Flavor Structure of the Nucleon Sea

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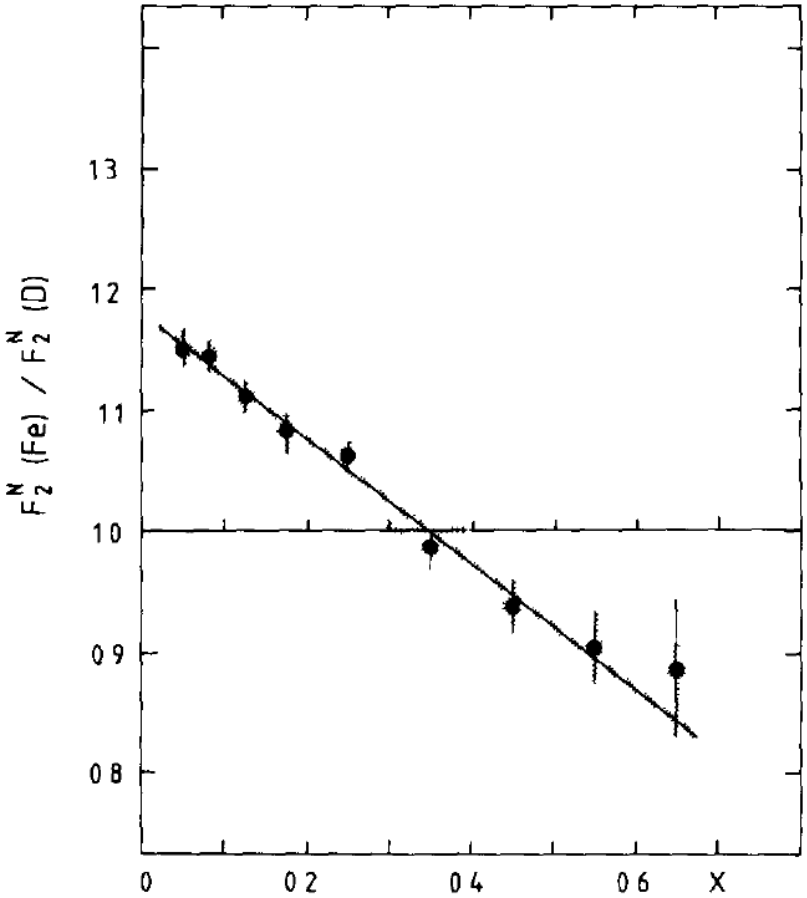
Nuclear Physics Symposium: Exploring the Heart of Matter
Chicago, September 26-27, 2014

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



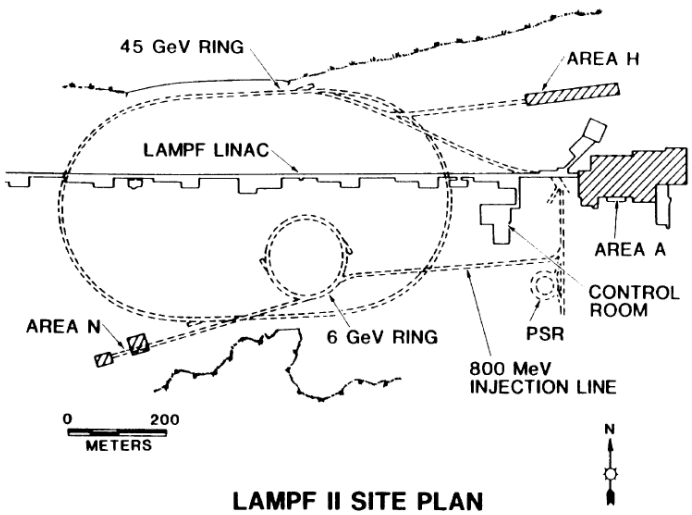
EMC Effect

- First evidence for modification of quark structures in nuclei
- Many theoretical models waiting to be tested
- Enhancement of meson cloud in nuclei?

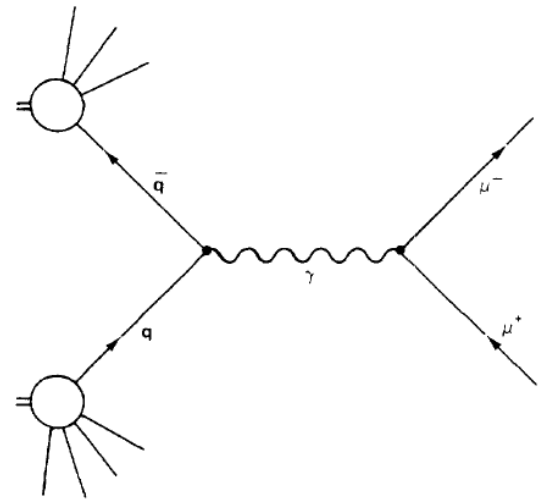
Los Alamos Meson Physics Facility (LAMPF)

LAMPF II and the High-Intensity Frontier

by Henry A. Thiessen



LAMPF II SITE PLAN



The choice of energy and current deserves some attention. The physics needs are for high-current beams of neutrinos, kaons, and perhaps antiprotons. The nuclear physics community is particularly interested in high energy secondary beams for Drell-Yan experiments on nuclei. These high energy beams should be at least 30 GeV, and higher energies are desirable.

VOLUME 53, NUMBER 27 PHYSICAL REVIEW LETTERS 31 DECEMBER 1984

Disentangling Explanations of Deep-Inelastic Lepton-Nucleus Scattering by Lepton-Pair Production

R. P. Bickerstaff, M. C. Birse, and G. A. Miller
Institute for Nuclear Theory, Department of Physics, University of Washington, Seattle, Washington 98195
(Received 18 June 1984)

Fe/D Ratio in DIS

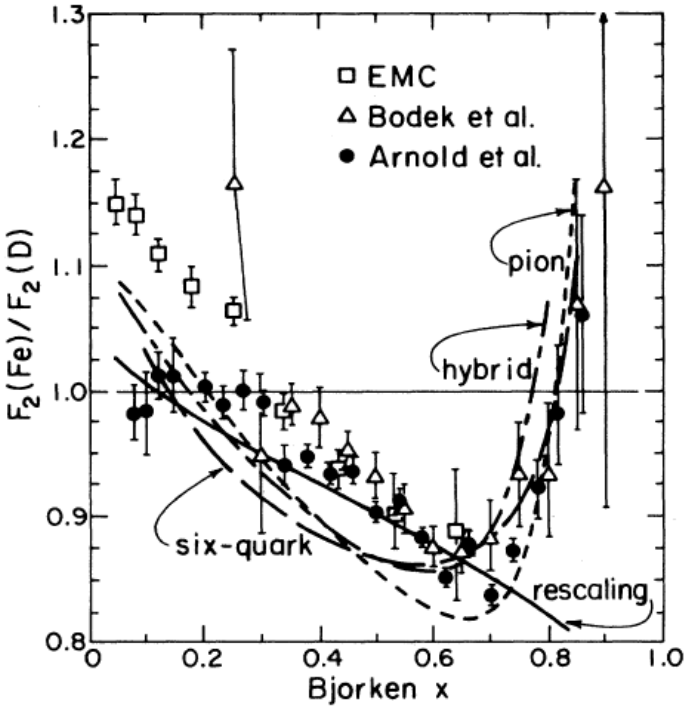


FIG. 1. Ratio of the structure function per nucleon, $F_2^A(x)/A$, for Fe to that for D. The experimental points assume $R = \sigma_L/\sigma_T$ is constant.

Fe/D Ratio in Drell-Yan

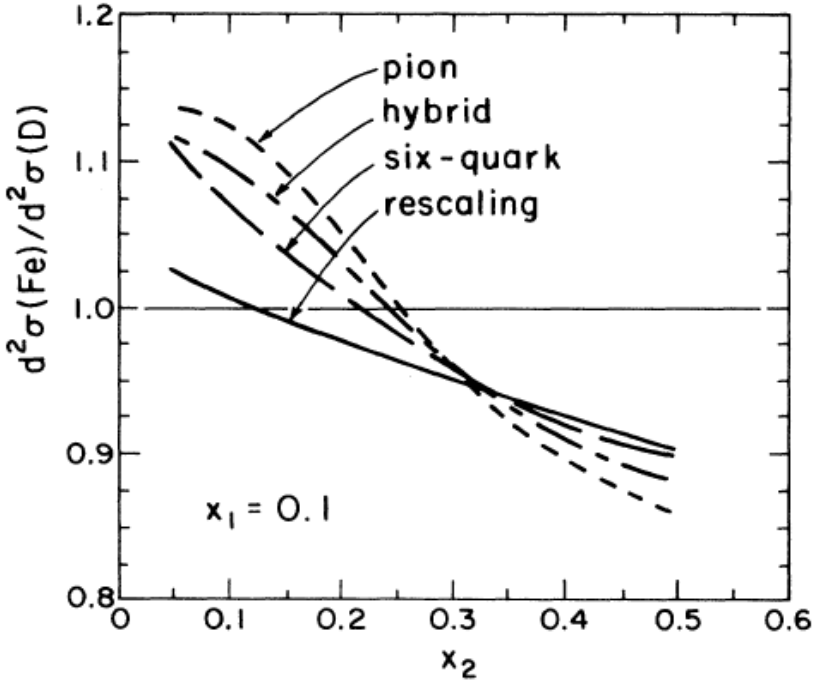
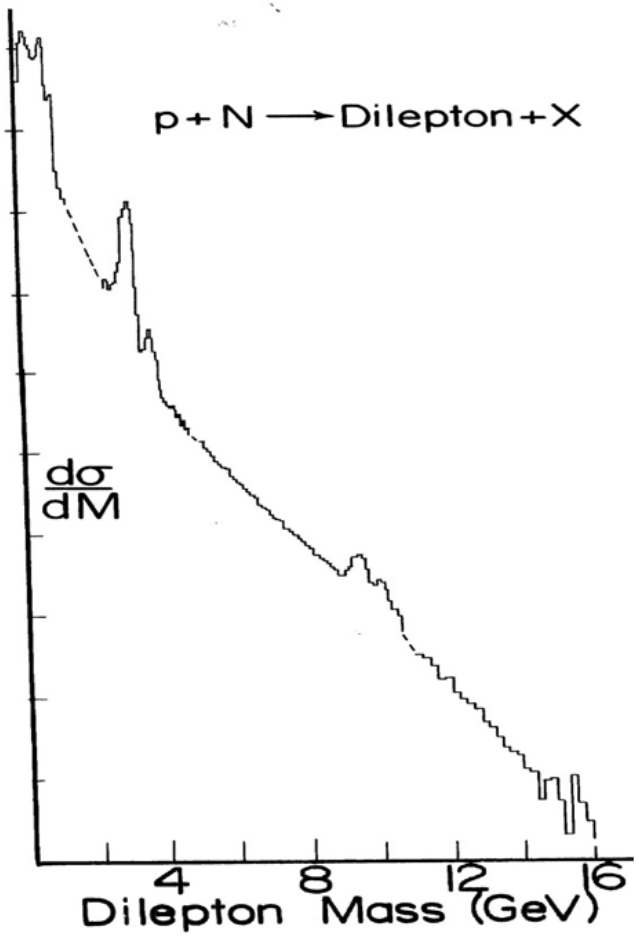


FIG. 2. Ratio of the Drell-Yan differential cross section for Fe to that for D, as a function of x_2, at $x_1 = 0.1$.

Visit of Chuck Brown to LANL in 1986

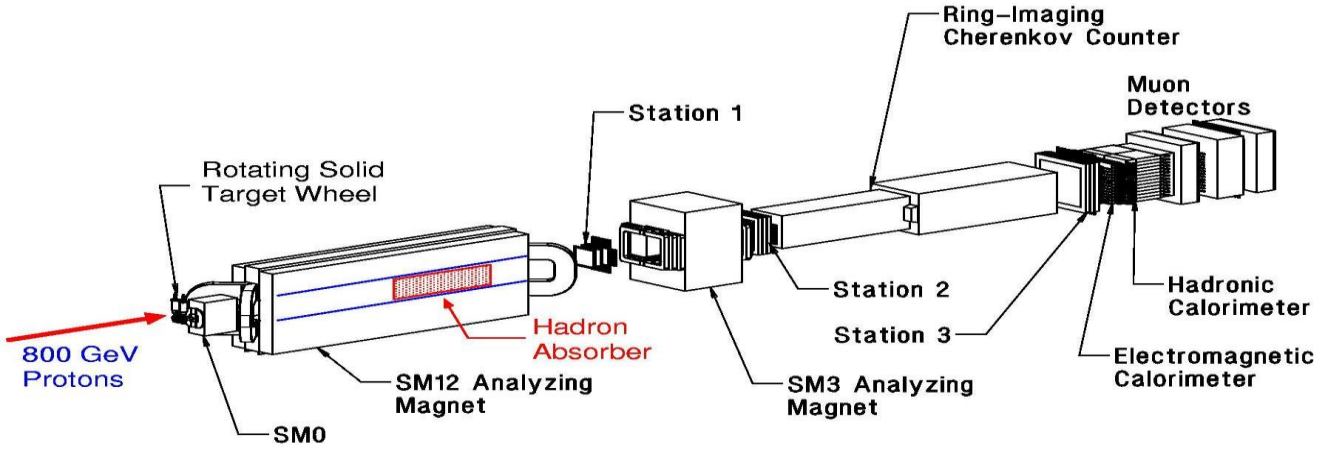
Upsilon's muon spectrometers in P-Center experimental pit

Fig. 1. Schematic yield of dilepton pairs in 400 GeV proton-nucleus collisions (from CFS and Chicago-Princeton data at FNAL).



Fermilab Dimuon Spectrometer

(E605 / 772 / 789 / 866 / 906)



1) Fermilab E772 (proposed in 1986 and completed in 1988)

"Nuclear Dependence of Drell-Yan and Quarkonium Production"

2) Fermilab E789 (proposed in 1989 and completed in 1991)

"Search for Two-Body Decays of Heavy Quark Mesons"

3) Fermilab E866 (proposed in 1993 and completed in 1996)

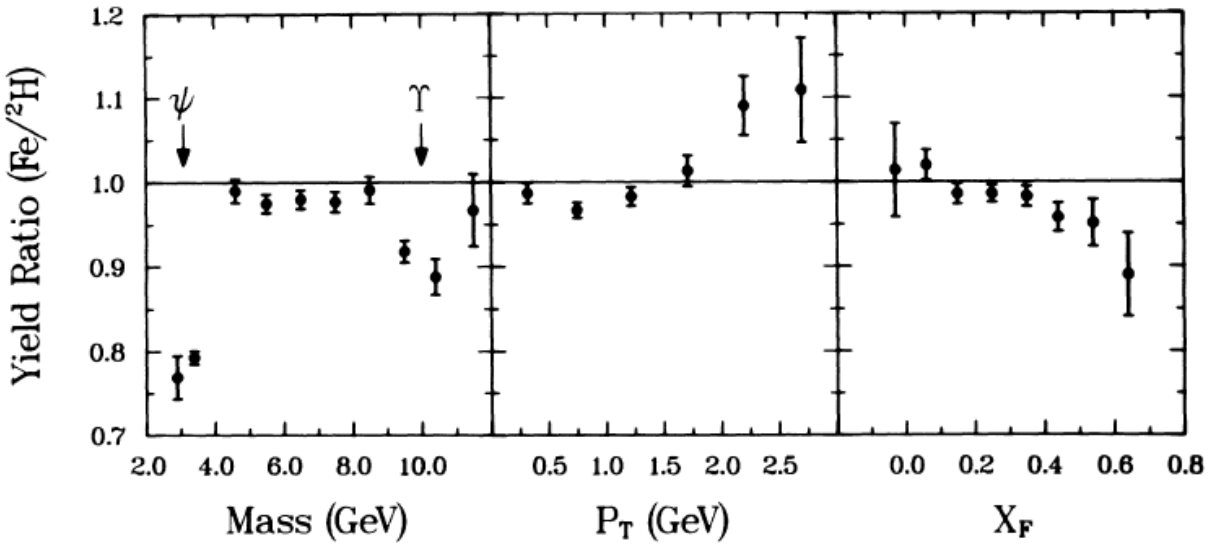
"Determination of $\bar{d}$ / $\bar{u}$ Ratio of the Proton via Drell-Yan"

4) Fermilab E906 (proposed in 1999, currently running)

"Drell-Yan with the FNAL Main Injector"

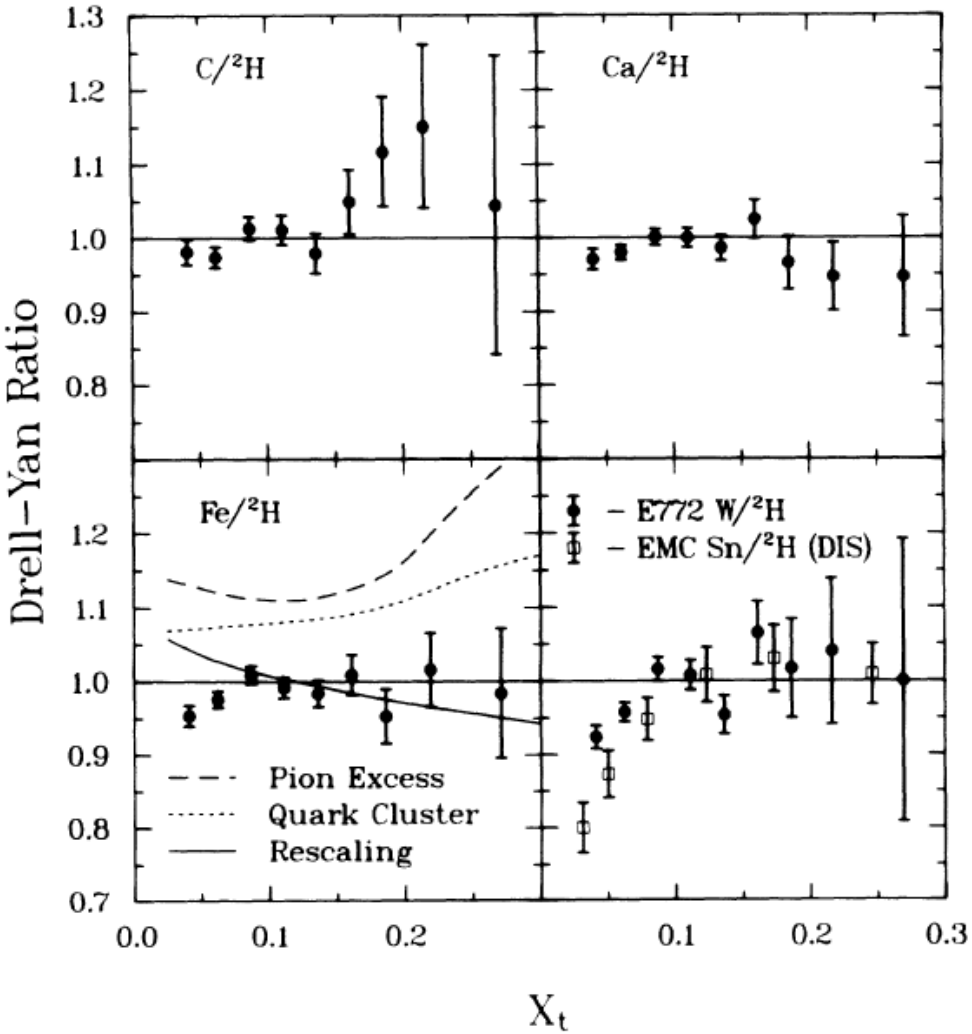
EXPERIMENT E789- Moving Cable at Meson.
"The Snake".

Nuclear Dependence of Dimuon Production at 800 GeV



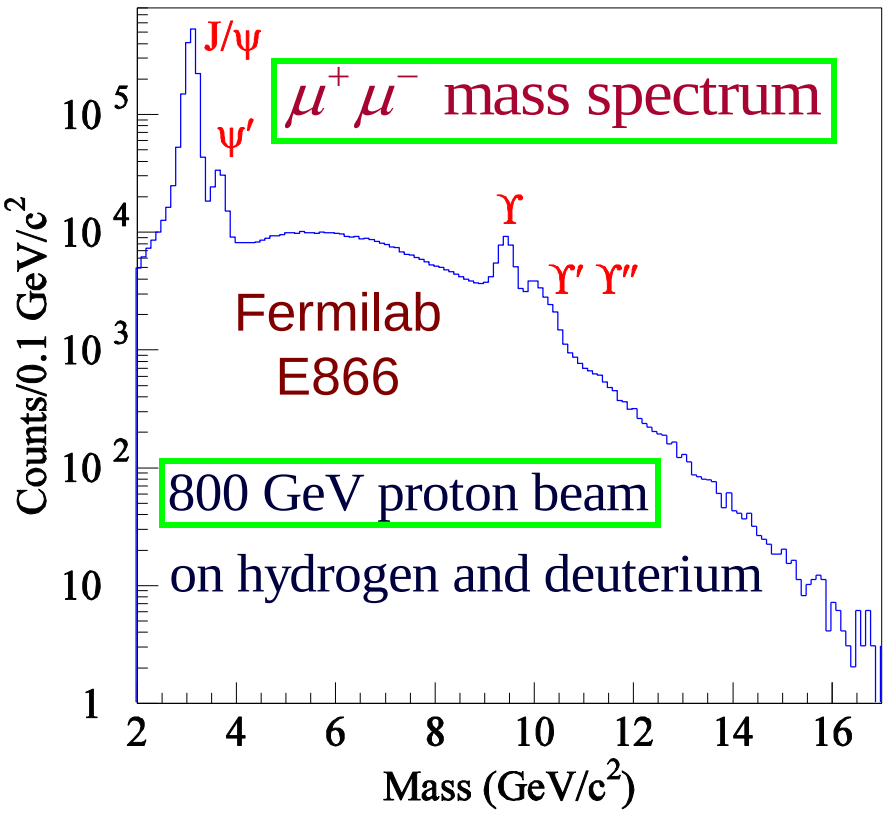
- Nuclear effects are relatively small for Drell-Yan, but much larger for J/ψ and ϒ resonances
- Nuclear effects for Drell-Yan have some p_T and x_F dependencies

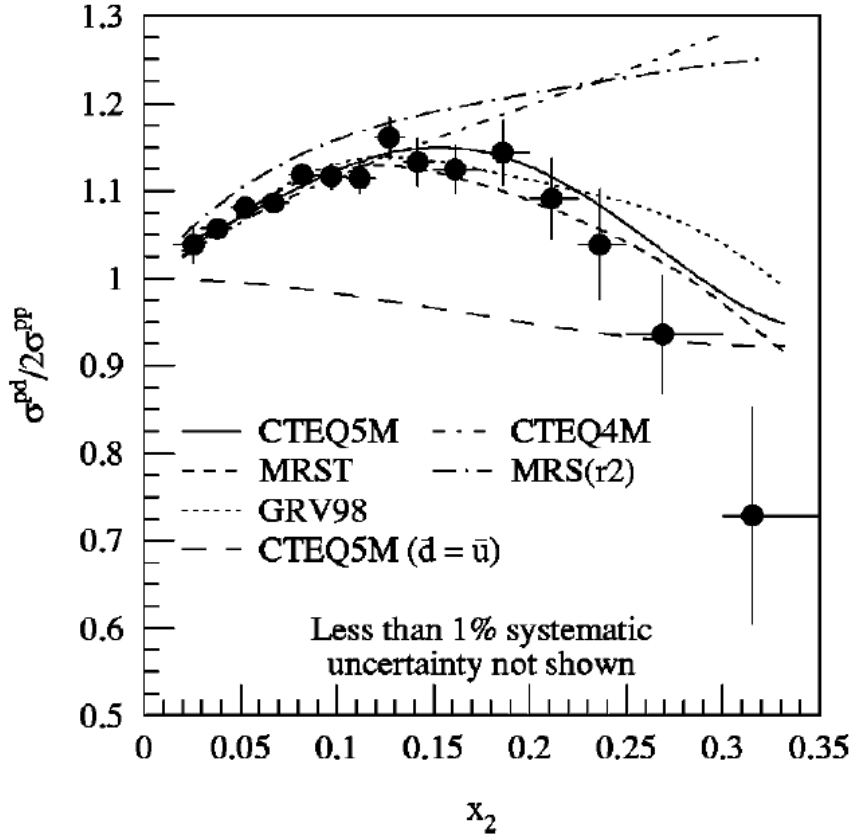
Nuclear Dependence of Dimuon Production at 800 GeV



- No evidence of enhancement of pion contents in nuclei!
- A surprisingly small difference between p+A and p+d Drell-Yan.
- (p+d)/(p+p) ratio was not measured.

A surprisingly large difference between p+p and p+d Drell-Yan

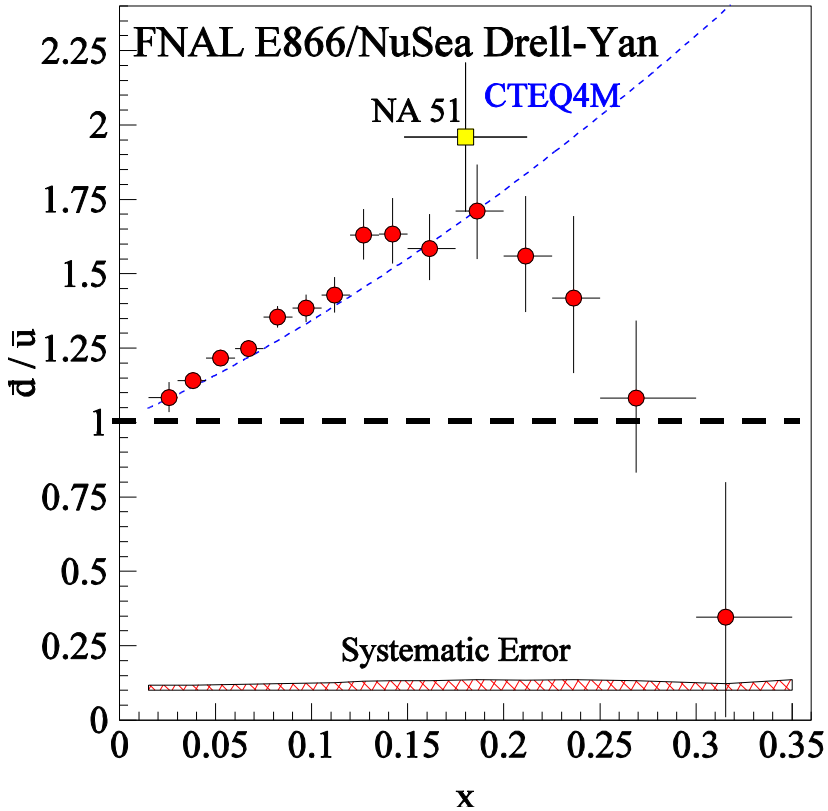




Drell-Yan: $\sigma^{pd} / 2\sigma^{pp} \sim \frac{1}{2}(1+\bar{d}(x_2)/\bar{u}(x_2))$

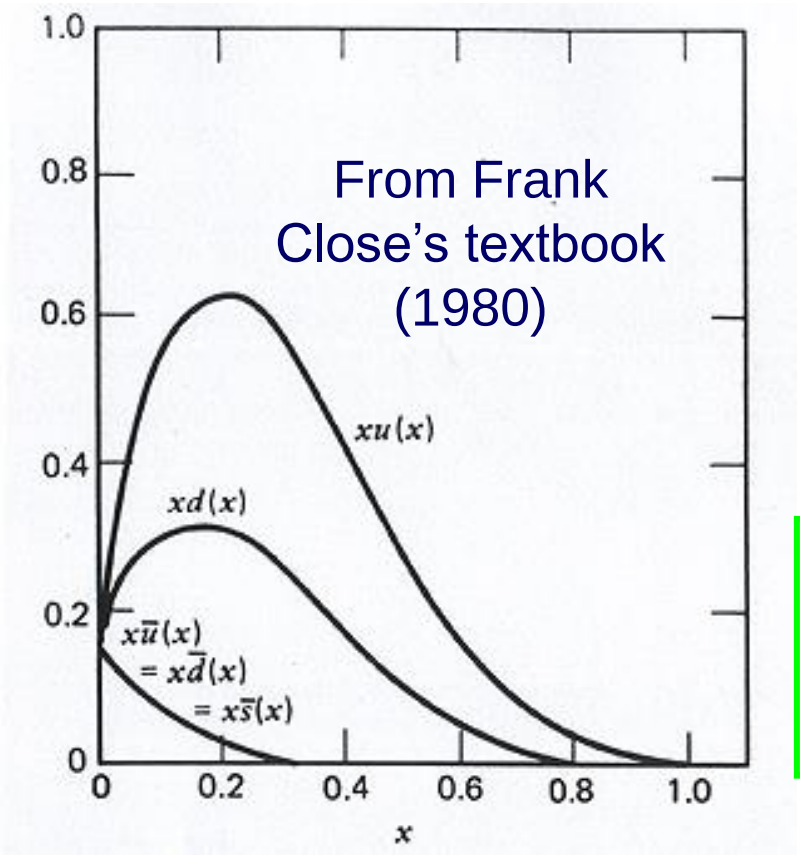
$\bar{d}/\bar{u}$ flavor asymmetry from Drell-Yan

$$\left(\frac{d^2\sigma}{dx_1 dx_2}\right)_{D.Y.} = \frac{4\pi\alpha^2}{9sx_1x_2}\sum_a e_a^2\left[q_a(x_1)\bar{q}_a(x_2)+\bar{q}_a(x_1)q_a(x_2)\right]$$



Drell-Yan: $\sigma^{pd}/2\sigma^{pp} \sim \frac{1}{2}(1+\bar{d}(x_2)/\bar{u}(x_2))$

Proton's sea might have a rich flavor structure



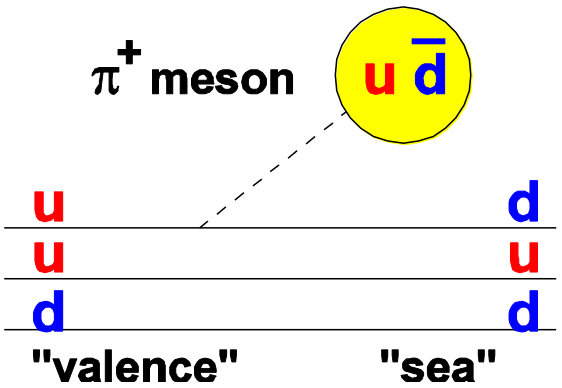
$$\bar{u}(x) = \bar{d}(x) = \bar{s}(x) = s(x)$$

$SU(3)$ symmetric sea

Expect $\bar{u} = \bar{d} = \bar{s}$ if sea quarks are produced in $g \to q\bar{q}$

Some Theoretical Models for $\bar{d}$ / $\bar{u}$ Asymmetry

Meson Cloud Models



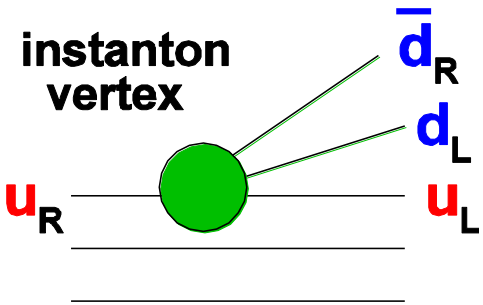
Chiral-Quark Soliton Model

nucleon = chiral soliton

expand in 1/*Nc*

Quark degrees of freedom in a pion mean-field

Instantons



<u>Meson cloud has significant contributions to sea-quark distributions</u>

These models also have specific predictions on

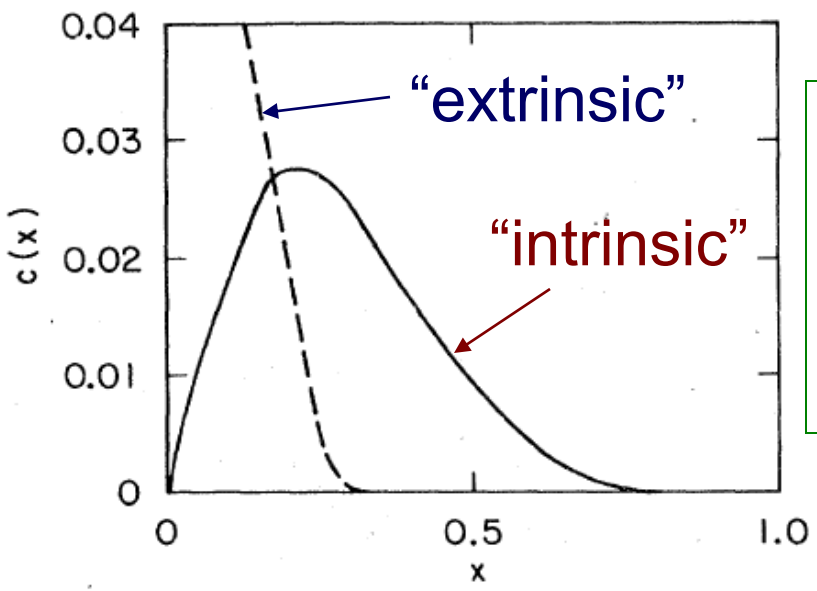
- Asymmetry between $s(x)$ and $\bar{s}(x)$
- Asymmetry between $\Delta\bar{u}(x)$ and $\Delta\bar{d}(x)$

Search for the "intrinsic" quark sea

In 1980, Brodsky, Hoyer, Peterson, Sakai (BHPS) suggested the existence of "intrinsic" charm

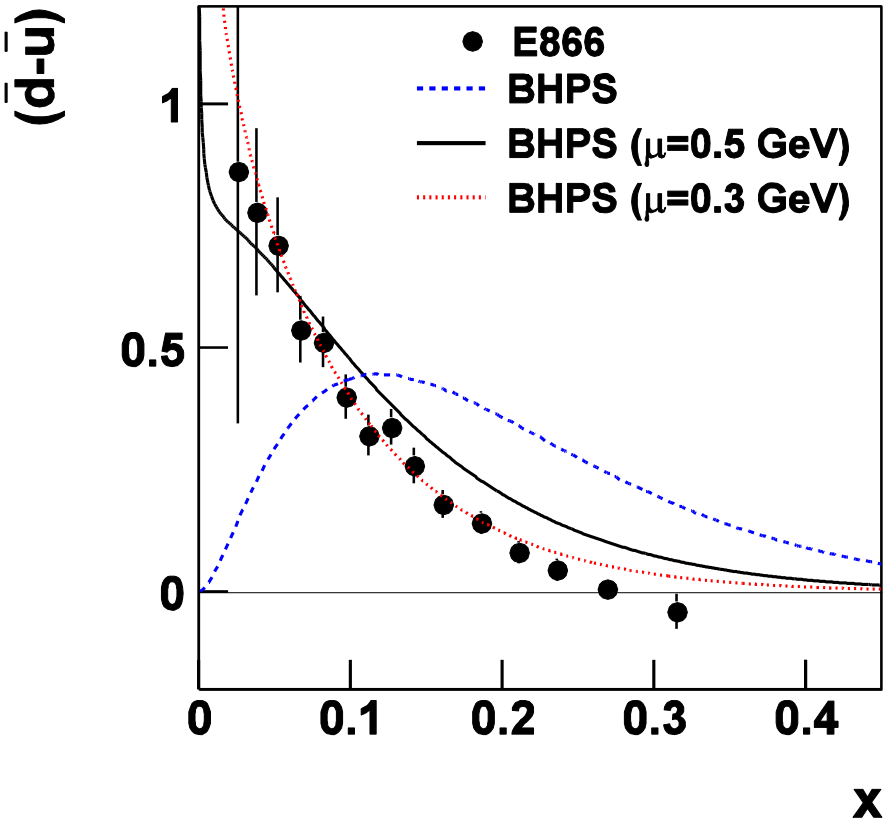
$$|p\rangle = P_{3q}\,|uud\rangle + P_{5q}\,|uudQ\bar{Q}\rangle + \cdots\cdots$$

The "intrinsic"-charm from $|uudc\bar{c}\rangle$ is "valence"-like and peak at large x unlike the "extrinsic" sea ($g \to c\bar{c}$)



The "intrinsic charm" in $|uudc\bar{c}\rangle$ can lead to large contribution to charm production at large x

Comparison between the $\bar{d}(x)-\bar{u}(x)$ data with the intrinsic 5-q model



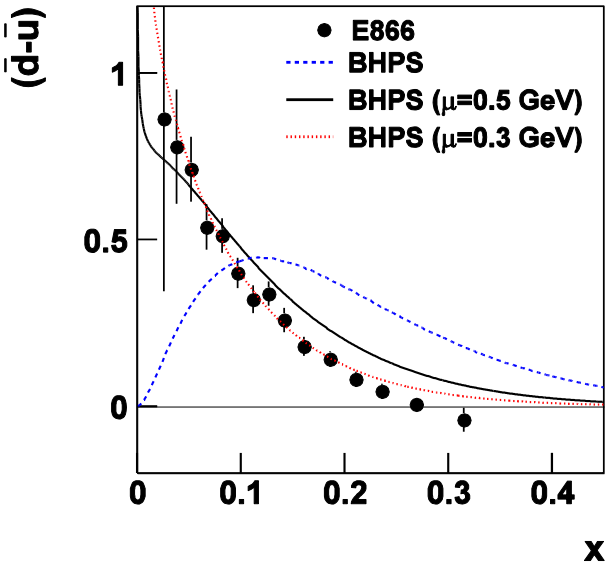
(W. Chang and JCP , PRL 106, 252002 (2011))

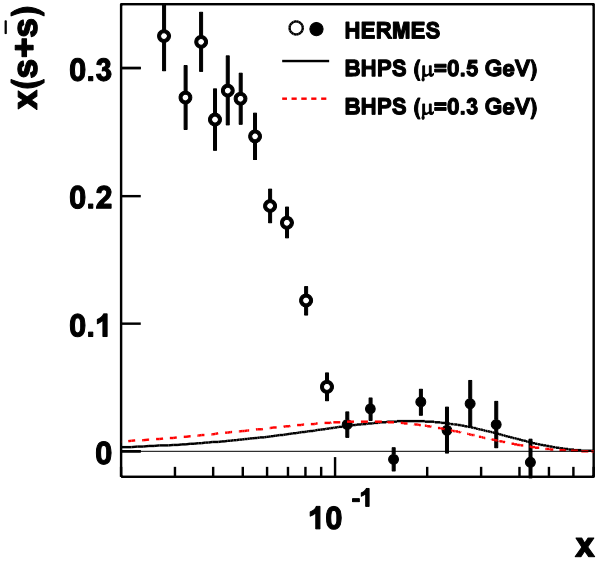
The data are in good agreement with the 5-q model after evolution from the initial scale μ to Q^2=54 GeV^2

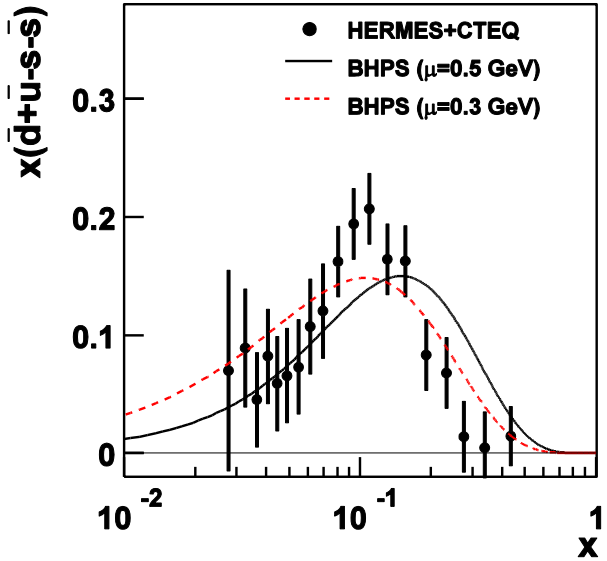
The difference in the two 5-quark components can also be determined

$$P_5^{uudd\bar{d}} - P_5^{uudu\bar{u}} = 0.118$$

Extraction of the various five-quark components for light quarks







$$P_5^{uudd\bar{d}} - P_5^{uudu\bar{u}} = 0.118$$

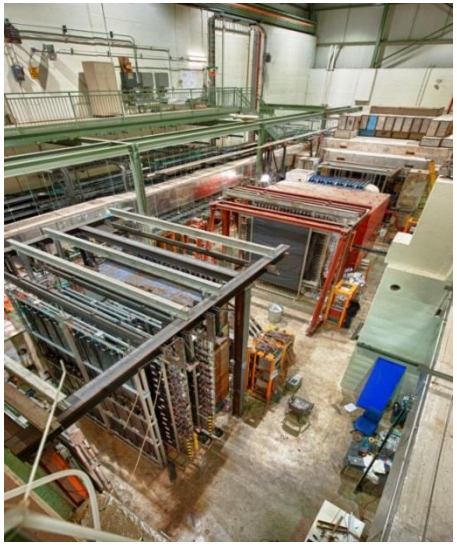
$$P_5^{uuds\bar{s}} = 0.024$$

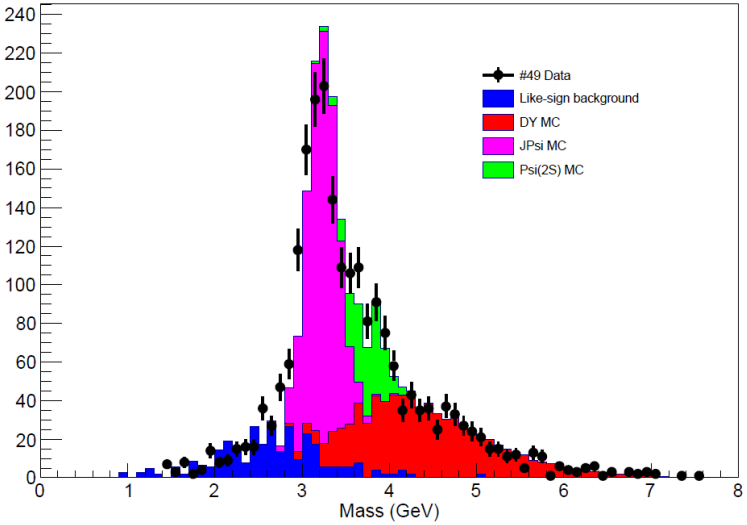
$$P_5^{uudu\bar{u}} + P_5^{uudd\bar{d}} - 2P_5^{uuds\bar{s}} = 0.314$$

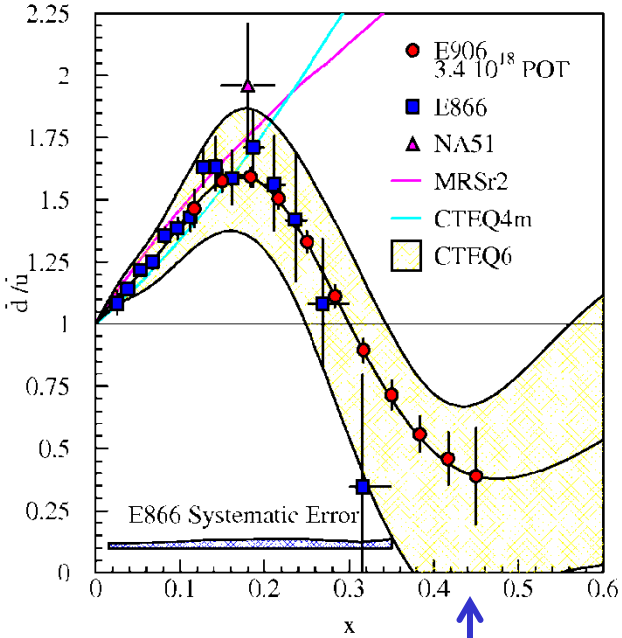
$$\boxed{P_5^{uudd\bar{d}} = 0.240;\ P_5^{uudu\bar{u}} = 0.122;\ P_5^{uuds\bar{s}} = 0.024}$$

Is there a sign-reversal for $\bar{d}(x) - \bar{u}(x)$ at large x?

SeaQuest Experiment (Unpolarized Drell-Yan using 120 GeV proton beam)





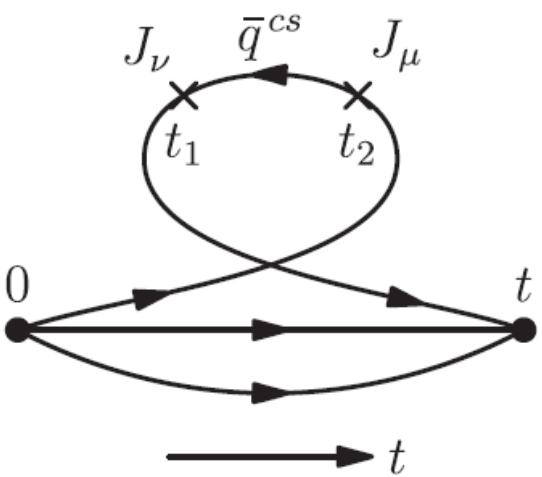


Main goals: 1) Measure $\bar{d}/\bar{u}$ flavor asymmetry up to $x \sim 0.45$

2) Measure EMC effect of antiquarks up to $x \sim 0.45$

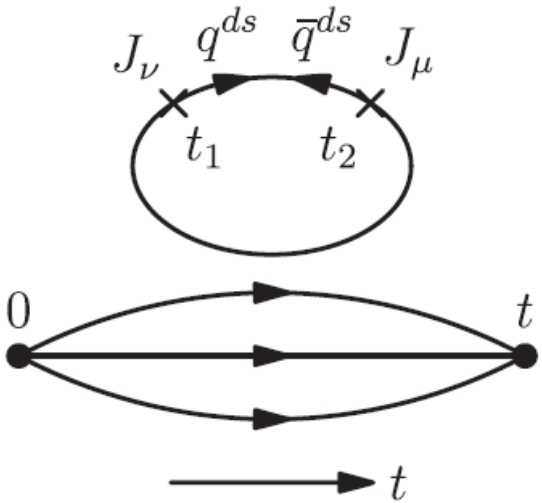
What mechanism could lead to $\bar{u} > \bar{d}$ at $x > 0.25$?

Connected sea



(valence-like)

Disconnected sea



(sea-like)

$\bar{u}(x) \neq \bar{d}(x)$ can only come from connected sea (CS)

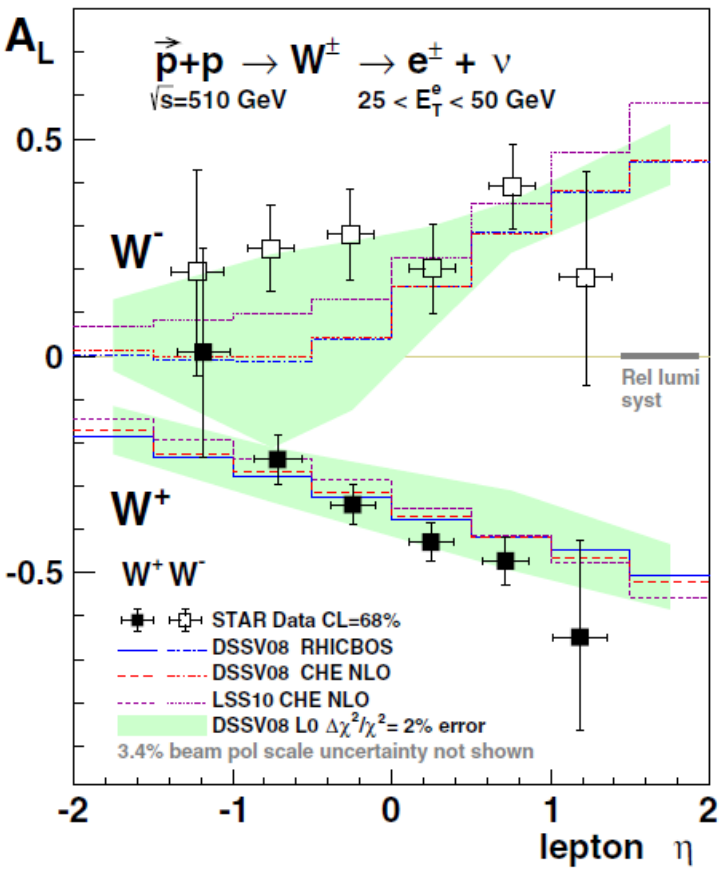
$(u \to \bar{u} + u + u,\ d \to \bar{d} + d + d)$ ($\bar{q}$ has the same flavor as q for CS)

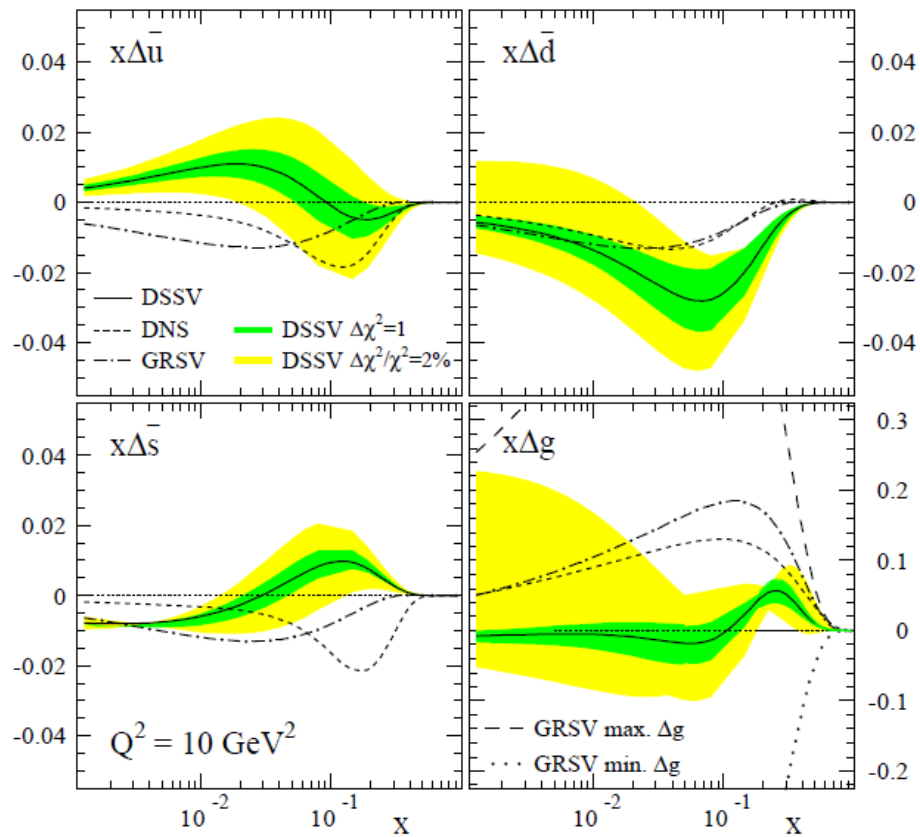
$\Rightarrow$ Connected sea could lead to $\bar{u} > \bar{d}$ at certain x region??

(since there are two u valence quarks and one d valence quak)

Is the sea-quark polarization flavor symmetric?

W production at RHIC clearly shows $\Delta\bar{u}(x)/\Delta\bar{d}(x)$ asymmetry





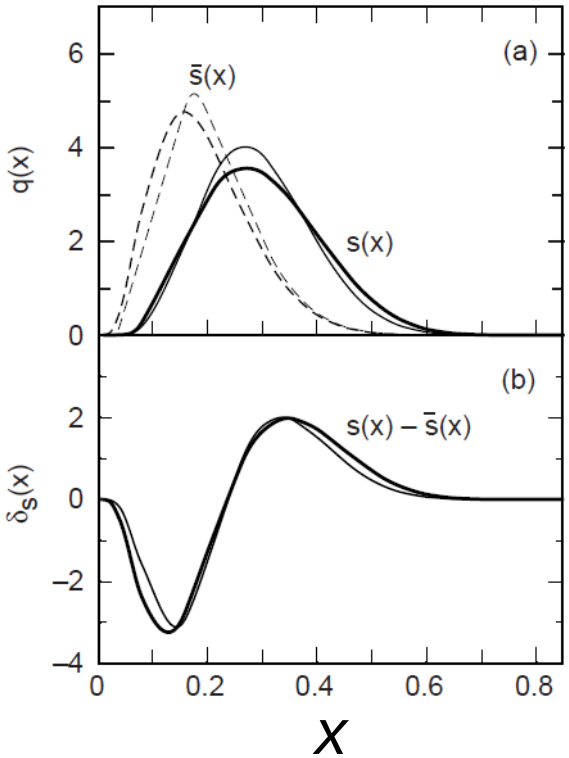
Data show $\Delta\bar{u}(x) > 0$ and $\Delta\bar{d}(x) < 0$ in agreement with chiral soliton model

Is $s(x) = \bar{s}(x)$?

Meson cloud model

$p \to K^+ \Lambda$

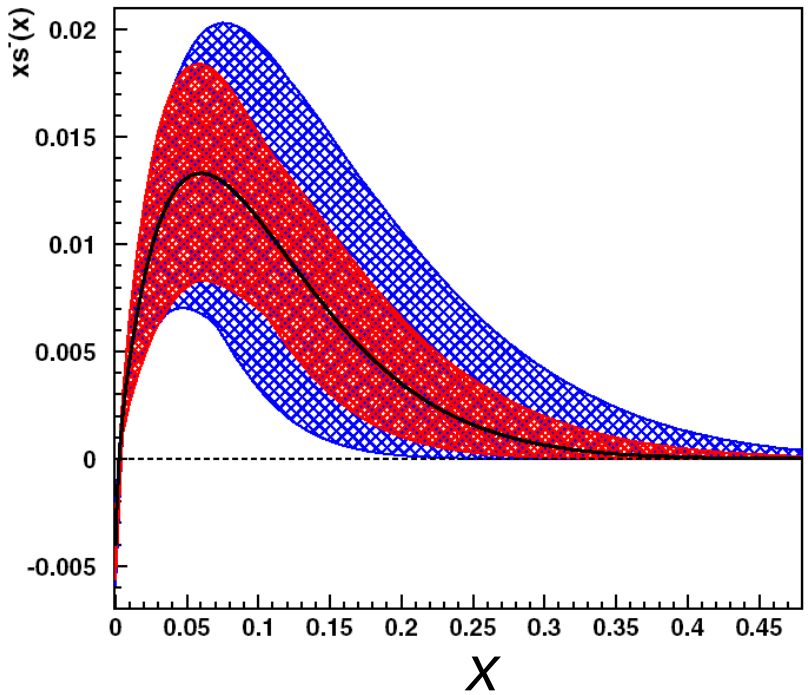
$(u\bar{s})(uds)$



Thomas / Brodsky and Ma

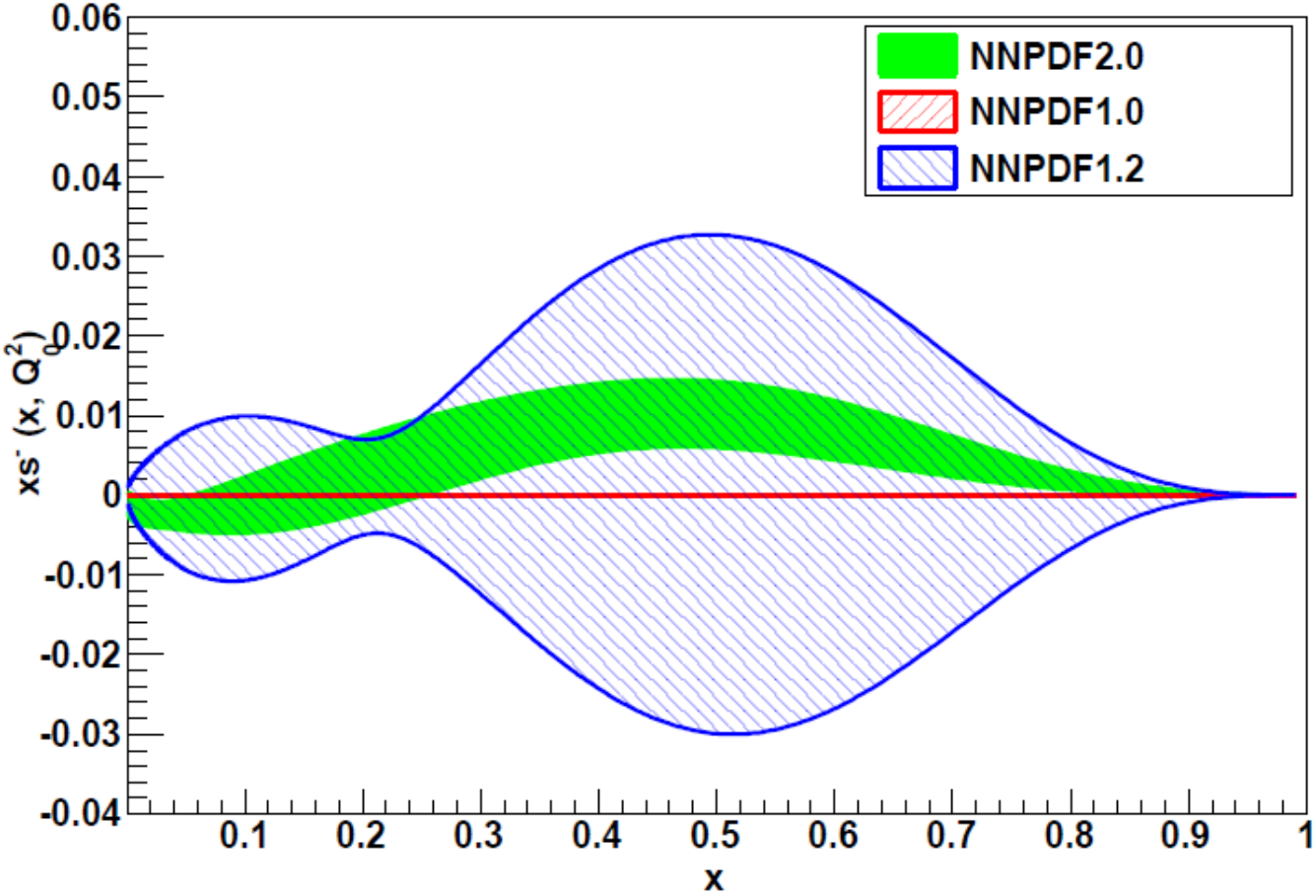
Analysis of neutrino DIS data

$x(s - \bar{s})$



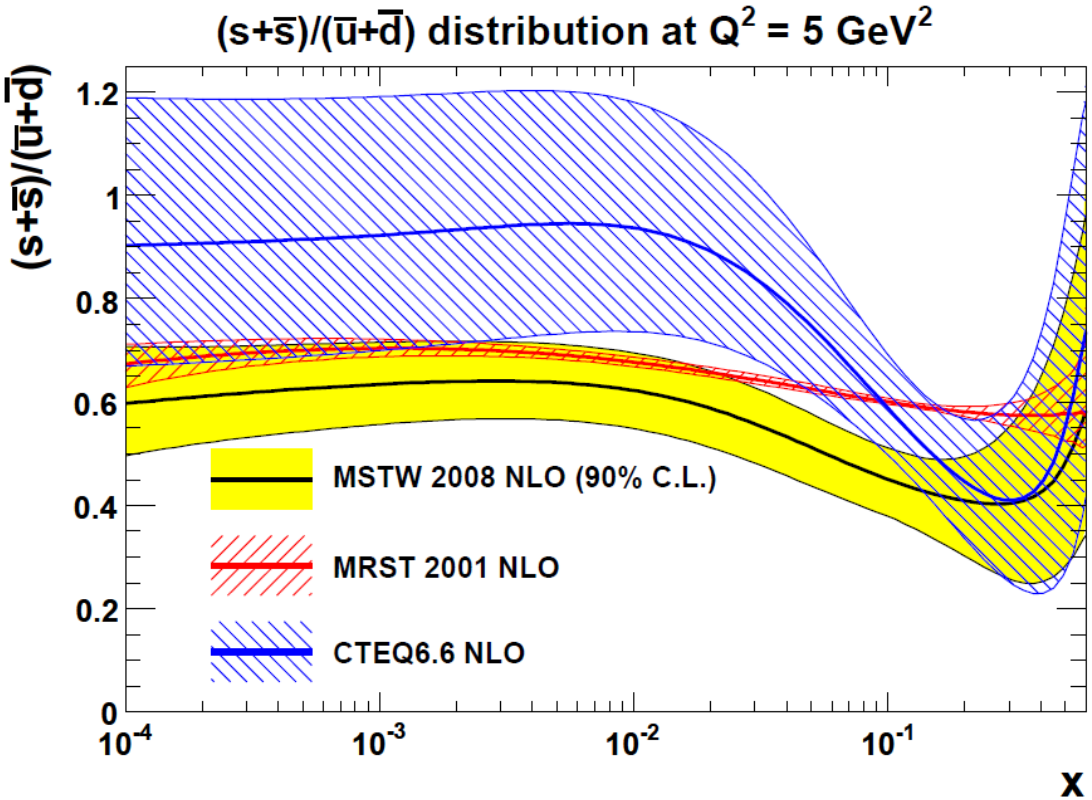
NuTeV, PRL 99 (2007) 192001

$s(x) - \bar{s}(x)$ from NNPDF global fits



NNPDF2.0 analysis includes fixed-target Drell-Yan and Tevatron W and Z data

What is the x-dependence of $[s(x)+\bar{s}(x)]/[\bar{u}(x)+\bar{d}(x)]$?



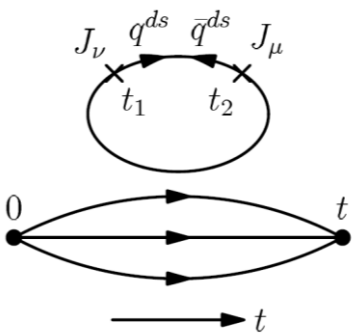
- CTEQ6.6 suggests an SU(3) symmetric sea at small x?
- A strong $x-$dependence for the $[s(x)+\bar{s}(x)]/[\bar{u}(x)+\bar{d}(x)]$ ratio?
- New kaon semi-inclusive DIS data at JLab 12 GeV and at EIC will be crucial

Flavor structure of nucleon sea is strongly x dependent

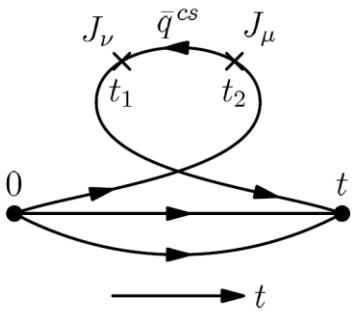
- Sea is roughly SU(3) symmetric at small x
- Sea is SU(3) asymmetric at large x

Can be understood from Lattice QCD (PRL 109 (2012)252002)

Disconnected sea



Connected sea



Generate roughly symmetric $s(x), \bar{s}(x), \bar{u}(x)$ and $\bar{d}(x)$ at small x

Generate additional "valence-like" $\bar{u}(x)$ and $\bar{d}(x)$ (no $\bar{s}(x)$) at larger x

Three parton distributions describing transverse momentum and/or transverse spin

Three transverse quantities:

1) Nucleon transverse spin

$\vec{S}_\perp^N$

2) Quark transverse spin

$\vec{s}_\perp^q$

3) Quark transverse momentum

$\vec{k}_\perp^q$

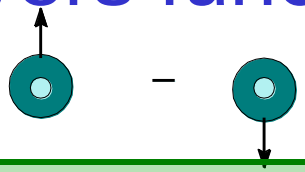
$\Rightarrow$ Three different correlations

1) Transversity

$h_{1T} =$

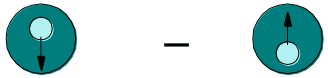
Correlation between $\vec{s}_\perp^q$ and $\vec{S}_\perp^N$

2) Sivers function

$f_{1T}^\perp =$ 

Correlation between $\vec{S}_\perp^N$ and $\vec{k}_\perp^q$

3) Boer-Mulders function

$h_1^\perp =$ 

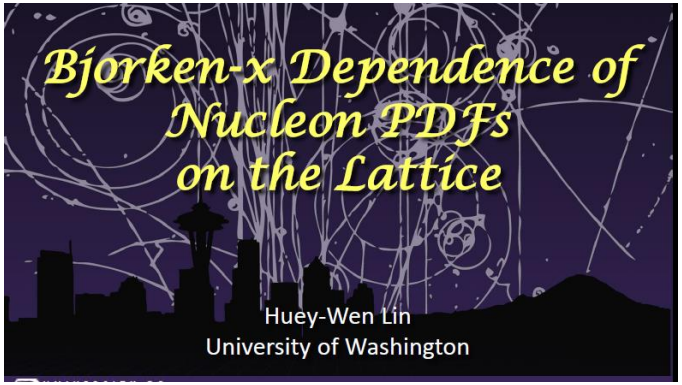
Correlation between $\vec{s}_\perp^q$ and $\vec{k}_\perp^q$

Recent progress in LQCD suggests the possibility to calculate the *x*-dependence of parton distributions

PRL **110**, 262002 (2013) PHYSICAL REVIEW LETTERS week ending 28 JUNE 2013

Parton Physics on a Euclidean Lattice

Xiangdong Ji[1,2]



Transversity Distribution

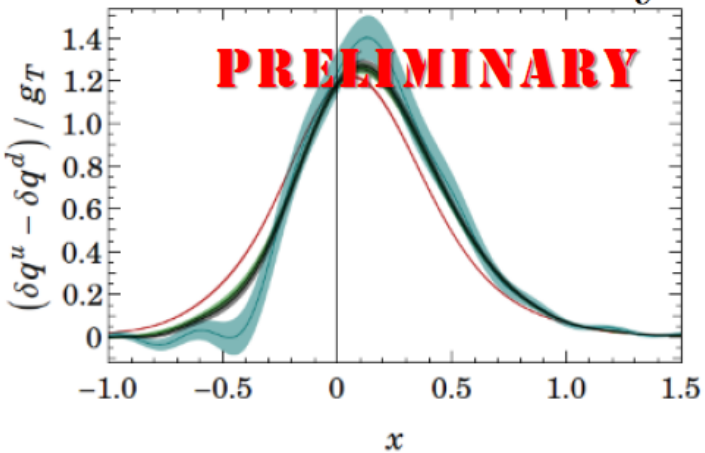
§ Exploratory study

- We found $\delta\bar{u} < \delta\bar{d}$ with large sea asymmetry
- Chiral quark-soliton model

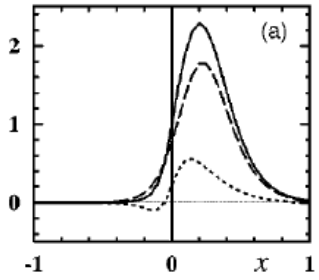
$$\int dx \, \frac{\delta\bar{u}(x) - \delta\bar{d}(x)}{g_T} \approx -0.320\,(18)$$

$$\int dx \left(\delta\bar{u}(x) - \delta\bar{d}(x)\right) \approx -0.082$$

B. Dressler et al., hep-ph/9809487



CQS model



P. Schweitzer et al. PRD 64, 034013 (2001)

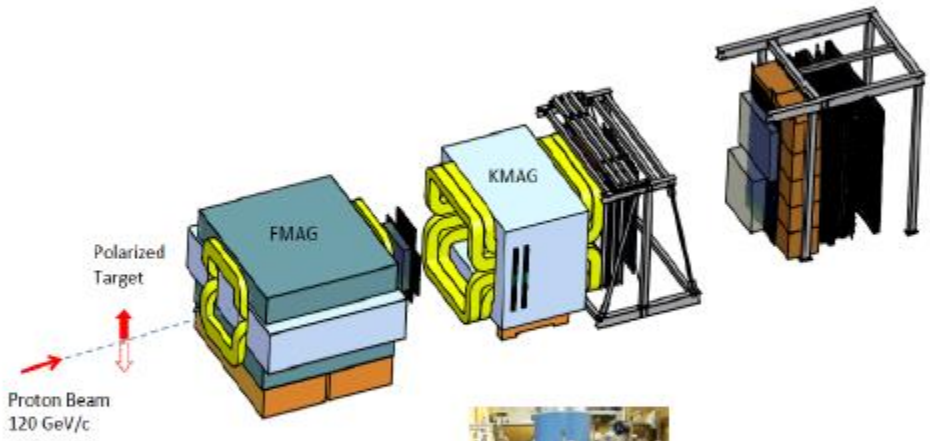
The *x*-dependence of the quark and antiquark transversity distributions can be calculated (not just their moments)

Predicts large sea-quark transversity!

Another proposal to measure sea-quark Sivers function in polarized Drell-Yan at Fermilab

P-1039 Collaboration:

Co-Spokespersons: A. Klein, X. Jiang
Los Alamos National Laboratory



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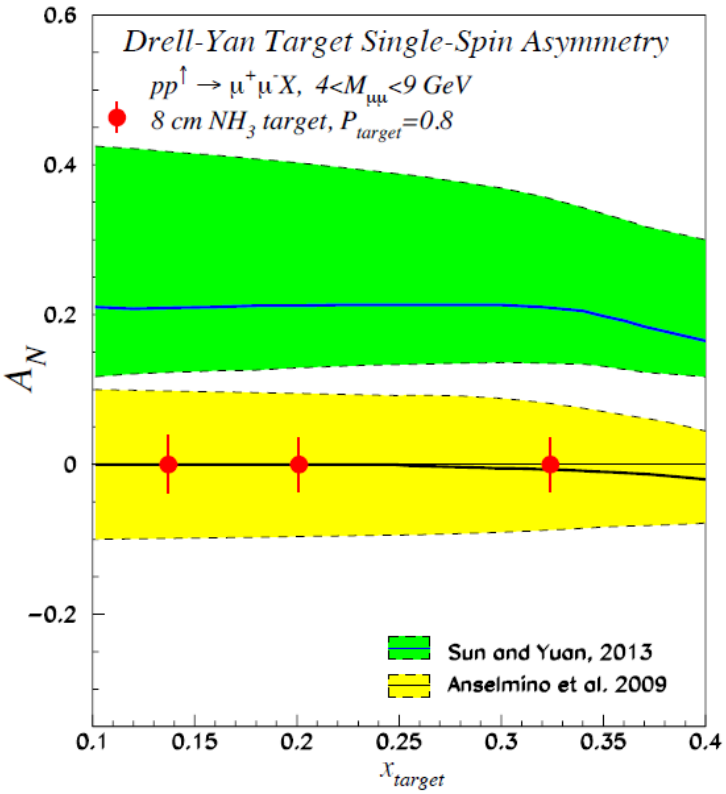


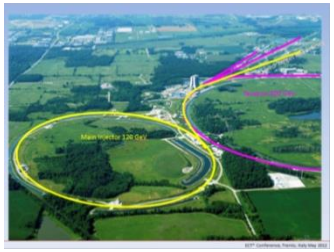
Statistics shown for one calendar year of running :
$\mathcal{L}$ = 1.4 *10^{43} /cm^2 ←→ POT = 2.1*10^{18}

Request for two calendar years of beam time

Global interest in polarized Drell-Yan measurements

- Fermilab (proton beam, unpolarized, polarized beam/target possible)
- COMPASS (pion beam, polarized target)
- FAIR (polarized antiproton beam)
- RHIC (polarized proton beam)
- J-PARC (proton beam, polarzied beam possible)
- JINR NICA (proton beam)

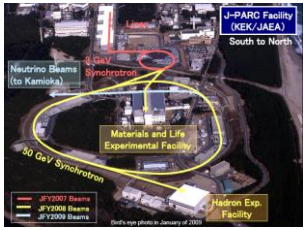
Fermilab



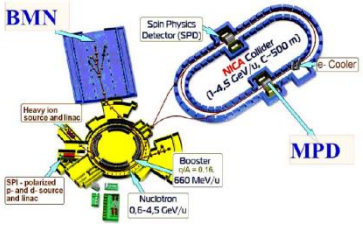
COMPASS

RHIC

J-PARC



NICA



More surprises in the nucleon sea are waiting for us?