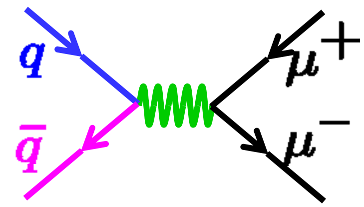
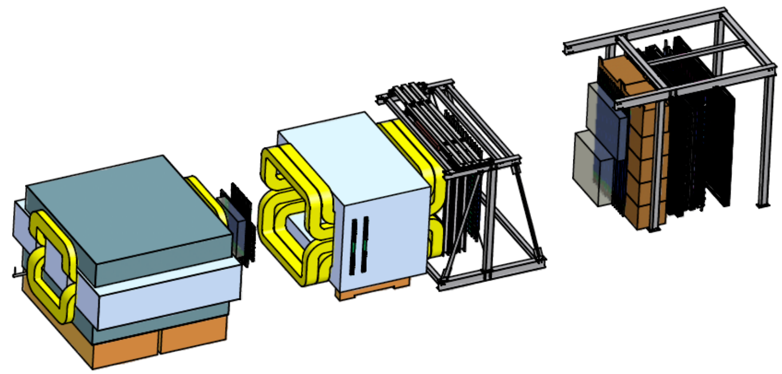
Drell-Yan Scattering at Fermilab:
SeaQuest and Beyond



Wolfgang Lorenzon
University of Michigan

(1-November-2010)
Santa Fe Drell-Yan Workshop

- **Introduction**
- **SeaQuest: Fermilab Experiment E906**
  - ➡ What will we learn?
  - ➡ What will we measure?
  - ➡ How will we measure it?

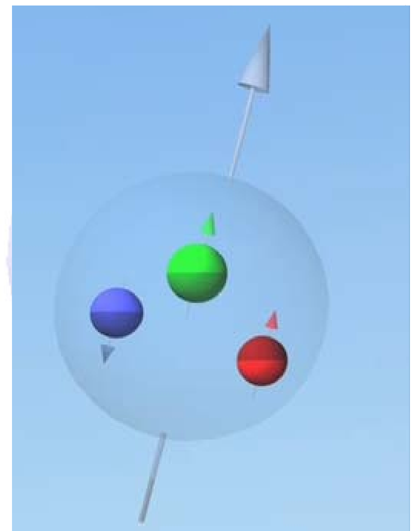


- **Beyond SeaQuest**
  - ➡ Polarized Drell-Yan at FNAL?
  - ➡ What would we learn?

This work is supported by

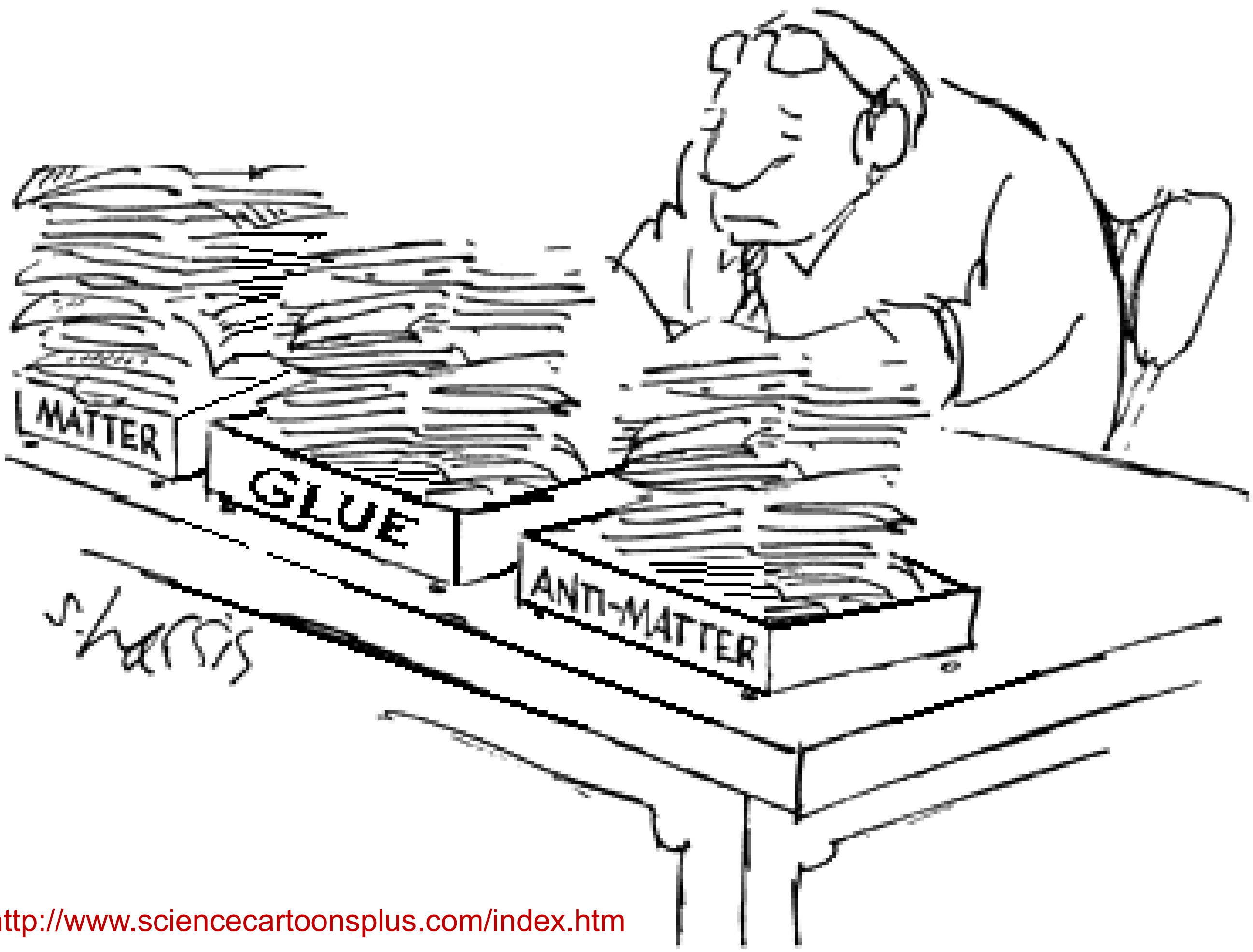
Internal Landscape of the Proton

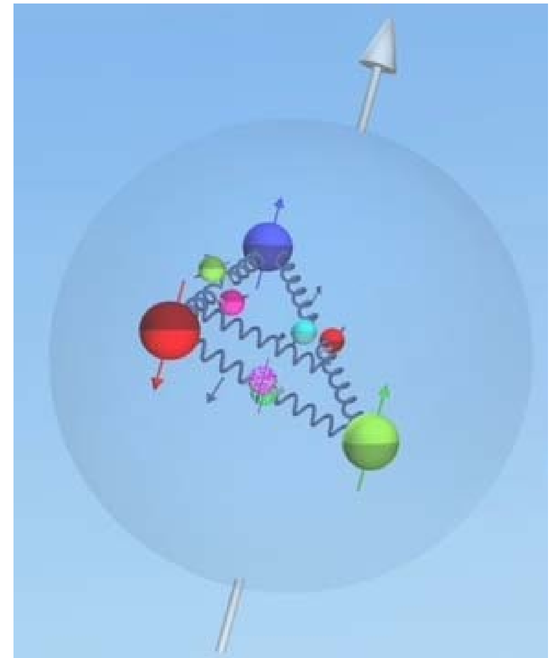
http://www.sciencecartoonsplus.com/index.htm



- Just three valence quarks?

Internal Landscape of the Proton

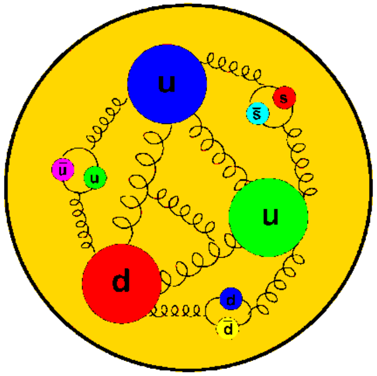




- Just three valence quarks?
- No!!
- And, quark distributions change in the nucleus

http://www.sciencecartoonsplus.com/index.htm

Flavor Structure of the Proton



➡ Constituent Quark Model

Pure valence description: proton = 2u + d

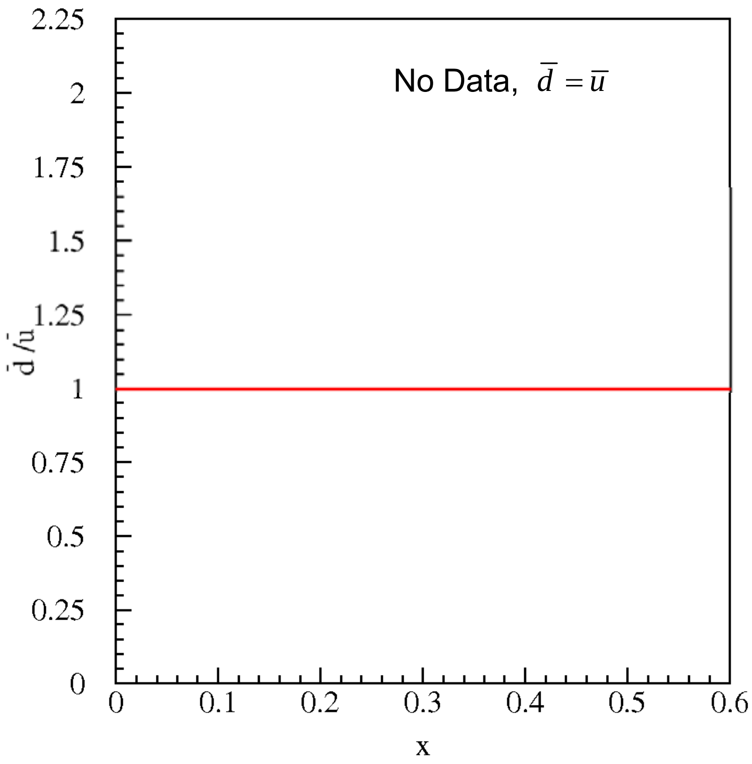
➡ Perturbative Sea

sea quark pairs from g → q$\bar{q}$

should be flavor symmetric:

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

➡ What does the data tell us?



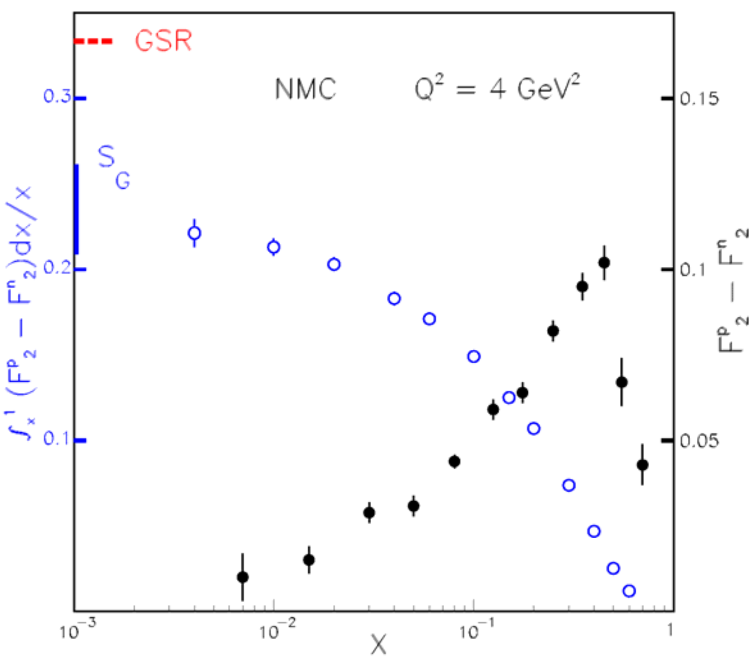
Flavor Structure of the Proton: Brief History

- Perturbative Sea

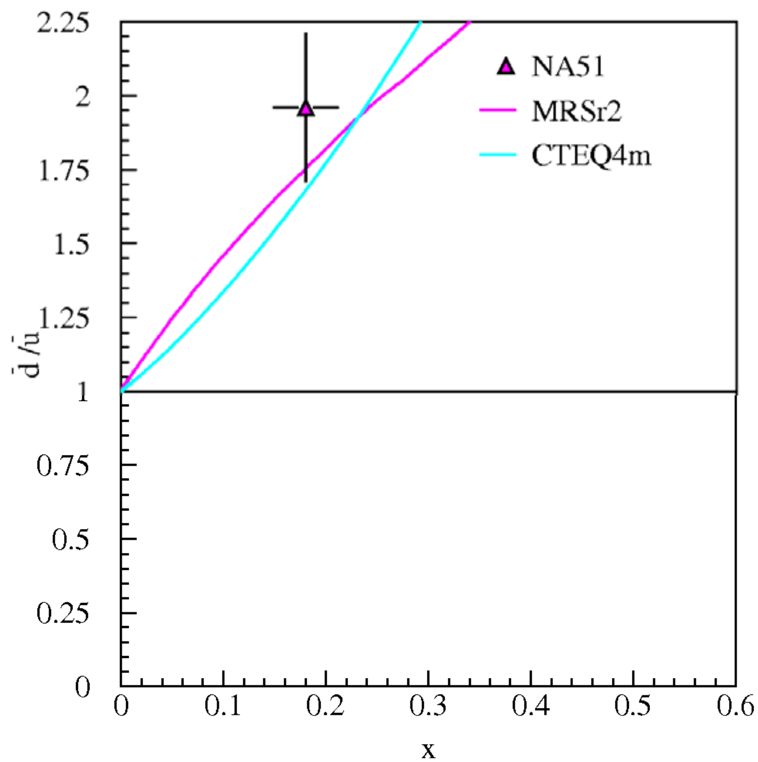
$$\bar{d}(x) = \bar{u}(x)$$

- NMC (Gottfried Sum Rule)

$$\int_0^1 \left[\bar{d}(x) - \bar{u}(x) \right] dx \neq 0$$



NA51: $\boxed{\bar{d} > \bar{u}}$



- Knowledge of parton distributions is data driven
  - Sea quark distributions are difficult for Lattice QCD

Flavor Structure of the Proton: Brief History

- Perturbative Sea

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

- NMC (inclusive DIS)

$$\int_0^1 \left[\bar{d}(x) - \bar{u}(x) \right] dx \neq 0$$

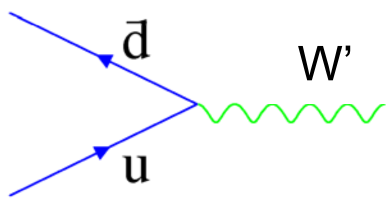
- NA51 (Drell-Yan)

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

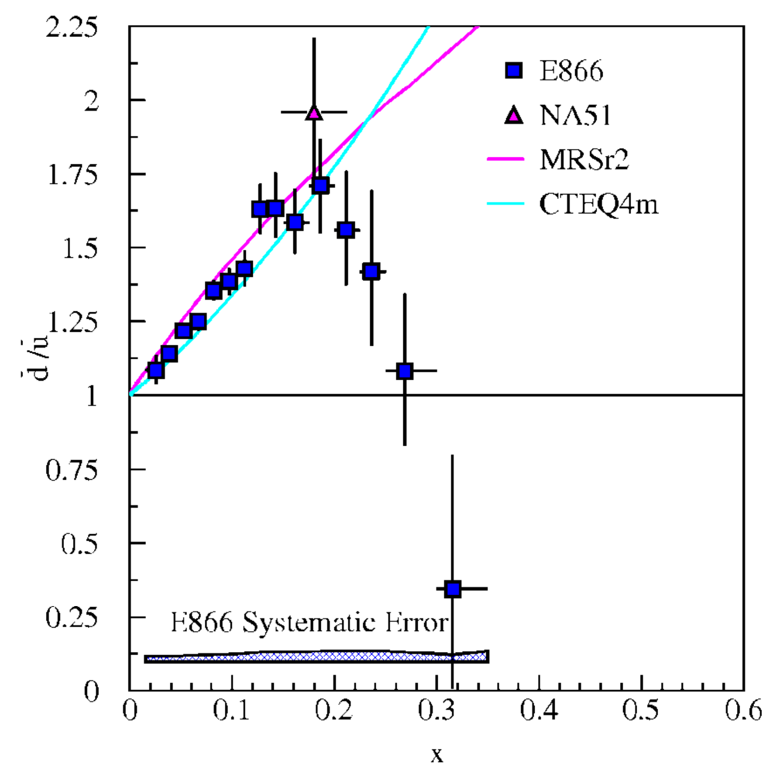
- E866/NuSea (Drell-Yan)

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

- What is the origin of the sea?
- Significant part of the LHC beam

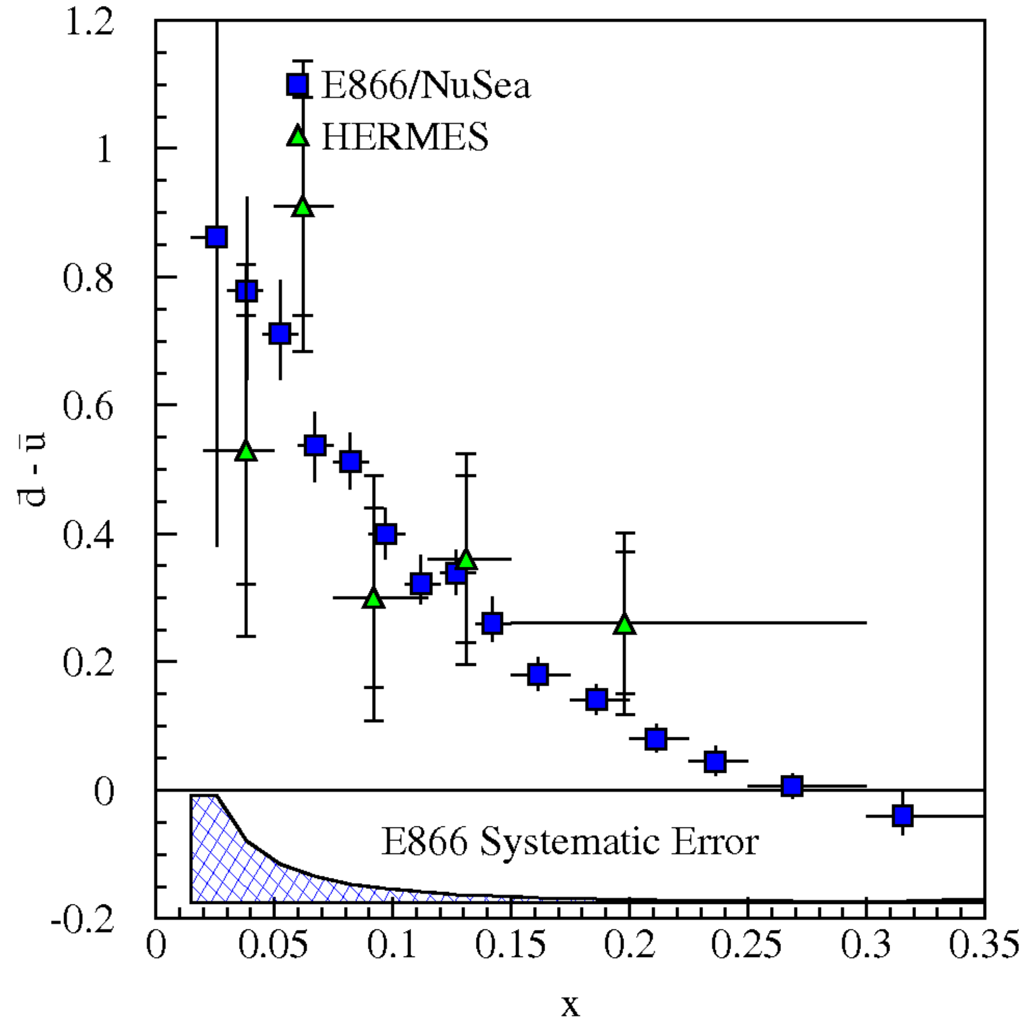


E866: $\boxed{\bar{d} > \bar{u}}$



Flavor Structure of the Proton - III

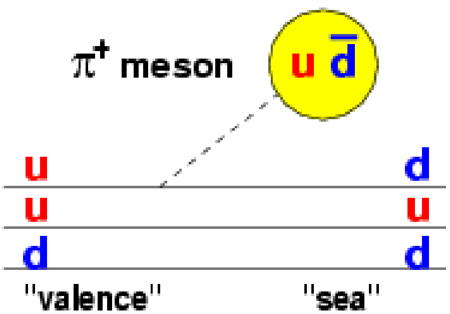
- There is a gluon splitting component which is symmetric
  $$\bar{d}(x) = \bar{u}(x) = \bar{q}(x)$$
- $\bar{d} - \bar{u}$
  - ➡ Symmetric sea via pair production from gluons subtracts off
  - ➡ No gluon contribution at 1st order in α_s
  - ➡ Non-perturbative models are motivated by the observed difference
- A proton with 3 valence quarks plus glue cannot be right at any scale!!



Flavor Structure of the Proton - IV

Non-perturbative models: alternate d.o.f.

Meson Cloud Models



Quark sea from cloud of 0^- mesons:

$\rightarrow$ $\boxed{\bar{d} > \bar{u}}$

Chiral-Quark Soliton Model

- quark d.o.f. in a pion mean-field: u $\rightarrow$ d + π^+
- nucleon = chiral soliton
- one parameter: dynamically generated quark mass
- expand in $1/N_c$:

$\rightarrow$ $\boxed{\bar{d} > \bar{u}}$

Statistical Model

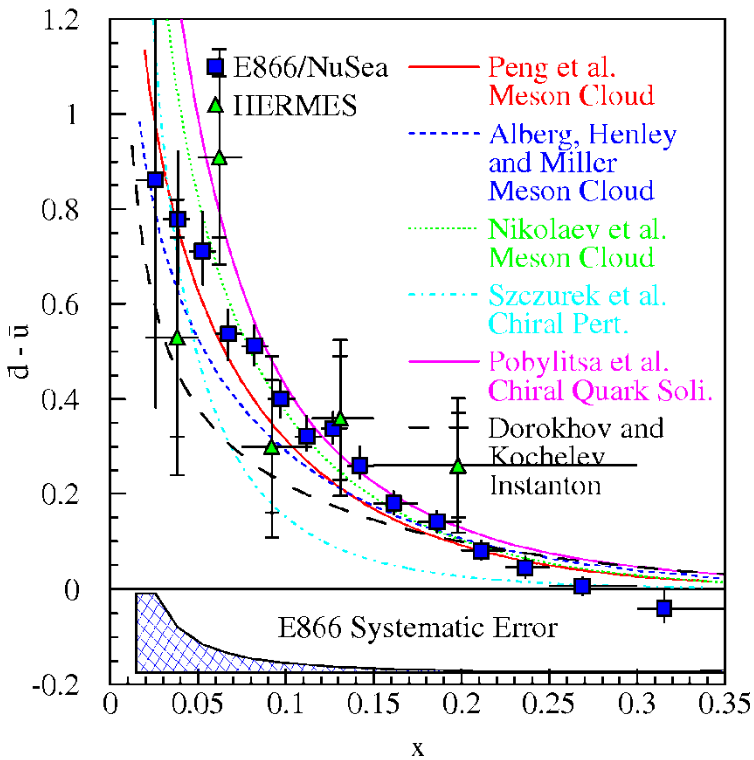
- nucleon = gas of massless partons
- few parameters: generate parton distribution functions
- input: QCD: chiral structure DIS: u(x) and d(x)

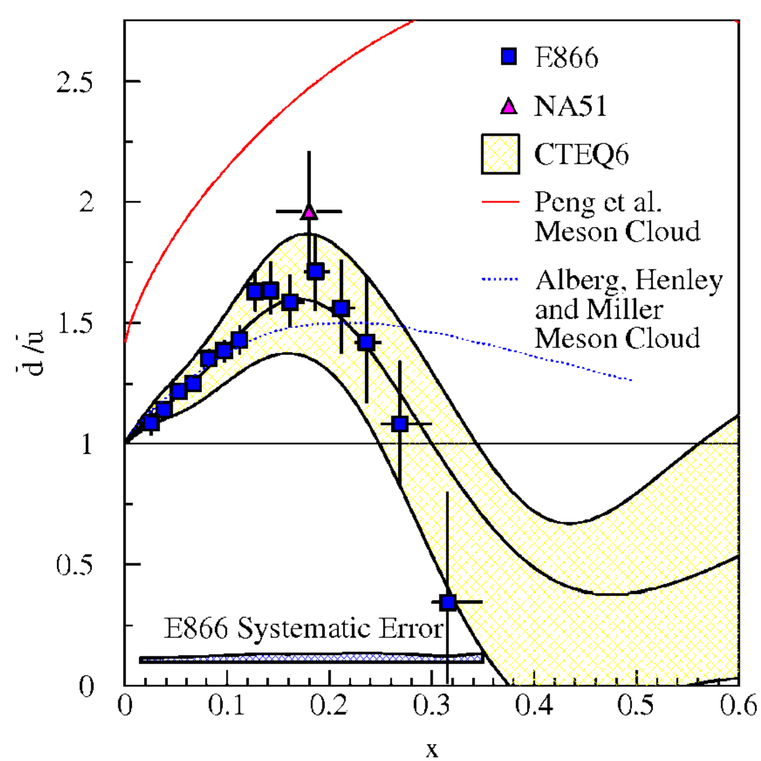
$\rightarrow$ $\boxed{\bar{d} > \bar{u}}$

$\Rightarrow$ important constraints on flavor asymmetry for polarization of light sea

$\boxed{\Delta\bar{q} = 0}$ $\boxed{\Delta\bar{u} \cong -\Delta\bar{d} > 0}$ $\boxed{\Delta\bar{d} < 0,\ \Delta\bar{u} > 0}$

Flavor Structure of the Proton - V





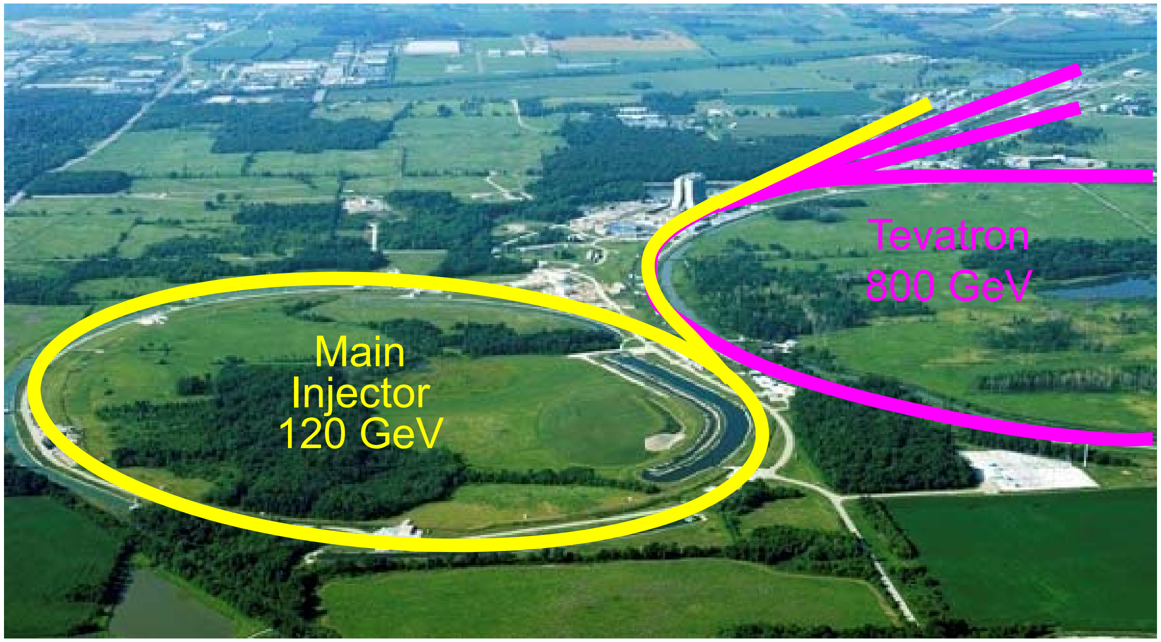
Comparison with models

- High x behavior is not explained
- Perturbative sea seems to dilute meson cloud effects at large x (but this requires large-x gluons)

- Measuring the ratio is powerful
- Are there more gluons and thus symmetric anti-quarks at higher x?
- Unknown other mechanisms with unexpected x-dependence?

SeaQuest: Fermilab Experiment E906

- E906 will extend Drell-Yan measurements of E866 (with 800 GeV protons) using upgraded spectrometer and 120 GeV proton beam from Main Injector
- Lower beam energy gives factor 50 improvement "per proton" !
  - ➡ Drell-Yan cross section for given x increases as $1/s$
  - ➡ Backgrounds from J/Ψ and similar resonances decreases as s
- Use many components from E866 to save money/time, in NM4 Hall
- Hydrogen, Deuterium and Nuclear Targets



Fermilab E906/Drell-Yan Collaboration

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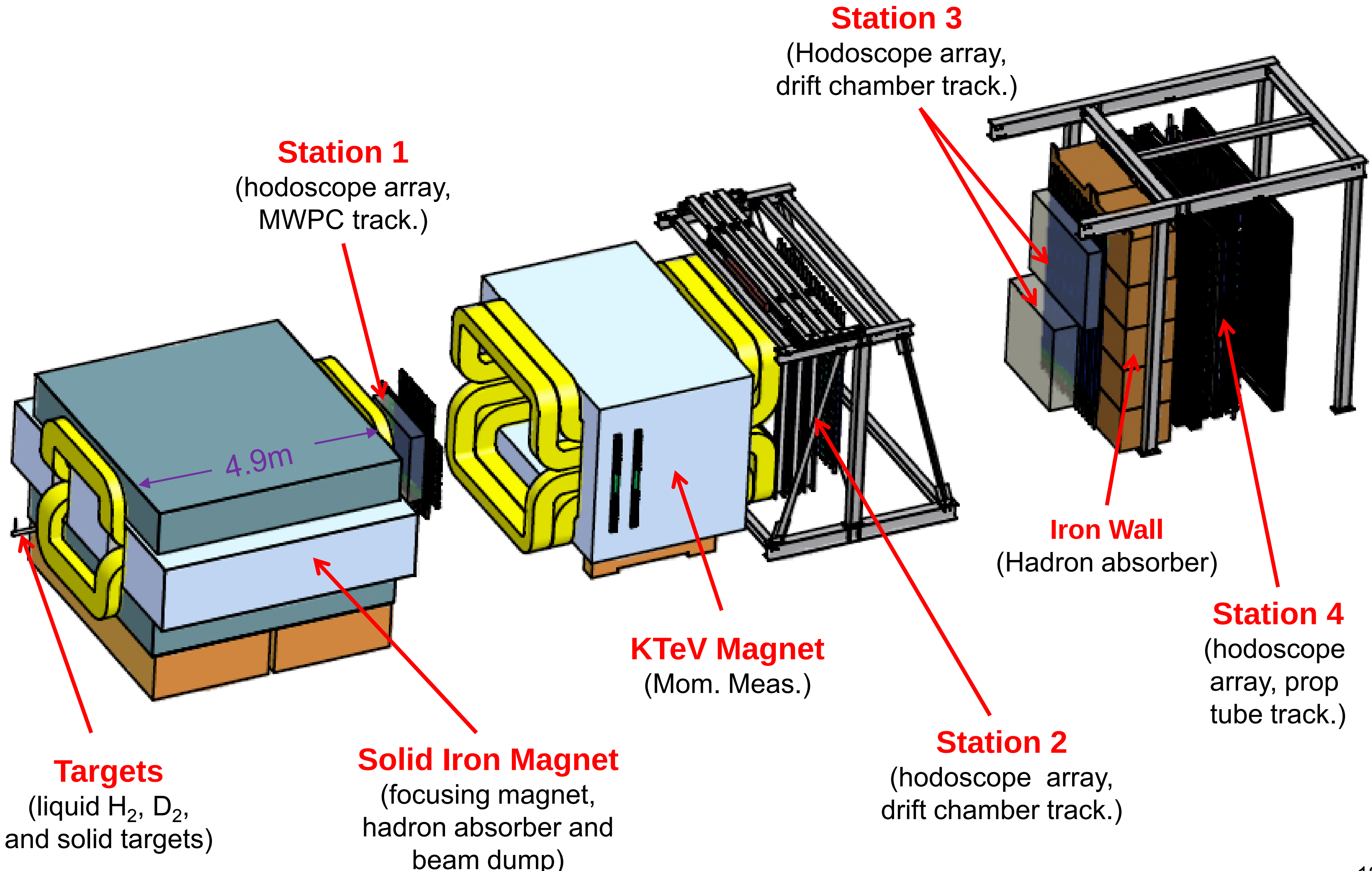
Ron Ransome, Elaine Schulte

*Co-Spokespersons

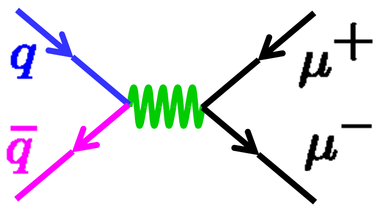
Jan, 2009

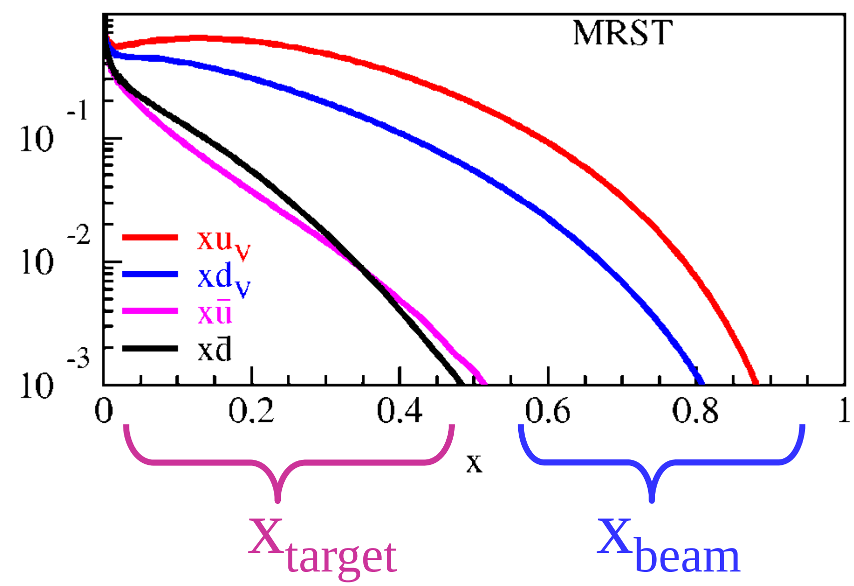
Collaboration contains many of the E-866/NuSea groups and several new groups (total 19 groups as of Aug 2010)

Drell-Yan Spectrometer for E-906
(25m long)



Fixed Target Drell-Yan: What we really measure

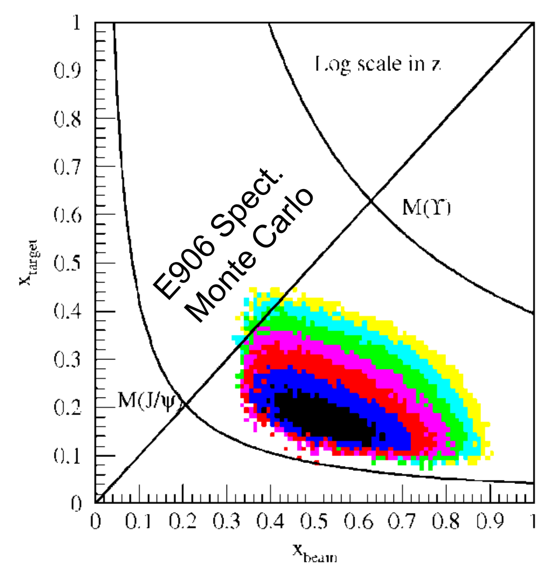




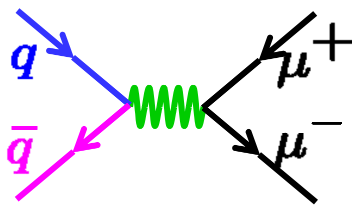
- Measure yields of $\mu^+\mu^-$ pairs from different targets
- Reconstruct p_γ , $M^2_\gamma = x_b x_t s$
- Determine x_b, x_t
- Measure differential cross section

$$\frac{d^2\sigma}{dx_1 dx_2} = \frac{4\pi\alpha^2}{9x_1x_2}\frac{1}{s}\sum e^2\left[\bar{q}_t(x_t)q_b(x_b) + q_t(x_t)\bar{q}_b(x_b)\right]$$

- Fixed target kinematics and detector acceptance give $x_b > x_t$
  - ➡ $x_F = 2p_{||}^{\gamma}/s^{1/2} \approx x_b - x_t$
  - ➡ Beam valence quarks probed at high x
  - ➡ Target sea quarks probed at low/intermediate x

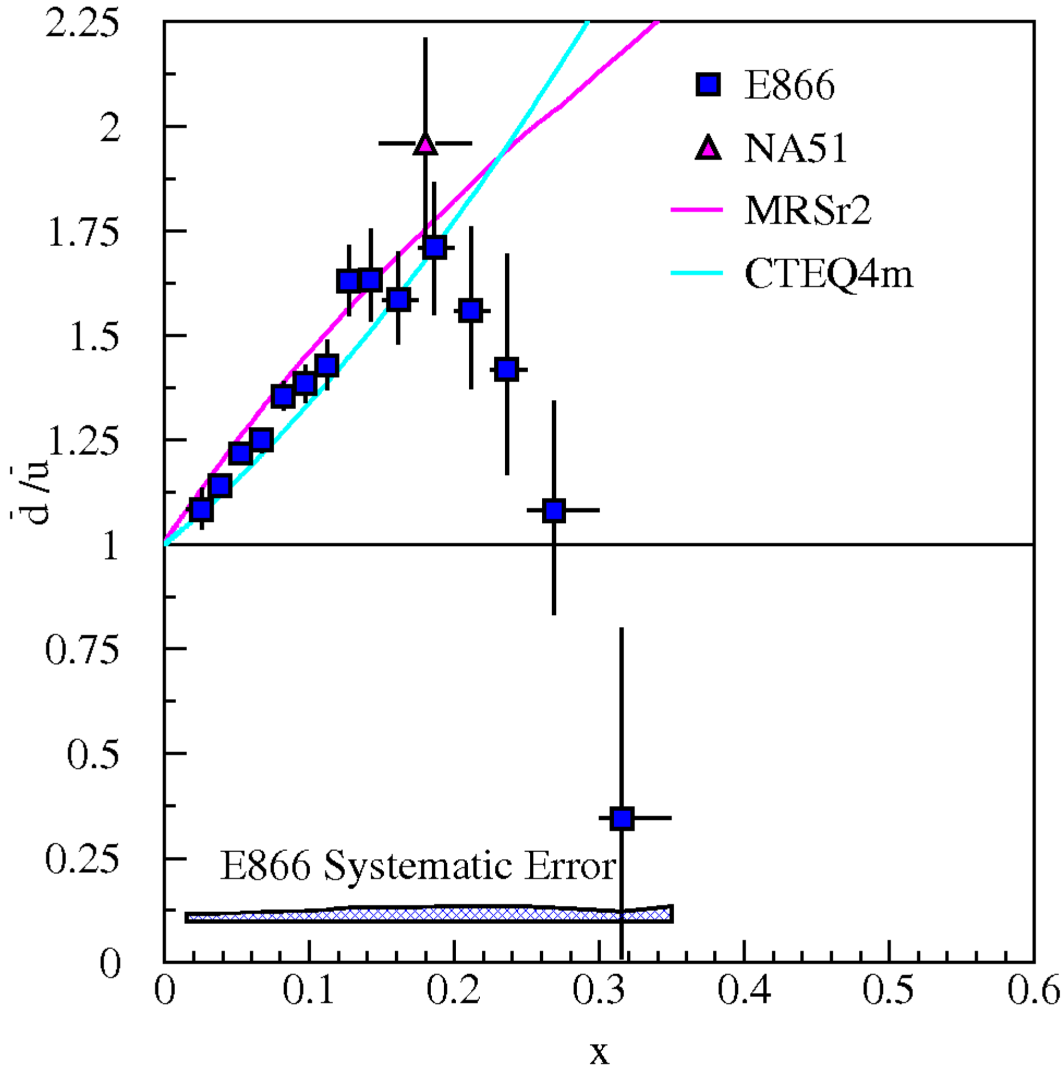


Fixed Target Drell-Yan: What we really measure - II



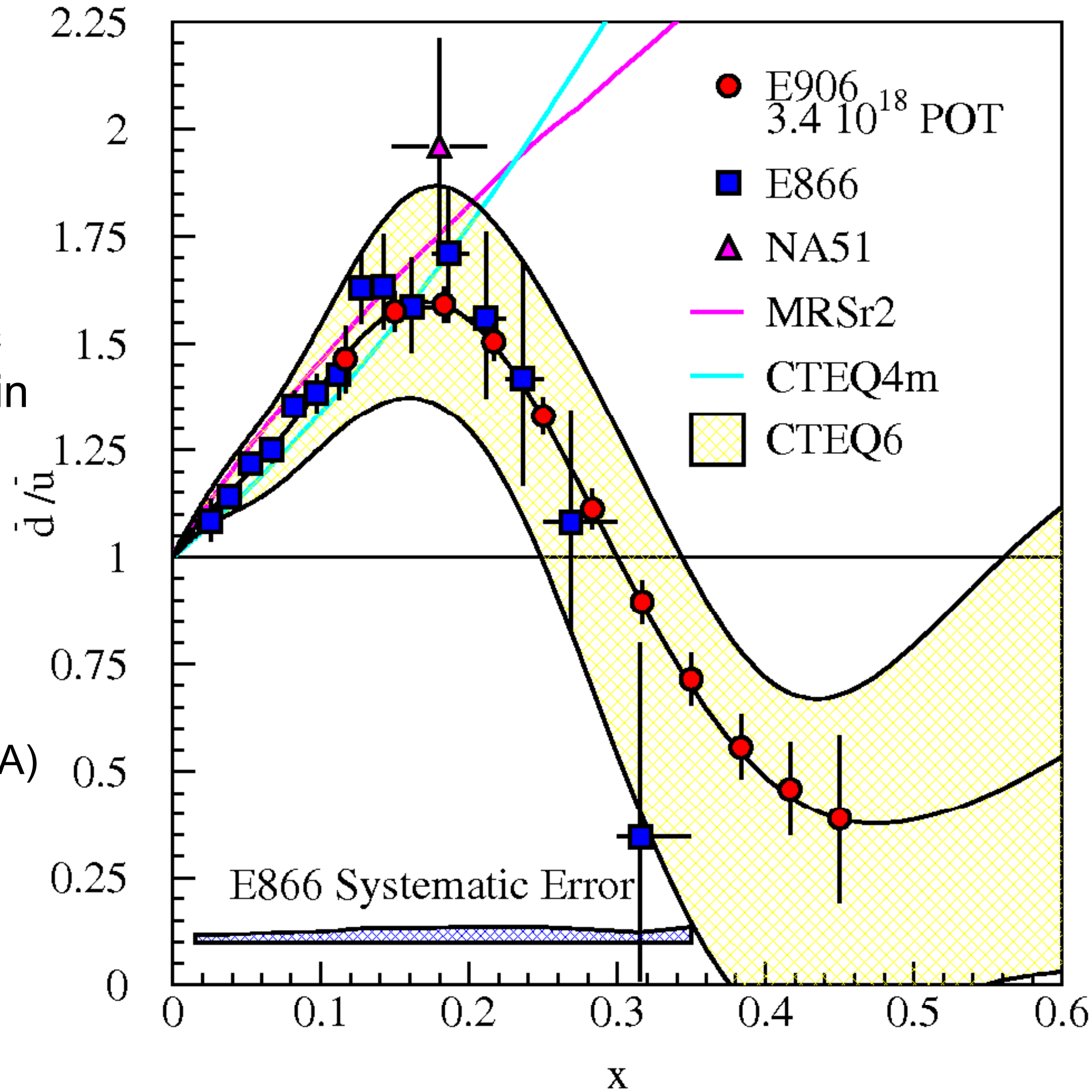
- Measure cross section ratios on Hydrogen, Deuterium (and Nuclear) Targets

$$\left.\frac{\sigma^{pd}}{2\sigma^{pp}}\right|_{x_b \gg x_t} \approx \frac{1}{2}\left[1+\frac{\bar{d}(x_t)}{\bar{u}(x_t)}\right]$$



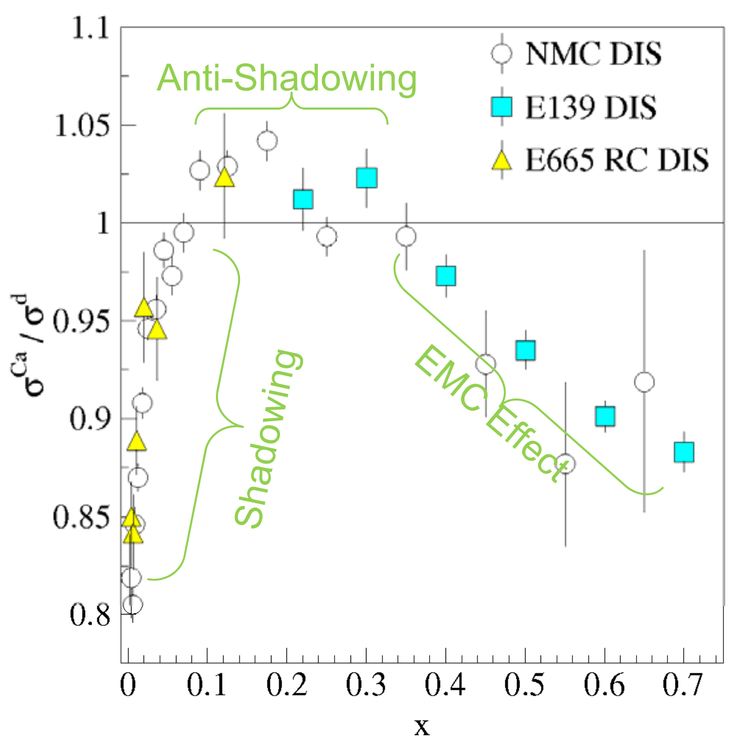
SeaQuest Projections for d-bar/u-bar Ratio

- SeaQuest will extend these measurements and reduce statistical uncertainty
- SeaQuest expects systematic uncertainty to remain at ≈1% in cross section ratio
- 5 s slow extraction spill each minute
- Intensity:
  - 2 x 10^{12} protons/s (=320 nA)
  - 1 x 10^{13} protons/spill

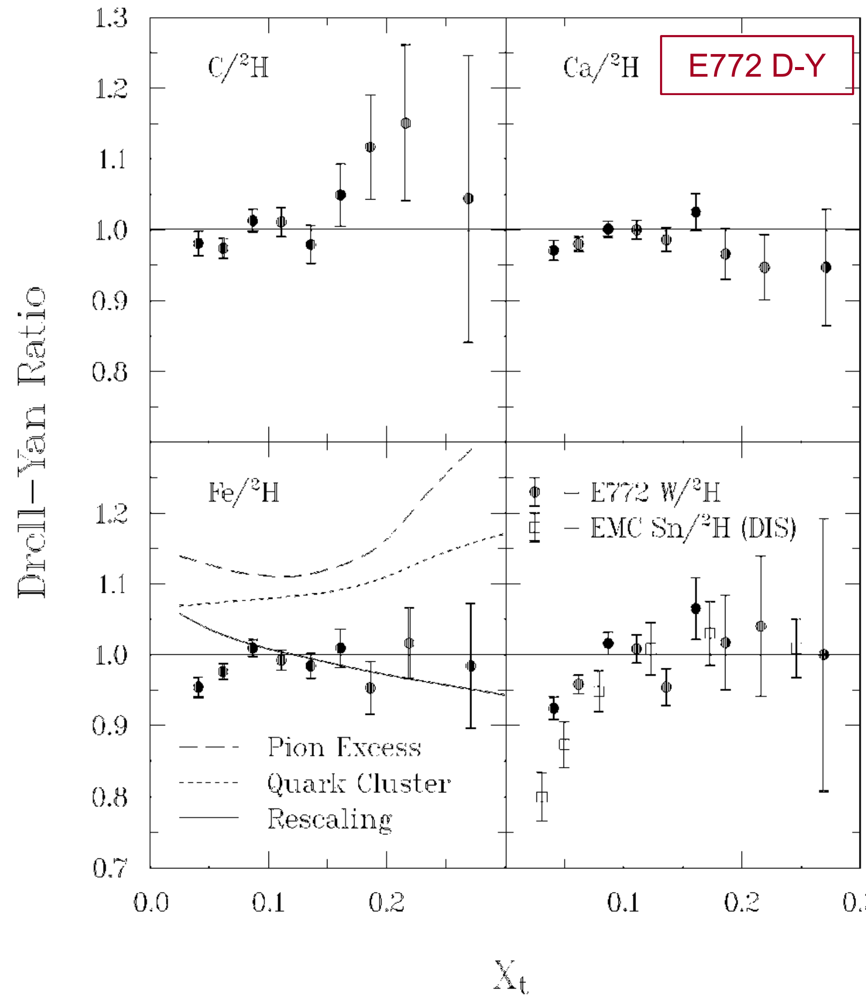


Sea quark distributions in Nuclei

- EMC effect from DIS is well established
- Nuclear effects in sea quark distributions may be different from valence sector
- Indeed, Drell-Yan apparently sees no Anti-shadowing effect (valence only effect)

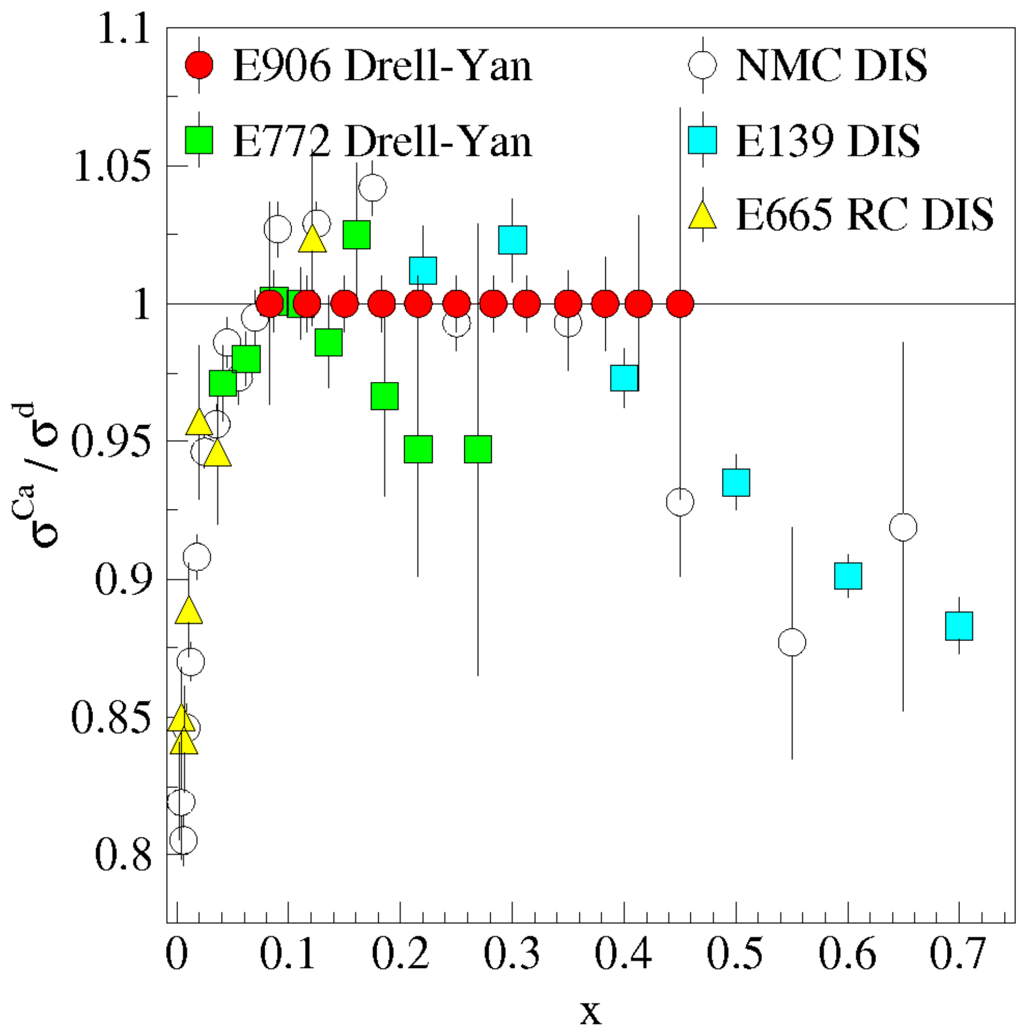


Alde *et al* (Fermilab E772) Phys. Rev. Lett. **64** 2479 (1990)



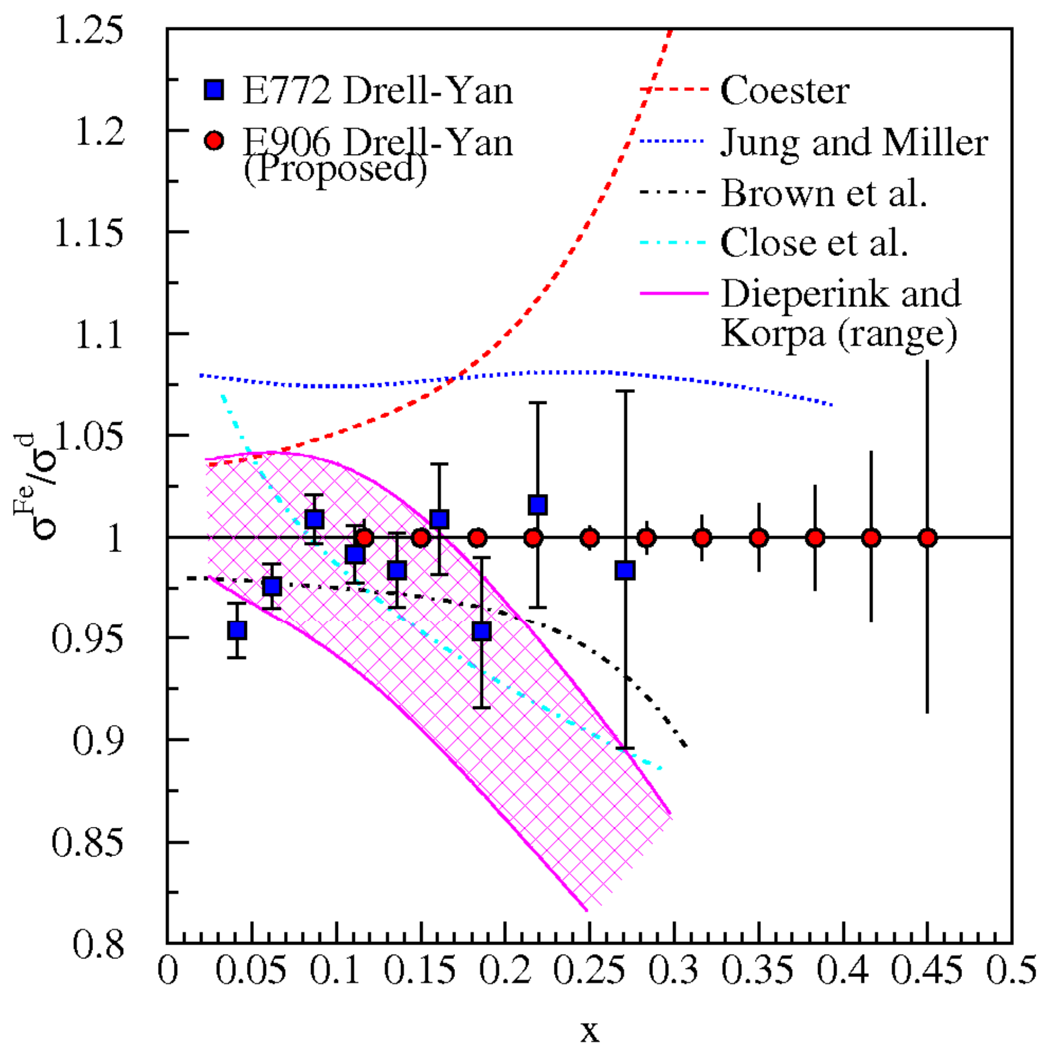
Sea quark distributions in Nuclei - II

- SeaQuest can extend statistics and x-range
- Are nuclear effects the same for sea and valence distributions?
- What can the sea parton distributions tell us about the effects of nuclear binding?



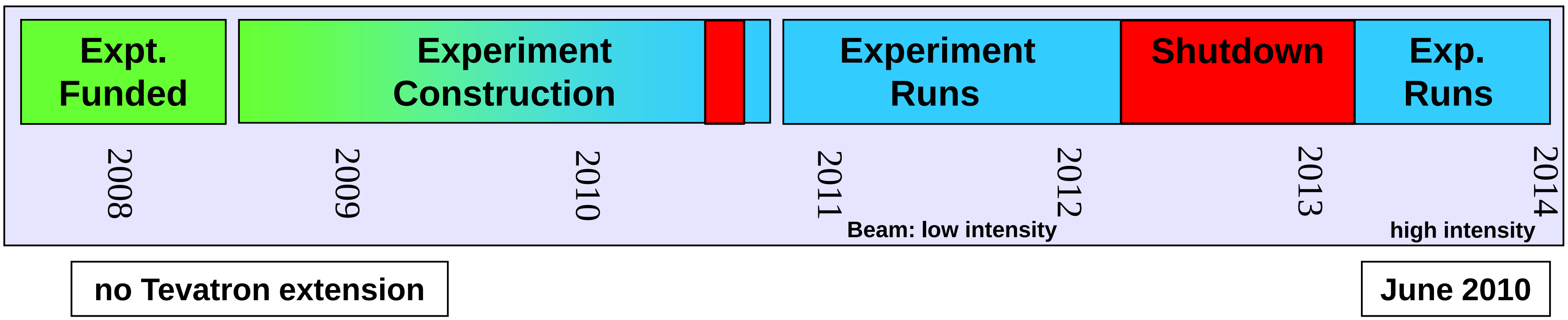
Where are the exchanged pions in the nucleus?

- The binding of nucleons in a nucleus is expected to be governed by the exchange of virtual "Nuclear" mesons.
- No antiquark enhancement seen in Drell-Yan (Fermilab E772) data.
- Contemporary models predict large effects to antiquark distributions as x increases
- Models must explain both DIS-EMC effect and Drell-Yan
- SeaQuest can extend statistics and x-range



Fermilab Seaquest Timelines

- Fermilab PAC approved the experiment in 2001, but experiment was not scheduled due to concerns about "proton economics"
- Stage II approval in December 2008
- Expect to start running around Thanksgiving for 2 years of data collection



Apparatus available for future programs at, *e.g.* Fermilab, J-PARC or RHIC

➡ significant interest from collaboration for continued program

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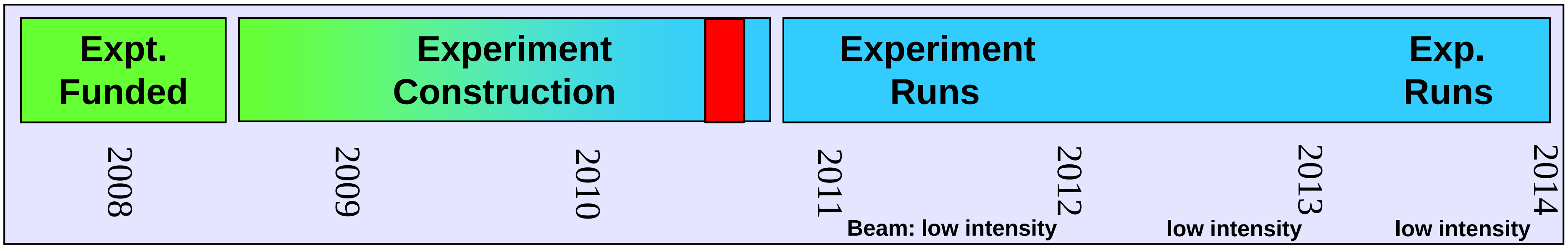


w/ Tevatron extension

Apparatus available for future programs at, *e.g.* Fermilab, J-PARC or RHIC

➡ significant interest from collaboration for continued program

Beyond SeaQuest

- **Polarized Drell-Yan Experiment**
  - ➡ Not yet done!
  - ➡ transverse momentum dependent distributions functions (Sivers, Boer-Mulders, etc)
  - ➡ Transversely Polarized Beam or Target
    - ✓ Sivers function in single-transverse spin asymmetries (SSA) (sea quarks or valence quarks)
      - sea quark effects might be small
      - valence quark effects expected to be large
    - ✓ transversity $\otimes$ Boer-Mulders function
  - ➡ Beam and Target Transversely Polarized
    - ✓ flavor asymmetry of sea-quark polarization
    - ✓ transversity (quark $\otimes$ anti-quark for pp collisions)
      - anti-quark transversity might be very small

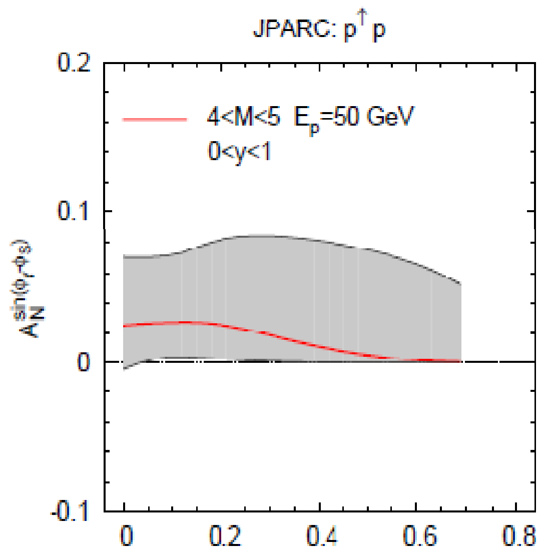
Sivers Function

- described by transverse-momentum dependent distribution function
- captures non-perturbative spin-orbit coupling effects inside a polarized proton
- leads to a sin $(\phi - \phi_S)$ asymmetry in SIDIS and Drell-Yan
- done in SIDIS (HERMES, COMPASS)
- Sivers function is time-reversal odd
  - ➡ leads to sign change

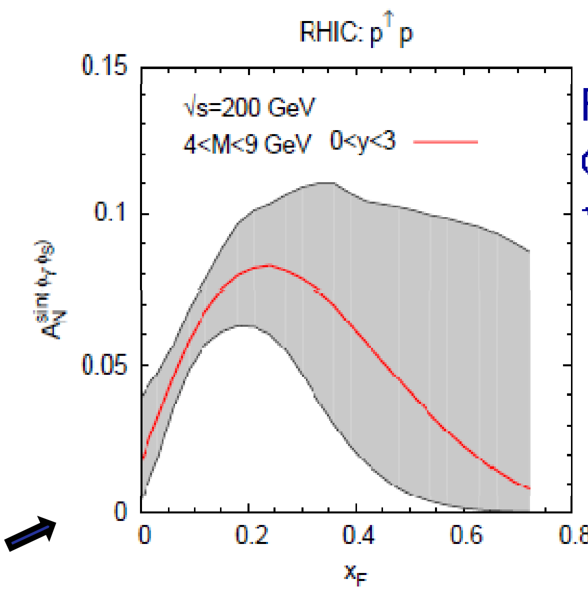
$$f_{1T}^{\perp q}\Big|_{DIS} = - f_{1T}^{\perp q}\Big|_{D-Y}$$

  - ➡ fundamental prediction of QCD
    (goes to heart of gauge formulation of field theory)

Predictions based on fit to SIDIS data



J-PARC
50-GeV
polarized beam
$\sqrt{s}$ ~ 10 GeV



RHIC
collider
$\sqrt{s}$ = 200 GeV

Anselmino et al. PRD79, 054010 (2009)

Sivers Function

- described by transverse-momentum dependent distribution function
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- leads to a sin $(\phi - \phi_S)$ asymmetry in SIDIS and Drell-Yan
- done in SIDIS (HERMES, COMPASS)
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$$f_{1T}^{\perp q}\Big|_{DIS} = -f_{1T}^{\perp q}\Big|_{D-Y}$$

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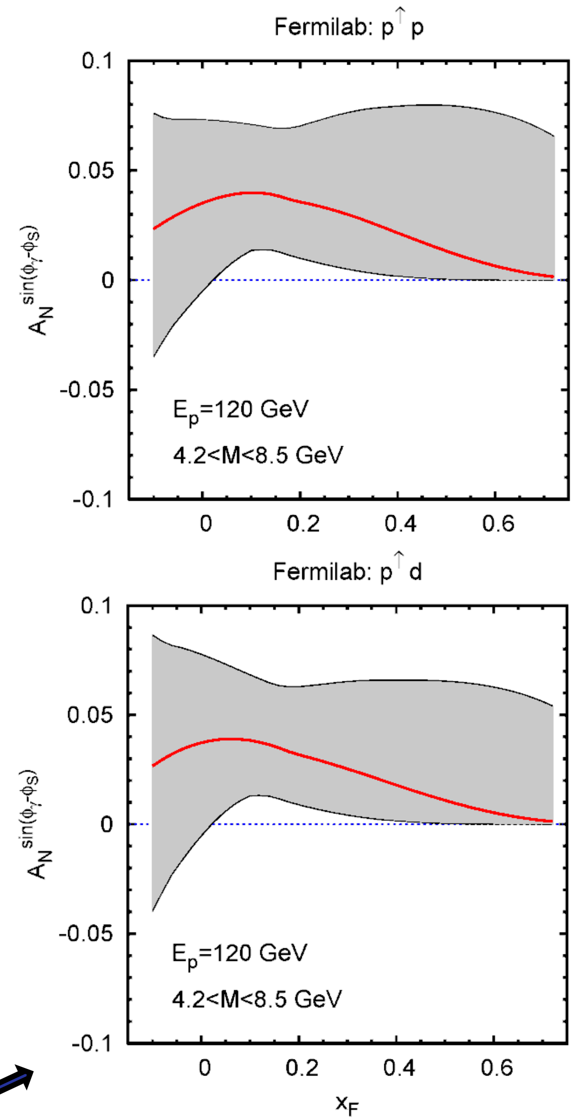
Predictions based on fit to SIDIS data



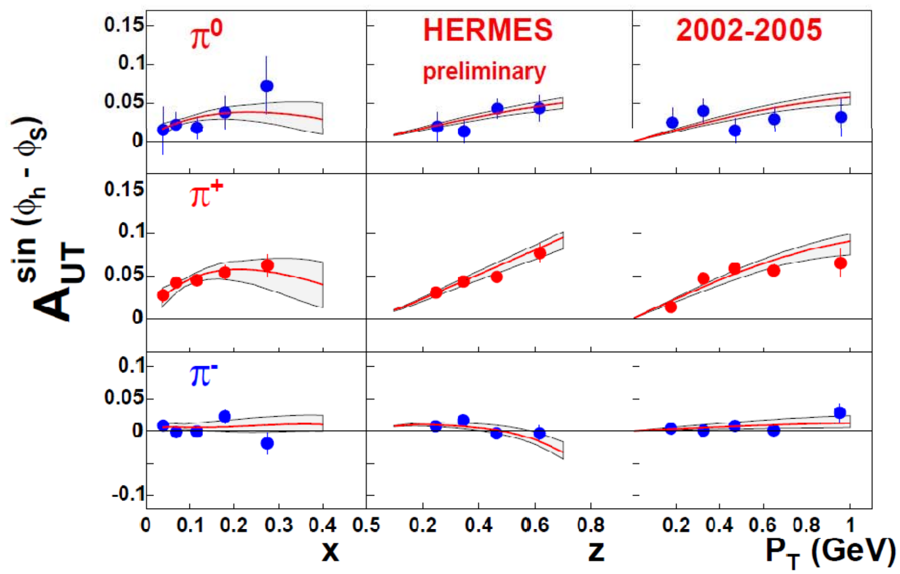
FNAL
120 GeV
polarized beam
√s ~ 15 GeV
(hydrogen)

FNAL
120 GeV
polarized beam
√s ~ 15 GeV
(deuterium)

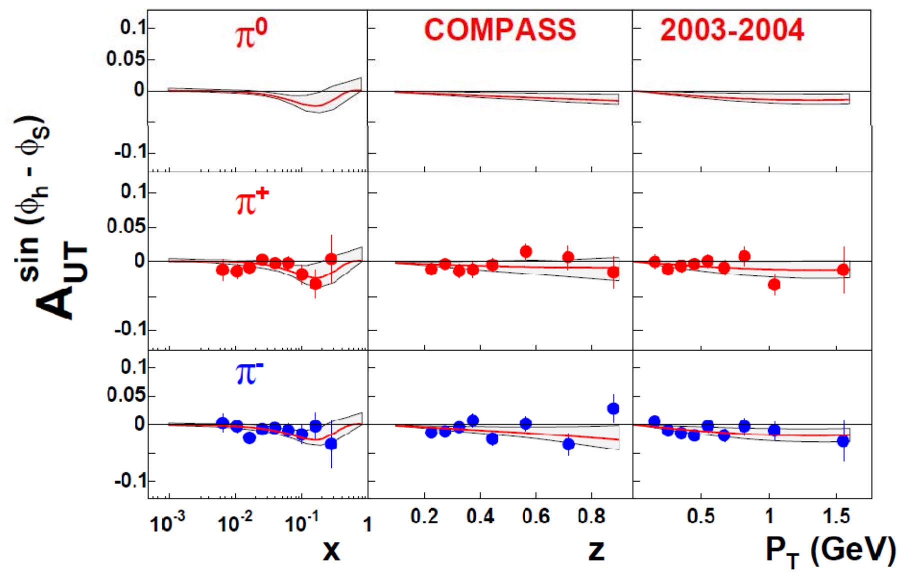
Anselmino et al. priv. comm. 2010

Sivers Asymmetry Measurements

HERMES (p)



COMPASS (d)



- Global fit to sin $(\phi_h - \phi_S)$ asymmetry in SIDIS (HERMES, COMPASS)
- Comparable measurements needed for single spin asymmetries in Drell-Yan process
- BUT: COMPASS (p) data do not agree with global fits (Sudakov suppression)

Importance of Factorization in QCD

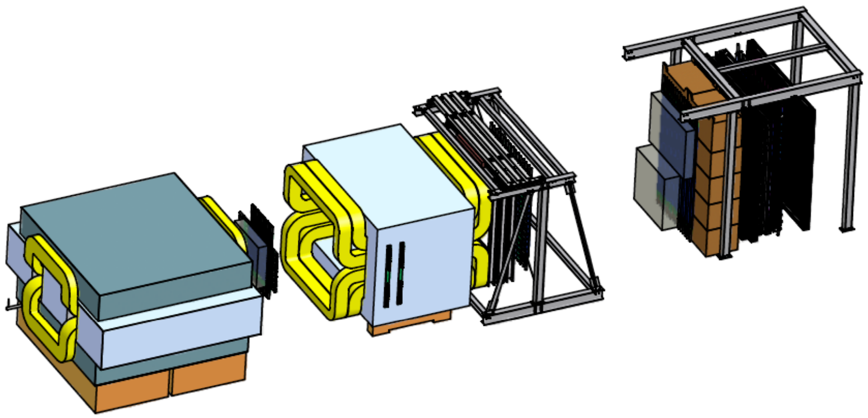
QCD without factorization
is *almost useless**

*I added this sentence after this morning comments, so
it might be too strong

Monday, 26 April 2010

Polarized Drell-Yan at Fermilab Main Injector

- SeaQuest di-muon Spectrometer
  - ➡ fixed target experiment
  - ➡ luminosity: $L = 3.4 \times 10^{35}$ /cm^2/s
    - $I_{av} = 1.6 \times 10^{11}$ p/s (=26 nA)
    - $N_p = 2.1 \times 10^{24}$ /cm^2
  - ➡ 2-3 years of running: 3.4×10^{18} pot



- Polarized Beam in Main Injector
  - ➡ use Seaquest spectrometer
  - ➡ use SeaQuest target
    - ✓ liquid H_2 target can take ~5×10^{11} p/s (=80 nA)
  - ➡ 1 mA at polarized source can deliver 8.1×10^{11} p/s (=130 nA) (A. Krisch: Spin@Fermi study in (1995))
  - ➡ Scenarios:
    - ✓ **$L = 1 \times 10^{36}$ /cm^2/s** (60% of available beam delivered to experiment)
    - ✓ $L = 1.7 \times 10^{35}$ /cm^2/s (10% of available beam delivered to experiment)
  - ➡ x-range:
    - ✓ $x_1 = 0.3 – 0.9$ (valence quarks) $x_2 = 0.1 – 0.5$ (sea quarks)

Planned Polarized Drell-Yan Experiments

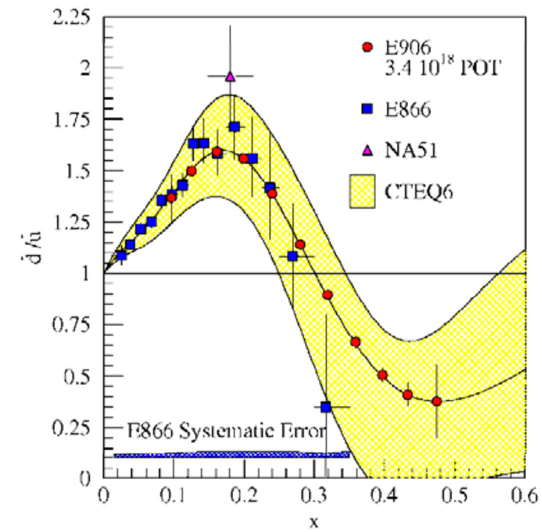
Yuji Goto
April 27, 2010
DY workshop
CERN

experiment	particles	energy	x1 or x2	luminosity	rates
COMPASS	π± + p↑	160 GeV √s = 17.4 GeV	x2 = 0.2 – 0.3	2×10^{33} cm^{-2}s^{-1}	
COMPASS (low mass)	π± + p↑	160 GeV √s = 17.4 GeV	x2 ~ 0.05	2×10^{33} cm^{-2}s^{-1}	
PAX	p↑ + pbar	collider √s = 14 GeV	x1 = 0.1 – 0.9	2×10^{30} cm^{-2}s^{-1}	
PANDA (low mass)	pbar + p↑	15 GeV √s = 5.5 GeV	x2 = 0.2 – 0.4	2×10^{32} cm^{-2}s^{-1}	
J-PARC	p↑ + p	50 GeV √s = 10 GeV	x1 = 0.5 – 0.9	10^{35} cm^{-2}s^{-1}	
NICA	p↑ + p	collider √s = 20 GeV	x1 = 0.1 – 0.8	10^{30} cm^{-2}s^{-1}	
SPASCHARM (low mass)	p + p↑	60 GeV √s = 11 GeV	x2 = 0.05 – 0.2		
SPASCHARM (low mass)	π± + p↑	34 GeV √s = 8 GeV	x2 = 0.1 – 0.3		
RHIC PHENIX Muon	p↑ + p	collider √s = 500 GeV	x1 = 0.05 – 0.1	2×10^{32} cm^{-2}s^{-1}	
RHIC Internal Target phase-1	p↑ + p	250 GeV √s = 22 GeV	x1 = 0.25 – 0.4	2×10^{33} cm^{-2}s^{-1}	
RHIC Internal Target phase-2	p↑ + p	250 GeV √s = 22 GeV	x1 = 0.25 – 0.4	6×10^{34} cm^{-2}s^{-1}	
Fermilab Main Injector polarized	p↑ + p	120 GeV √s = 15 GeV	x_1 = 0.3 – 0.9	~1 x 10^{36} cm^{-2} s^{-1}	

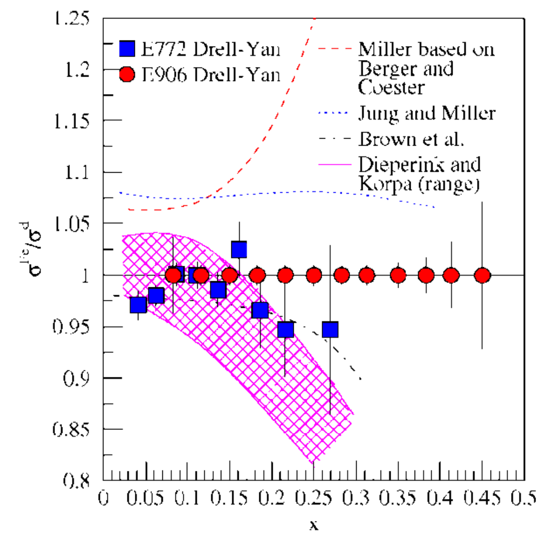
Polarized M.I. beam intensity: 2.3 x 10^{12} p/pulse (w/ 2.8 s/pulse) on SeaQuest target (60% delivered to NM4)
-> L = 1 x 10^{36} /cm^2/s (SeaQuest IH_2 target limited)

Drell-Yan fixed target experiments at Fermilab

- **What is the structure of the nucleon?**
  - What is $\bar{d} / \bar{u}$?
  - What is the origin of thesea quarks?
  - What is the high x structure of the proton?



- **What is the structure of nucleonic matter?**
  - Where are the nuclear pions?
  - Is anti-shadowing a valence effect?



- **SeaQuest: 2010 - 2013**
  - significant increase in physics reach
- **Beyond SeaQuest**
  - Polarized Drell-Yan (beam/target)

Thank you!