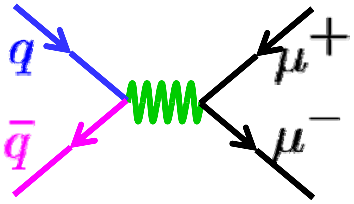
Drell-Yan Scattering at Fermilab:

SeaQuest and Beyond

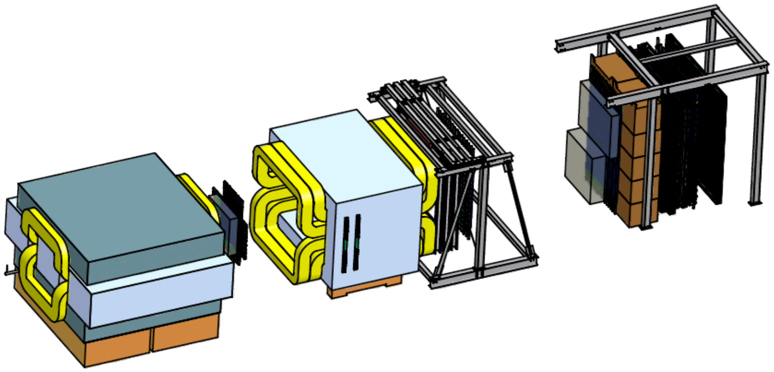
Wolfgang Lorenzon
University of Michigan

(1-September-2011)
Transversity-2011 Workshop



- **Introduction**
- **SeaQuest: Fermilab Experiment E906**
  - ➡ Sea quarks in the proton
  - ➡ Sea quarks in the nucleus
  - ➡ other topics
- **Beyond SeaQuest**
  - ➡ Polarized Drell-Yan at FNAL?

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



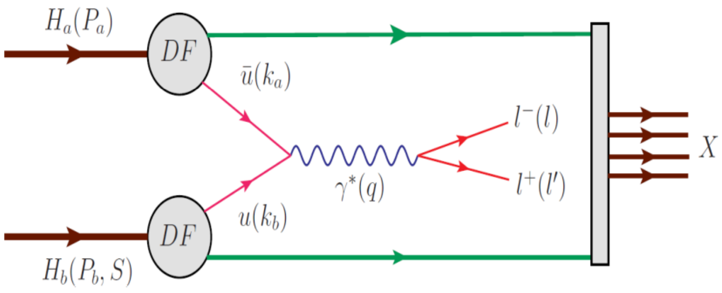
With help from Chiranjib Dutta (U-M), and Paul Reimer (Argonne)

This work is supported by

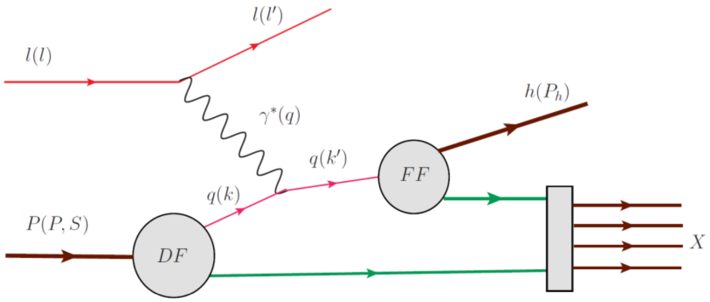
Drell Yan Process

- Similar Physics Goals as SIDIS:
  - parton level understanding of nucleon
  - electromagnetic probe
- Timelike (Drell-Yan) vs. spacelike (DIS) virtual photon

Drell-Yan



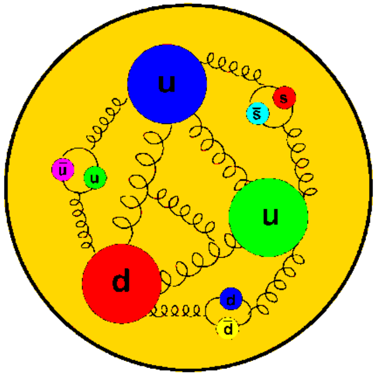
SIDIS



A. Kotzinian, DY workshop, CERN, 4/10

- Cleanest probe to study hadron structure:
  - hadron beam and convolution of parton distributions
  - no QCD final state effects
  - no fragmentation process
  - ability to select sea quark distribution
  - allows direct production of transverse momentum-dependent distribution (TMD) functions (Sivers, Boer-Mulders, etc)

Flavor Structure of the Proton



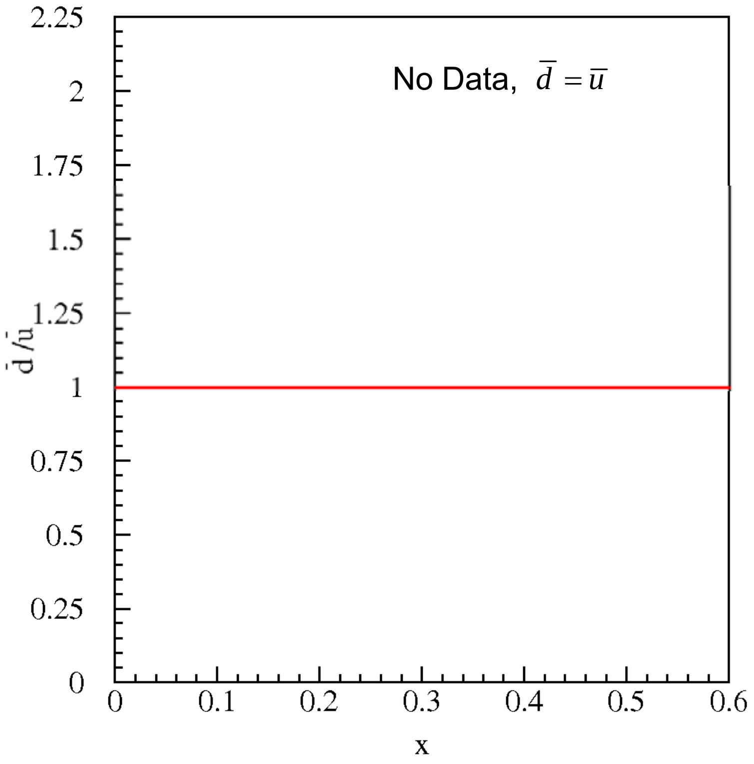
- Constituent Quark Model

  Pure valence description: proton = 2u + d

- Perturbative Sea

  sea quark pairs from g → q$\bar{q}$
  should be flavor symmetric: $\boxed{\bar{d} = \bar{u}}$

- What does the data tell us?



Flavor Structure of the Proton: Brief History

- Perturbative Sea

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

- NMC (inclusive DIS)

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

- NA51 (Drell-Yan)

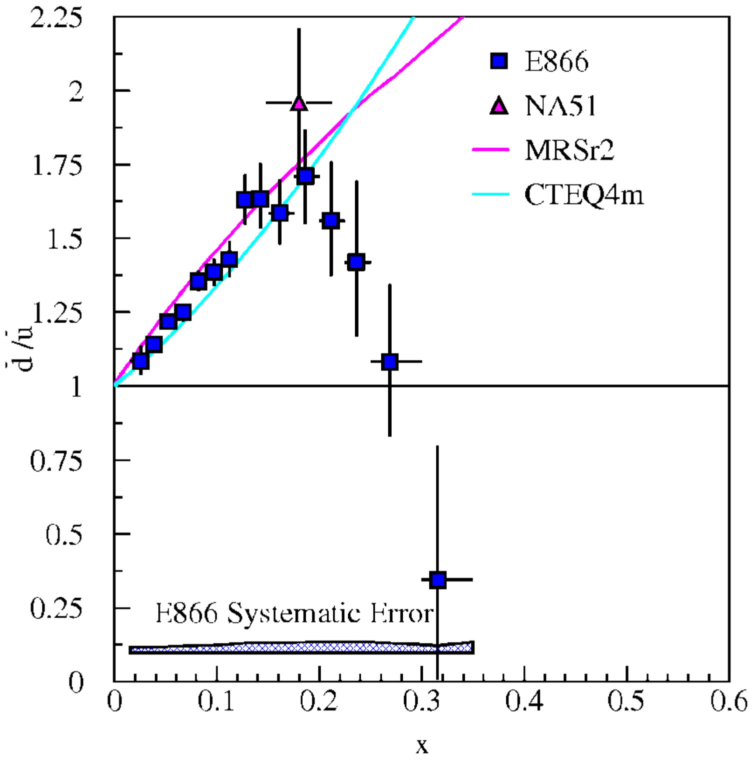
$$\bar{d}(x) > \bar{u}(x)$$

- E866/NuSea (Drell-Yan)

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

- What is the origin of the sea

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



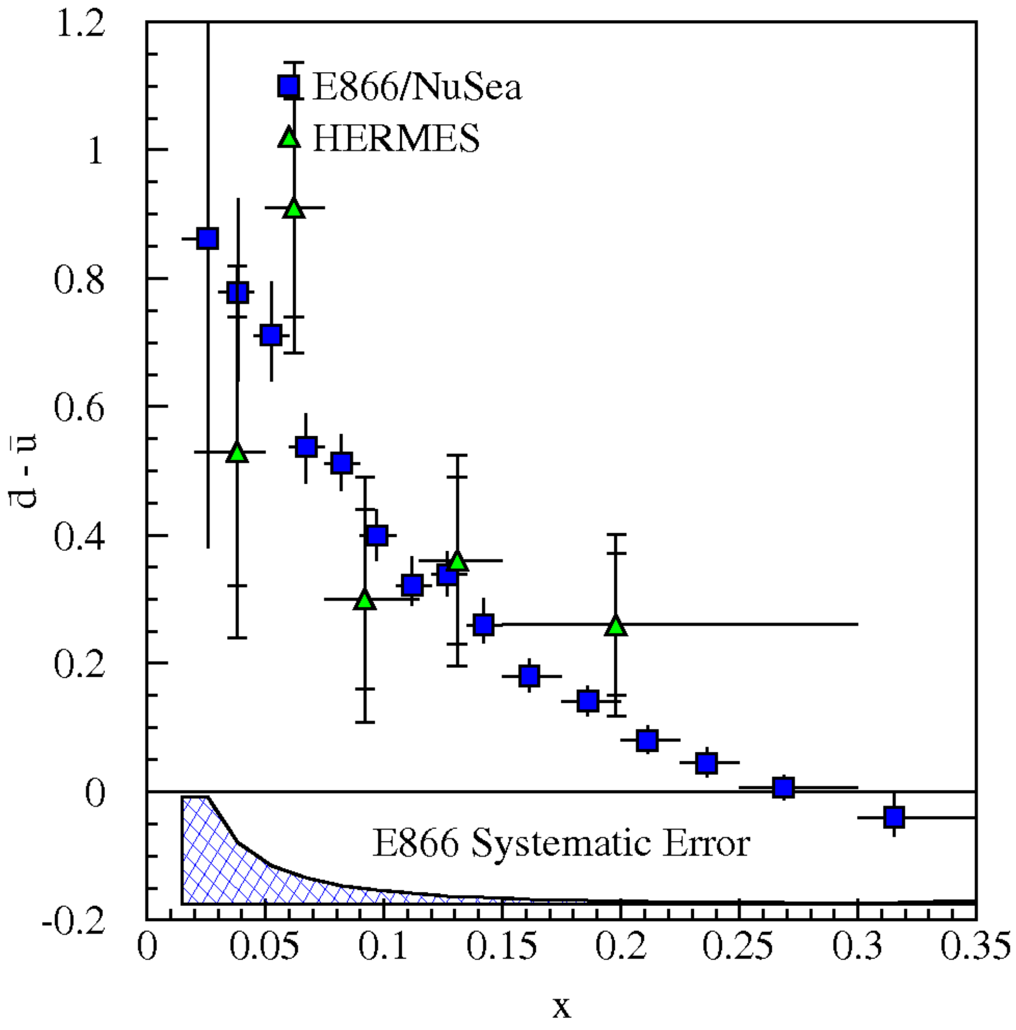
- Knowledge of parton distributions is data driven
  - Sea quark distributions are difficult for Lattice QCD

Flavor Structure of the Proton: What creates Sea?

- There is a gluon splitting component which is symmetric

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

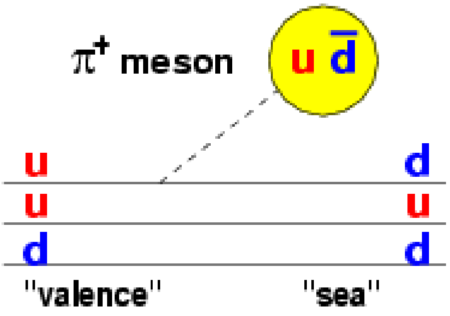
- $\bar{d} - \bar{u}$
  - ➡ Symmetric sea via pair production from gluons subtracts off
  - ➡ No gluon contribution at 1st order in α_s
  - ➡ Non-perturbative models are motivated by the observed difference
- A proton with 3 valence quarks plus glue cannot be right at any scale!!



Flavor Structure of the Proton: Models

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 → d + π^+
- nucleon = chiral soliton
- one parameter: dynamically generated quark mass
- expand in $1/N_c$:

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

Statistical Model

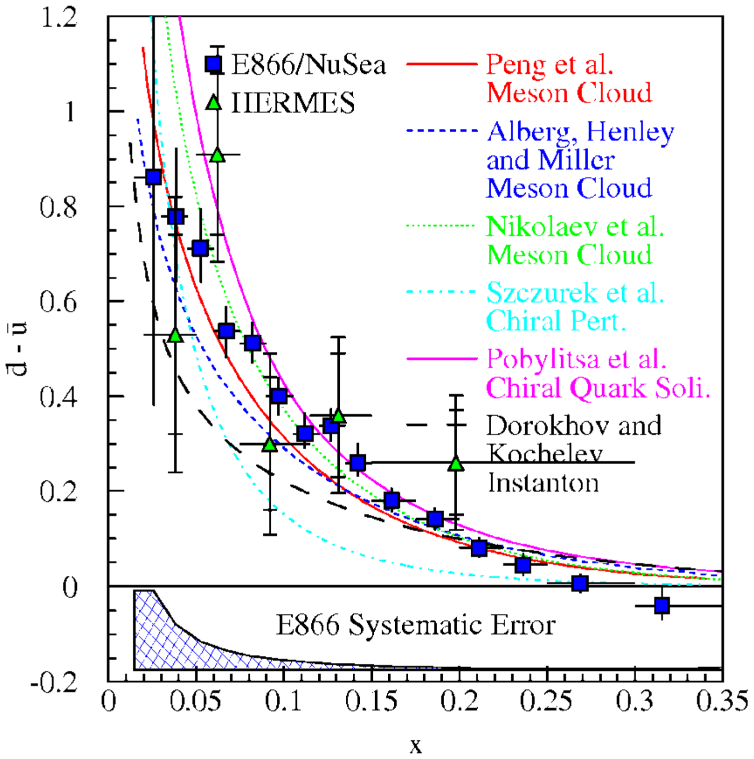
- nucleon = gas of massless partons
- few parameters: generate parton distribution functions
- input:
  QCD: chiral structure
  DIS: u(x) and d(x)

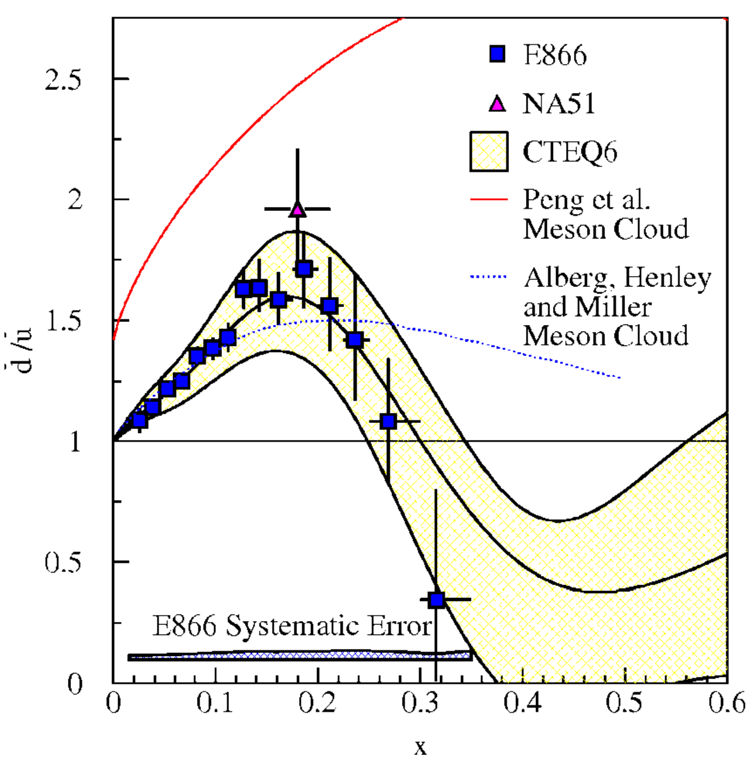
$\rightarrow \boxed{\bar{d} > \bar{u}}$

⇒ 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: What creates Sea?





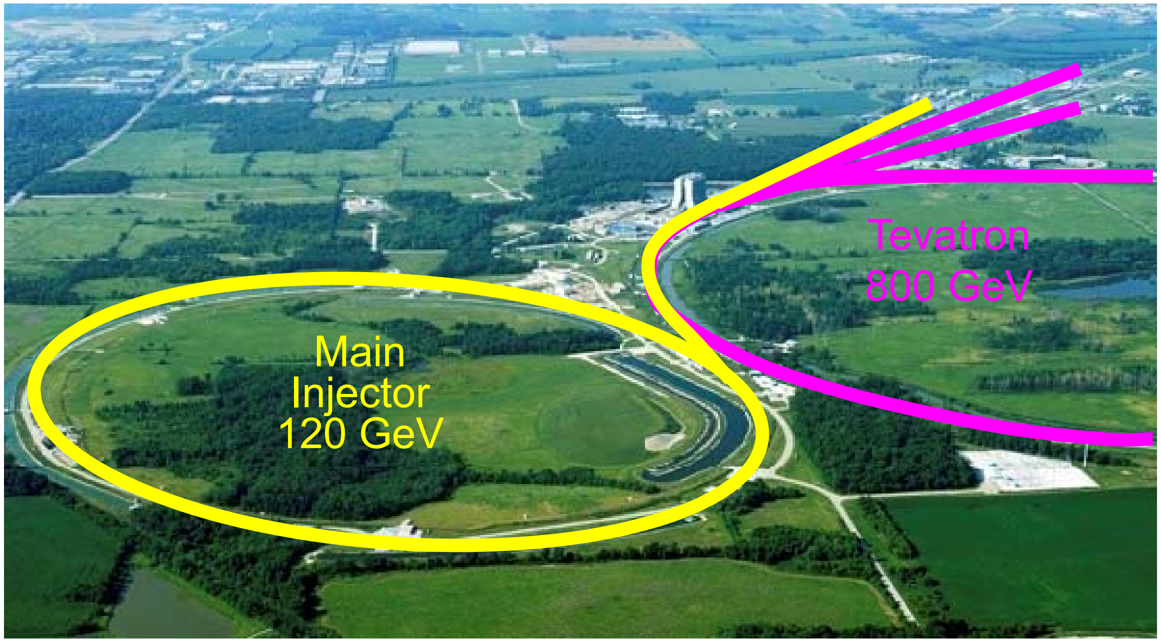
Comparison with models

- 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/NuSea (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

Abilene Christian University
Donald Isenhower, Tyler Hague
Rusty Towell, Shon Watson

Academia Sinica
Wen-Chen Chang, Yen-Chu Chen
Shiu Shiuan-Hal, Da-Shung Su

Argonne National Laboratory
John Arrington, Don Geesaman*
Kawtar Hafidi, Roy Holt, Harold Jackson
David Potterveld, Paul E. Reimer*
Josh Rubin

KEK
Shinya Sawada

Ling-Tung University
Ting-Hua Chang

Los Alamos National Laboratory
Christian Aidala, Gerry Garvey, Mike Leitch, Han Liu, Ming Liu
Pat McGaughey, Joel Moss, Andrew Puckett

National Kaohsiung Normal University
Rurngsheng Guo, Su-Yin Wang

University of New Mexico
Imran Younus

RIKEN
Yoshinori Fukao, Yuji Goto, Atsushi Taketani, Manabu Togawa

Rutgers University
Lamiaa El Fassi, Ron Gilman, Ron Ransome, Brian Tice, Ryan Thorpe

Makins, R. Evan McClellan, Jen-Chieh Peng

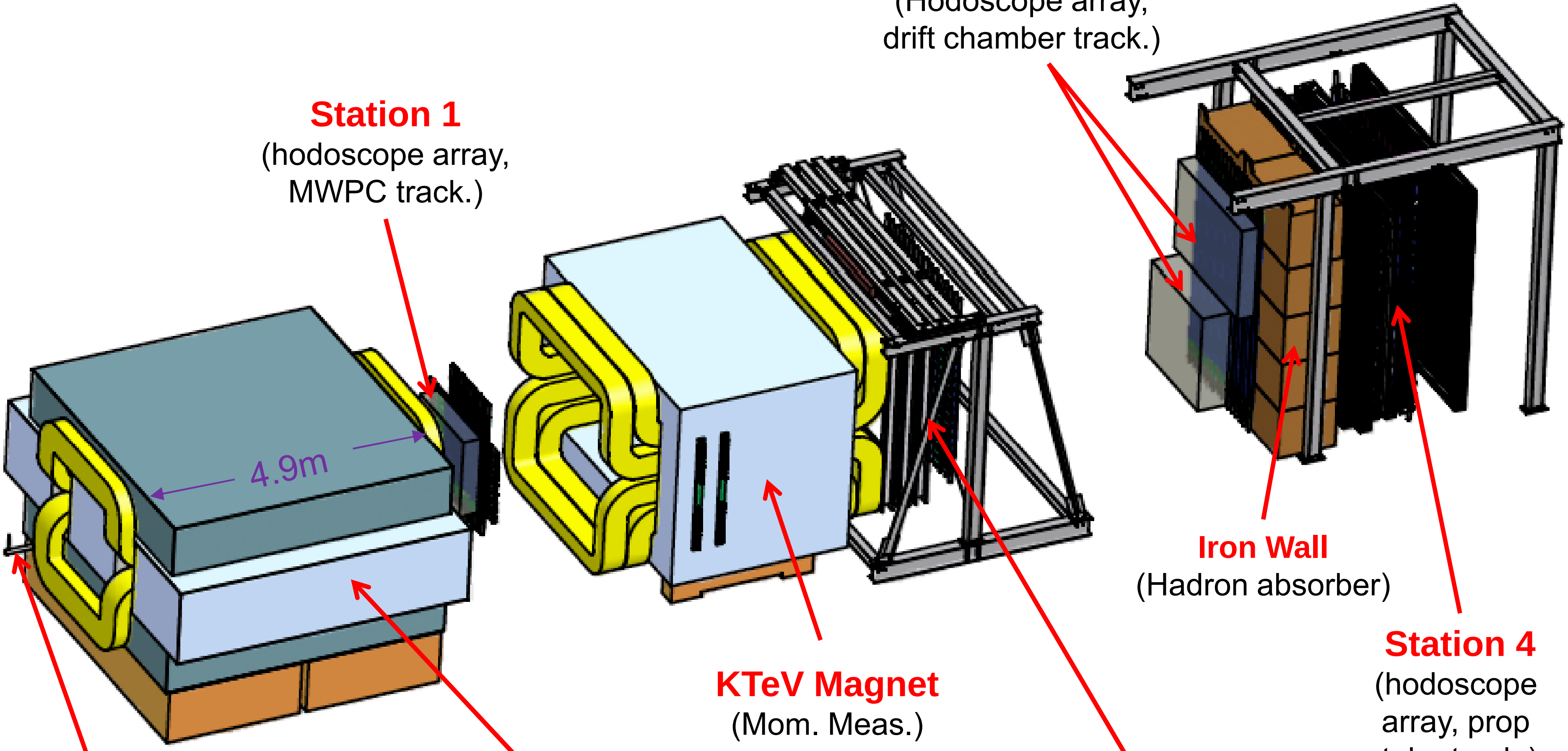
*Co-Spokespersons

Jan, 2009

Collaboration contains many of the E-866/NuSea groups and several new groups (total 17 groups as of Aug 2011)

Drell-Yan Spectrometer for E906

(25m long)



Targets
(liquid H_2, D_2,
and solid targets)

Solid Iron Magnet
(focusing magnet,
hadron absorber and
beam dump)

Station 1
(hodoscope array,
MWPC track.)

KTeV Magnet
(Mom. Meas.)

Station 2
(hodoscope array,
drift chamber track.)

Station 3
(Hodoscope array,
drift chamber track.)

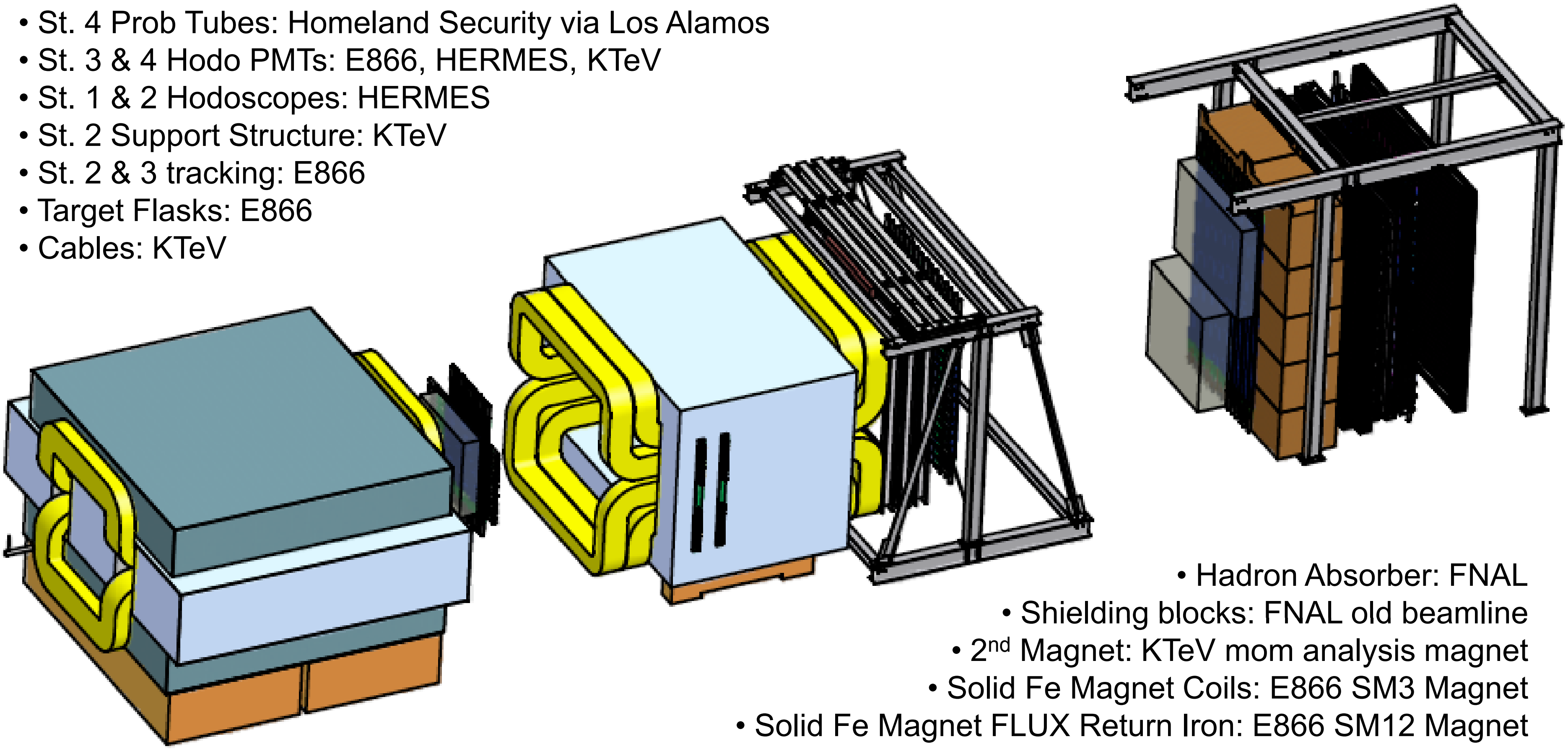
Iron Wall
(Hadron absorber)

Station 4
(hodoscope
array, prop
tube track.)

Drell-Yan Spectrometer for E906

(Reduce, Reuse, Recycle)

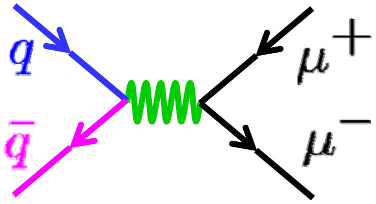
- St. 4 Prob Tubes: Homeland Security via Los Alamos
- St. 3 & 4 Hodo PMTs: E866, HERMES, KTeV
- St. 1 & 2 Hodoscopes: HERMES
- St. 2 Support Structure: KTeV
- St. 2 & 3 tracking: E866
- Target Flasks: E866
- Cables: KTeV

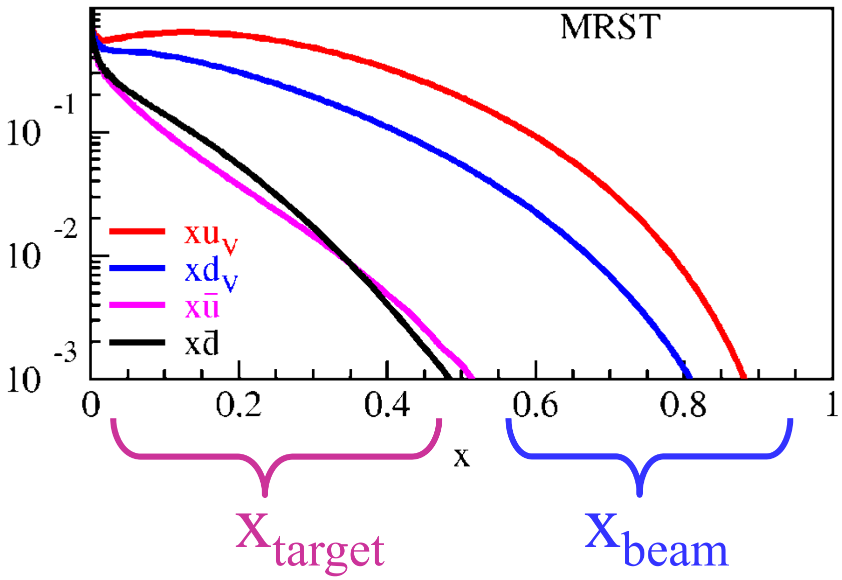


- Hadron Absorber: FNAL
- Shielding blocks: FNAL old beamline
- 2nd Magnet: KTeV mom analysis magnet
- Solid Fe Magnet Coils: E866 SM3 Magnet
- Solid Fe Magnet FLUX Return Iron: E866 SM12 Magnet

Expect to start collecting data: November 2011

Fixed Target Drell-Yan: What we really measure

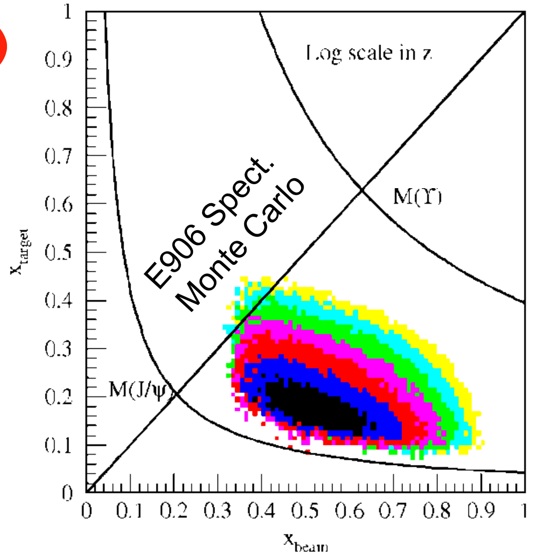




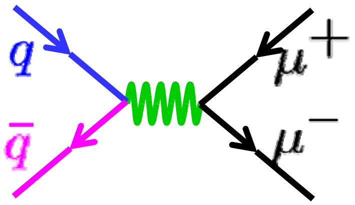
- Measure yields of $\mu^+\mu^-$ pairs from different targets
- Reconstruct p_γ, $M^2_\gamma = x_b x_t s$
- Determine x_b, x_t
- Measure differential cross section

$$\frac{d^2\sigma}{dx_b\,dx_t} = \frac{4\pi\alpha^2}{x_b x_t s}\sum_{q\in\{u,d,s,\ldots\}} e_q^2\left[\bar{q}_t(x_t)\,q_b(x_b) + \cancel{q_t(x_t)\,\bar{q}_b(x_b)}\right]$$

- 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

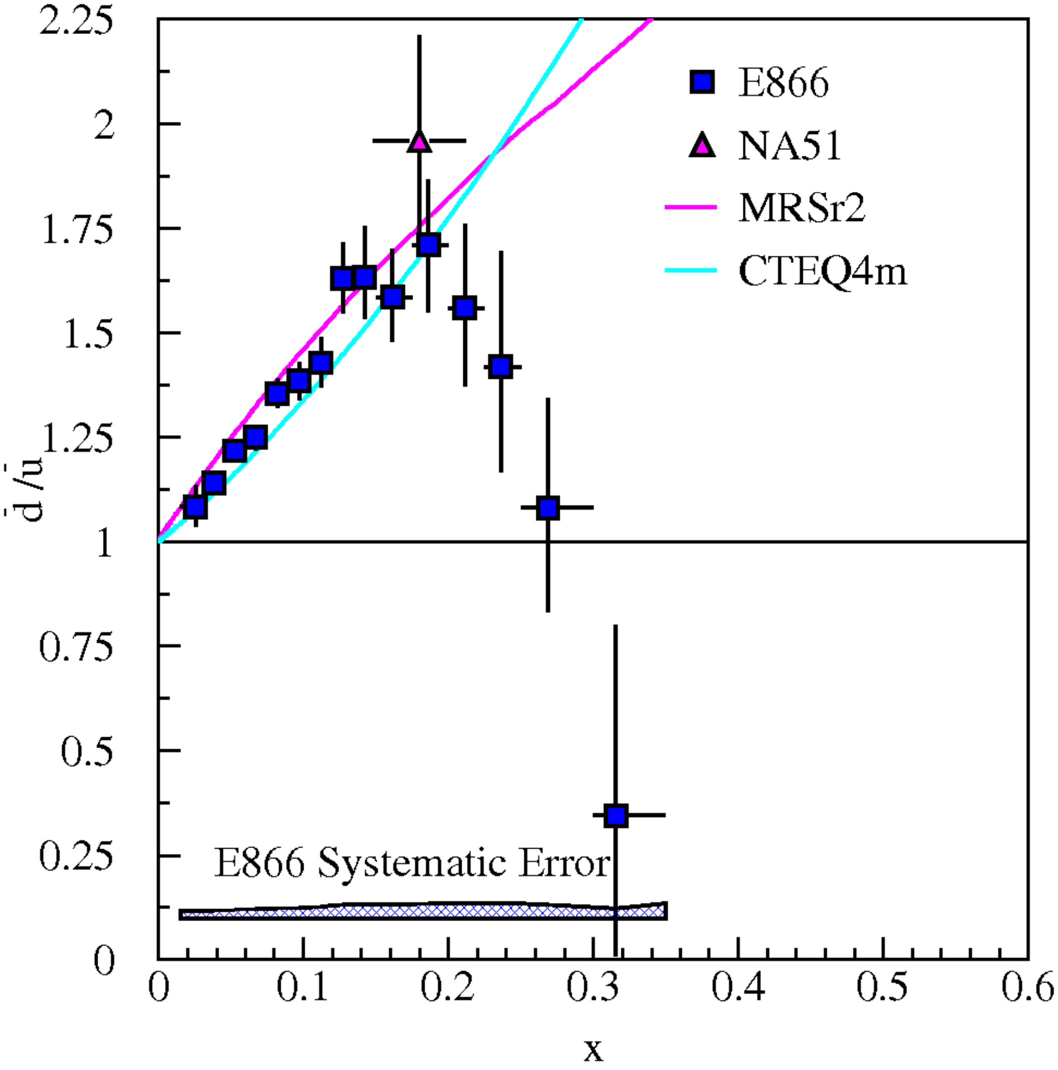


Fixed Target Drell-Yan: What we really measure - II



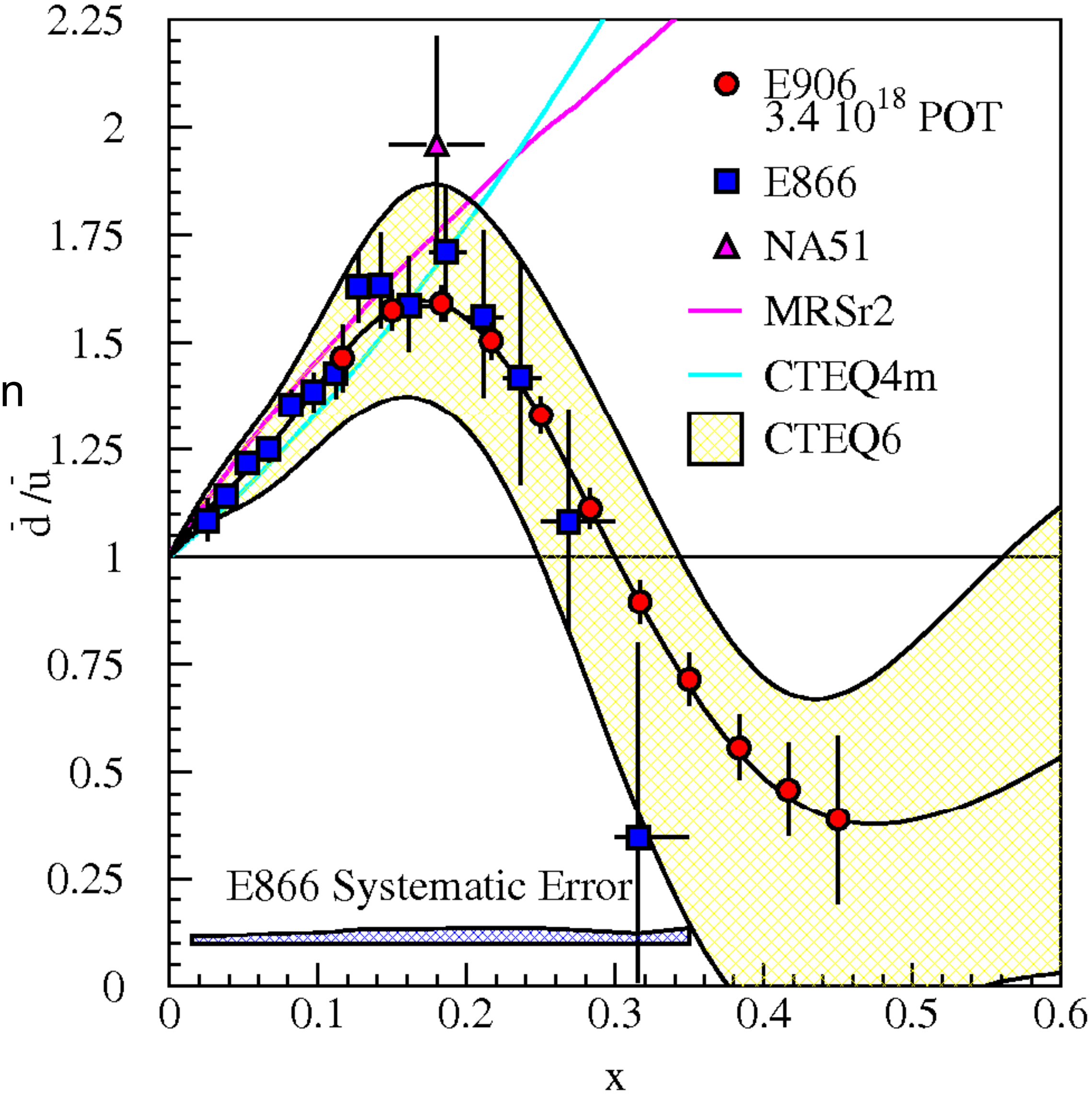
- Measure cross section ratios on Hydrogen, Deuterium (and Nuclear) Targets

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



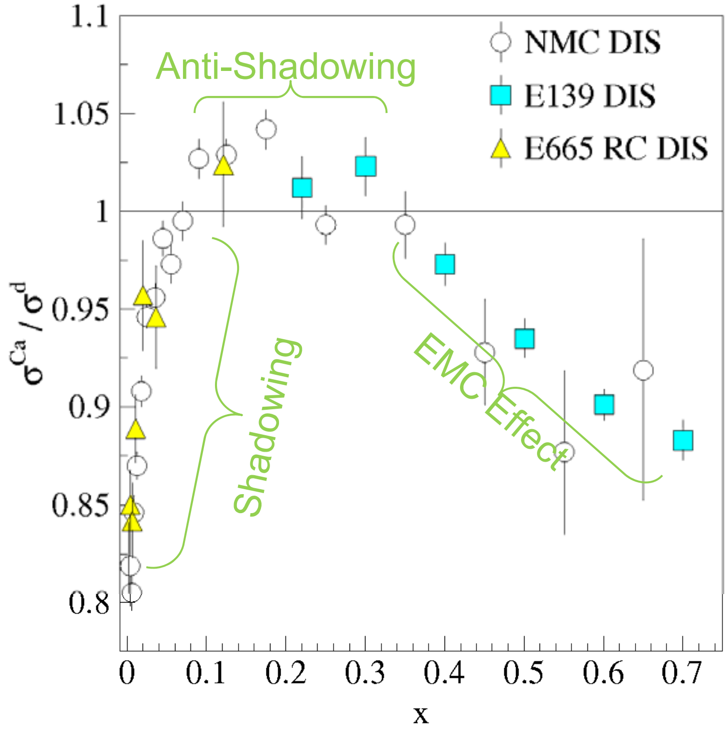
SeaQuest Projections for d-bar/u-bar Ratio

- 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 (I_{inst} =320 nA)
  - 1 x 10^{13} protons/spill

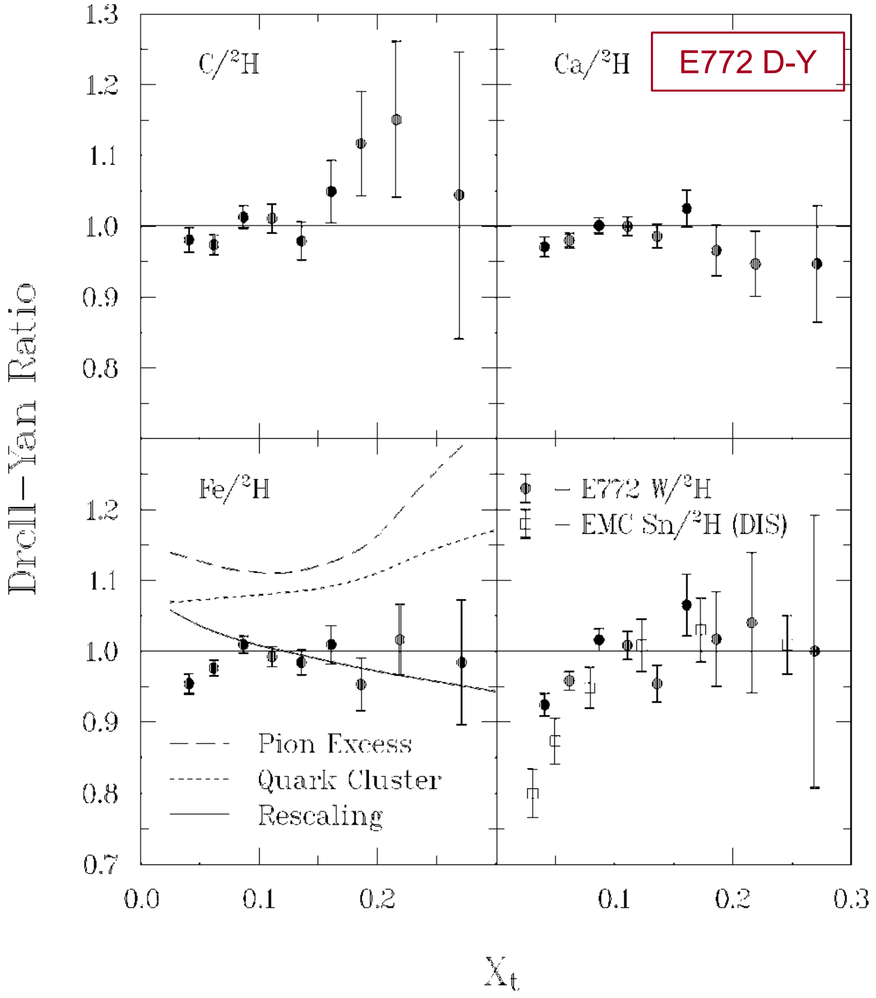


Sea quark distributions in Nuclei

- 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)

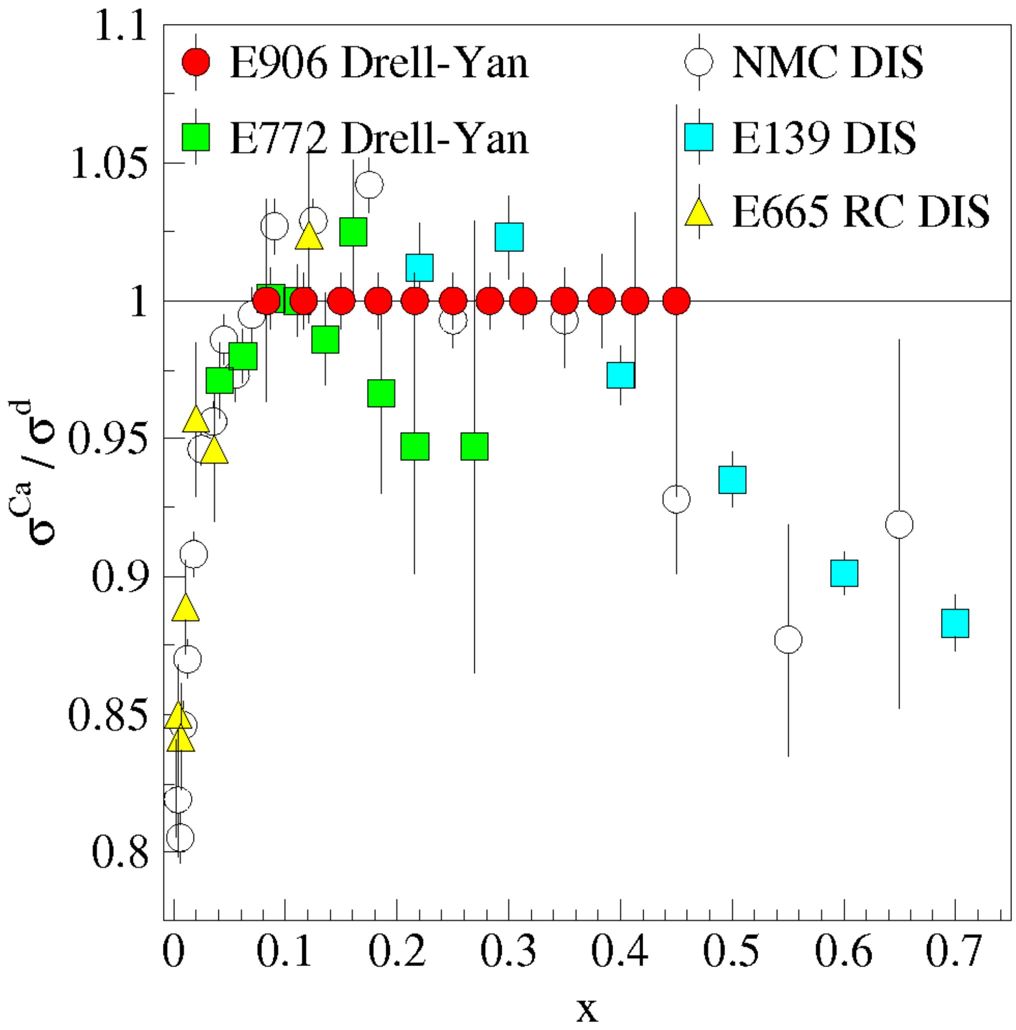


Alde *et al* (Fermilab E772) Phys. Rev. Lett. **64** 2479 (1990)



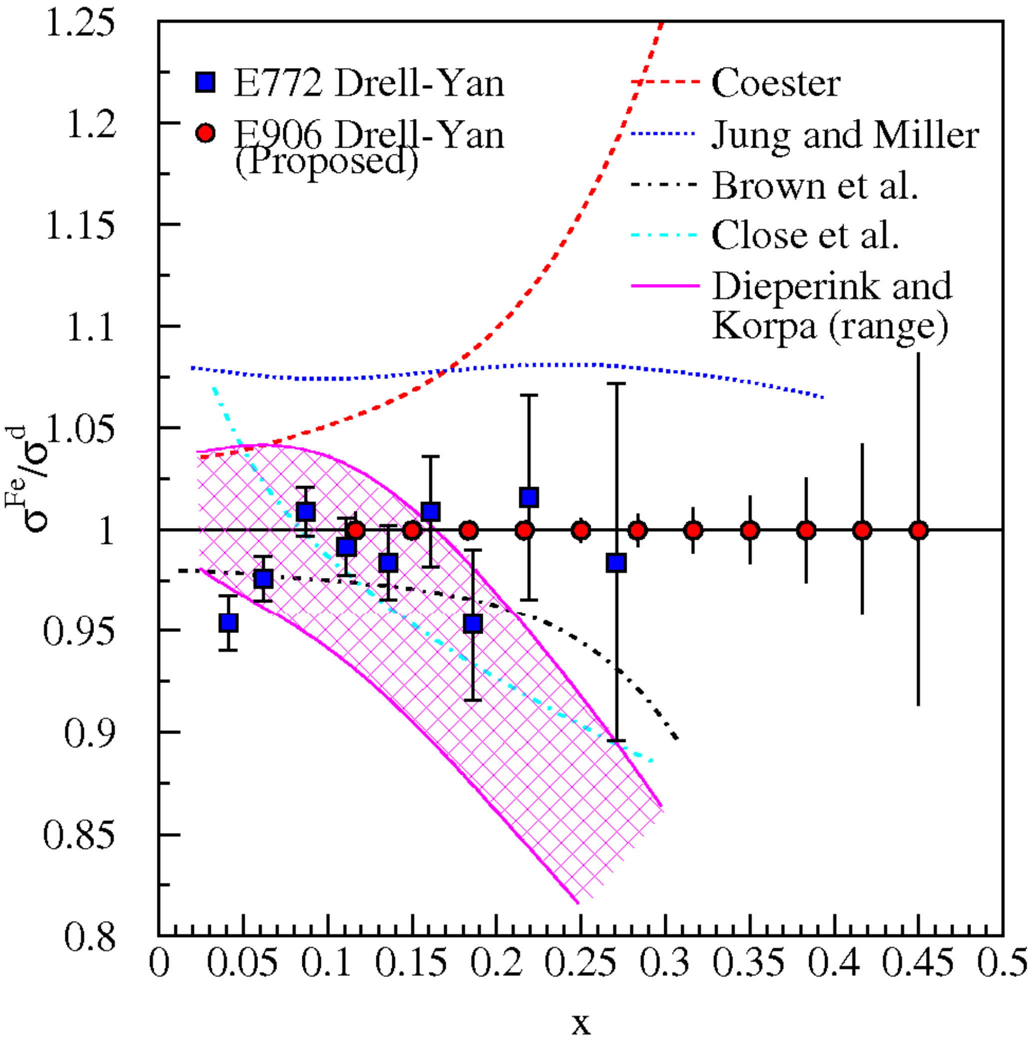
Sea quark distributions in Nuclei - II

- 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?

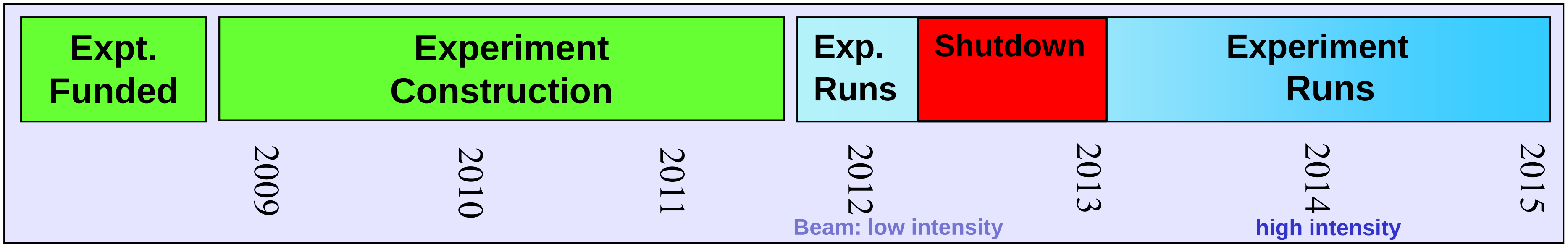
- The binding of nucleons in a nucleus is expected to be governed by the exchange of virtual "Nuclear" mesons.
- No antiquark enhancement seen in Drell-Yan (Fermilab E772) data.
- Contemporary models predict large effects to antiquark distributions as x increases
- Models must explain both DIS-EMC effect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



If large nuclear effects were found
→ nuclear effects may be important in D/H

Fermilab Seaquest Timelines

- Fermilab PAC approved the experiment in 2001, but experiment was not scheduled due to concerns about "proton economics"
- Fermilab Stage II approval in December 2008
- Expect first beam in November 2011 (for 2 years of data collection)


Expt. Funded

Experiment Construction

Exp. Runs

Shutdown

Experiment Runs

2009 2010 2011 2012 2013 2014 2015

Beam: low intensity

high intensity

Aug 2011

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

➡ significant interest from collaboration for continued program:

- Polarized beam in Main Injector
- Polarized Target at NM4

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)
      - – valence quark effects expected to be large
      - – sea quark effects might be small
    - ✓ transversity $\otimes$ Boer-Mulders function
    - ✓ baryon production, incl. pseudoscalar and vector meson production, elastic scattering, two-particle correlations, J/ψ and charm production
  - ➡ 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

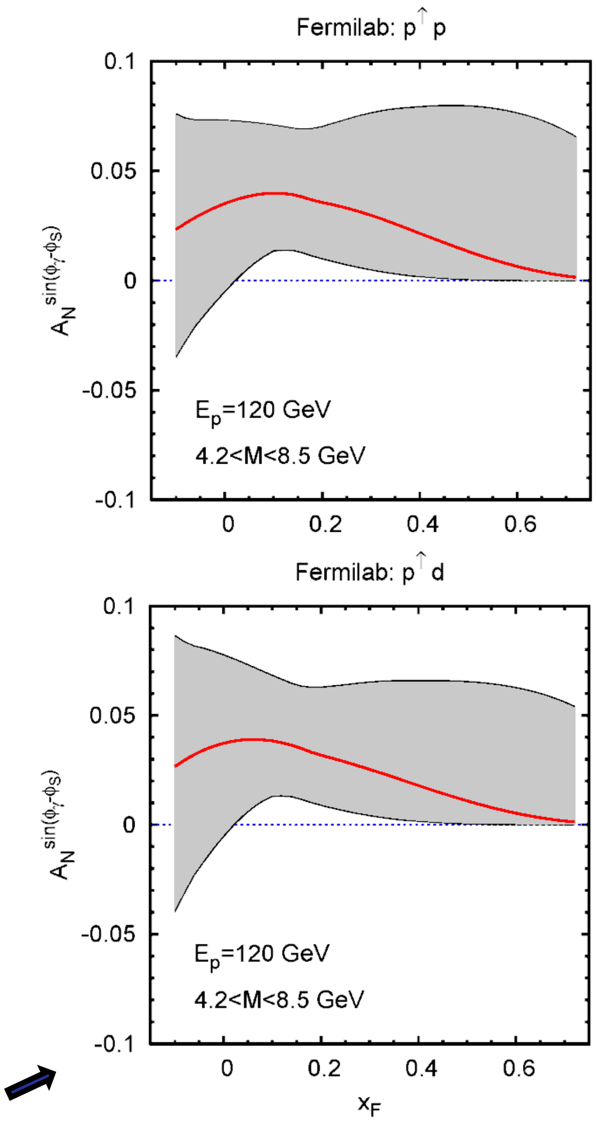
➡ leads to sign change

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

➡ fundamental prediction of QCD

(goes to heart of gauge formulation of field theory)

Predictions based on fit to SIDIS data



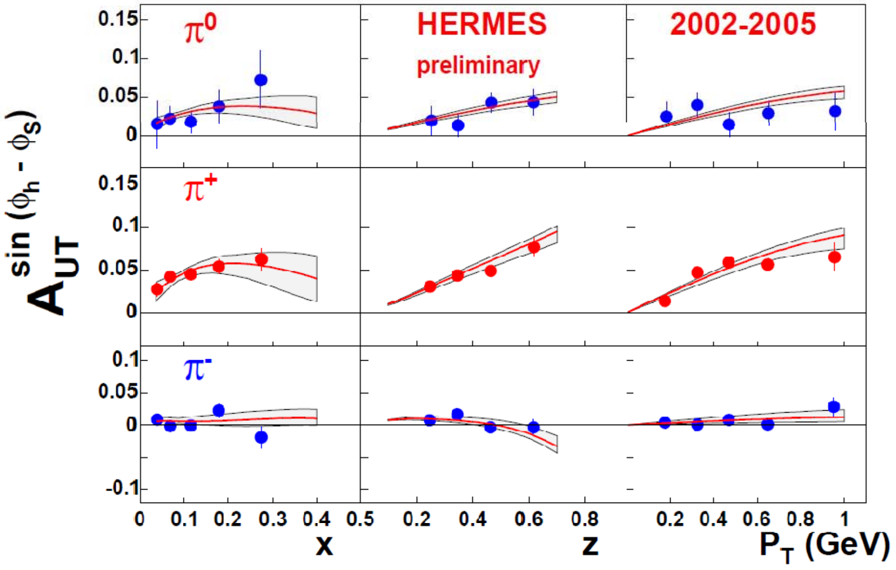
FNAL
120 GeV
polarized beam
√s ~ 15 GeV
(hydrogen)

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

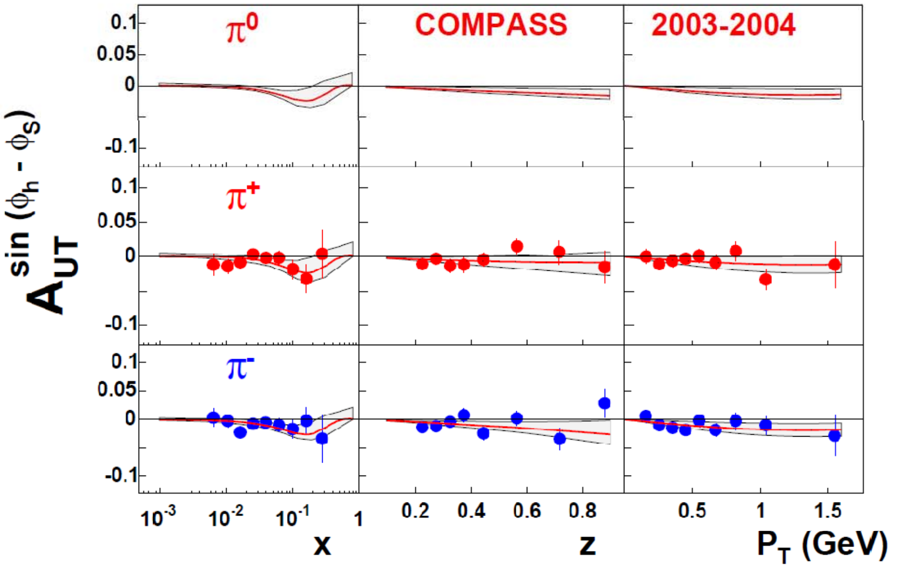
Anselmino et al. priv. comm. 2010

Sivers Asymmetry Measurements

HERMES (p)



COMPASS (d)

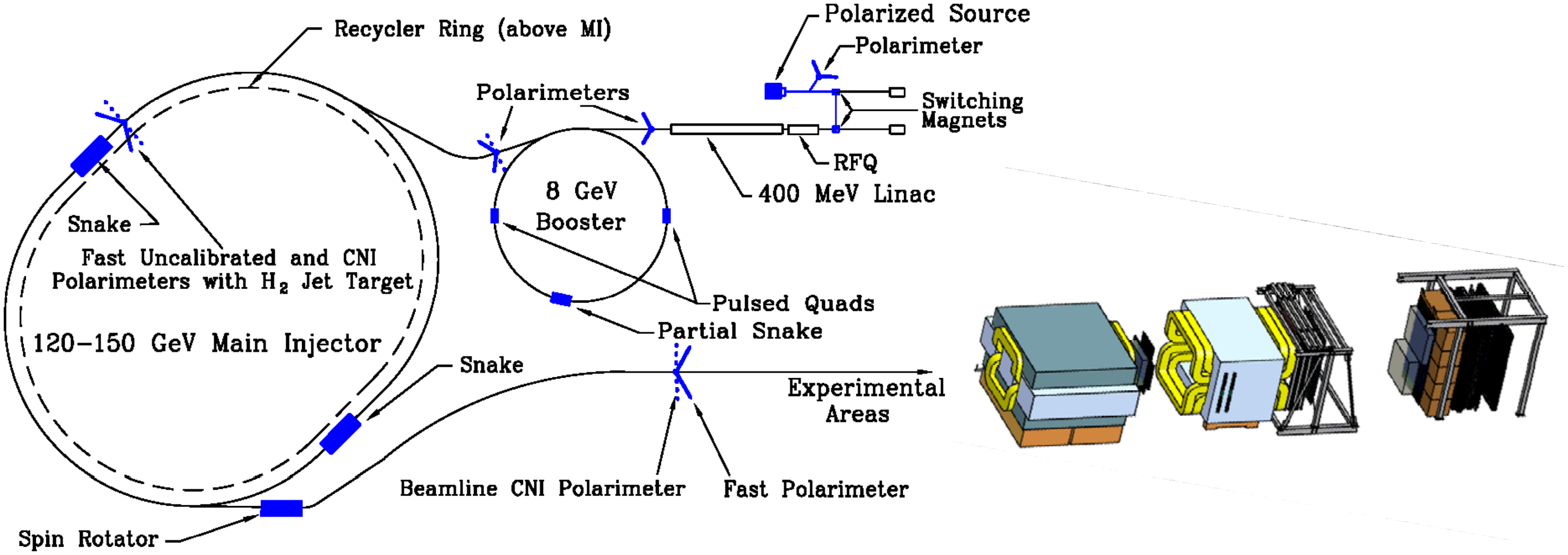


Anselmino et al. EPJA 39, 89 (2009)

- Global fit to sin ($\phi_h - \phi_S$) asymmetry in SIDIS (HERMES, COMPASS)
  - ➡ u- and d-Sivers DF almost equal size, but different sign (d slightly larger)
- Comparable measurements needed for single spin asymmetries in Drell-Yan process
- BUT: COMPASS (p) data (2007 & 2100) smaller Sivers asym. than HERMES
  - ➡ maybe due to *y* or *z* dependence?
  - ➡ do global fits with all available data

Polarized Drell-Yan at Fermilab Main Injector

- Polarize Beam in Main Injector (A. Krisch's talk)



- Use SeaQuest di-muon Spectrometer
  - ➡ fixed target experiment
  - ➡ luminosity: $L_{av} = 3.4 \times 10^{35}$ /cm^2/s
    - ✓ $I_{av} = 1.6 \times 10^{11}$ p/s (=26 nA)
    - ✓ $N_p = 2.1 \times 10^{24}$ /cm^2
  - ➡ approved for 2-3 years of running: 3.4×10^{18} pot
  - ➡ by 2015: fully understood, optimized for Drell-Yan, and ready to take pol. beam

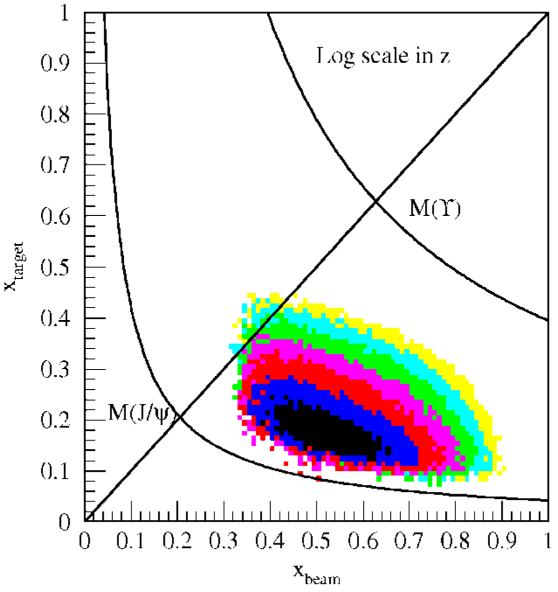
Polarized Drell-Yan at Fermilab Main Injector - II

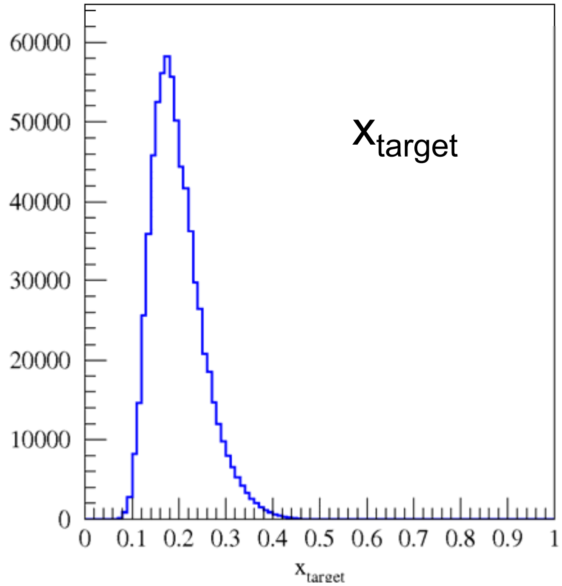
- SeaQuest di-muon Spectrometer
  - ➡ luminosity: $L_{av} = 3.4 \times 10^{35}$ /cm^2/s [$I_{av} = 1.6 \times 10^{11}$ p/s (=26 nA) / $N_p = 2.1 \times 10^{24}$ /cm^2]
  - ➡ approved for 3.4×10^{18} pot

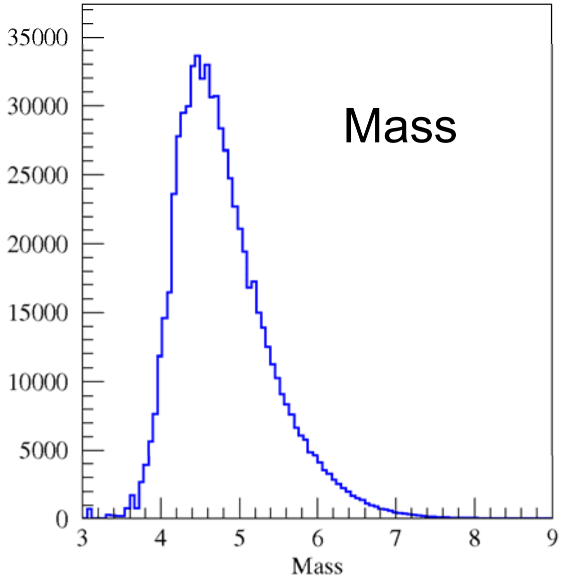
- Polarized Beam in Main Injector
  - ➡ use Seaquest spectrometer
  - ➡ use SeaQuest target
    - ✓ liquid H_2 target can take $I_{av} = \sim 5 \times 10^{11}$ p/s (=80 nA)
  - ➡ 1 mA at polarized source can deliver about $I_{av} = \sim 1 \times 10^{12}$ p/s (=150 nA) for 100% of available beam time (A. Krisch: Spin@Fermi report in (Aug 2011))
    - ✓ 26 μs linac pulses, 15 Hz rep rate, 12 turn injection into booster, 6 booster pulses into Recycler Ring, followed by 6 more pulses using slip stacking in MI
    - ✓ 1 MI pulse = 1.9×10^{12} p
    - ✓ using three 2-s cycles (1.33-s ramp time, 0.67-s slow extraction) /min (=10% of beam time): → 2.8×10^{12} p/s (=450 nA) instantaneous beam current , and $I_{av} = \sim 0.95 \times 10^{11}$ p/s (=15 nA)
  - ➡ Scenarios:
    - ✓ $L = 2.0 \times 10^{35}$ /cm^2/s (10% of available beam time: I_{av} = 15 nA)
    - ✓ **$L = 1 \times 10^{36}$ /cm^2/s** (50% of available beam time: I_{av} = 75 nA)
  - ➡ *x*-range:
    - ✓ $x_b = 0.3 - 0.9$ (valence quarks) $x_t = 0.1 - 0.4$ (sea quarks)

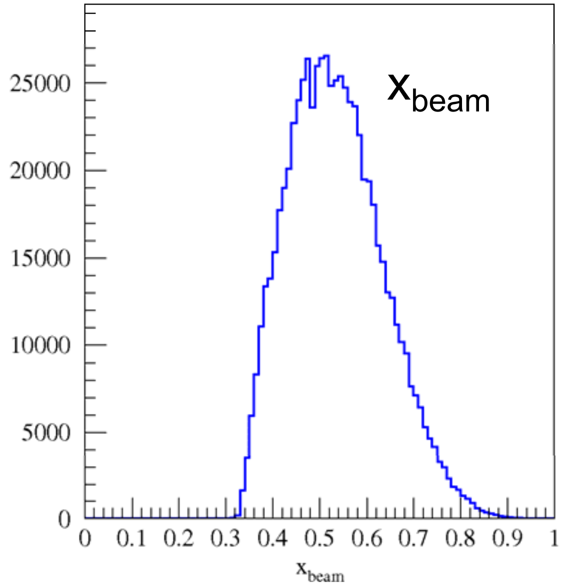
SeaQuest: Drell-Yan Acceptance

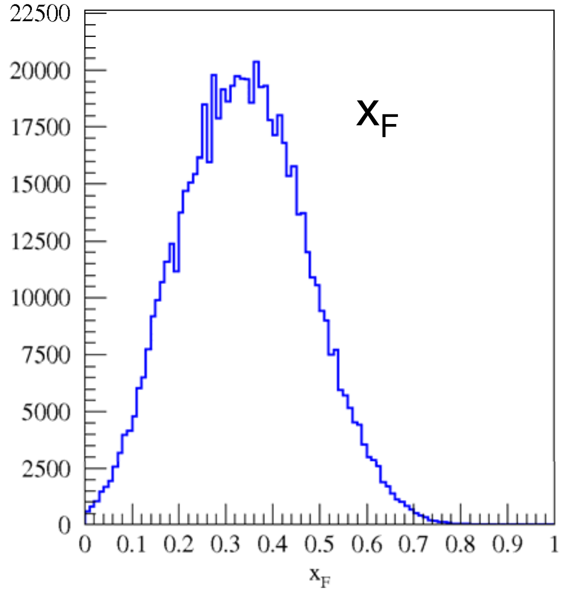
- Programmable trigger removes likely J/ψ events
- Transverse momentum acceptance to above 2 GeV
- Spectrometer could also be used for J/ψ, ψ^{i} studies



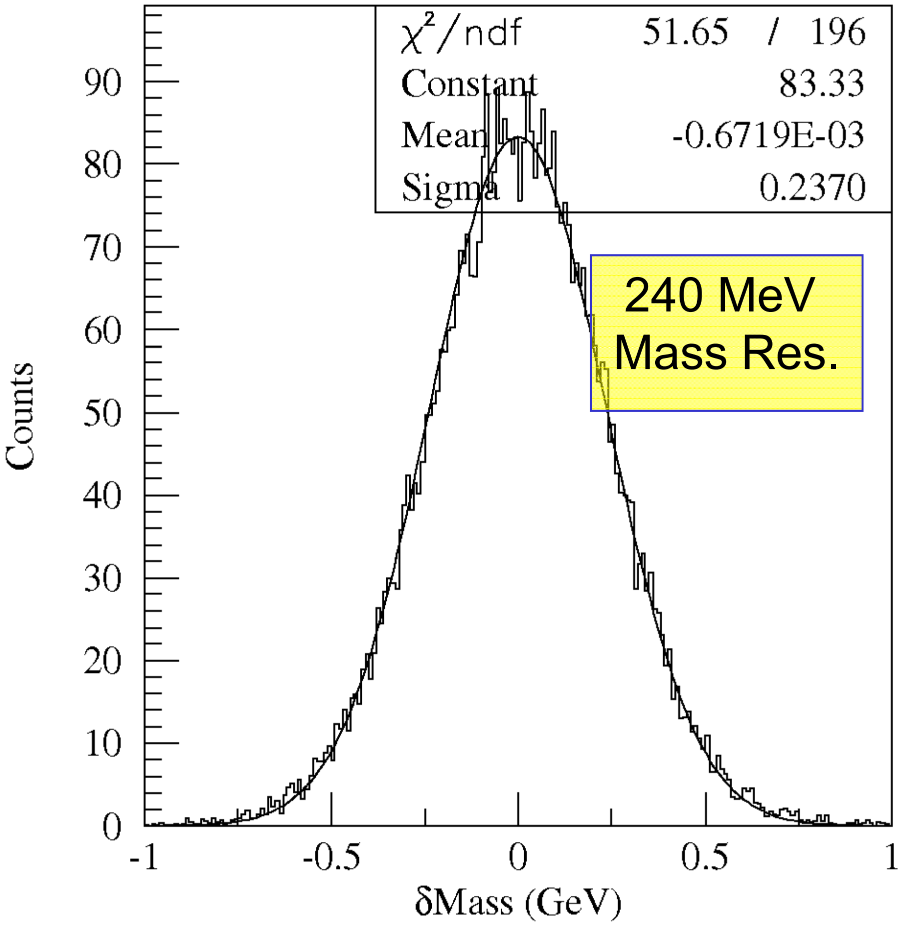




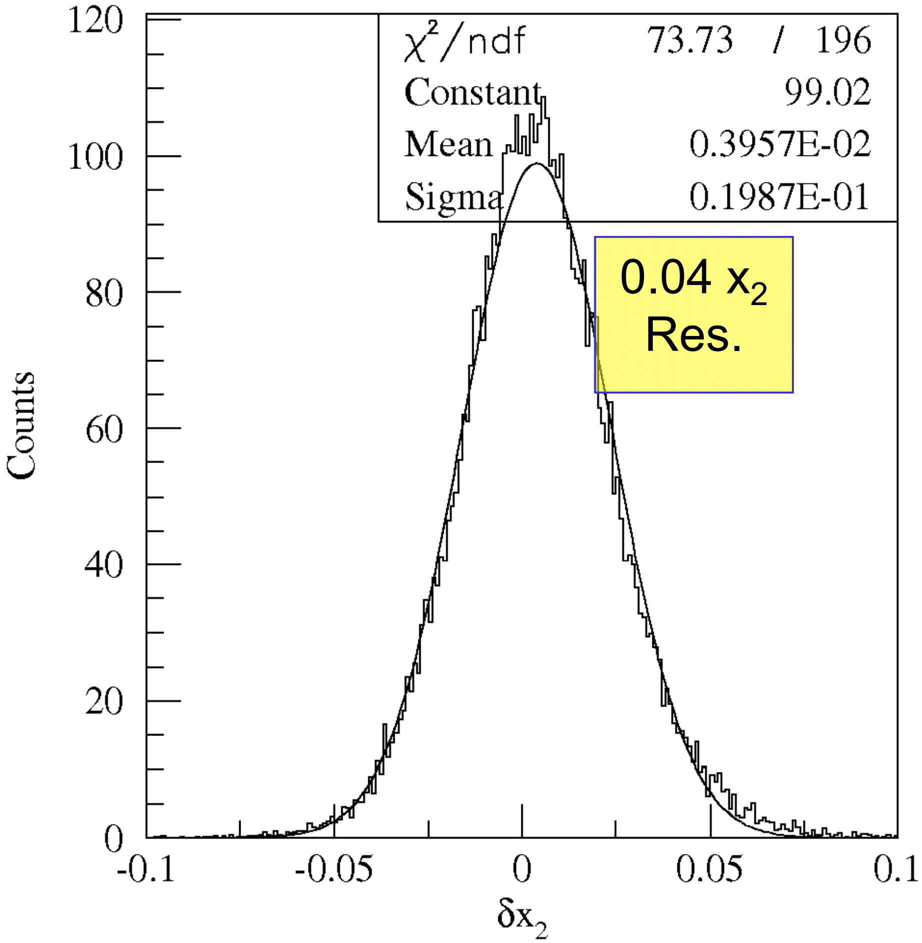




SeaQuest: Detector Resolution



240 MeV Mass Res.

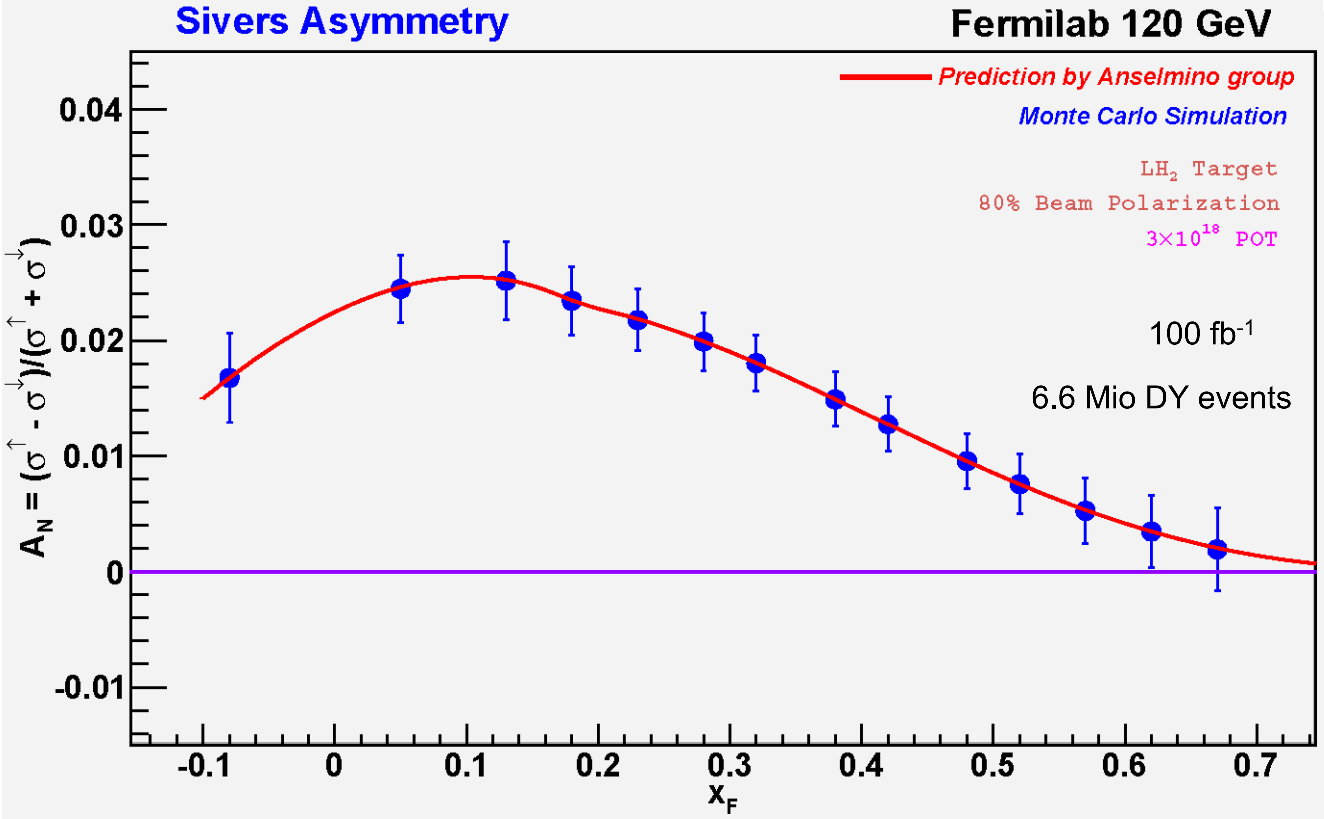


0.04 x_2 Res.

- Triggered Drell-Yan events

Polarized Drell-Yan at Fermilab Main Injector - III

- Experimental Sensitivity
  - ➡ luminosity: $L_{av} = 2 \times 10^{35}$ (10% of available beam time: I_{av} = 15 nA)
  - ➡ 100 fb^{-1} for 5×10^5 min: (= 2 yrs at 50% efficiency)



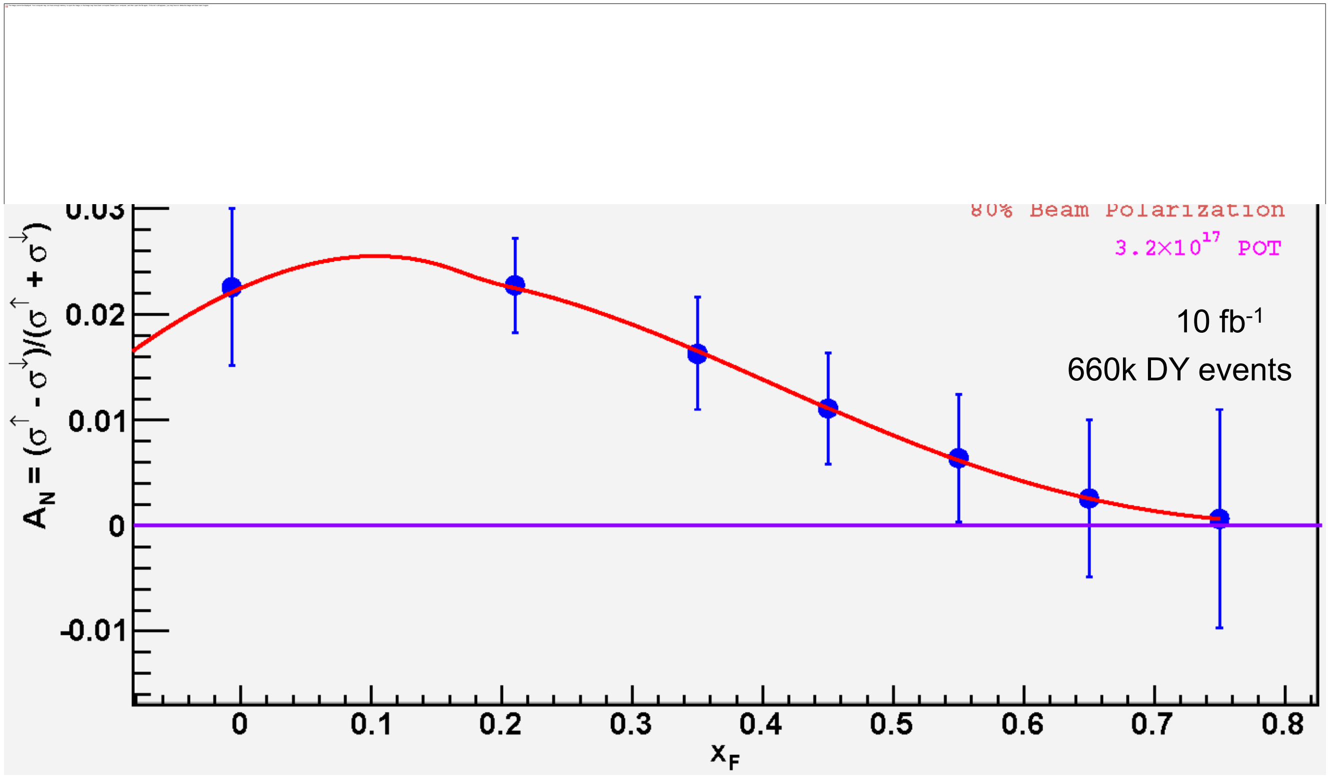
Note:

$$A_N = \frac{2}{\pi} A_{TU}^{\sin(\phi-\phi_S)}$$

➡ Can measure not only sign, but also the size & shape of the Sivers function !

Polarized Drell-Yan at Fermilab Main Injector - III

- What if?
  - ➡ luminosity: L_{av} = 2×10^{34} (= 10x lower than expected)
  - ➡ 10 fb^{-1} for 5×10^5 min: (= 2 yrs at 50% efficiency)



- ➡ Can still measure sign, AND shape of the Sivers function, with 10x less L_{int} !
- ➡ What if the sign changes, BUT $\left| f_{1T}^{\perp q} \right|_{DIS} \neq \left| f_{1T}^{\perp q} \right|_{D-Y}$?

Planned Polarized Drell-Yan Experiments

experiment	particles	energy	x_1 or x_2	luminosity	timeline
COMPASS (CERN)	$\pi^{\pm} + p^{\uparrow}$	160 GeV $\sqrt{s}$ = 17.4 GeV	$x_2 = 0.2 – 0.3$ $x_2 \sim 0.05$ (low mass)	2×10^{32} cm^{-2} s^{-1}	2014
PAX (GSI)	$p^{\uparrow} + p_{par}$	collider $\sqrt{s}$ = 14 GeV	$x_1 = 0.1 – 0.9$	2×10^{30} cm^{-2} s^{-1}	>2017
PANDA (GSI)	$p_{par} + p^{\uparrow}$	15 GeV $\sqrt{s}$ = 5.5 GeV	$x_2 = 0.2 – 0.4$	2×10^{32} cm^{-2} s^{-1}	>2016
J-PARC	$p^{\uparrow} + p$	50 GeV $\sqrt{s}$ = 10 GeV	$x_1 = 0.5 – 0.9$	1×10^{35} cm^{-2} s^{-1} ?	>2015 ?
NICA (JINR)	$p^{\uparrow} + p$	collider $\sqrt{s}$ = 20 GeV	$x_1 = 0.1 – 0.8$	1×10^{30} cm^{-2} s^{-1}	>2014
PHENIX (RHIC)	$p^{\uparrow} + p$	collider $\sqrt{s}$ = 500 GeV	$x_1 = 0.05 – 0.1$	2×10^{32} cm^{-2} s^{-1}	>2018
RHIC internal target phase-1	$p^{\uparrow} + p$	250 GeV $\sqrt{s}$ = 22 GeV	$x_1 = 0.25 – 0.4$	2×10^{33} cm^{-2} s^{-1}	>2015
RHIC internal target phase-1	$p^{\uparrow} + p$	250 GeV $\sqrt{s}$ = 22 GeV	$x_1 = 0.25 – 0.4$	3×10^{34} cm^{-2} s^{-1}	>2018
A_nDY RHIC (IP-2)	$p^{\uparrow} + p$	collider $\sqrt{s}$ = 500 GeV	$x_1 = 0.1 - 0.3$	2×10^{32} cm^{-2} s^{-1}	2013
SeaQuest (unpol.) (FNAL)	$p + p$	120 GeV $\sqrt{s}$ = 15 GeV	$x_1 = 0.3 – 0.9$ $X_2 = 0.1 – 0.45$	3.4×10^{35} cm^{-2} s^{-1}	2011
pol. SeaQuest (FNAL)	$\boldsymbol{p^{\uparrow} + p}$	**120 GeV $\sqrt{s}$ = 15 GeV**	$\boldsymbol{x_1 = 0.3 – 0.9}$	**1×10^{36} cm^{-2} s^{-1}**	**>2014**

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 the sea quarks?
- **What is the structure of nucleonic matter?**
  - ➡ Where are the nuclear pions?
  - ➡ Is anti-shadowing a valence effect?
- **SeaQuest: 2011 - 2014**
  - ➡ significant increase in physics reach
- **Beyond SeaQuest**
  - ➡ Polarized beam at Fermilab Main Injector
  - ➡ Polarized target at Main Injector
  - ➡ high-luminosity Drell-Yan program: complementary to spin programs at RHIC and JLAB