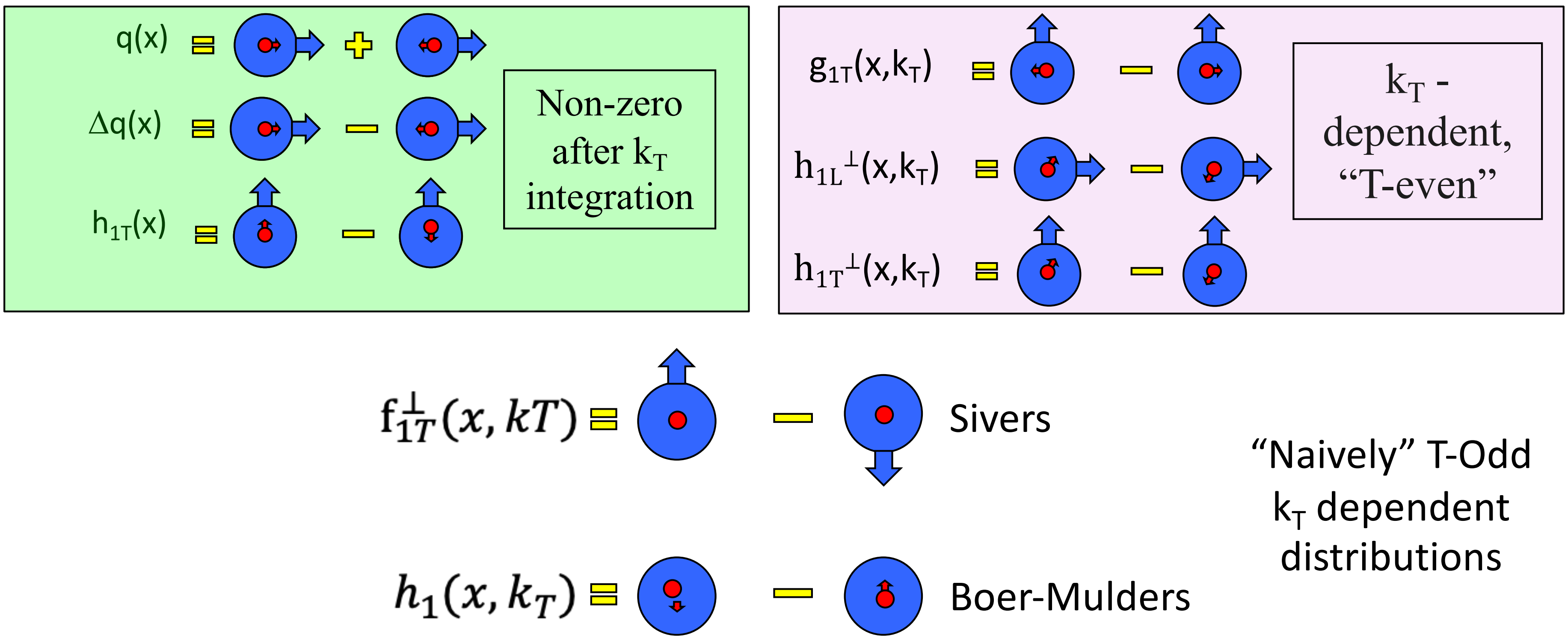


- No enhancement seen as expected in some pion excess models!
- Caveat—**partonic energy loss effects may be important at the lower beam energy of SeaQuest. We are still investigating this.**

$$x_b = x_b^{measured} + \frac{E'L}{E_b}$$

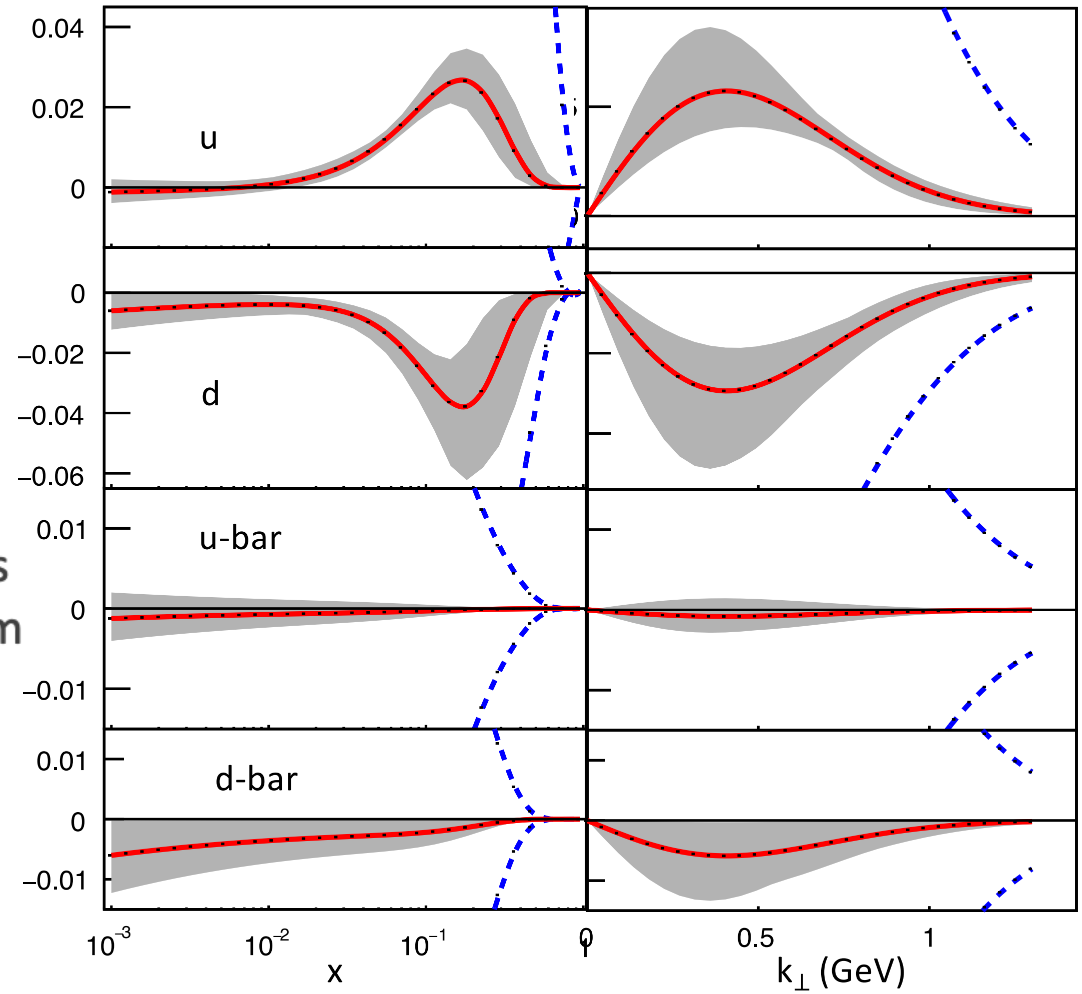
- In agreement with E772 results in the overlap region

How to look for Orbital Angular Momentum?



Fits of Sivers asymmetries

Anselmino et al, JHEP 1704 (2017) 046

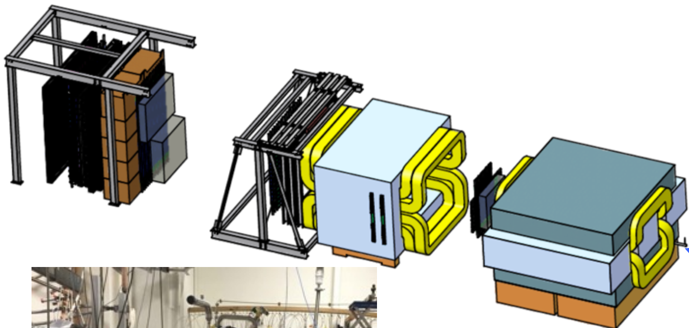


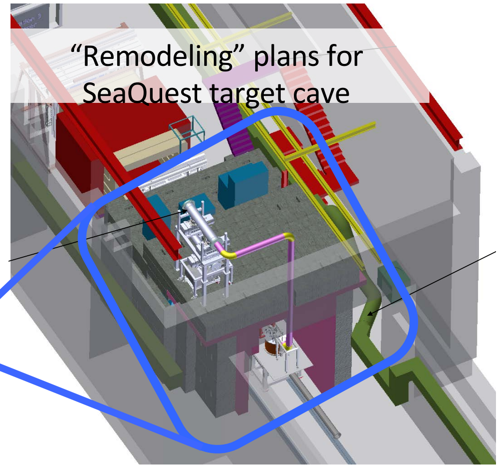
- Data fit to extract Sivers distributions

- While it can be shown that a non-zero Sivers function implies orbital angular momentum, there is not yet a rigourous method to quantitatively extract L_q from $F_{iT}^{\perp}$

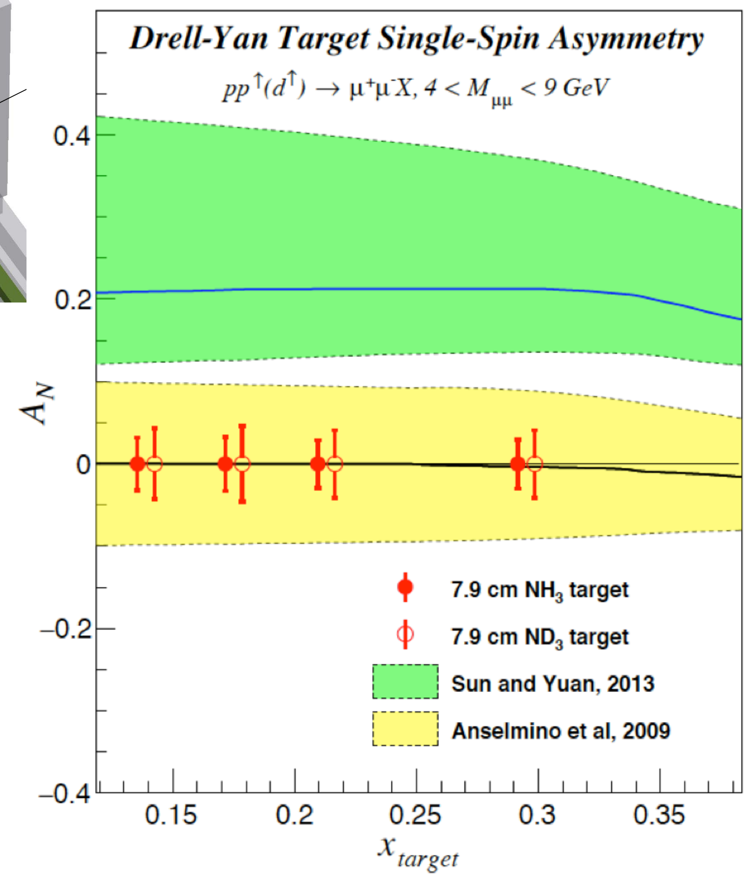
- QCD predicts the Sivers Asymmetry is opposite in sign in DY vs DIS

SpinQuest E1039



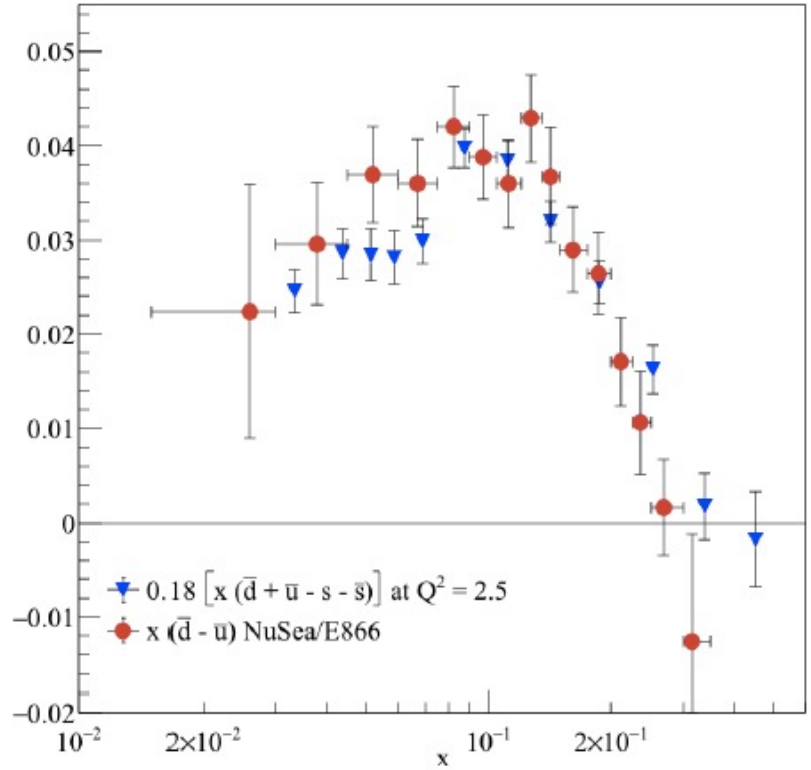


- Fall 2021—Commissioning run
- 2022—Data production runs



What else should I have talked about

- Strange quark distributions.
  - Pure sea
  - HERMES SIDIS, COMPASS SIDIS, and di-muon neutrino results do not agree
  - Important to look for difference in x shape for s(x) compared to $\bar{s}(x)$
  - Relationship to strange form factors measured at JLAB
  - See Chang and Peng, Extraction of the intrinsic light-quark sea in the proton Phys. Rev. D 92 054020 (2015).
- Charm quark distributions



- Similataneous SIDIS parton distribution and fragmentation function fits have been investigated by the JAM collaboration. See their publications.

Simultaneous parton distribution and fragmentation function fits to SIDIS have been investigated by the JAM Collaboration. Phys. Rev. Lett. 119 132001 (2017)

$\Delta\bar{u} - \Delta\bar{d} = 0.05\ (8)$

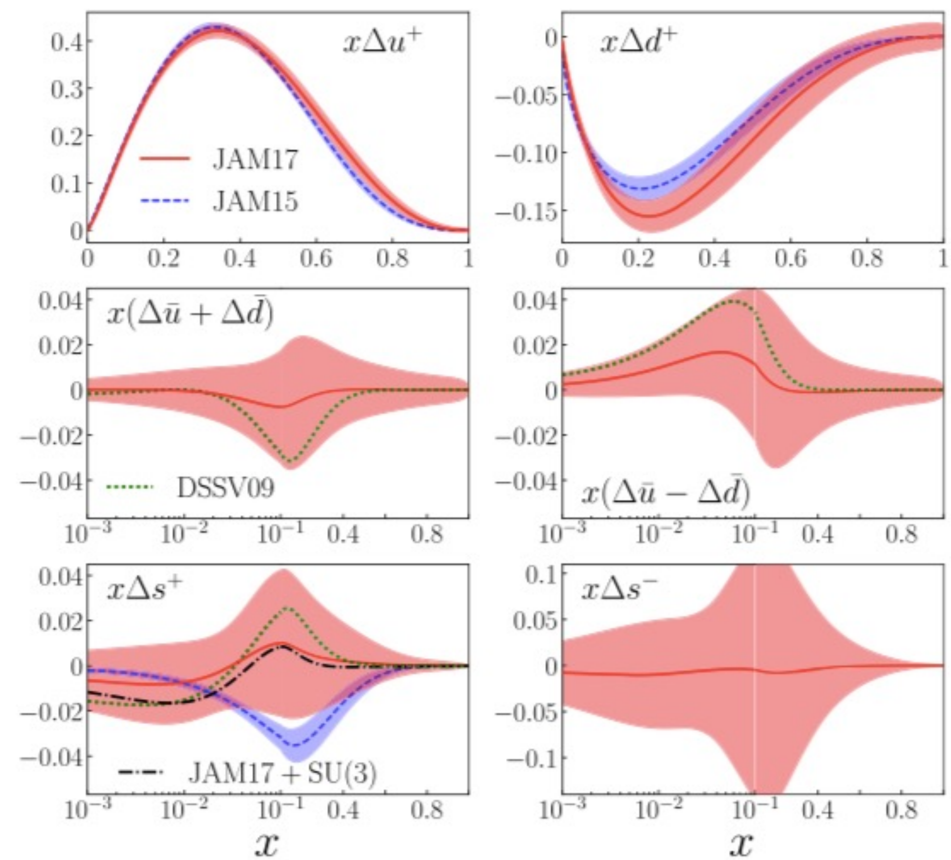


FIG. 1. Spin-dependent PDFs with 1σ uncertainty bands from the JAM17 fit at the input scale $Q_0^2 = 1$ GeV^2. The full results (red solid curves) are compared with the JAM15 Δq^+ PDFs [5] (blue dashed curves) and with the DSSV09 fit [10] for sea quark PDFs (green dotted curves). The Δs^+ PDF is also compared with the JAM17 fit including the SU(3) constraint on the octet axial charge (black dot-dashed curve).

SUMMARY

- The antiquarks will not go away. A proton is never three quarks plus glue. Isovector sea difference is about 10% of isovector valence difference.
- SeaQuest shows that that $\bar{d}(x) > \bar{u}(x)$ over the entire range measured.
- Meson- Baryon and statistical parton distribution predictions made before the data show similar features to the data.
- We need to separate effects of nuclear parton distributions and energy-loss effects. In progress.
- We need to do a better job measuring the spin carried by the antiquarks.
- Looking for evidence of antiquark orbital angular momentum in SpinQuest.

And so it was

Suddenly the EMC Collaboration showed us.

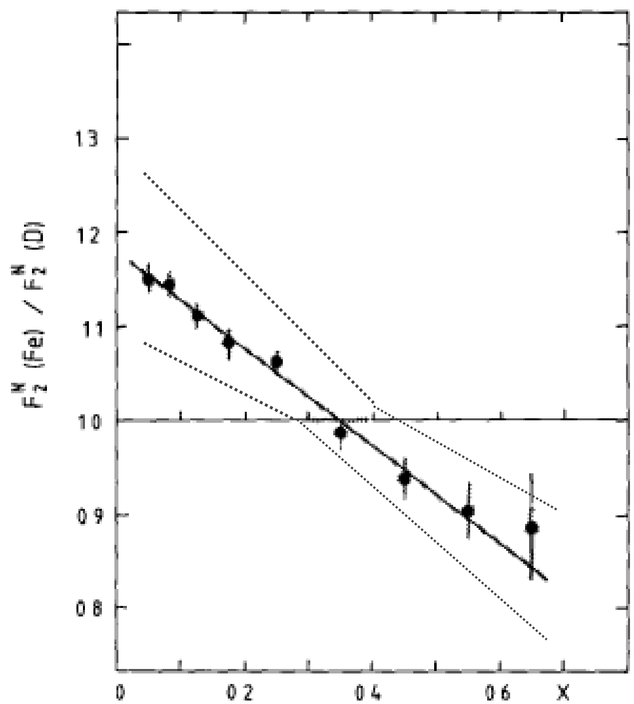


Fig. 2. The ratio of the nucleon structure functions F_2^N measured on iron and deuterium as a function of $x = Q^2/2M_p\nu$. The iron data are corrected for the non-isoscalarity of $^{56}_{26}$Fe, both data sets are not corrected for Fermi motion. The full curve is a linear fit $F_2^N(\mathrm{Fe})/F_2^N(\mathrm{D}) = a + bx$ which results in a slope $b = -0.52 \pm 0.04$ (stat.) $\pm$ 0.21 (syst.) The shaded area indicates the effect of systematic errors on this slope.

Volume 123B, number 3,4 PHYSICS LETTERS 31 March 1983

THE RATIO OF THE NUCLEON STRUCTURE FUNCTIONS F_2^N FOR IRON AND DEUTERIUM

The European Muon Collaboration

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Received 19 January 1983

This led a lot of people to hope that many of the then apparent mysteries in nuclear physics could be resolved if the structure of the proton changes significantly in the nucleus.

Part of the EMC data were quickly confirmed at SLAC

First from historic data (endcaps of H target) Bodek et al. PRL 50, 1431 (83)

Then there were dedicated experiments (Arnold et al PRL52, 727 (84))

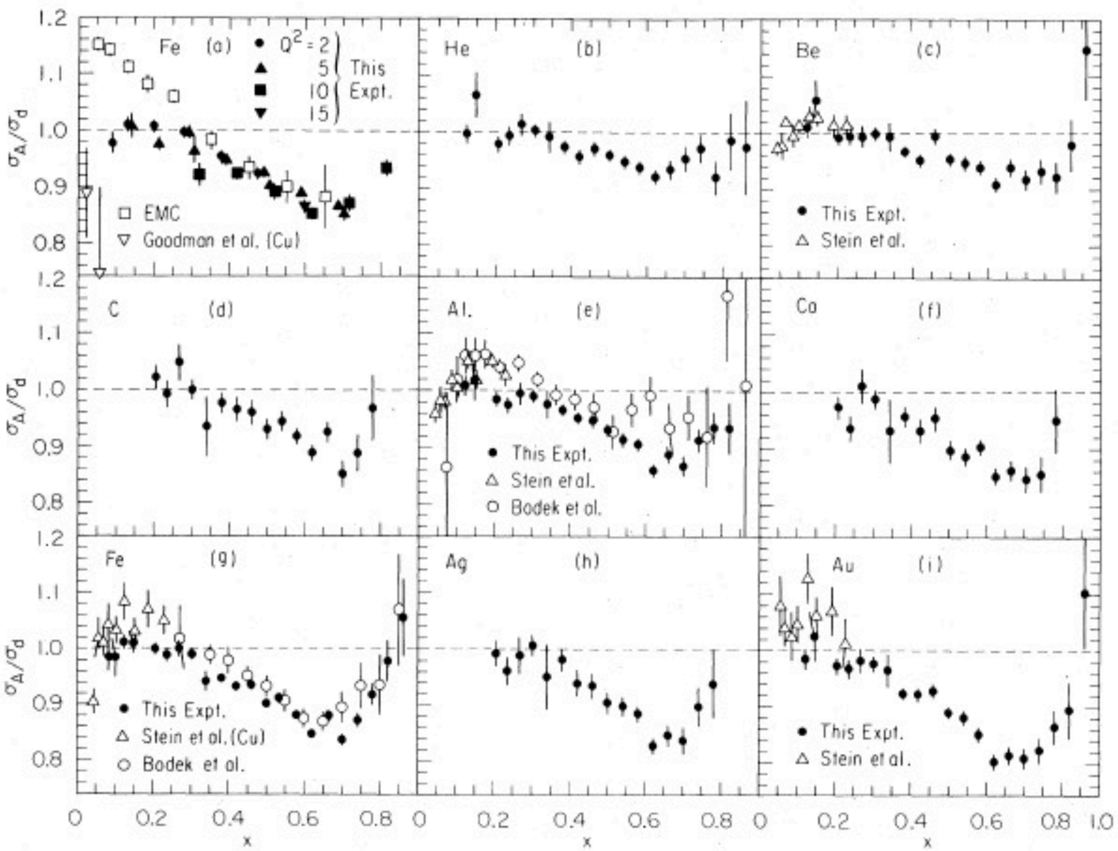


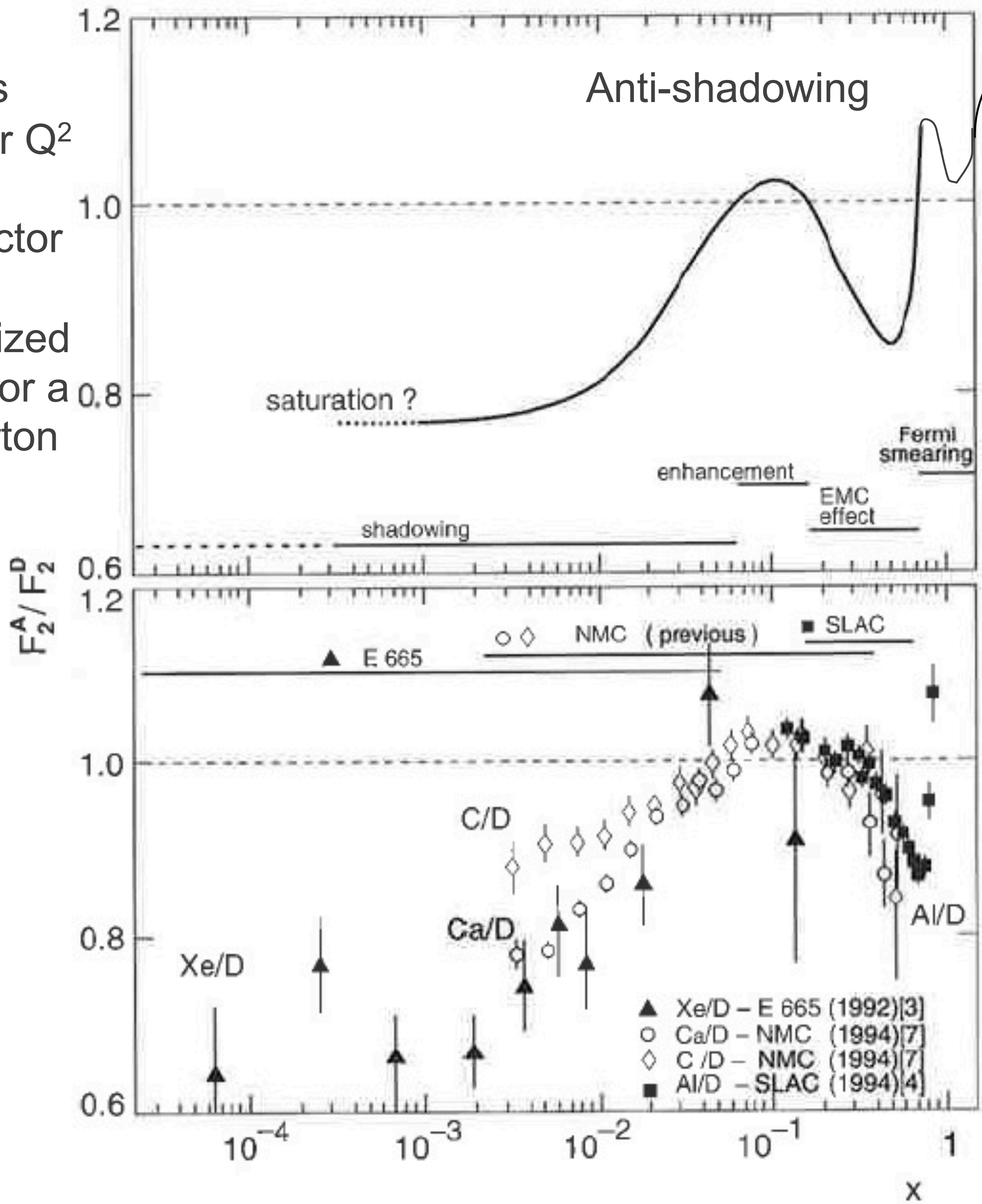
FIG. 1. (a) σ_{Fe}/σ_D as a function of x for various values of Q^2, as well as higher-energy muon data from Refs. 1 and 9. (b)–(i) σ_A/σ_D averaged over Q^2 as a function of x for various nuclei, as well as electron data from Refs. 2 and 5. The errors shown are statistical only.

Decrease at x>0.3 and rise at high x

Rise at low x much smaller than EMC data (Could be explained by A dependence of R but later not found to be so.)

As Time Went On the General Features of the Data were established over all x ranges

Shadowing was happening at larger Q^2 which was not consistent with vector dominance., It required generalized vector dominance or a real change in parton distributions.



Super-fast quarks correlations

What length scales are important?

$$A \propto \int d^4\xi\, e^{iq\bullet\xi} \langle p\left[J_\mu(\xi), J_\nu(0)\right]\| p\rangle$$

$$q = (\nu, \sqrt{Q^2 + \nu^2})$$

$$In\ terms\ of\ light\ \ cone\ \ componants\ q^{+/-} = q_0 + / - q_3$$

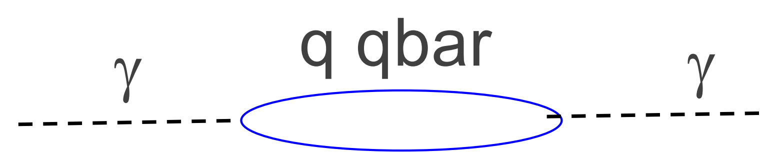
$$In\ the\ Bjorken\ \ Limit\ \ Q^2, \nu \to \infty \quad x = \frac{Q^2}{2m\nu}\ fixed$$

$$q^+ = -\frac{Mx}{\sqrt{2}} \qquad \left|\xi^-\right| < \frac{\sqrt{2}}{Mx}$$

$$q^- \to \sqrt{2}\nu \to \infty \qquad \left|\xi^+\right| \to 0$$

DIS is dominated by $\xi^+=0$ which is near the light cone.
The relevant time scale is 1/Q
The relevant distance scale is 1/x.

You get the exact same result in the lab frame. How long does a q-qbar fluctuation live?



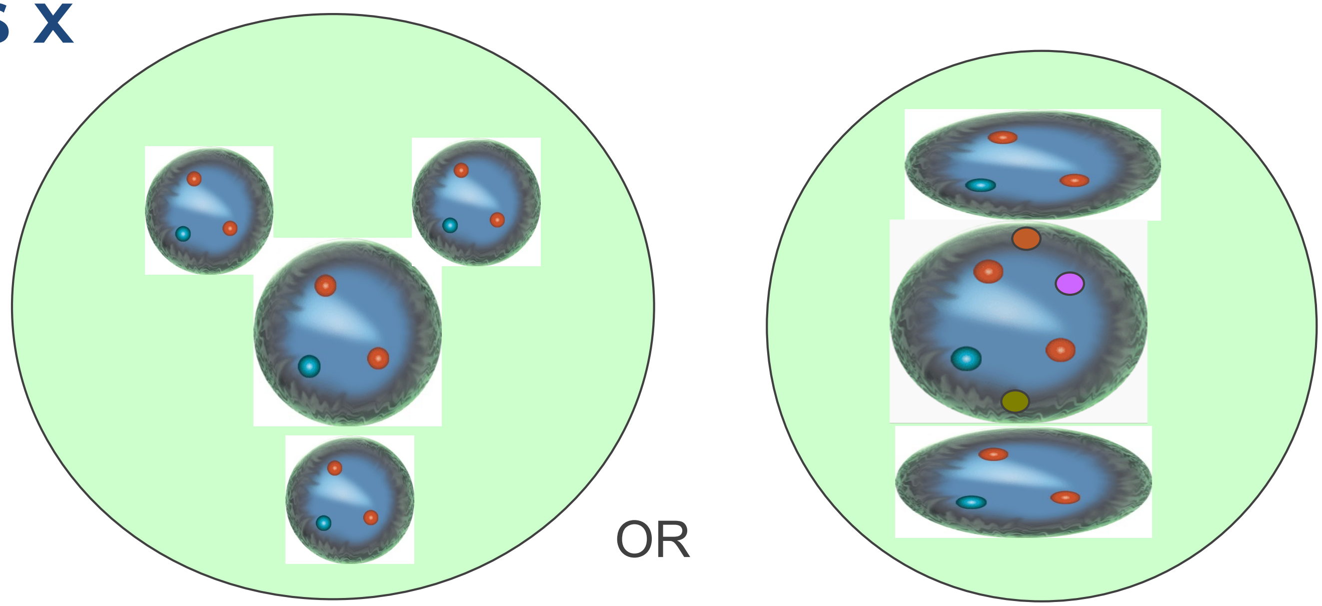
$$l \sim \frac{1}{\Delta E} \sim \frac{2\nu}{m_q^2 + Q^2} \sim \frac{1}{m_p x}$$

In the lab frame it is also clear that the interaction of a color dipole goes as $1/Q^2$
Color transparency!

Distance scales vs x

Radius of proton 0.8 fm
Distance between protons 1.8 fm
Distance between nucleon surfaces 0.4 fm
Diameter of a heavy nucleus 13 fm

Even in Pb ½ the nucleons are found at densities < 0.5 central density.



- X > 0.3 corresponds to distances smaller than size of a nucleon ~ 0.6 fm
  EMC effect

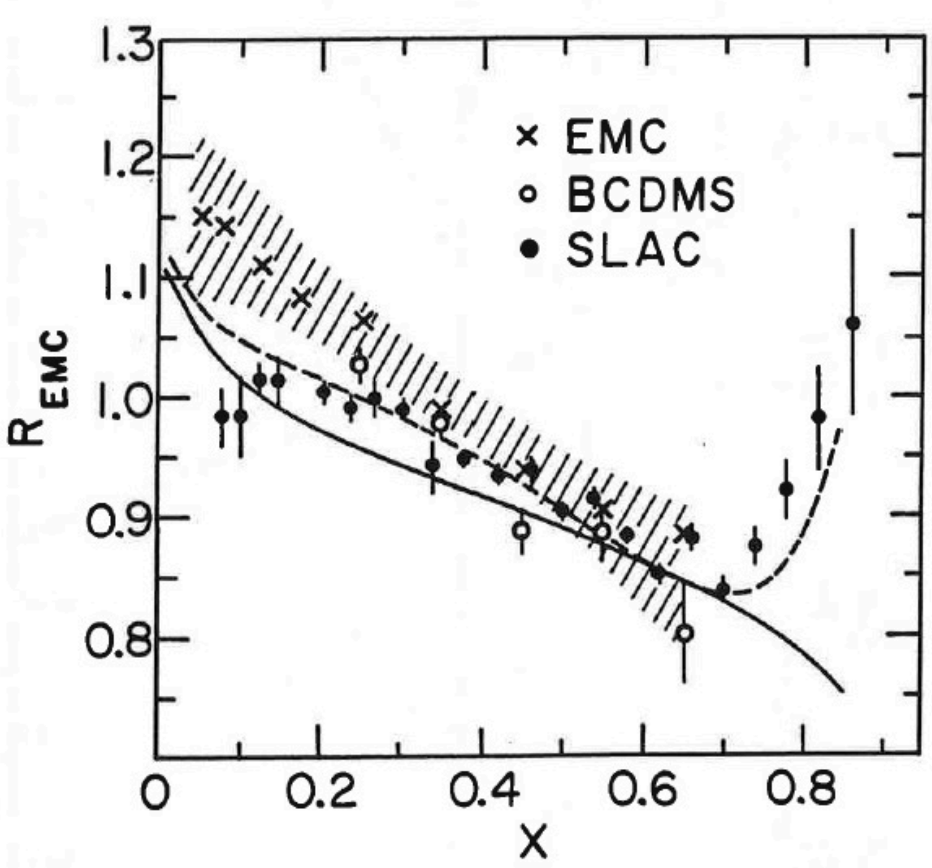
- X~0.1-0.2 corresponds to distances scales comparable to spacing between nucleons ~1- 2 fm **Antishadowing**

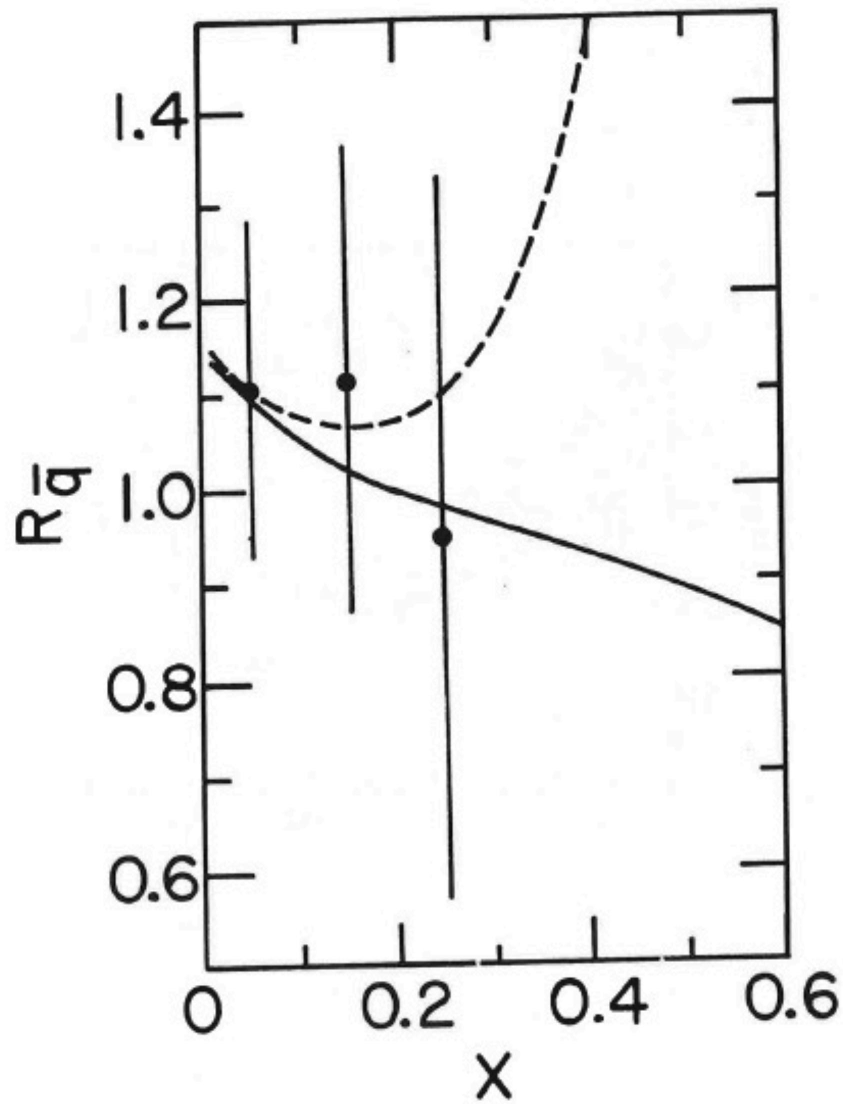
- Diameter of a nucleus. Might expect saturation of coherent effects once the 1/x becomes large compared to this, perhaps few $*10^{-3}$. **Shadowing**

Rescaling vs change in momentum fraction

From Berger 1986: Fe/D

Solid rescaling, dashed pion+nucleons





Shadowing regions: Again two seemingly different descriptions

- Parton recombination As density of partons gets higher due to overlap compared to than in free nucleon, two low x gluons will recombine into 1 higher gluon.
- Explains shadowing and antishadowing
- Not clear it saturates but expected to when density gets high enough. One model of this is the color glass condensate.

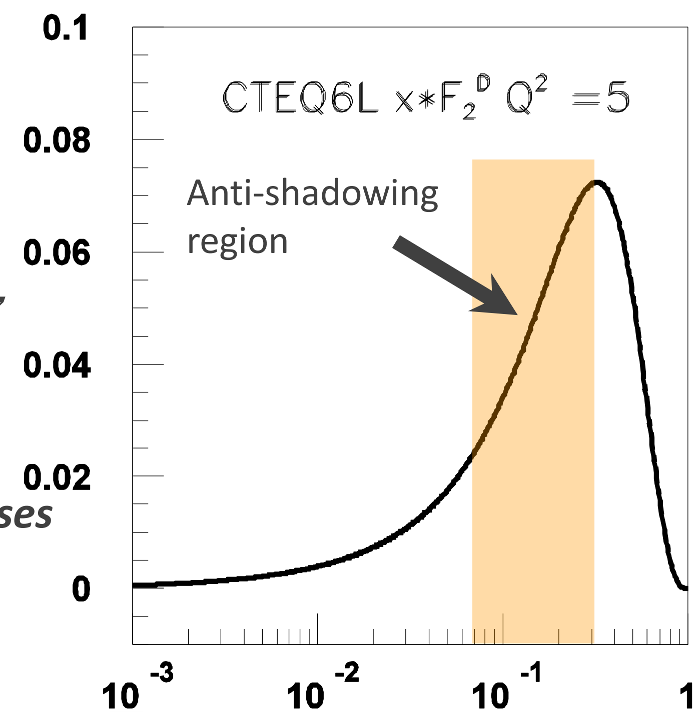
- Rest frame description: double scattering interferes with single scattering and lowers cross section. Saturates as nuclear length scale is exceeded.
- Note color dipole scattering descriptions of hard processes are believed to be completely equivalent to parton description. The same factorization theorems. Much of HERA data is analyzed this way. Drell-Yan can be also
- Can get constructive interference to get anti-shadowing – not quantitative

Antishadowing

- Is it a rise at low x from a change in scale tempered by shadowing?
- Is it constructive interference?
- Is it parton-recombination tempered by change in scale or reduced proton momenta?

- Momentum conservation
  You can't just arbitrarily shift momentum around.
  A 3-5% reduction in <x> "*explains the EMC effect for 0.2<x<0.7*"
  If you think the nucleons carries less fractional momentum in a nucleus, you have to consistently put in other particles.

There is, of course, a "trivial" ($M_A/A*m_N$-1) effect which increases to 1% in Fe and then decreases to 0.5% in heavy nuclei.



The transition regions receive contributions from several effects

S.A. Kulagin, R. Petti / Nuclear Physics A 765 (2006) 126–187 161

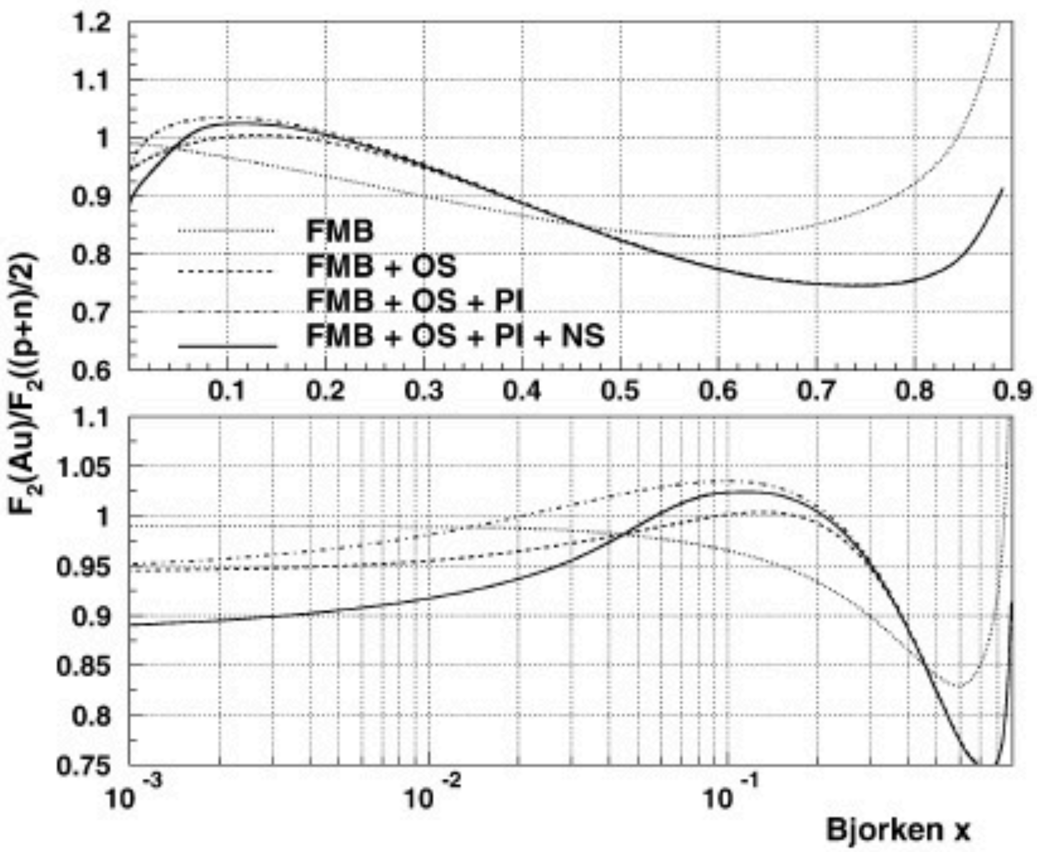
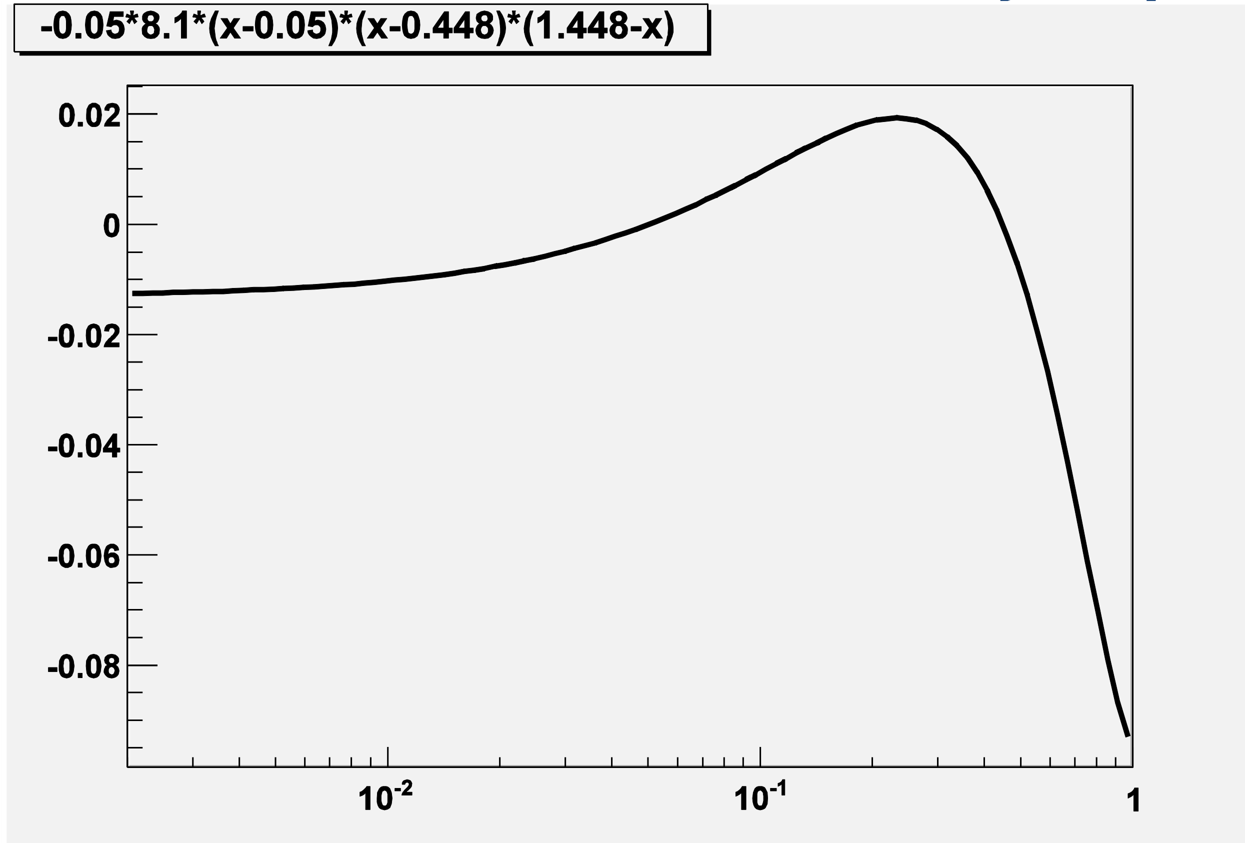


Fig. 3. Different nuclear effects on the ratio of ^{197}Au to isoscalar nucleon for F_2 at $Q^2 = 10$ GeV^2. The labels on the curves correspond to effects due to Fermi motion and nuclear binding (FMB), off-shell correction (OS), nuclear pion excess (PI) and coherent nuclear processes (NS). Target mass and the neutron excess corrections are included.

The fitted off-shell function is very important



Indeed it has a very similar shape to measured nuclear dependence.

Effects of **shadowing and off-shell are not considered in momentum sum rule, but are chosen to approximately cancel in conserving number of valence quarks.**

I think the way the binding correction is typically done deserves some more attention.

$$f(y,\nu) = \int [dp] P(\varepsilon, \vec{p})(1 + \frac{p_z}{M})\delta(y - 1 - \frac{\varepsilon + p_z}{M})\delta(\nu - p^2)$$

$$< y >_N = 1 + \frac{< \varepsilon > + \frac{2}{3} < T >}{M}$$

The spectral functions used by some authors contain a significant correlation tail. However they typically use the Koltun Sum rule (which is exact for a system with only **two body interactions**) to deduce <ε> or <T>

$$< \varepsilon > + < T > = 2 \, {B.E}/{A}$$

$$< \varepsilon > + \frac{2}{3} < T > = 2 \, {B.E.}/{A} - \frac{< T >}{3}$$

An increased binding correction requires an increased pion correction and could remove/reduce the need for the off-shell correction.

For carbon, K&P use <T>=28.8 MeV. Steve Pieper calculates 30.4 with two body forces and 36.4 MeV with 3-body forces. But how badly is the Koltun sum rule violated with three body forces? Unfortunately Steve cannot calculate <ε>

We should also add the F&S virtual photon effect,

Note this provides a natural link between the x>1 results and the EMC effect

- As you increase the number of short range correlated pairs, you increase the contribution to the kinetic energy from SRC. This reduces <Y>

- It is also possible that the slopes of the EMC region are not extracted correctly because “antishadowing” has another origin.

Other issues

- Is there an Isospin dependence ala QMC model of Thomas, Cloet et al?
  - Holt: JLAB Comparison of Tritium and ^{3}He
  - Arrington ^{40}Ca, ^{48}Ca
- The same model suggests significant spin dependence. Polarized Li
- Comparison of ^{3}H/ (d +n) to ^{3}He/ (d+p)
  - Holt: JLAB Comparison of Tritium and ^{3}He
- n-p vs p-p correlations?
  - Holt: JLAB Comparison of Tritium and ^{3}He
- Increased precision on A dependence of antiquarks
  - SeaQuest
- Are nuclear effects the same in neutrino scattering as in electromagnetic probes?

PRL 102, 252301 (2009) PHYSICAL R

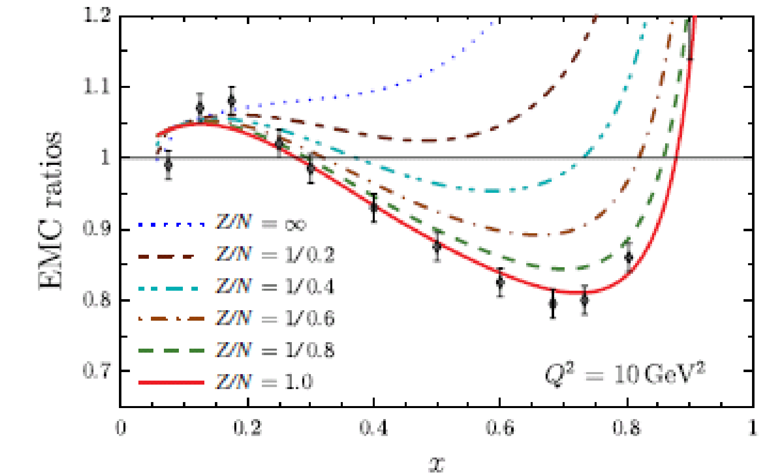


FIG. 1 (color online). Isospin dependence of the EMC effec for proton-neutron ratios greater than one. The data are fron Ref. [31] and correspond to $N = Z$ nuclear matter.

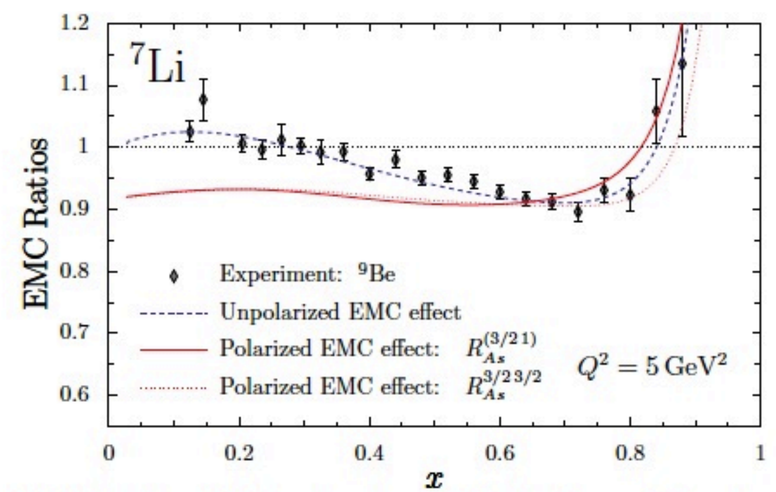


FIG. 6: The EMC and polarized EMC effect in ^{7}Li. The empirical data is from Ref. [31].

Are nuclear corrections in charged lepton and neutrino scattering different? A direct comparison is difficult. There is some tension between neutrino results on Fe and Drell-Yan on p and D in global fits.

Schienbein et al.

Charged lepton Fe/D

Neutrino Fe/D

PARTON DISTRIBUTION FUNCTION NUCLEAR ...

PHYSICAL REVIEW D 80, 094004 (2009)

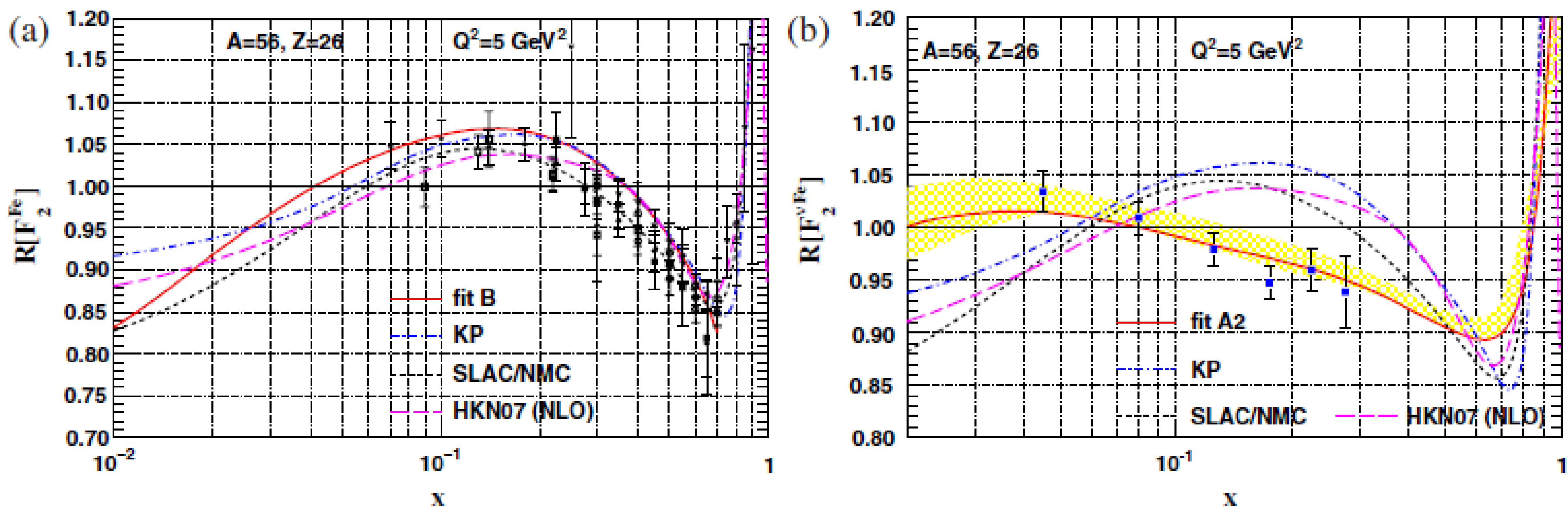


FIG. 4 (color online). The computed nuclear correction ratio, F_2^{Fe}/F_2^{D}, as a function of x for $Q^2 = 5\ \mathrm{GeV}^2$. (a) shows the fit (fit B) using charged-lepton-nucleus ($\ell^{\pm}A$) and DY data whereas (b) shows the fit using neutrino-nucleus (νA) data (fit A2 from Ref. [33]). Both fits are compared with the SLAC/NMC parametrization, as well as fits from Kulagin-Petti (KP) (Ref. [31,32]) and Hirai *et al.* (HKN07), (Ref. [15]). The data points displayed in (a) are the same as in Fig. 1 and those displayed in (b) come from the NuTeV experiment [53,54].

F2(Fe from neutrinos)/F2(D determined w/o D neutrino data)

Some inconsistency since K&P claim to describe NuTeV data well

This same approach predicts big spin dependence of the EMC effect.

Cloet et al. Phys.Lett. B642 (2006) 210-217

7

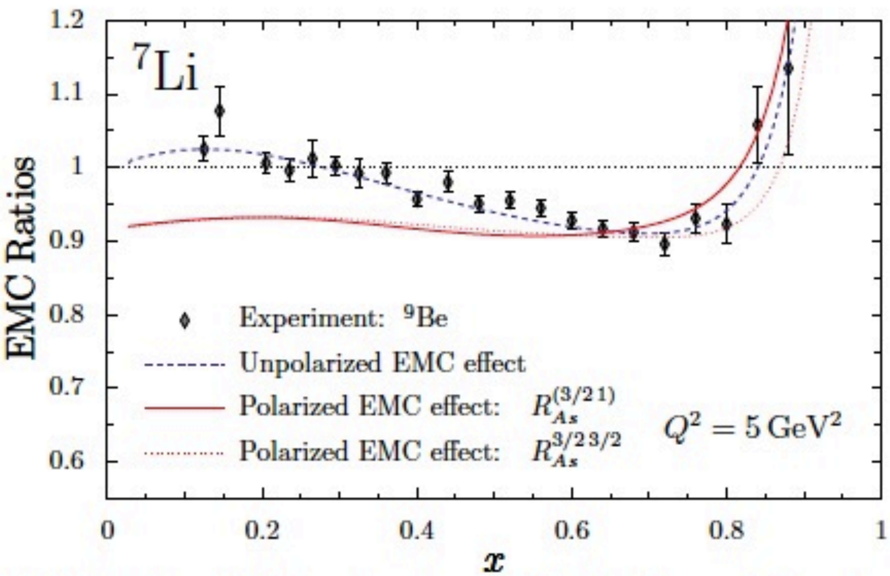


FIG. 6: The EMC and polarized EMC effect in ^{7}Li. The empirical data is from Ref. [31].

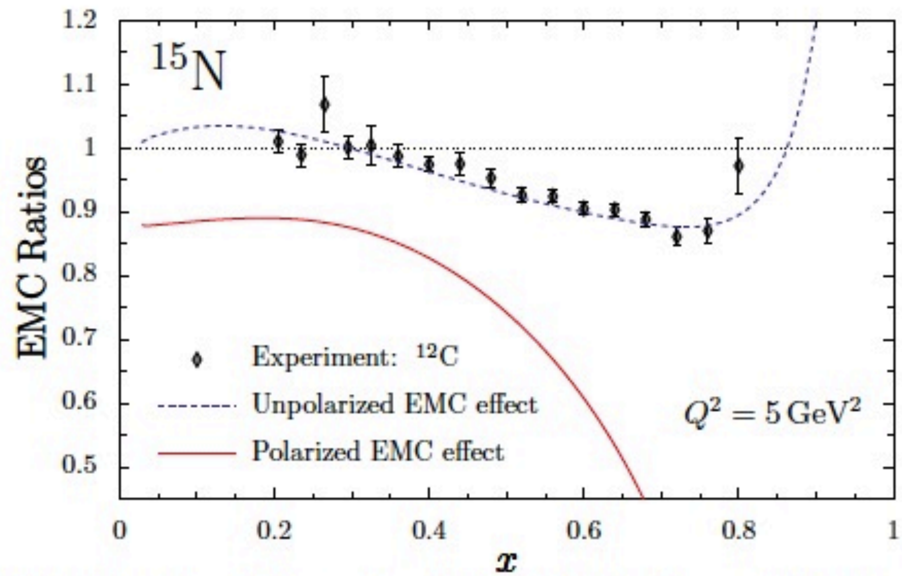
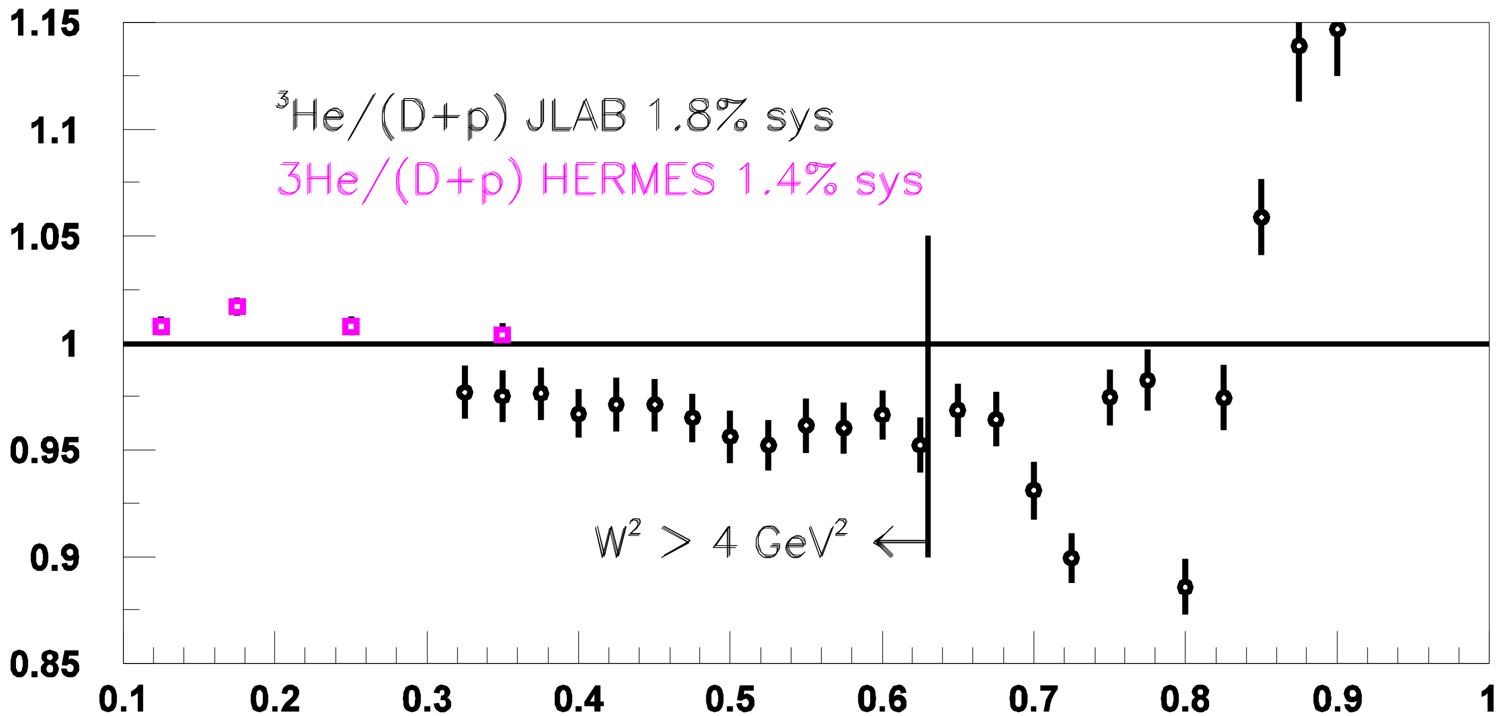


FIG. 8: The EMC and polarized EMC effect in ^{15}N. The empirical data is from Ref. [31].

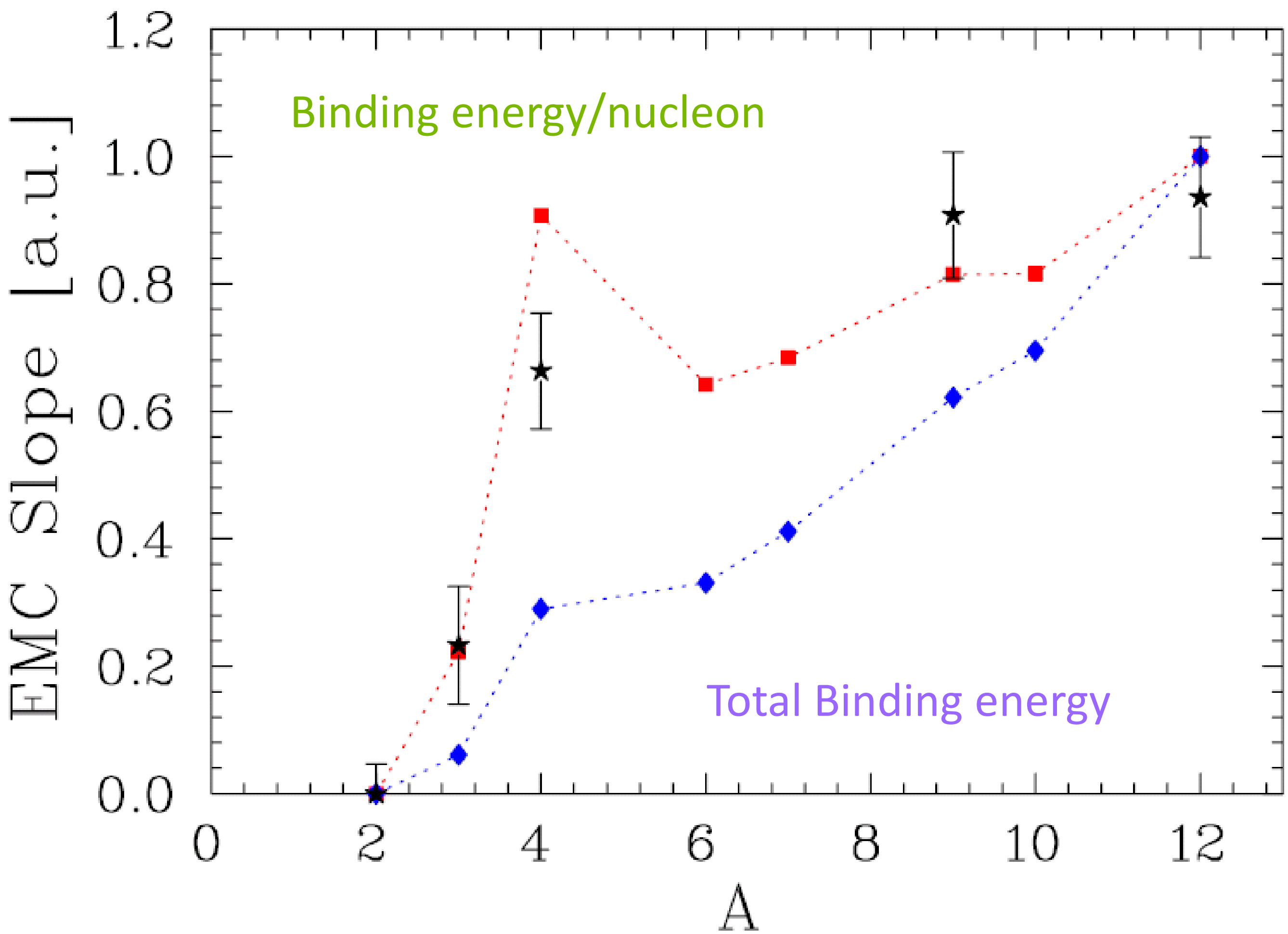
Happens because it is a relativistic mean field model and you get significant differences between effects on upper and lower components of the Dirac wave function.

What does ^{3}He tell us?



If you measure the EMC effect by the slope from x of 0.3-0.6, then it is remarkably small.

EMC effect vs Binding energy or Binding energy per nucleon



Fairness in advertising- Kulagin and Petti say their model successfully predicts ^{4}He to ^{9}Be to ^{12}C.

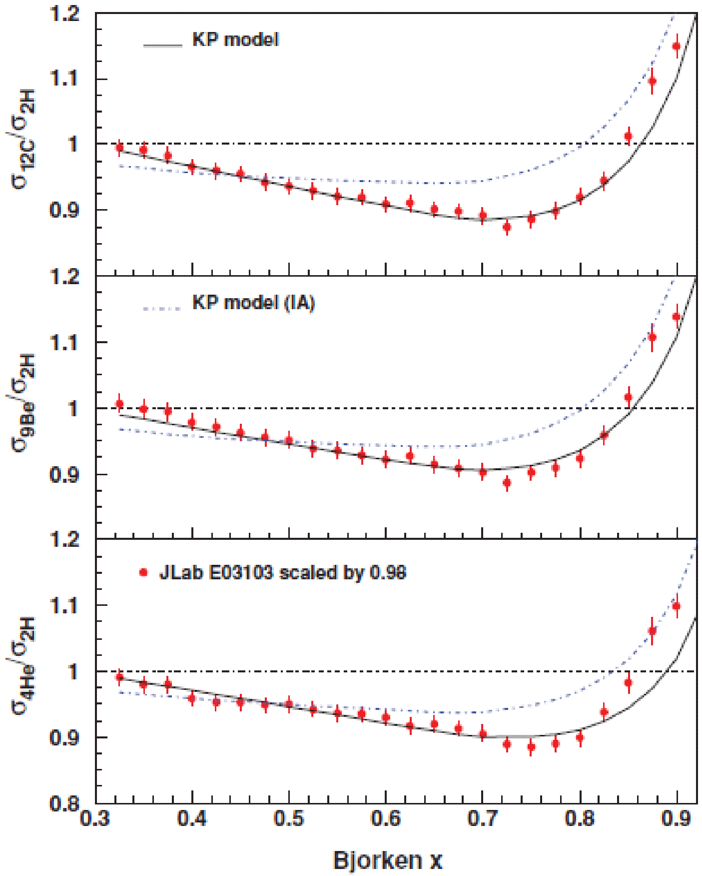


FIG. 3. (Color online) Data on the $\mathcal{R}$ ratios of ^{12}C, ^{9}Be, and ^{4}He with respect to deuterium compared with predictions of the model of Ref. [17] for the same kinematics. A common normalization factor of 0.98 has been applied to all data points of Ref. [12], and statistical and systematic uncertainties are added in quadrature. The result of a calculation in impulse approximation with no off-shell correction is also shown as dashed-dotted line for comparison.

TABLE I. The nuclear binding energy per nucleon E_A/A, a bound nucleon energy ε, and kinetic energy $p^2/2M$ averaged with the nuclear spectral function normalized to one nucleon (all in MeV units).

Nucleus	E_A/A	$\langle\varepsilon\rangle$	$\langle p^2\rangle/2M$
^{2}H	−1.11	−11.46	9.24
^{3}He	−2.57	−17.95	12.87
^{4}He	−7.07	−40.06	25.01
^{9}Be	−6.46	−41.20	27.40
^{12}C	−7.68	−45.35	28.83
^{14}N	−7.48	−45.13	28.40

Part of the difference in interpretation is from comparing slope on previous slide vs magnitude here.

PRL 105, 072001 (2010) PHYSICAL REV

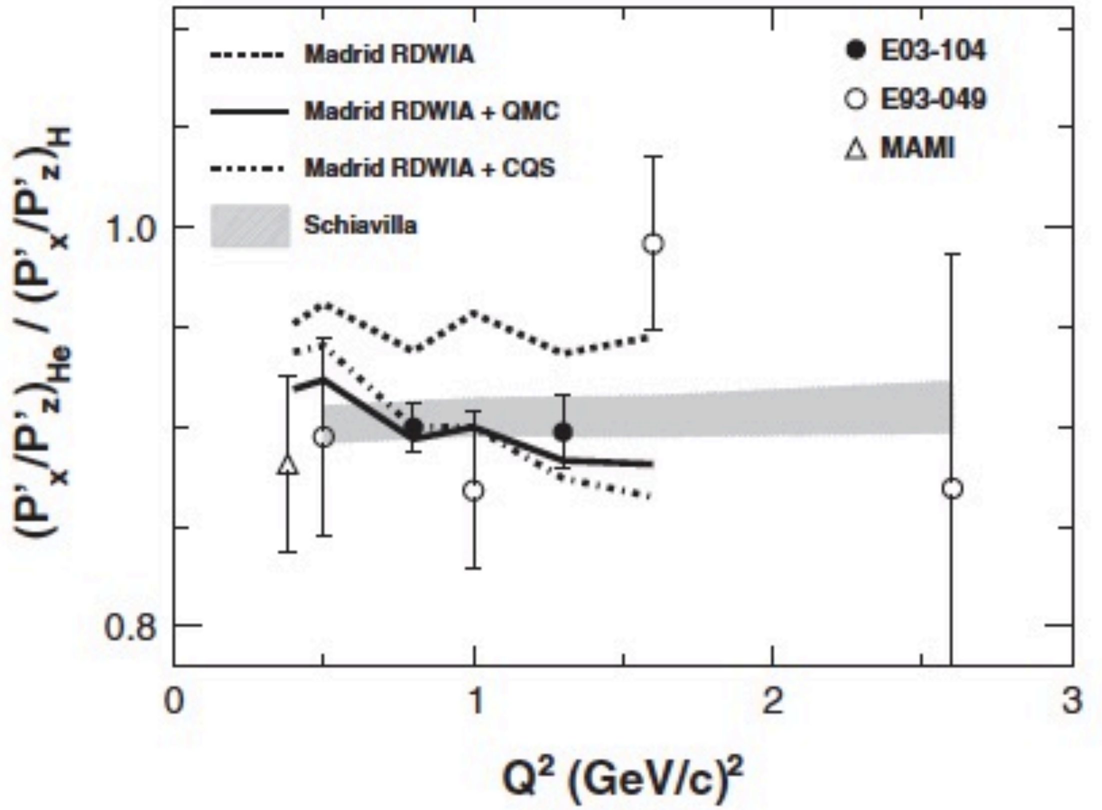
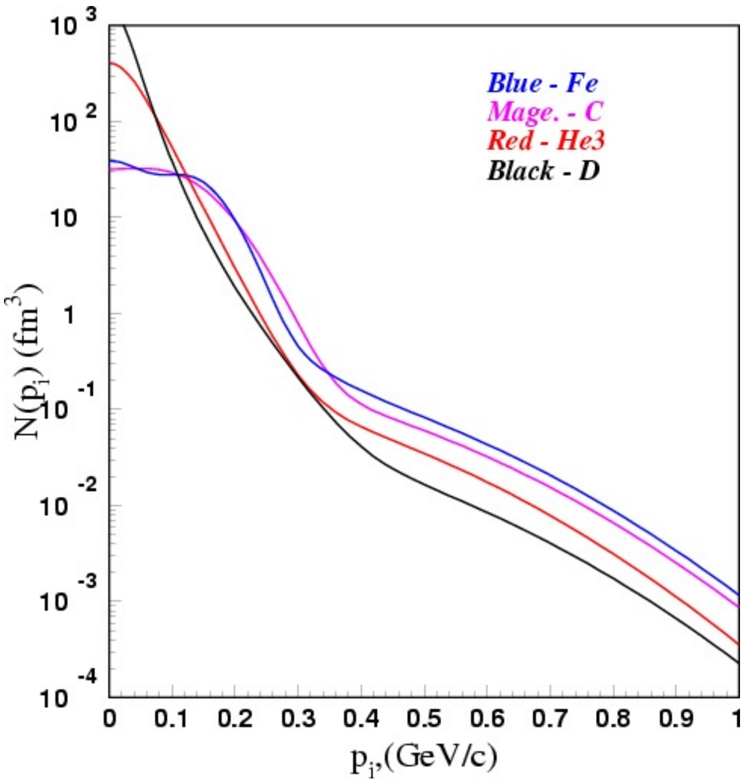


FIG. 2. Experimental results for R versus Q^2 for E03-104 (black circles), E93-049 (open circles) [31], and MAMI (open triangle) [30]. The curves represent RDWIA (dashed), RDWIA + QMC (solid), and RDWIA + CQS (dash-dotted) calculations with the current operator $cc2$ and the MRW optical potential [25]. The gray band represents Schiavilla's model [17]; see text for details.

More subtleties: The convolution formula depends on the choice of dynamics



Instant form

$$f(y) = \int d^4k\ \delta(y - \frac{Ak^+}{M_A})\ (1 + \frac{k^3}{k^0}) S(k)$$

$$S(k) = \sum_\lambda |\phi_\lambda|^2\ \delta(k^0 - M_N - \varepsilon_\lambda + T_R)$$

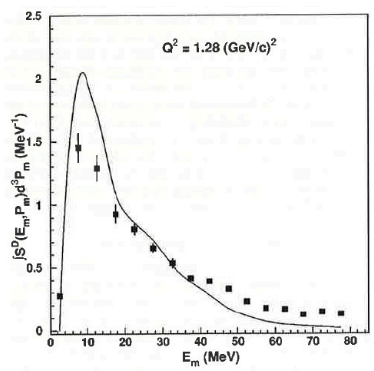


FIG. 12. Measured missing energy spectral function for gold at Q^2=1.28 (GeV/c)^2 compared to the IPSM.

Front form

$$f(y) = \int d^3\tilde{k}\ \delta(y - \frac{Ak^+}{P_A^+}) \rho(\tilde{k})$$

$$\rho(\tilde{k}) = \int dk^- \frac{Ak^+}{P_A^+} S_N(k)$$

What about momentum carried by the nuclear Coulomb field!
Frankfurt and Strikman Phys. Rev. C 82, 065203 (2010)

- Coherent virtual photons of Nuclear Coulomb field carry momentum.

  They use the Weizacker-Williams approximation to estimate the momentum carried by the virtual photons:

$$\lambda_\gamma = \int_0^1 dx\, x P_\gamma(x, Q^2) = \alpha_{\rm em} \frac{Z(Z-1)}{A} \frac{1.759}{m_N R_A}.$$

$$\lambda_\gamma(^4\mathrm{He}) = .08\%; \quad \lambda_\gamma(^{12}\mathrm{C}) = .27\%;$$
$$\lambda_\gamma(^{27}\mathrm{Al}) = .51\%; \quad \lambda_\gamma(^{56}\mathrm{Fe}) = .84\%;$$
$$\lambda_\gamma(^{197}\mathrm{Au}) = 1.56\%.$$

- Note Z^2 dependence.
- Effect is about 4 times larger than simple Coulomb energy contribution to nuclear mass.

- Quantitatively their estimates of the impact on F_2^A/F_2^D are not to be taken too seriously because they overestimate dF_2^p/dx by factors of 3 to 1.25 as x goes from 0.2 to 0.5 by assuming a simple $(1-x)^3$ dependence of F_2.

Statistical Model

- Proposed by Zhang et al. Phys. Lett B 523, 260 (2001). Recent work of Alberg et al.

Fock state expansion:

$$|p\rangle = \sum c_{i,j,k} |\{uud\},\{i,j,k\}\rangle, \qquad \rho_{i,j,k} = |c_{i,j,k}|^2$$

Detailed balance: $\rho_A R_{A\to B} = \rho_B R_{B\to A}$

in which the rates R are determined by the number of partons that can split or recombine:

$$|uudg\rangle \underset{1\times 3}{\overset{1}{\rightleftharpoons}} |uud\bar{u}u\rangle \qquad |uudg\rangle \underset{1\times 2}{\overset{1}{\rightleftharpoons}} |uud\bar{d}d\rangle \qquad |uud\rangle \underset{1\times 3}{\overset{3}{\rightleftharpoons}} |uudg\rangle$$

Predicts $\int_0^1 \left[\bar{d}(x) - \bar{u}(x)\right] dx = 0.124$ Experiment 0.118+/-0.012

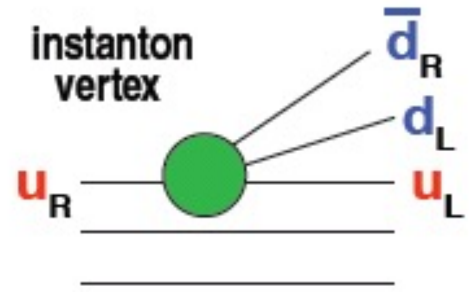
Predicts ratio approximately constant with x at ~1.4

Instantons

Either two or 3 flavors.

Turn right handed u quarks into excess of right handed dbar quarks.

Predicts at large x $\bar{d}/\bar{u} = 4$



'tHooft instanton vertex

$\sim \bar{u}_R u_L \bar{d}_R d_L$

What instantons do is mediate the propagation of pion-like modes through the nucleon so it is not unrelated to meson/chiral models.

Global Fit DSSV (2009)

DE FLORIAN, SASSOT, STRATMANN, AND VOGELSANG

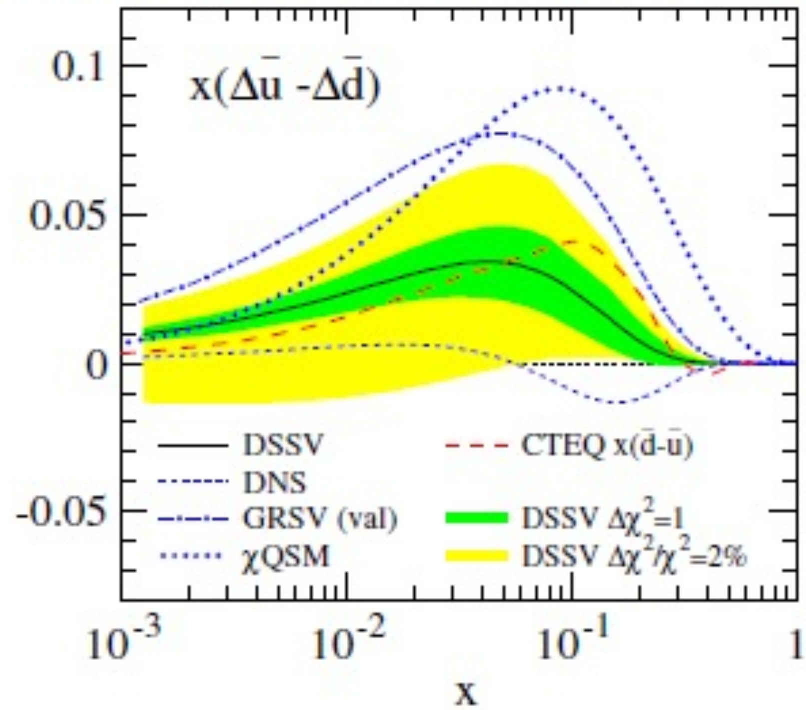
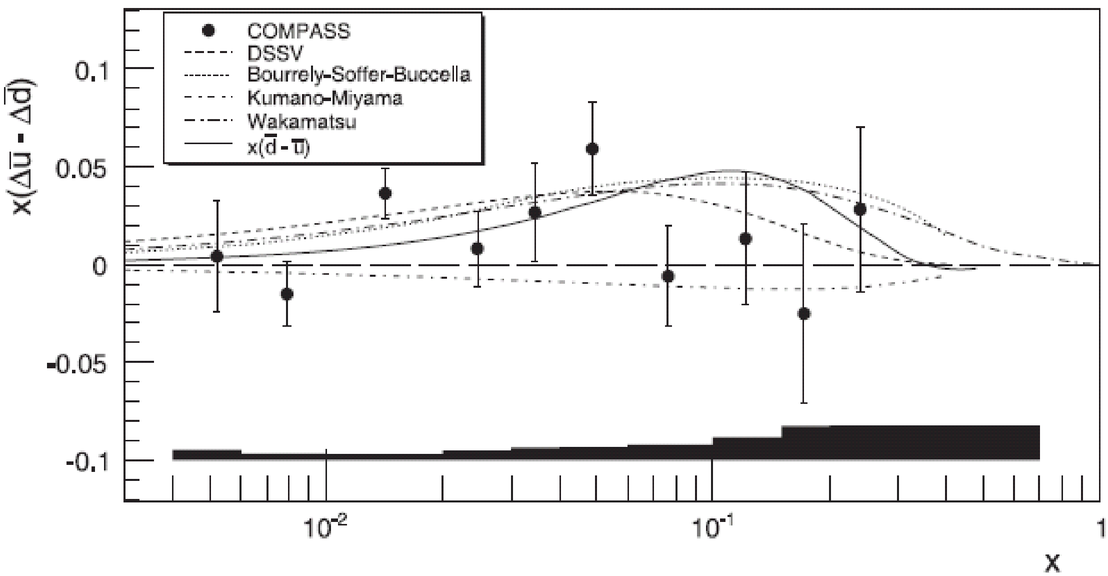
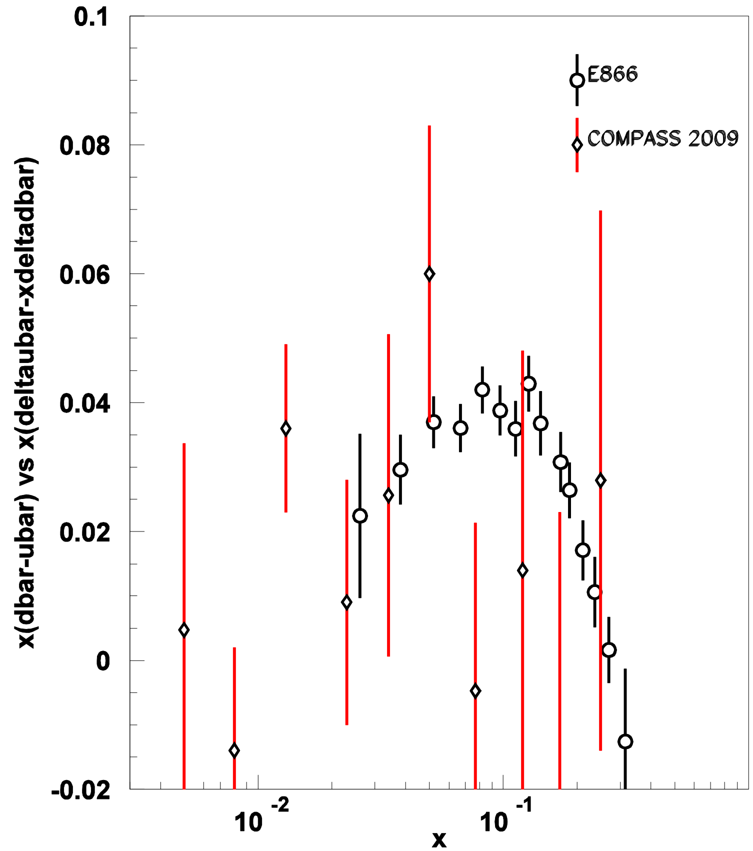


FIG. 7 (color online). The difference between $x\Delta\bar{u}$ and $x\Delta\bar{d}$ at $Q^2 = 10\ \mathrm{GeV}^2$, along with the uncertainty bands for $\Delta\chi^2 = 1$ and $\Delta\chi^2/\chi^2 = 2\%$. The dot-dashed and dotted lines show the predictions of the valence scenario of [31] and the chiral quark soliton model of [75], respectively. We also show the result obtained in an earlier global analysis [36] of DIS and SIDIS data (light dotted line), for which the fragmentation functions of [37] were not yet available. The dashed line displays for comparison the flavor asymmetry $x(\bar{d} - \bar{u})$ in the spin-averaged case, using the PDFs of [46].

Can we improve this: COMPASS Data - 2010

PL B 693, 227 (2010)





DNS 2005 $\int_0^1 (\Delta\bar{d} - \Delta\bar{u})dx =$ -.03 to -.19

DSSV 2009 $\int_0^1 (\Delta\bar{d} - \Delta\bar{u})dx = -0.117 \pm 0.036$

DSSV (arXiv:1109.3955v1) say new COMPASS drive fits to smaller net polarization for dbar and ubar.

What about the strange quarks

- Lots of hints that there might be substantial strange quark contributions to proton structure
  - Spin Crisis – strangeness contribution to proton spin
  - Sigma term – strangeness contribution to proton mass
  - SAMPLE results from MIT Bates indicating the possibility of a large strangeness anomalous magnetic moment.

- SAMPLE pioneered PV electron scattering as a quantitative tool of QCD (as opposed to electroweak physics).
  - Now with proton, neutron and parity violating form factors, we could separate the three quark flavors in the proton and look at their spatial distributions.

Strange Quark Content in Elastic Form Factors

HAPPEX III. PRL 108, 102001 (2012)

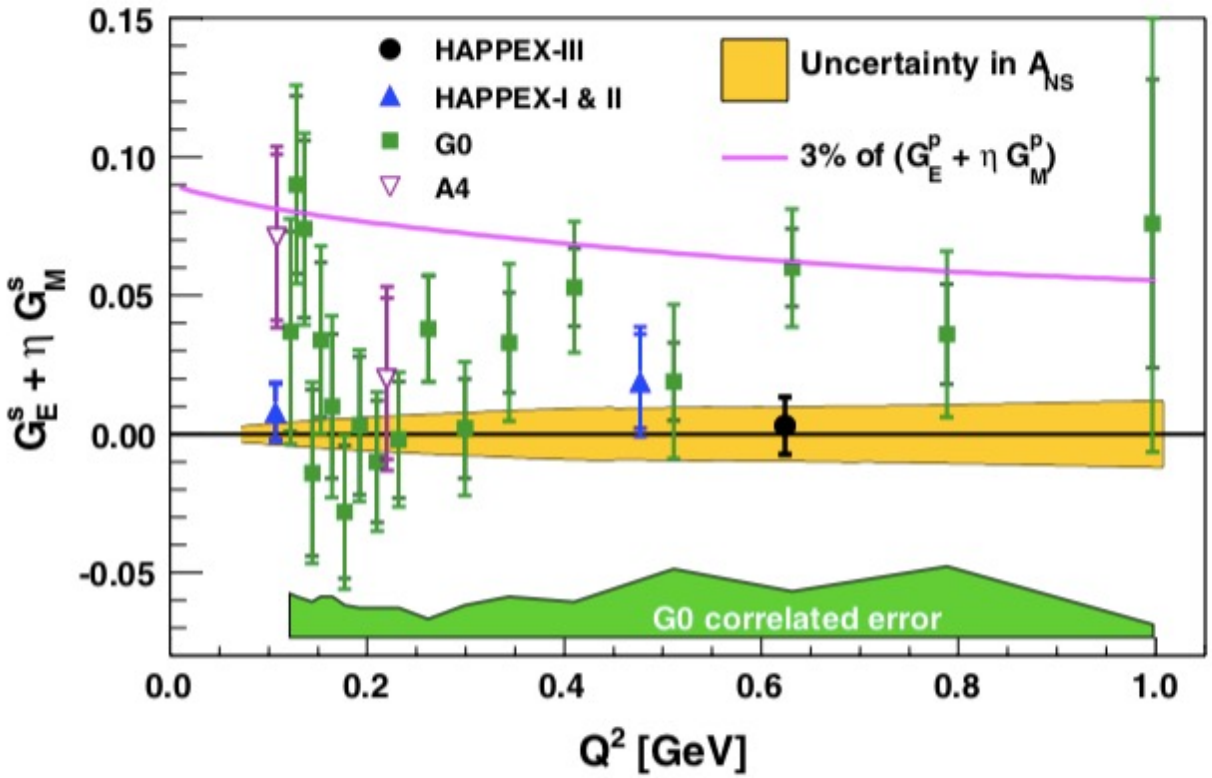


FIG. 2 (color online). Results of strange-quark vector form factors for all measurements of forward-angle scattering from the proton. The solid curve represents a 3% contribution to the comparable linear combination of proton form factors.

But remember $G_e^n \sim 0.06$ at Q^2 of 0.6

Strange quark sea distributions: Best handle has been considered to be anti-neutrino multi-muon data? $\bar{\nu} + \bar{s} \rightarrow \mu^+ + \bar{c} \rightarrow \mu^-$

Usually $s(x)+\bar{s}(x) \sim \kappa\,(\bar{u}+\bar{d})$ with $\kappa \sim 0.2\text{-}0.5$

NUTEV, PRD 64 112006(2001)

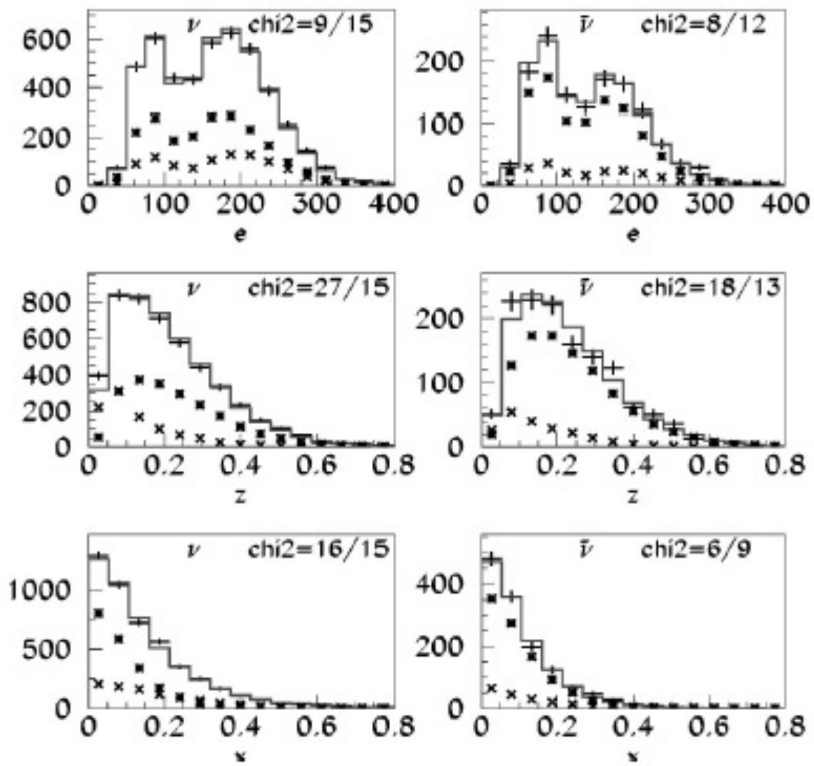
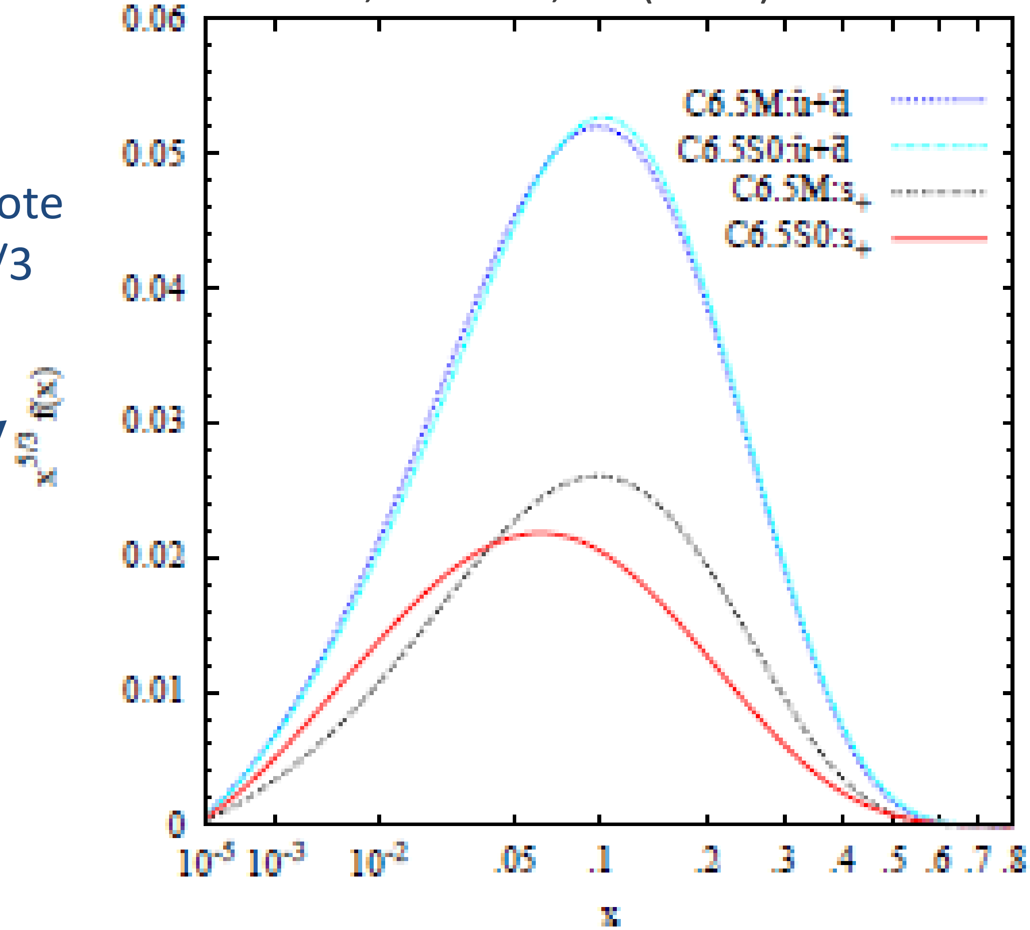


FIG. 6. x, z, and E distributions for dimuons (points) compared to Monte Carlo (histogram). Neutrinos are shown on the left, anti-neutrinos on the right. These distributions are used in the logarithmic-likelihood fit. The crosses show the Monte Carlo πK background component, and the stars show the strange sea contribution.

Note 5/3

CTEQ, JHEP **42**, 89 (2007) Q^2=1.69



Also information on $s(x)-\bar{s}(x)$ but currently not conclusive

NNPDF Collaboration 2009
Uncertainties in strange quark distributions are sizably larger than those found by other groups

"Allowing the shape of the strange quark distribution to be different than the light quark sea reveals the data do not well constrain the strange quark distributions."

NNPDF Collaboration / Nuclear Physics B 823 (2009) 195–233 211

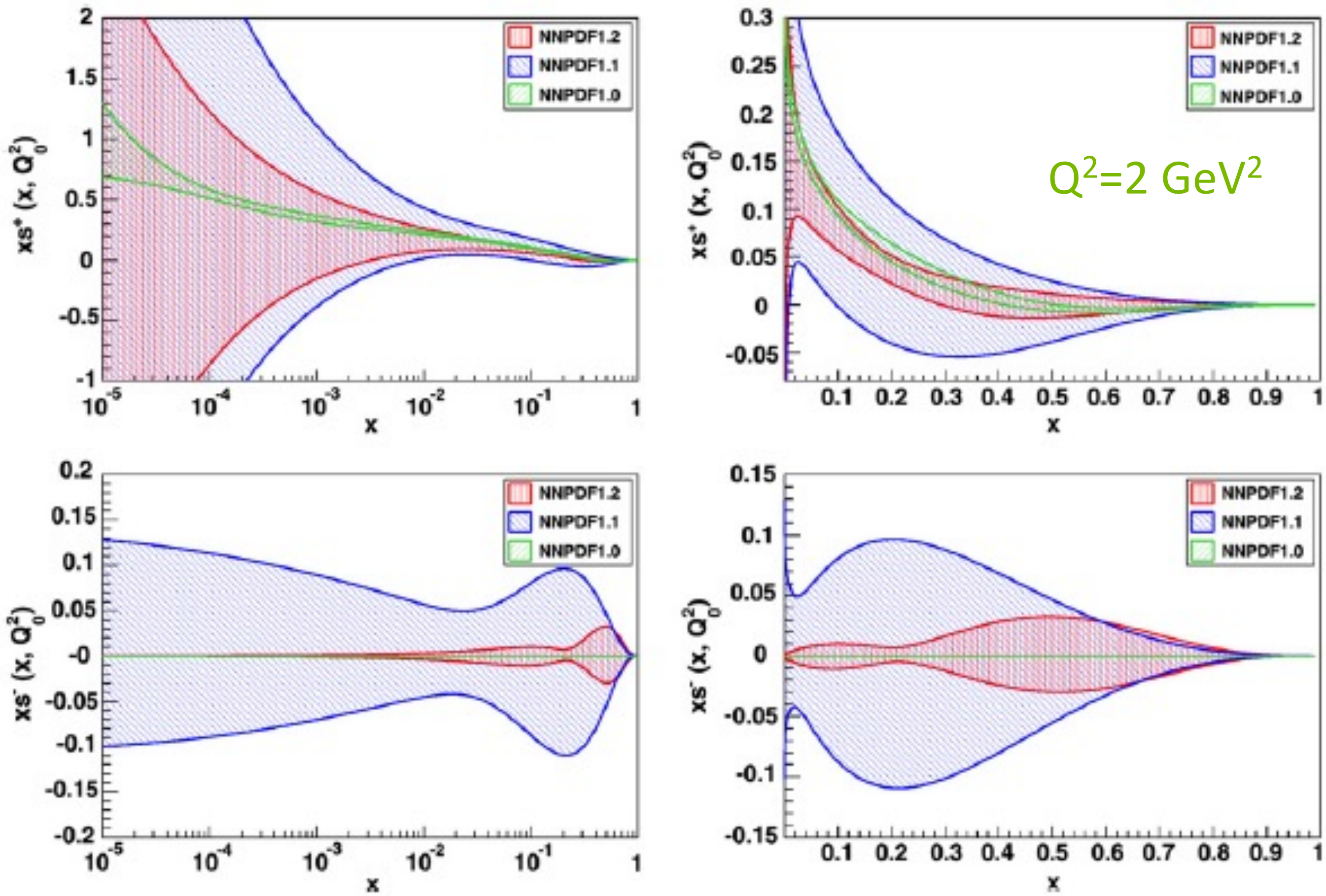


Fig. 7. Same as Fig. 5, but for the strange sector PDFs. Note that in NNPDF1.0 $s^{\pm}$ were assumed to be respectively $s^+(x, Q_0^2) = \frac{1}{2}(\bar{u} + \bar{d})$ and $s^-(x, Q_0^2) = 0$.

HERMES uses SIDIS to measure the strange quark sea distributions. A. Airapetian et al Phys. Lett. B 666, 446 (2008)

Usually s(x)+sbar(x) ~ κ (ubar+ dbar) with κ~ 0.2-0.5

HERMES looks at DIS on deuterium and compares inclusive with semi-inclusive kaon multiplicities

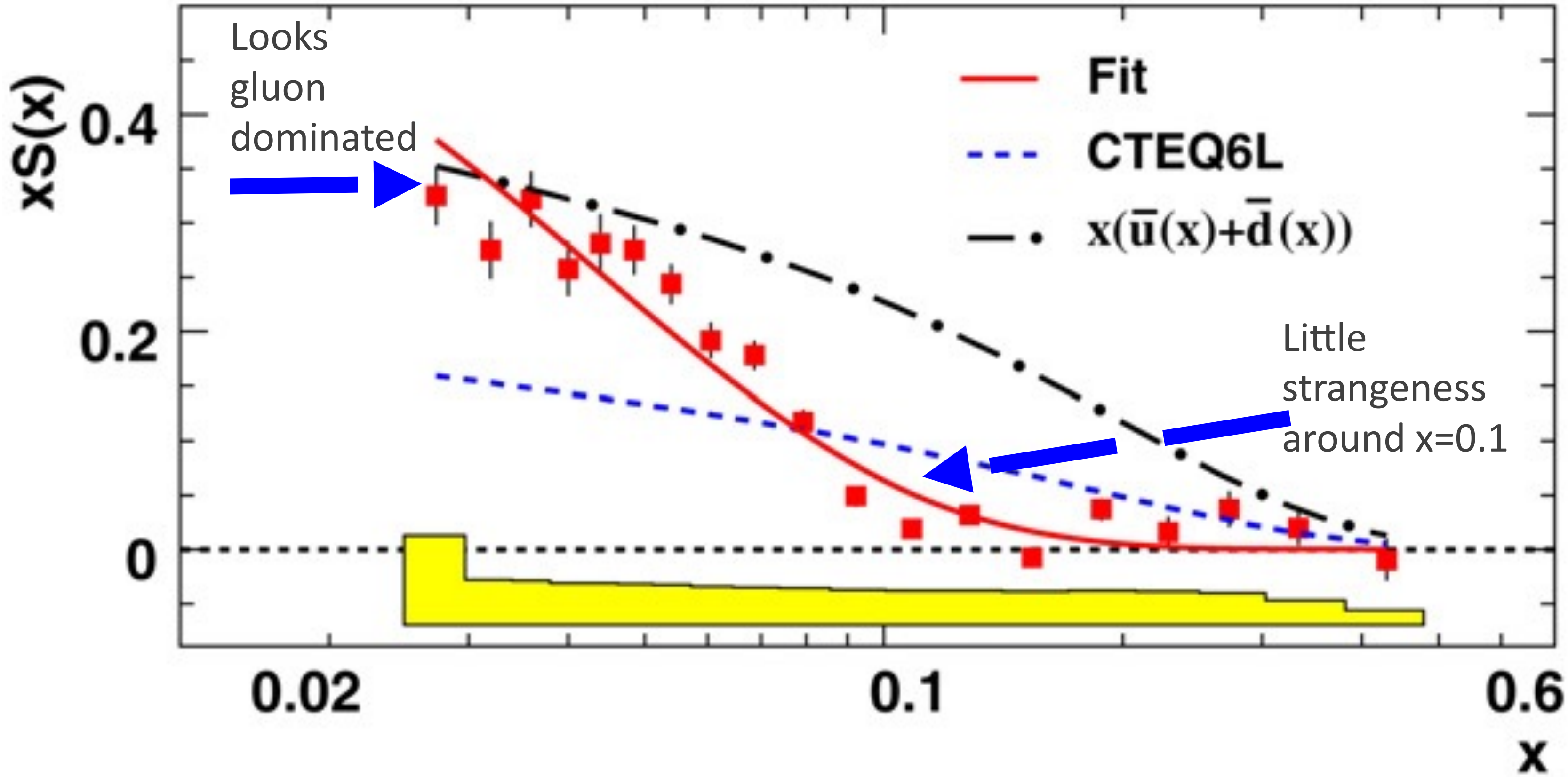
$$\frac{d^2N^{DIS}(x)}{dxdQ^2} = \kappa_U(x,Q^2)\left[5Q(x) + 2S(x)\right]$$

$$\frac{d^2N^{K}(x)}{dxdQ^2} = \kappa_U(x,Q^2)\left[Q(x)\int D_Q^K(z)dz + S(x)\int D_S^K(z)dz\right]$$

$$Q(x) = u(x) + \overline{u}(x) + d(x) + \overline{d}(x)$$
$$S(x) = s(x) + \overline{s}(x)$$

HERMES sees little strange quark content for x>0.1 and s(x)+sbar(x) ~ ubar(x)+dbar(x) at x< 0.03!

A. Airapetian et al Phys. Lett. B 666, 446 (2008) **Q^2=2.5 GeV^2**



A big question is why is this so different from S(x) deduced from multi-muon events in neutrino charged current scattering

Comparison of ubar+dbar-s-sbar with dbar-ubar

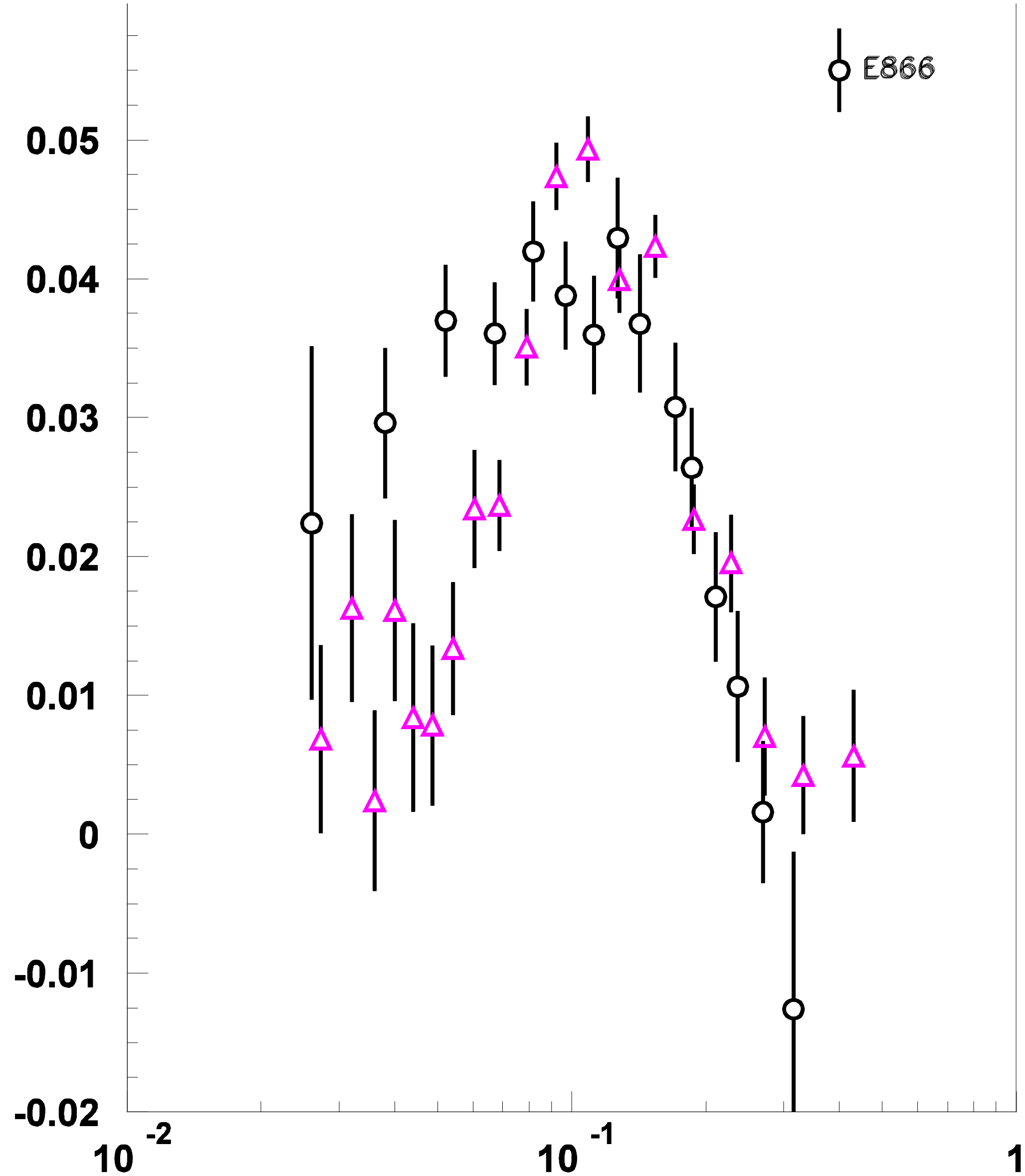
Based on the HERMES result and assuming the strange quark distribution represents the gluon-splitting induced distribution, the shape of the non-perturbative

$$x[\bar{u}(x)+\bar{d}(x)-s(x)-\bar{s}(x)]$$

is similar to

$$x[\bar{d}(x)-\bar{u}(x)]$$

$x[\bar{d}(x)-\bar{u}(x)]$ vs 0.25 *HERMES $x[\bar{u}(x)+\bar{d}(x)-s(x)-\bar{s}(x)]$



Factor of 0.25 simply makes

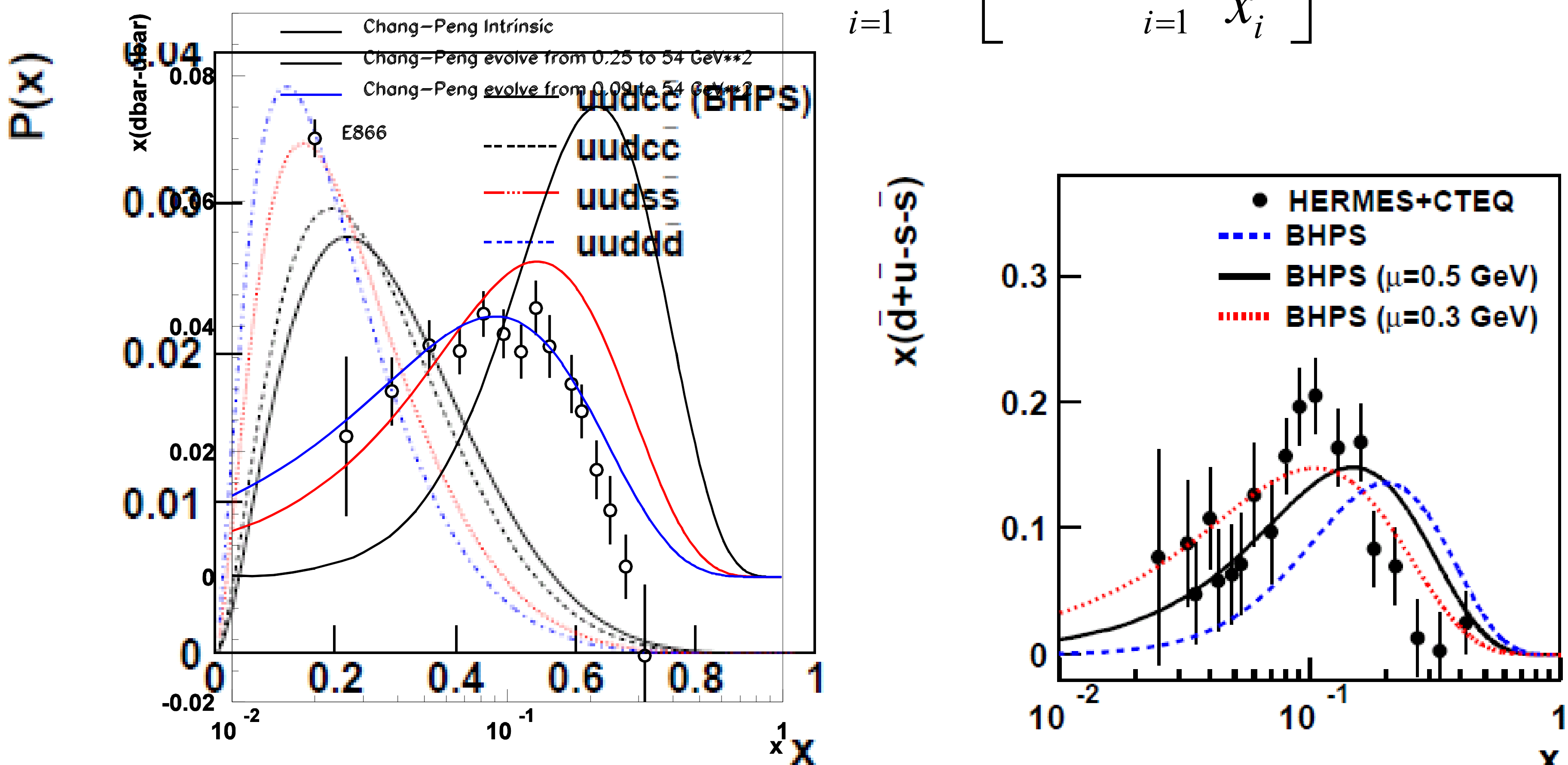
$$\bar{d}/\bar{u} = 1.67$$

at high x.

Intrinsic 5 quark Fock States

Chang and Peng (PRL **106**, 252002 (2011)) have shown that the Brodsky, Hoyer, Peterson and Sakai picture of 5 quark states developed for charm can, when evolve to scale of data explain the antiquark data. The BHPS ansatz is:

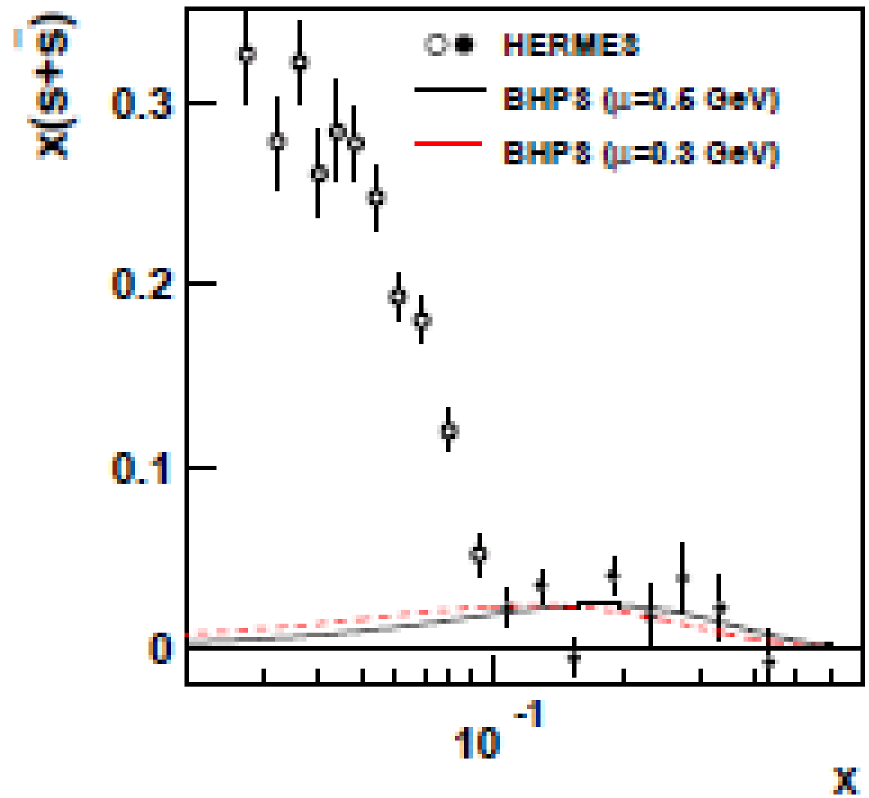
$$P(x_1,x_2,x_3,x_4,x_5) = N_5\delta(1-\sum_{i=1}^{5} x_i)\left[m_p^2 - \sum_{i=1}^{5}\frac{m_i^2}{x_i}\right]^{-2}$$



Including HERMES Data Chang and Peng can extract probabilities for each light 5 quark Fock state

arXiv:1105.2381v3

5 quark component	Data	Probability (Intrinsic scale 0.5 GeV)	Probability (Intrinsic scale 0.3 GeV
$uud s\bar{s}$	HERMES	0.024	0.029
$uud d\bar{d}$ – $uud u\bar{u}$	E866	0.118	0.118
$uud u\bar{u}$	E886+CTEQ HERMES	0.122	0.162
$uud d\bar{d}$	E886+CTEQ HERMES	0.240	0.280



Nuclear corrections in charged lepton and neutrino scattering are different

Schienbein et al.

Charged lepton Fe/D

Neutrino Fe/D

PARTON DISTRIBUTION FUNCTION NUCLEAR . . . PHYSICAL REVIEW D 80, 094004 (2009)

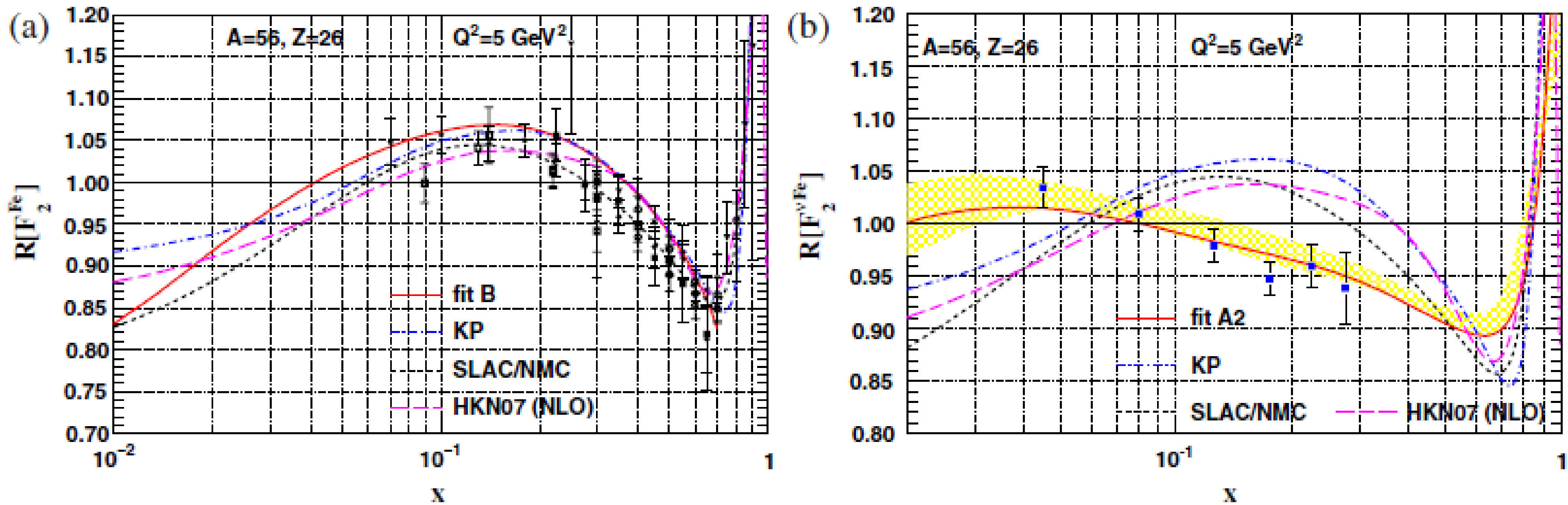


FIG. 4 (color online). The computed nuclear correction ratio, F_2^{Fe}/F_2^D, as a function of x for $Q^2 = 5\ \mathrm{GeV}^2$. (a) shows the fit (fit B) using charged-lepton-nucleus ($\ell^\pm A$) and DY data whereas (b) shows the fit using neutrino-nucleus (νA) data (fit A2 from Ref. [33]). Both fits are compared with the SLAC/NMC parametrization, as well as fits from Kulagin-Petti (KP) (Ref. [31,32]) and Hirai *et al.* (HKN07), (Ref. [15]). The data points displayed in (a) are the same as in Fig. 1 and those displayed in (b) come from the NuTeV experiment [53,54].

F2(Fe from neutrinos)/F2(D determined w/o neutrino data)

The Effective Strong Coupling Constant at low Q^2

Deur et al., PLB 665, 349 (2008)

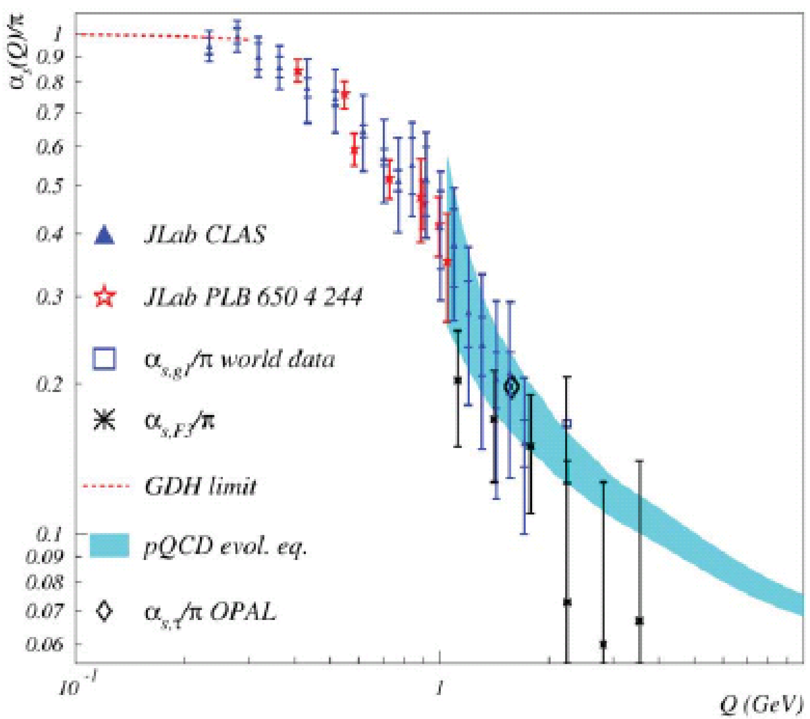


Fig. 1. (Color online.) $\alpha_{s,g_1}(Q)/\pi$ obtained from JLab (triangles and open stars) and world (open square) data on the Bjorken sum. Also shown are $\alpha_{s,\tau}(Q)/\pi$ from OPAL data, the GLS sum result from the CCFR Collaboration (stars) and $\alpha_{s,g_1}(Q)/\pi$ from the Bjorken (band) and GDH (dashed line) sum rules.

Follows ideas of Brodsky et al. to define effective QCD couplings that are well behaved in the infrared – relations between physical observables cannot depend on scale.

Use the QCD corrections to Bjorken Sum Rule to measure the strong coupling constant:

In first order

$$\Gamma_p(Q^2) - \Gamma_n(Q^2) = -\frac{g_A}{6}\left(1 - \frac{\alpha_s(Q^2)}{\pi}\right)$$

But be careful in applying this.
Ignores higher twist.
Other perturbative expansions not protected by Crewther relations have different higher order coefficients