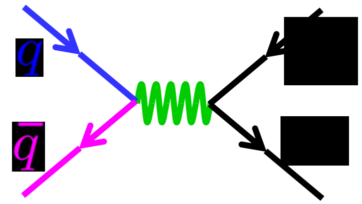
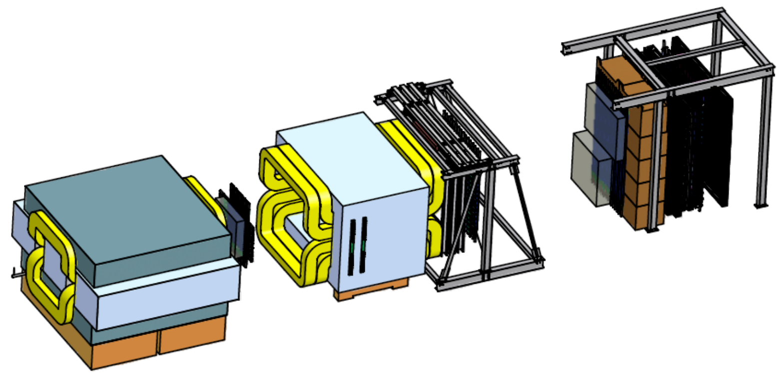
Drell-Yan Scattering at Fermilab:
SeaQuest and Beyond



Wolfgang Lorenzon
UNIVERSITY OF MICHIGAN

(1-September-2011)
Transversity2011 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?



$$f_{1T}^{\perp}|_{DIS} =$$

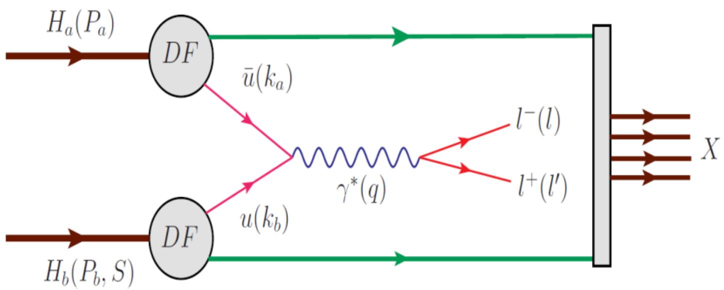
This work is supported by

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

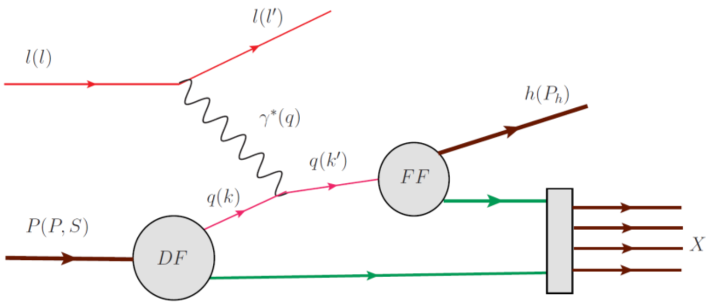
Drell Yan Process

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

Drell-Yan



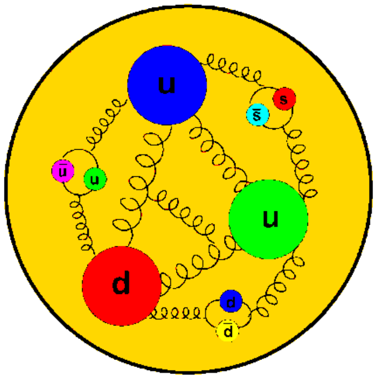
SIDIS



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



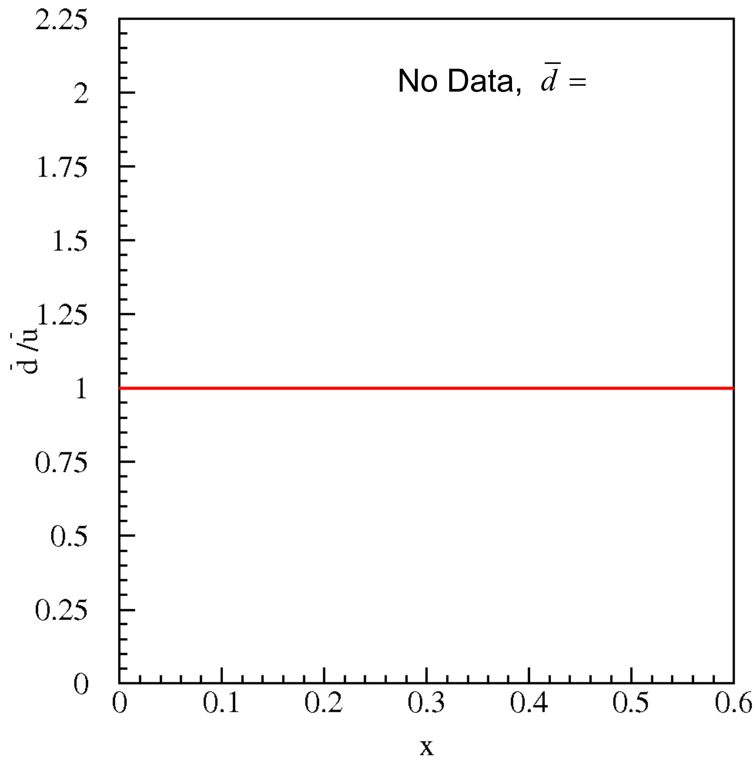
➡ Constituent Quark Model

Pure valence description: proton = 2u + d

➡ Perturbative Sea

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

➡ What does the data tell us?



Flavor Structure of the Proton: Brief History

E866: $\bar{d} >$

- Perturbative Sea

  $\bar{d}(x) =$

- NMC (inclusive DIS)

  $\int$]

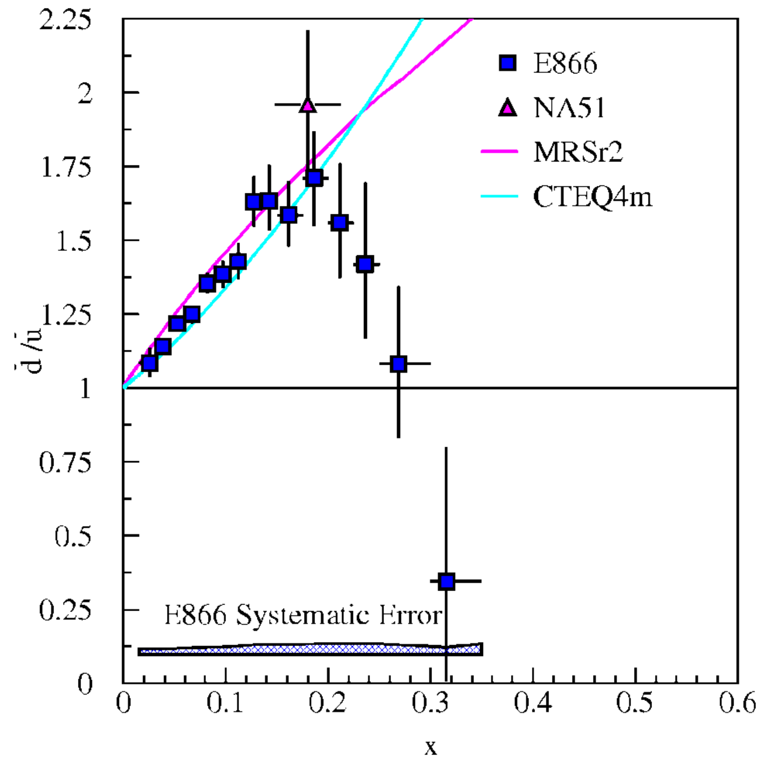
- NA51 (Drell-Yan)

  $\bar{d}(x) >$

- E866/NuSea (Drell-Yan)

  $\bar{d}(x) >$

- What is the origin of the sea



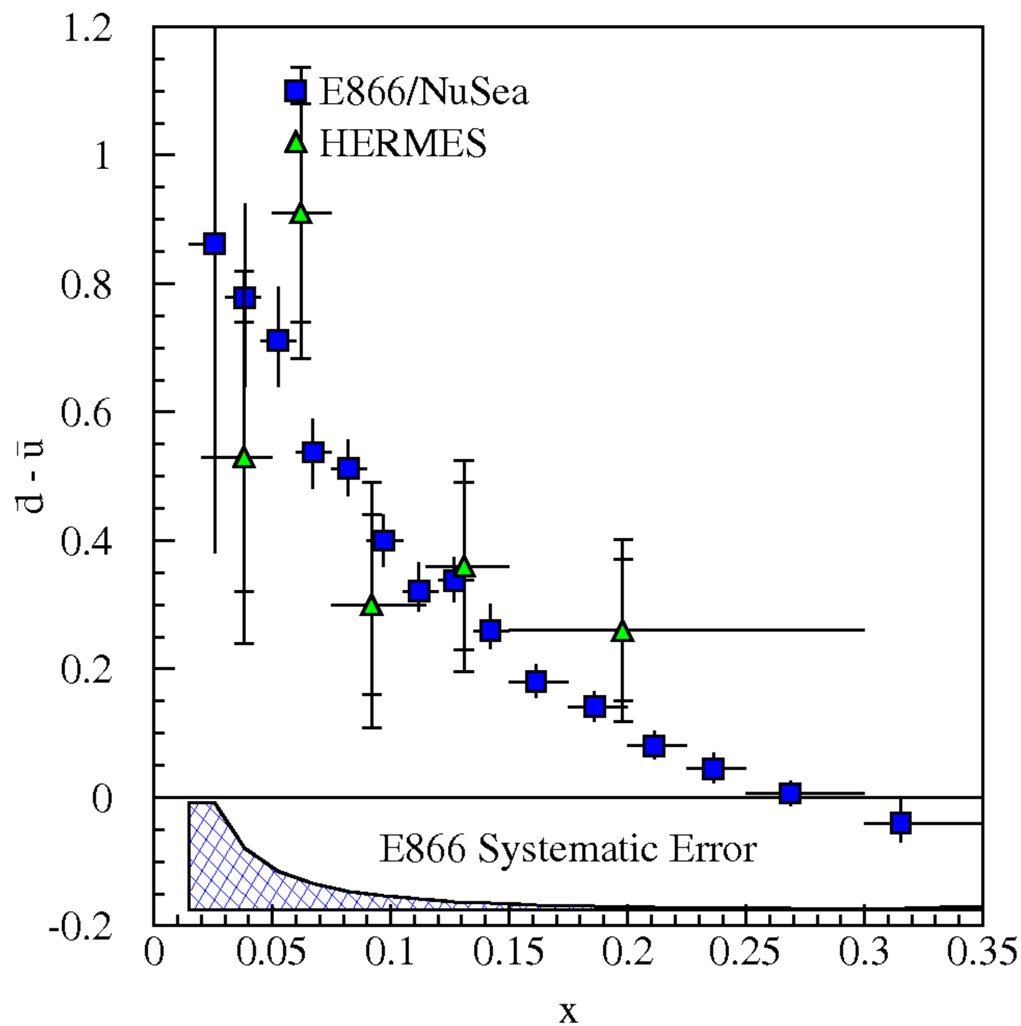
- Knowledge of parton distributions is data driven
  - Sea quark distributions are difficult for Lattice QCD

Flavor Structure of the Proton: What creates Sea?

- There is a gluon splitting component which is symmetric

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

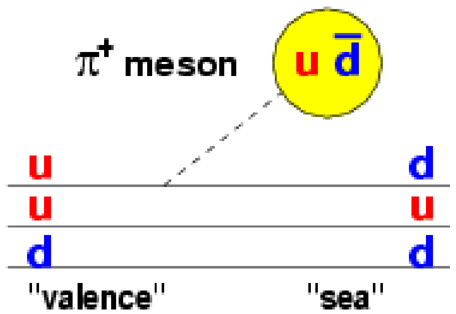
- $\bar{d} -$
  - ➡ Symmetric sea via pair production from gluons subtracts off
  - ➡ No gluon contribution at 1st order in α_s
  - ➡ Non-perturbative models are motivated by the observed difference
- A proton with 3 valence quarks plus glue cannot be right at any scale!!



Flavor Structure of the Proton: Models

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

Meson Cloud Models



Quark sea from cloud of 0^- mesons:

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

Chiral-Quark Soliton Model

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

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

Statistical Model

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

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

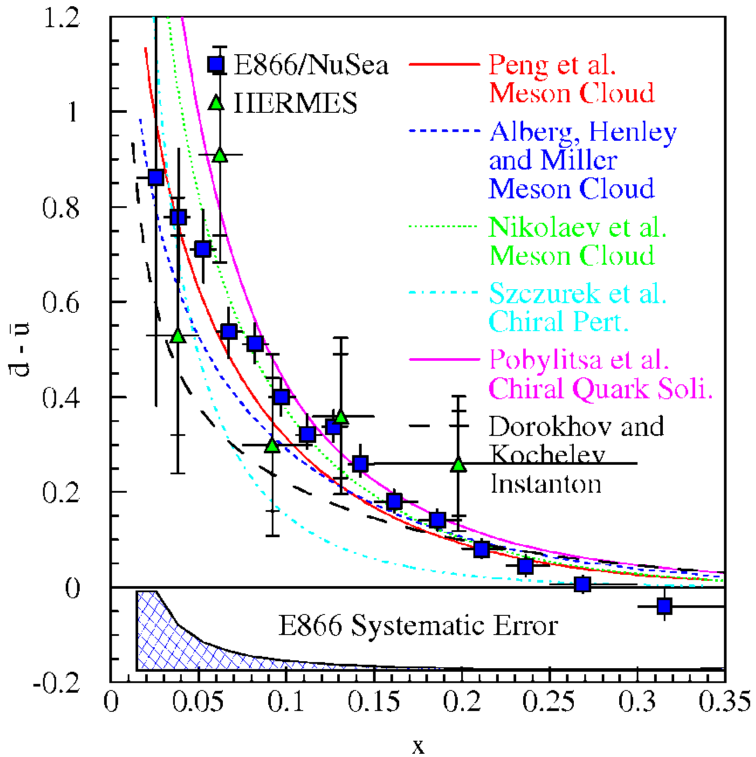
$\Rightarrow$ important constraints on flavor asymmetry for polarization of light sea

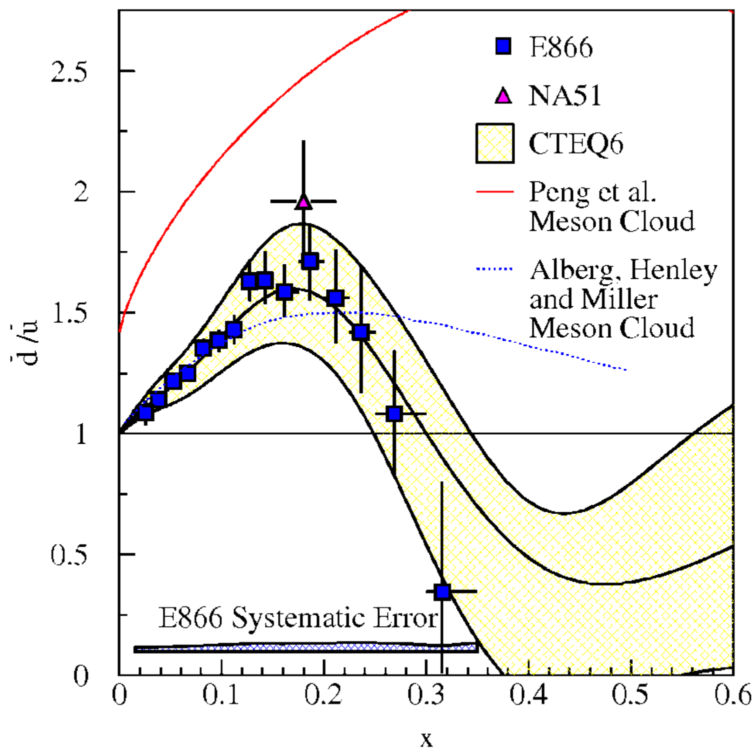
$\Delta \quad =$

$\Delta \quad \cong -\Delta \quad >$

$\Delta \quad < \quad \Delta \quad >$

Flavor Structure of the Proton: What creates Sea?





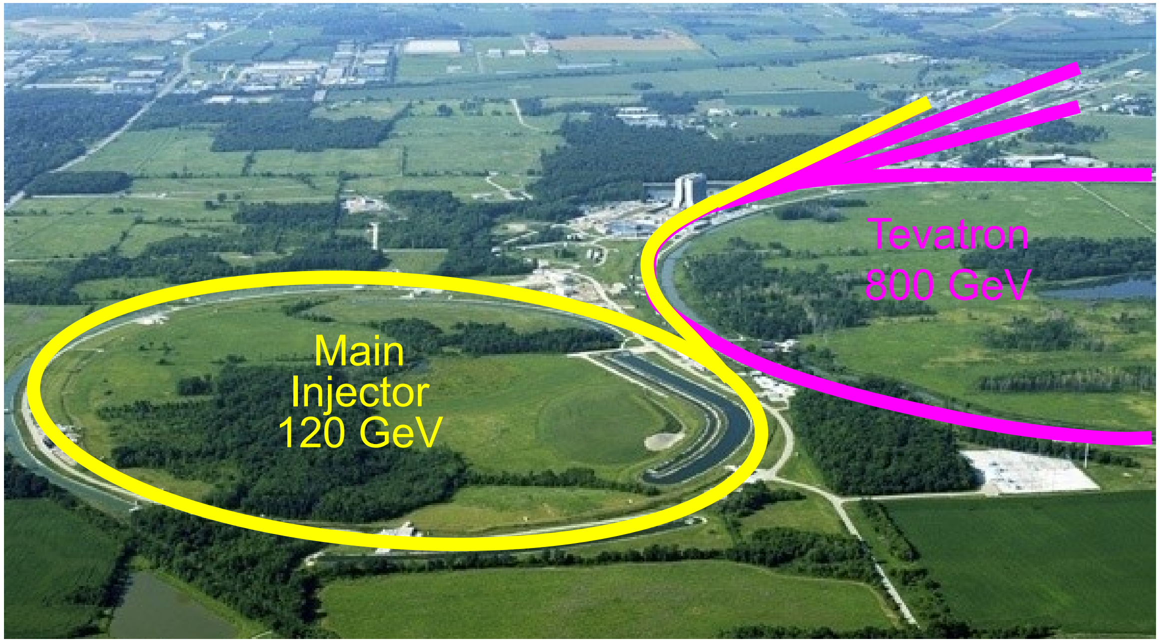
Comparison with models

- 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

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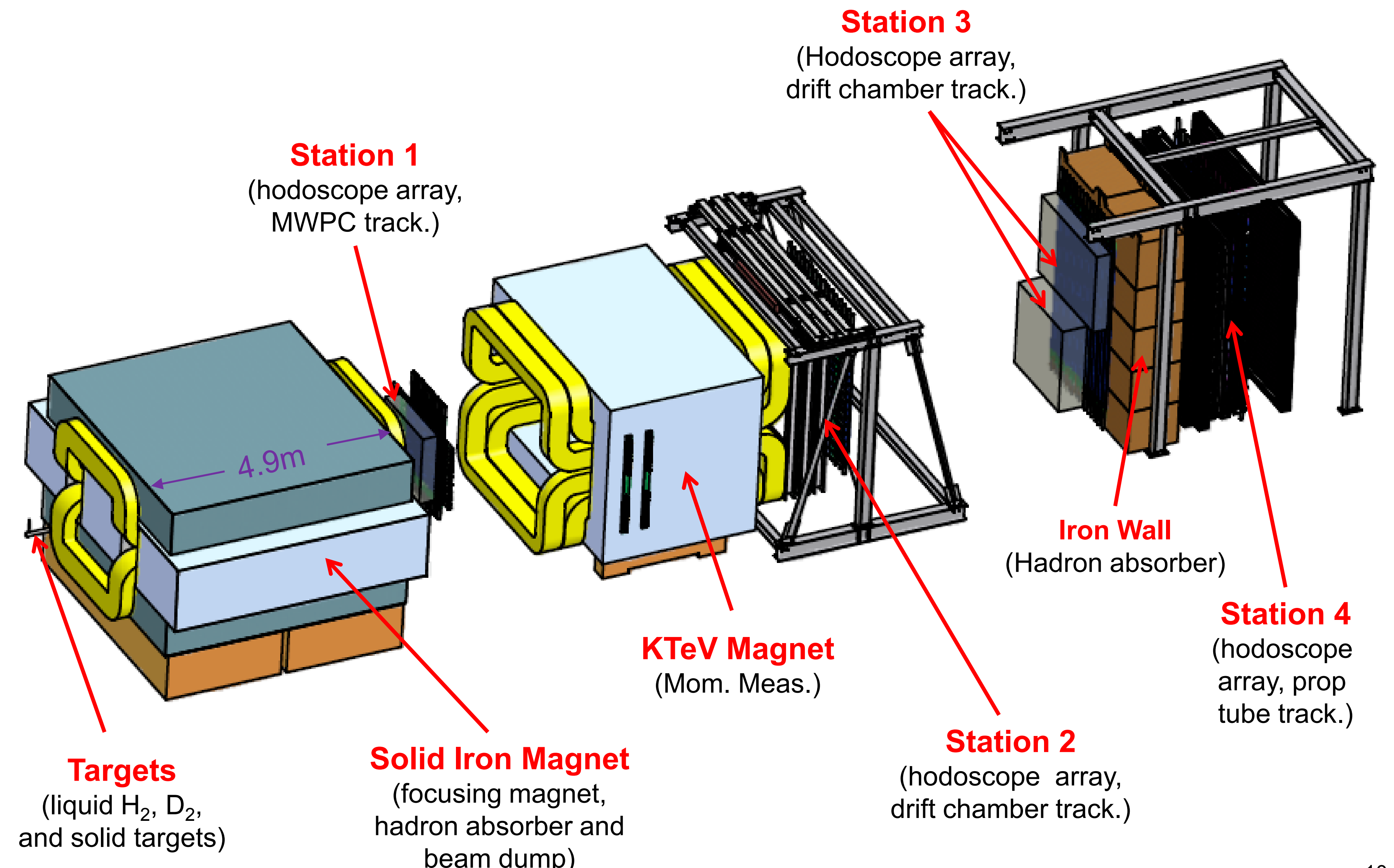
Jan, 2009

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

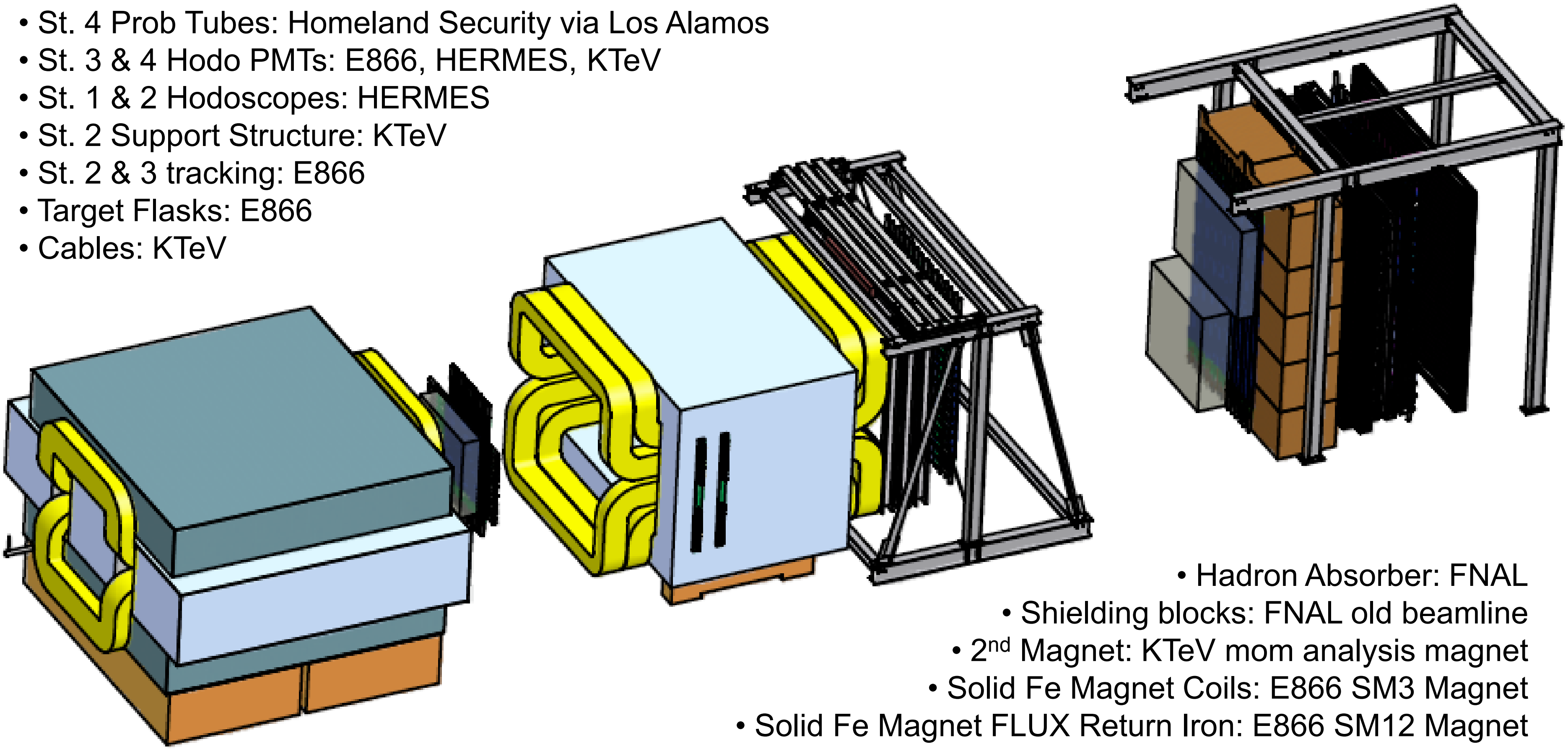
Drell-Yan Spectrometer for E906
(25m long)



Drell-Yan Spectrometer for E906

(Reduce, Reuse, Recycle)

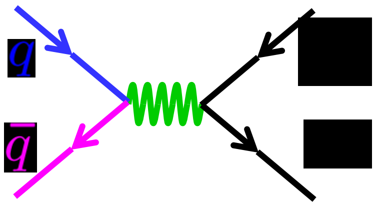
- St. 4 Prob Tubes: Homeland Security via Los Alamos
- St. 3 & 4 Hodo PMTs: E866, HERMES, KTeV
- St. 1 & 2 Hodoscopes: HERMES
- St. 2 Support Structure: KTeV
- St. 2 & 3 tracking: E866
- Target Flasks: E866
- Cables: KTeV

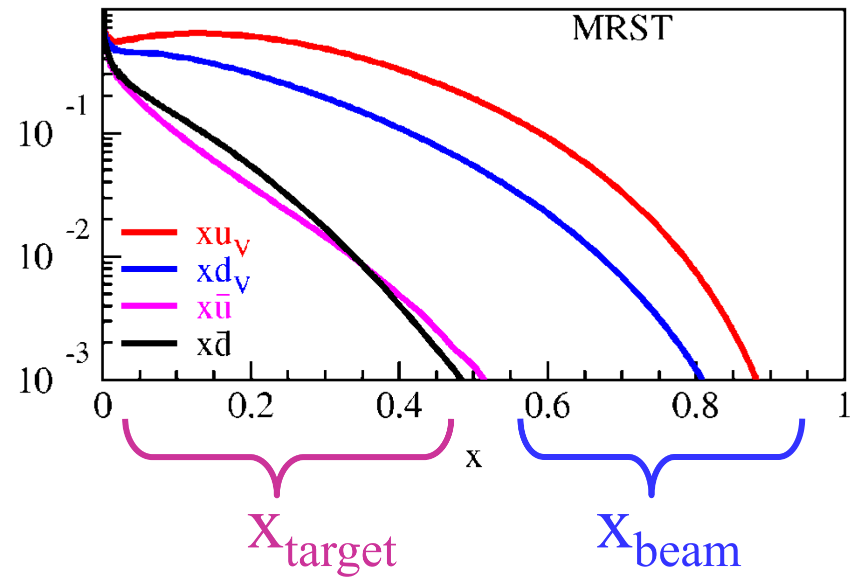


- Hadron Absorber: FNAL
- Shielding blocks: FNAL old beamline
- 2nd Magnet: KTeV mom analysis magnet
- Solid Fe Magnet Coils: E866 SM3 Magnet
- Solid Fe Magnet FLUX Return Iron: E866 SM12 Magnet

Expect to start collecting data: November 2011

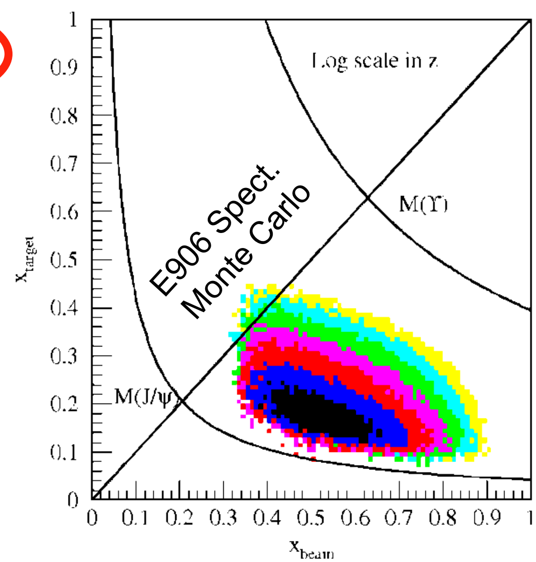
Fixed Target Drell-Yan: What we really measure





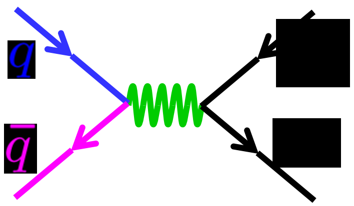
- Measure yields of $\mu^+\mu^-$ pairs from different targets
- Reconstruct p_γ, $M^2_\gamma = x_b x_t s$
- Determine x_b, x_t
- Measure differential cross section

$$\frac{d^2\sigma}{dx_b\,dx_t} = \frac{\quad}{x_b x_t s} \sum_{q\in} \quad + \quad$$



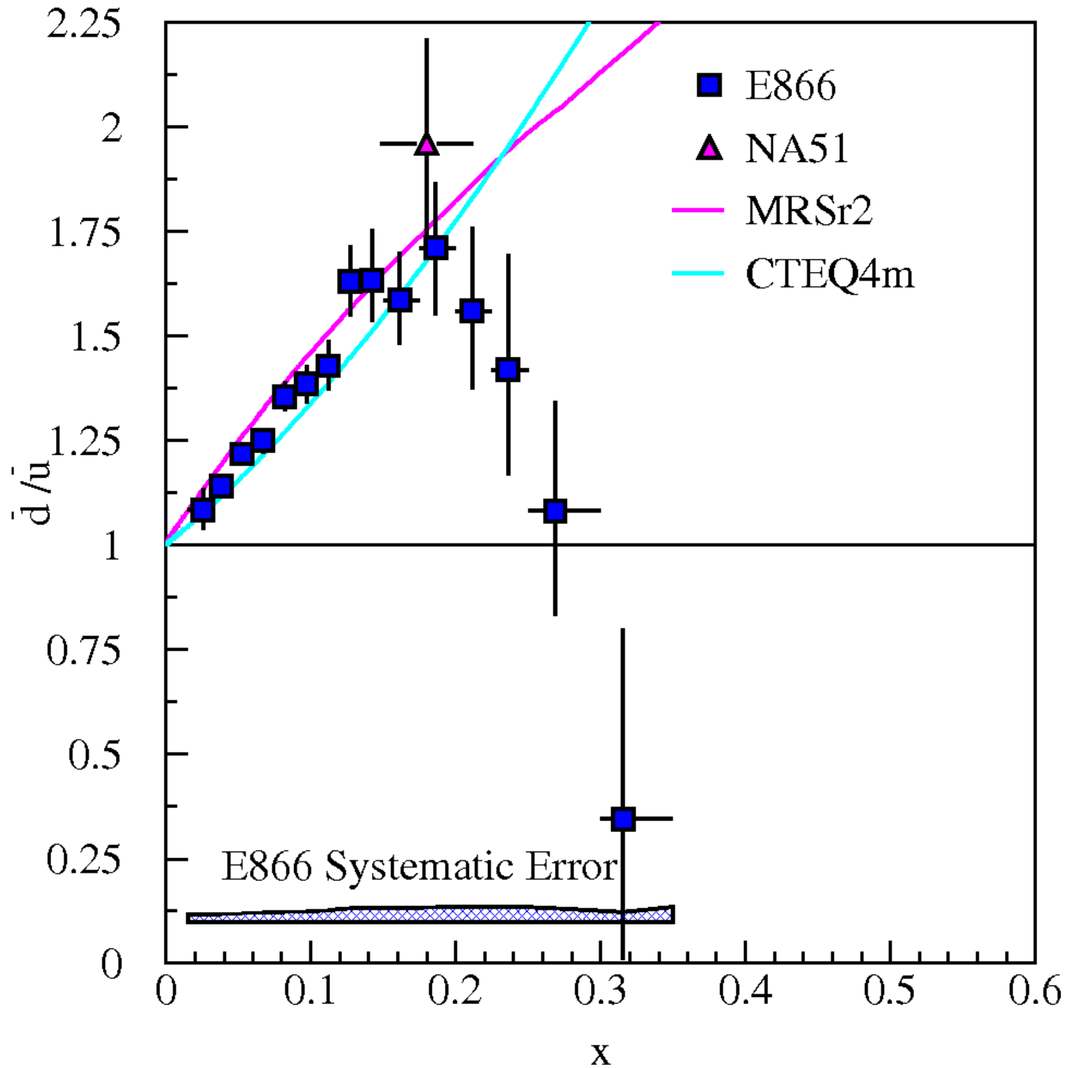
- Fixed target kinematics and detector acceptance give $x_b > x_t$
  - ➡ $x_F = 2p_{||}^{\gamma}/s^{1/2} \approx x_b - x_t$
  - ➡ Beam valence quarks probed at high x
  - ➡ Target sea quarks probed at low/intermediate x

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



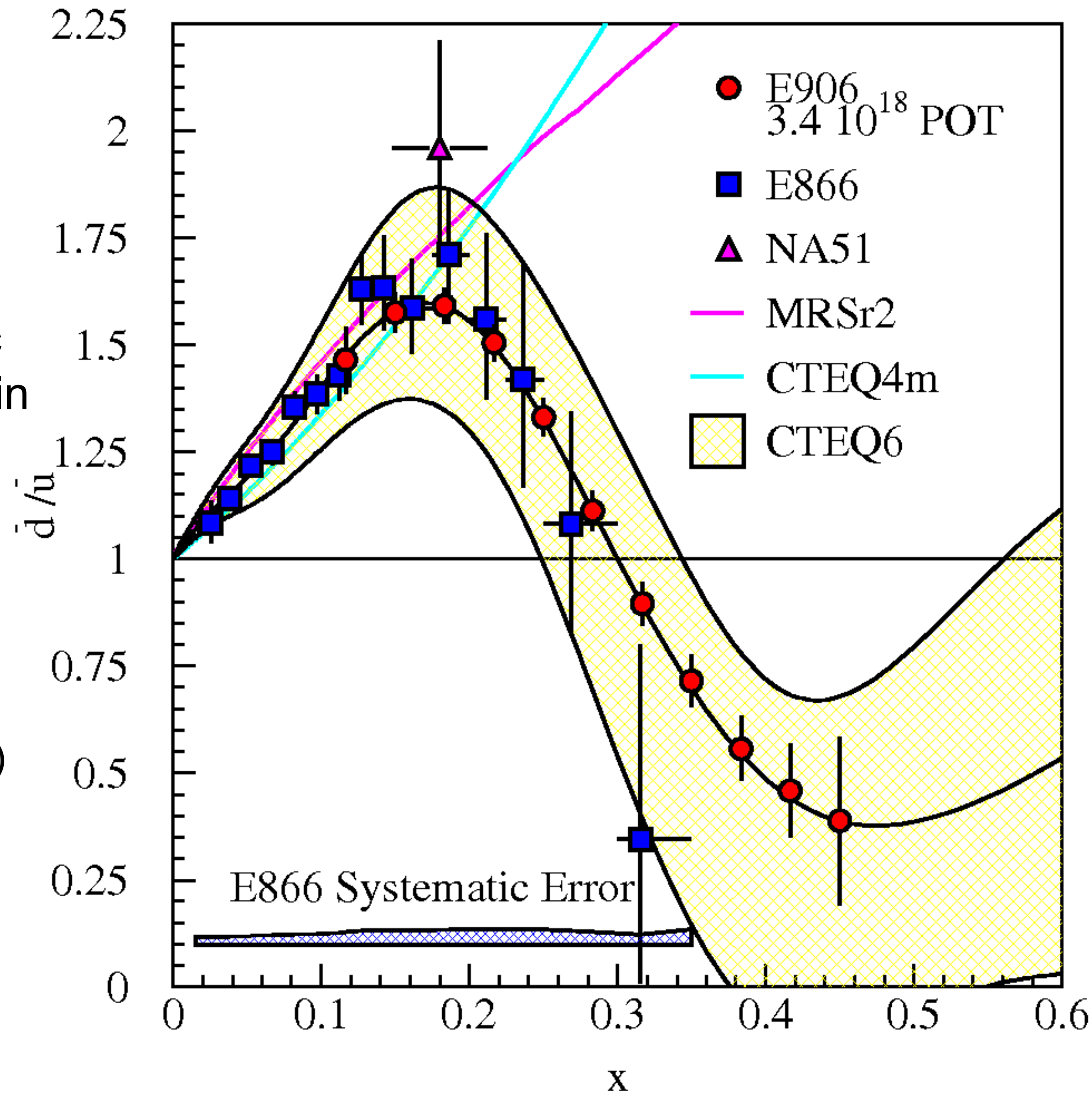
- Measure cross section ratios on Hydrogen, Deuterium (and Nuclear) Targets

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



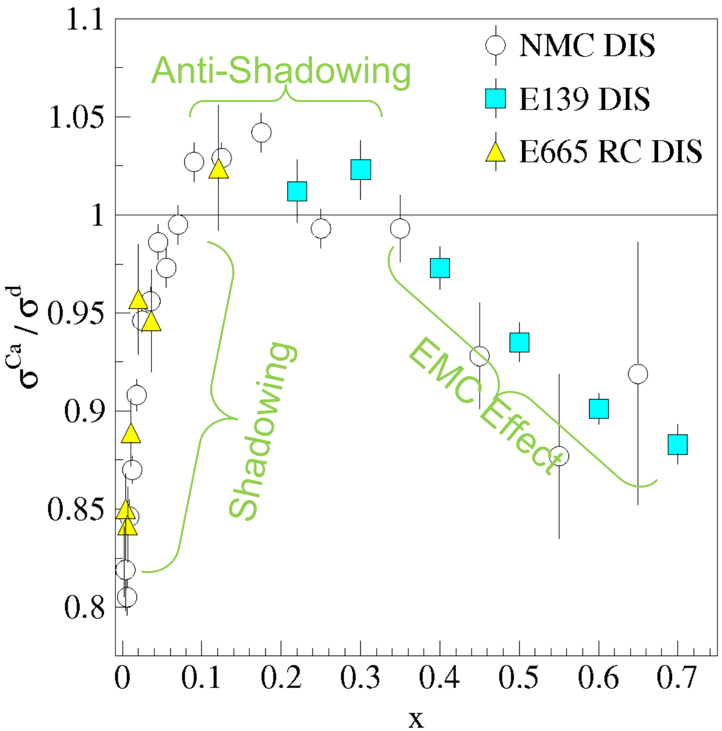
SeaQuest Projections for d-bar/u-bar Ratio

- 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:
  - 2×10^{12} protons/s (I_{inst} =320 nA)
  - 1×10^{13} protons/spill

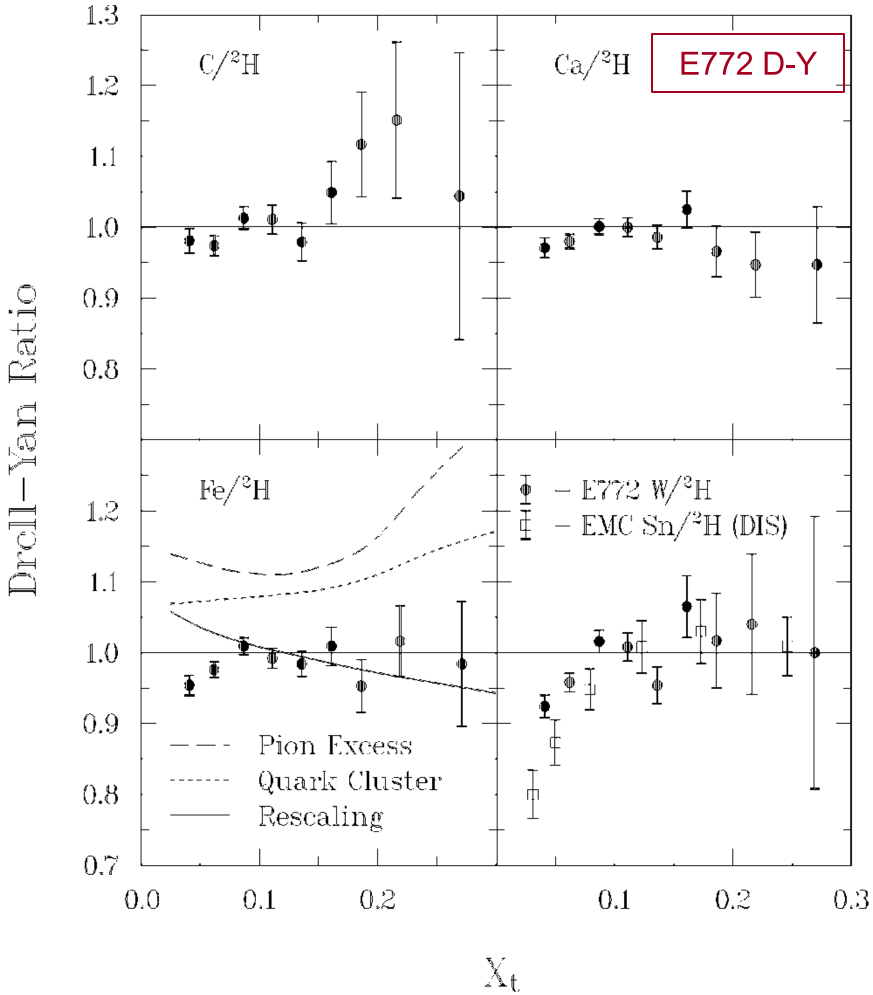


Sea quark distributions in Nuclei

- 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)

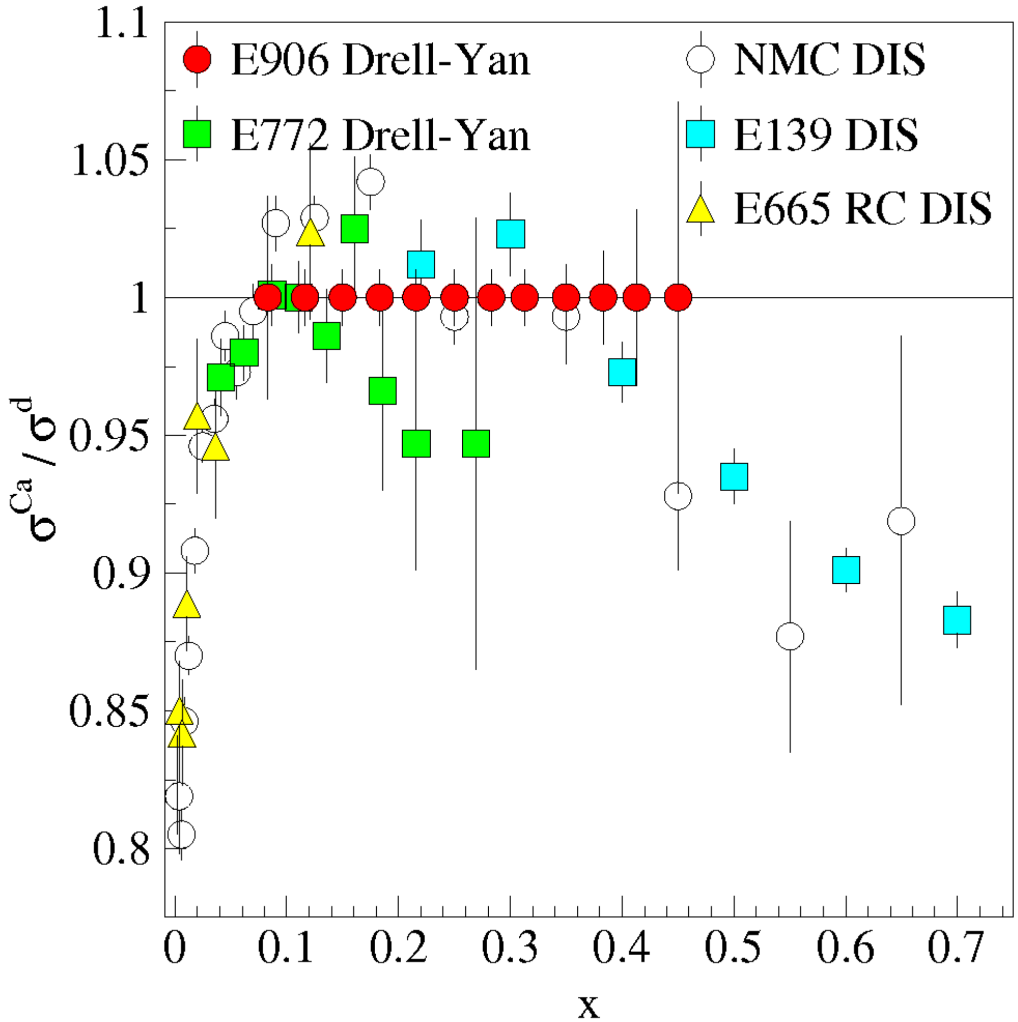


Alde *et al* (Fermilab E772) Phys. Rev. Lett. **64** 2479 (1990)



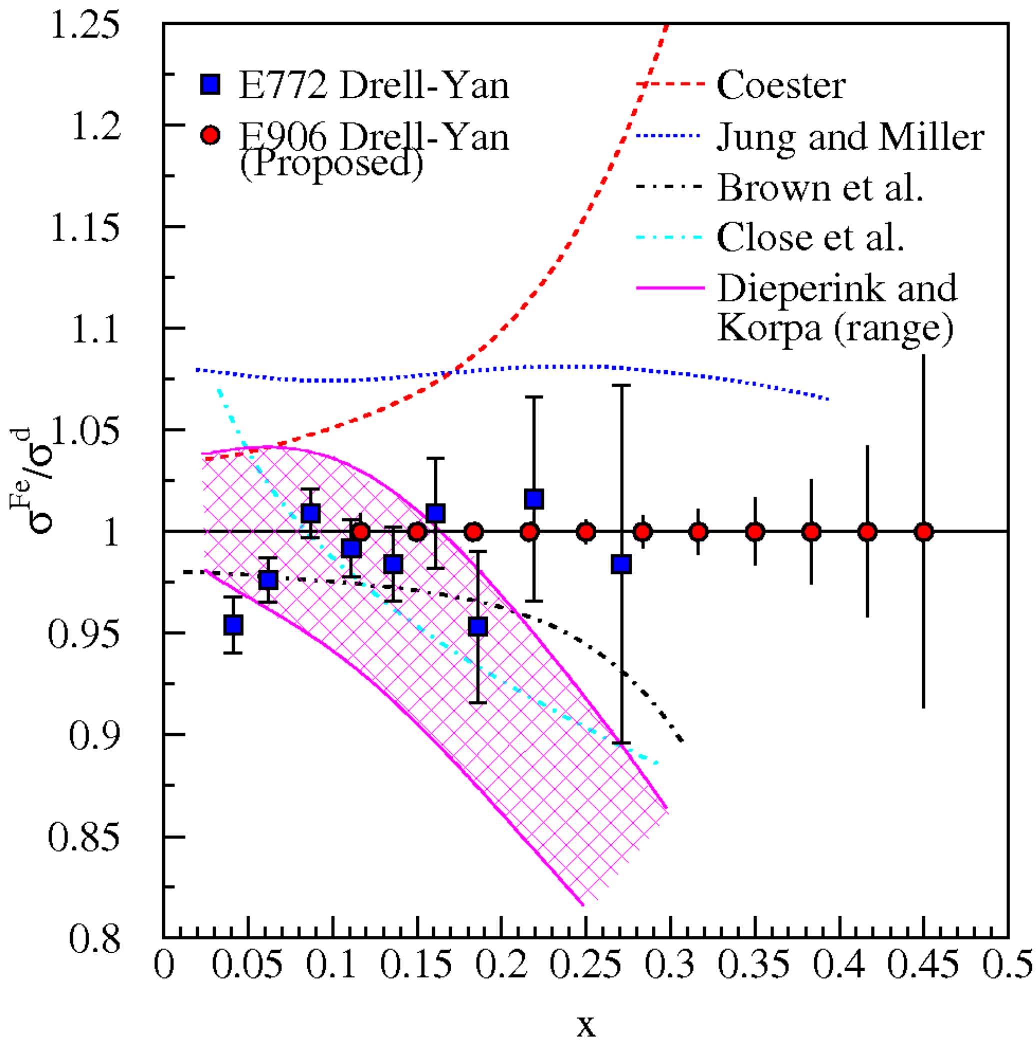
Sea quark distributions in Nuclei - II

- 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?

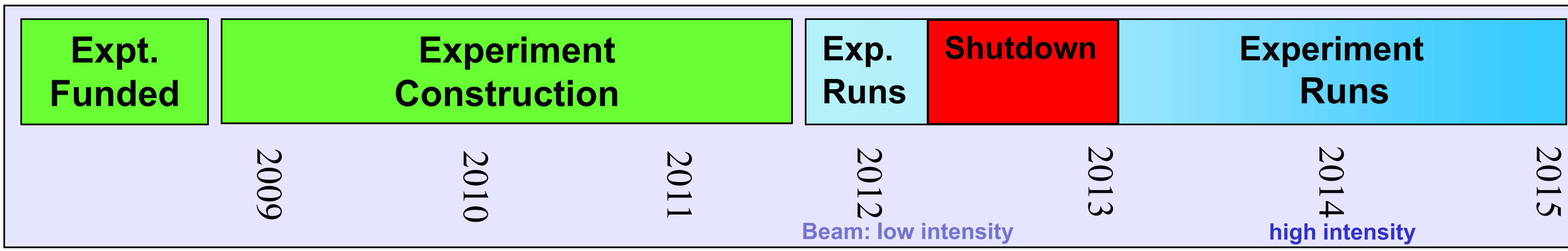
- The binding of nucleons in a nucleus is expected to be governed by the exchange of virtual "Nuclear" mesons.
- No antiquark enhancement seen in Drell-Yan (Fermilab E772) data.
- Contemporary models predict large effects to antiquark distributions as x increases
- Models must explain both DIS-EMC effect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



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

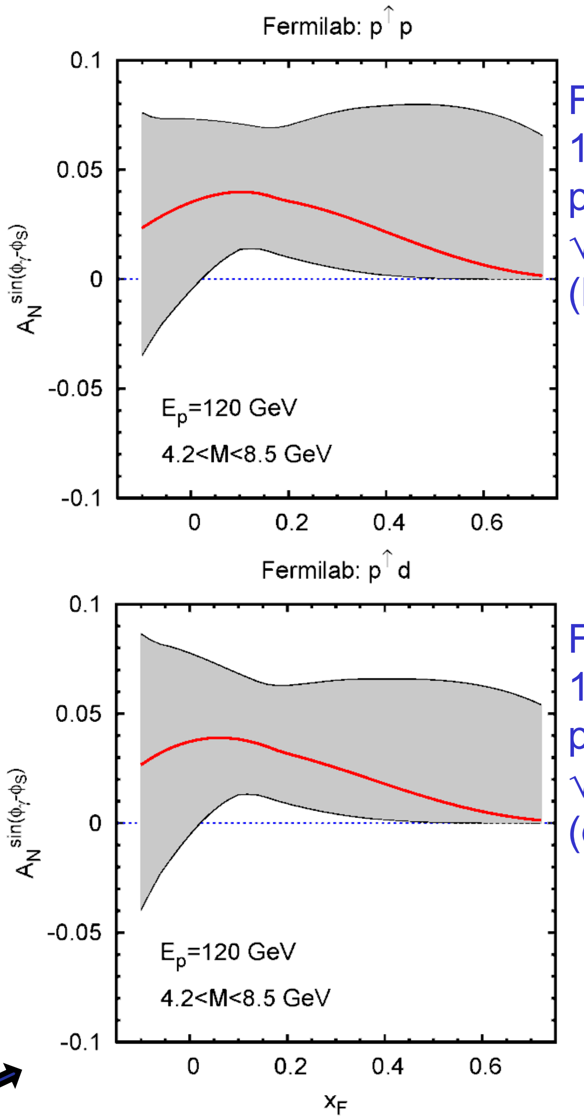
- described by transverse-momentum dependent distribution function
- captures non-perturbative spin-orbit coupling effects inside a polarized proton
- leads to a sin $(\phi - \phi_S)$ asymmetry in SIDIS and Drell-Yan
- done in SIDIS (HERMES, COMPASS)
- Sivers function is time-reversal odd

➡ leads to sign change

$$f_{1T}^{\perp}|_{DIS} =$$

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

Predictions based on fit to SIDIS data ➚



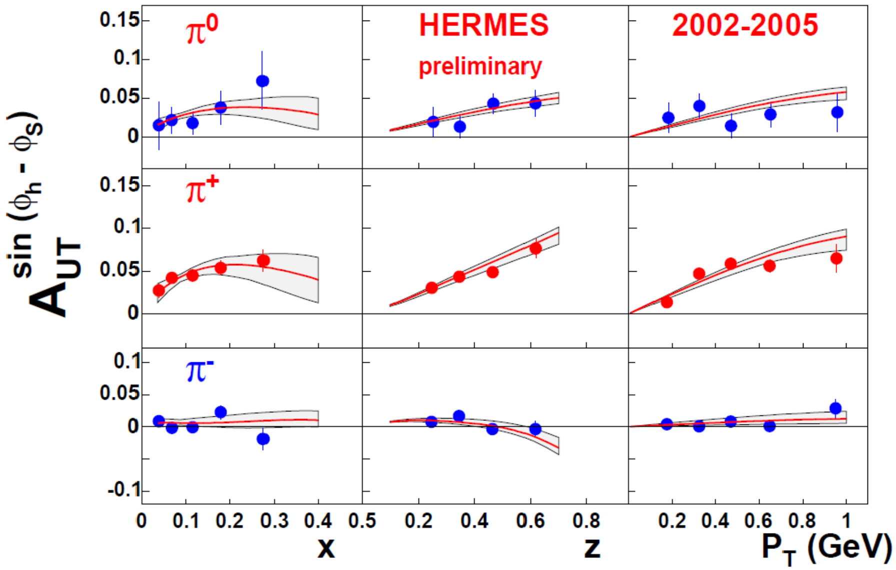
FNAL
120 GeV
polarized beam
√s ~ 15 GeV
(hydrogen)

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

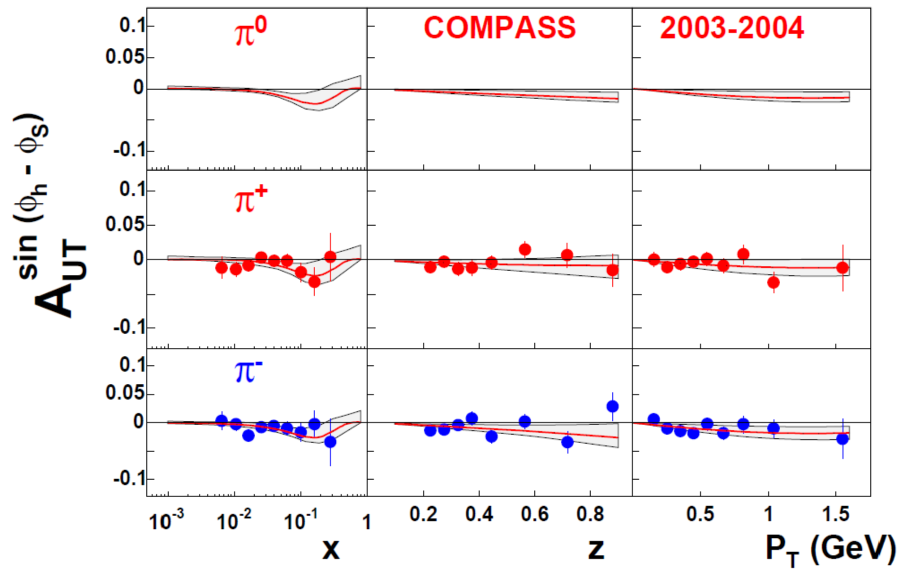
Anselmino et al. priv. comm. 2010

Sivers Asymmetry Measurements

HERMES (p)



COMPASS (d)

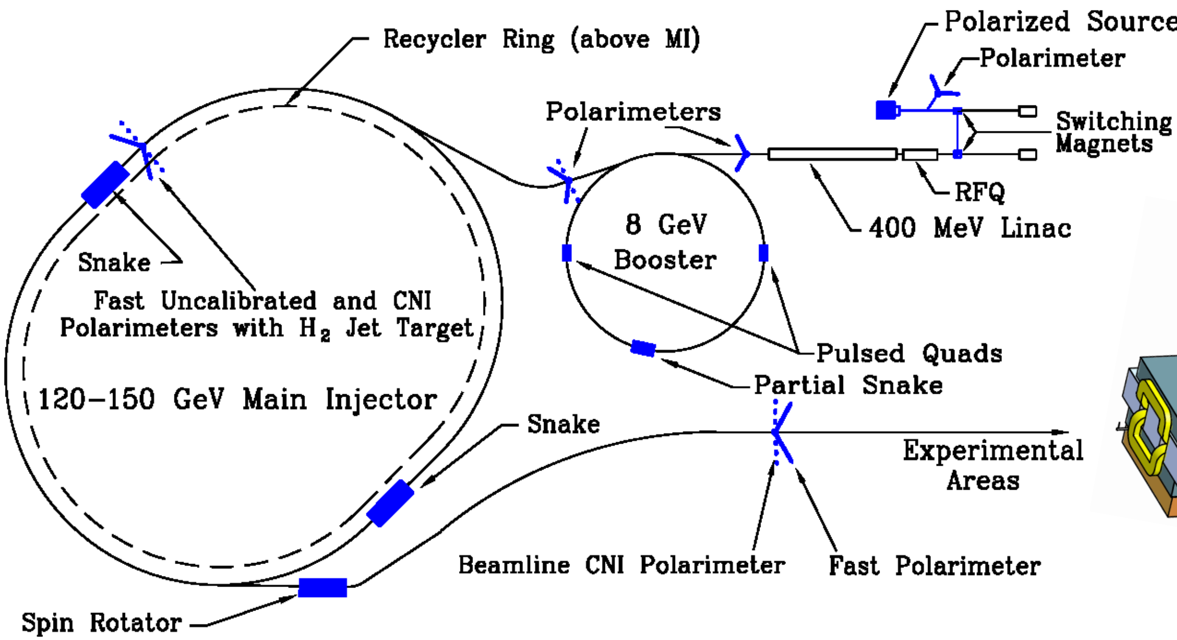


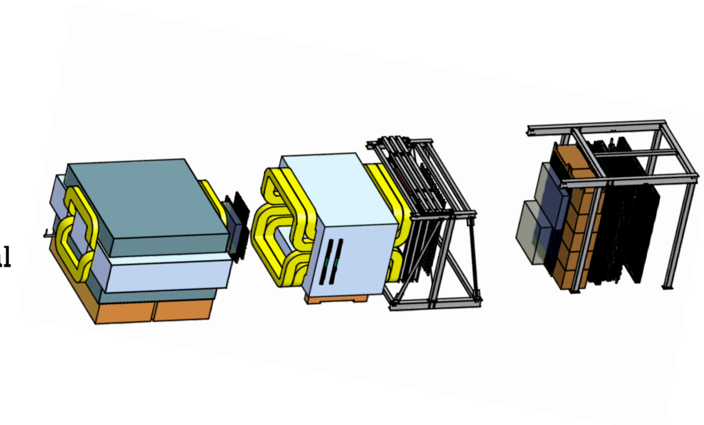
Anselmino et al. EPJA 39, 89 (2009)

- 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

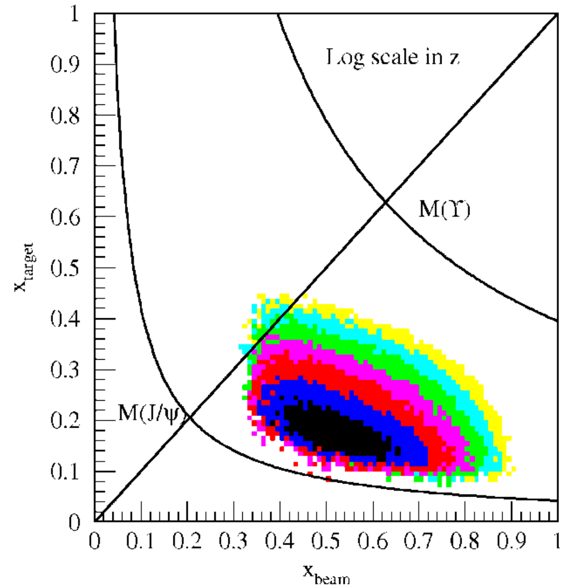
Polarized Drell-Yan at Fermilab Main Injector - II

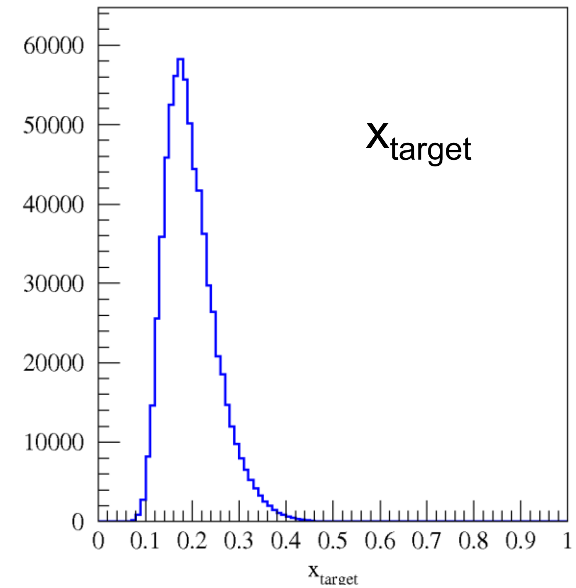
- SeaQuest di-muon Spectrometer
  - ➡ luminosity: $L_{av} = 3.4 \times 10^{35}$ /cm^2/s [$I_{av} = 1.6 \times 10^{11}$ p/s (=26 nA) / $N_p = 2.1 \times 10^{24}$ /cm^2]
  - ➡ approved for 3.4×10^{18} pot

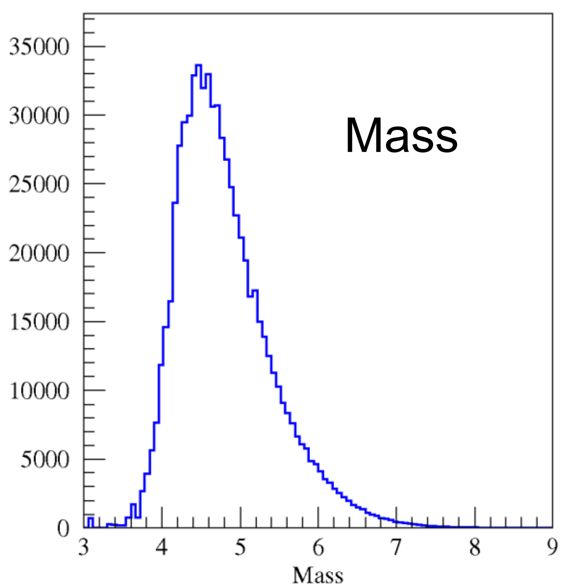
- Polarized Beam in Main Injector
  - ➡ use Seaquest spectrometer
  - ➡ use SeaQuest target
    - ✓ liquid H_2 target can take $I_{av} = \sim 5 \times 10^{11}$ p/s (=80 nA)
  - ➡ 1 mA at polarized source can deliver about $I_{av} = \sim 1 \times 10^{12}$ p/s (=150 nA) for 100% of available beam time (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)

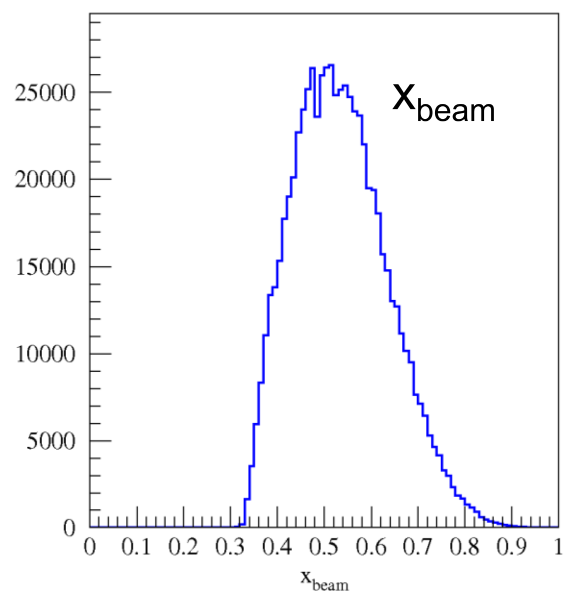
SeaQuest: Drell-Yan Acceptance

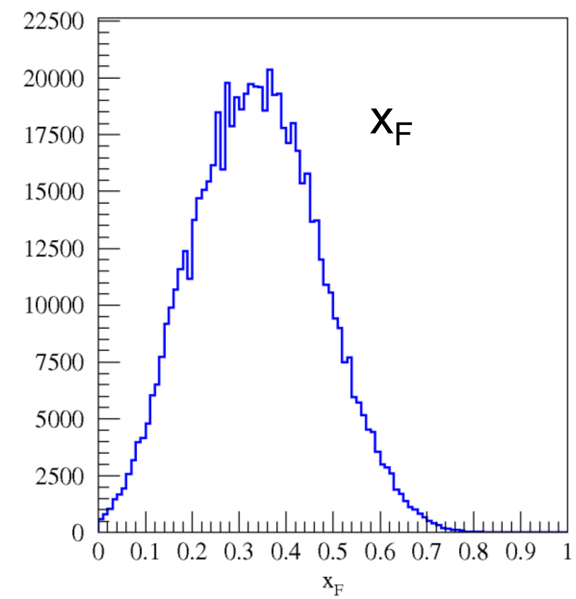
- Programmable trigger removes likely J/ψ events
- Transverse momentum acceptance to above 2 GeV
- Spectrometer could also be used for J/ψ, ψ′ studies



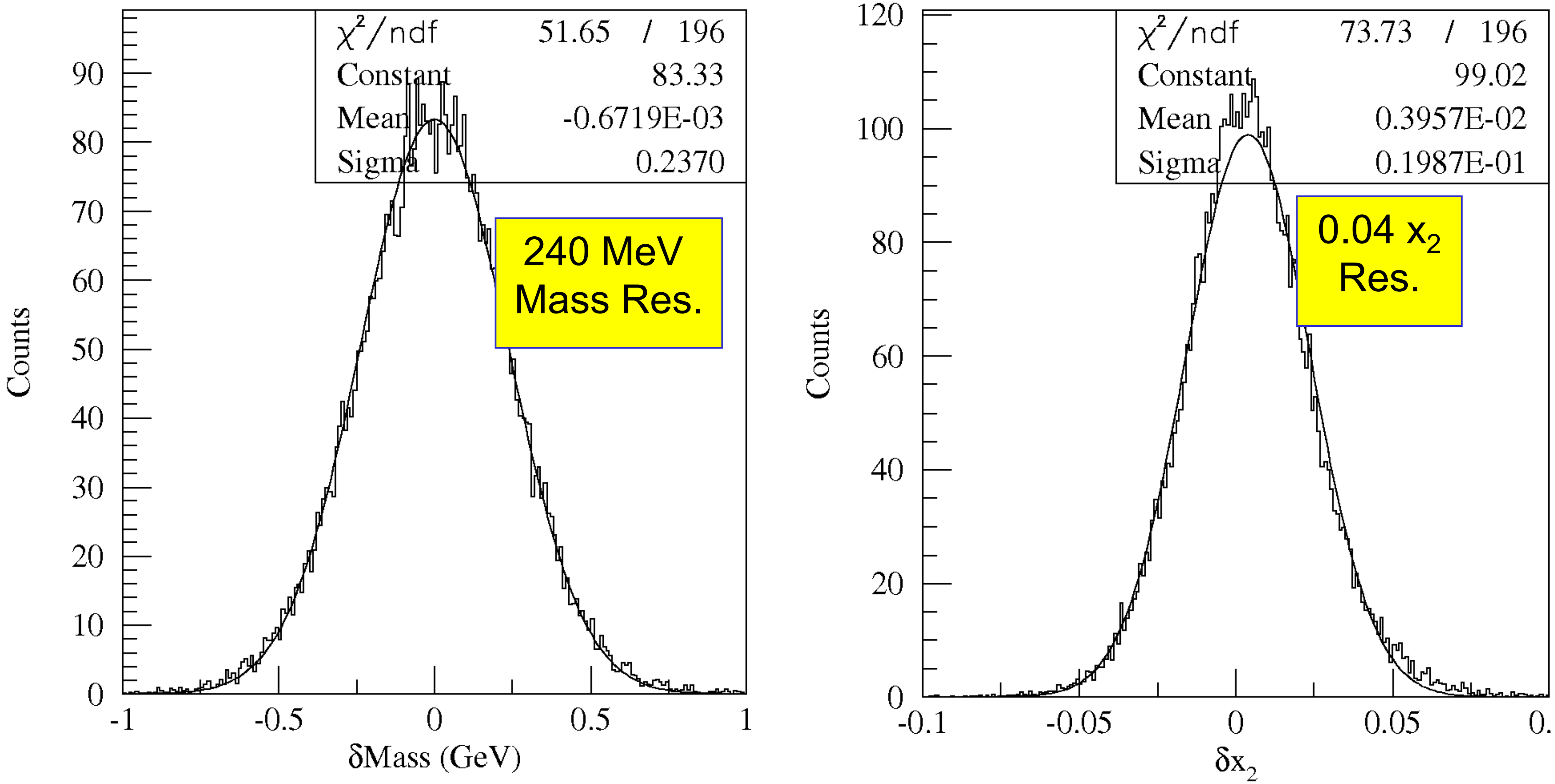








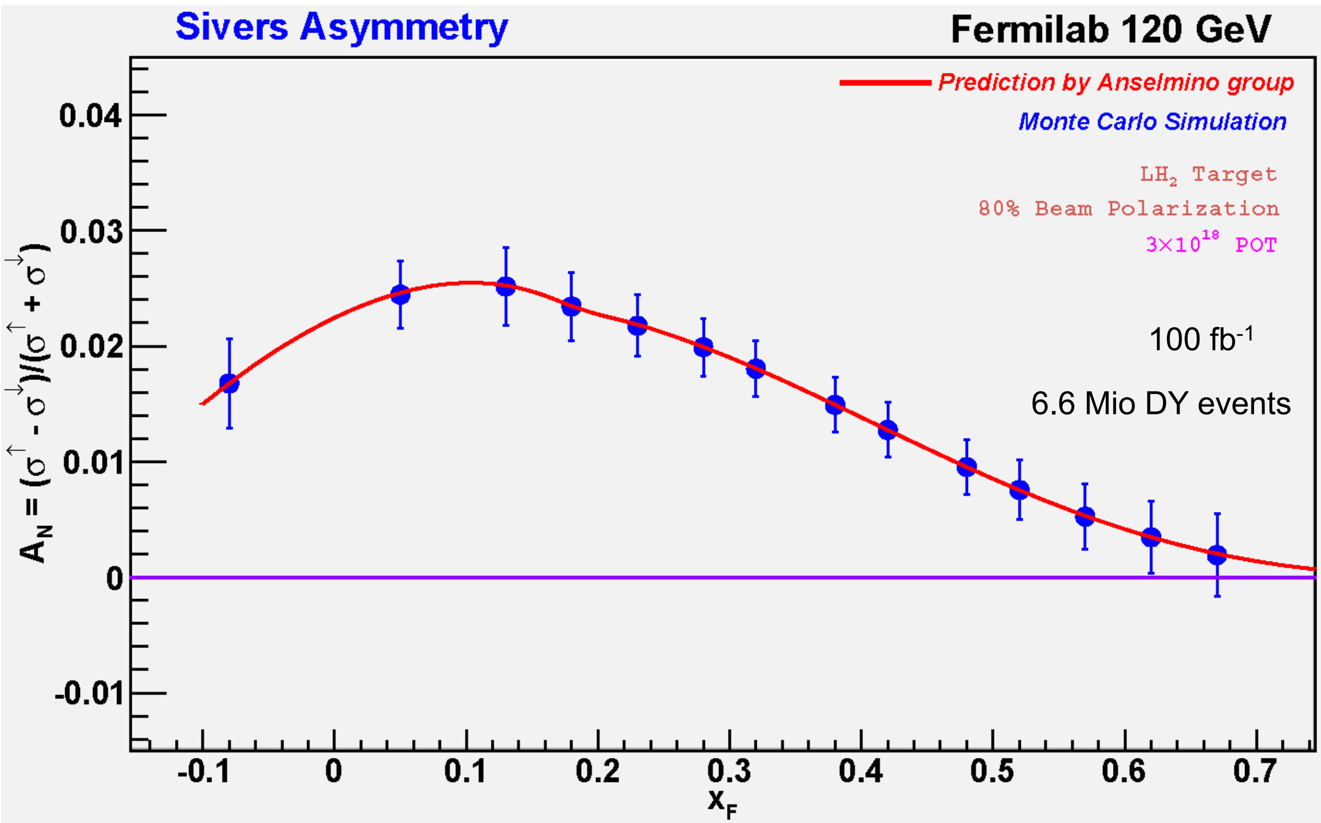
SeaQuest: Detector Resolution



- 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)



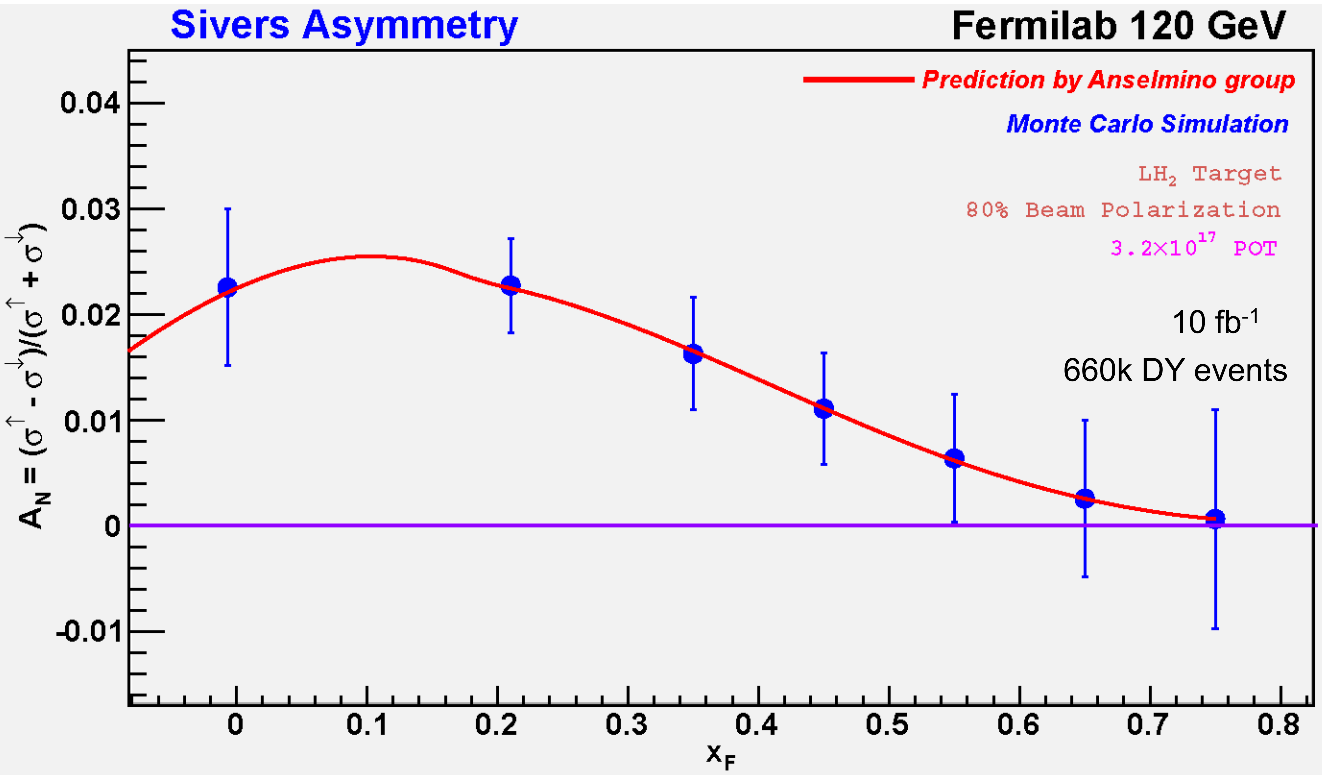
Note:

$$A_N = \frac{?}{\pi}$$

➡ 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 x 10^{34} (= 10x lower than expected)
  - ➡ 10 fb^{-1} for 5 x 10^5 min: (= 2 yrs at 50% efficiency)



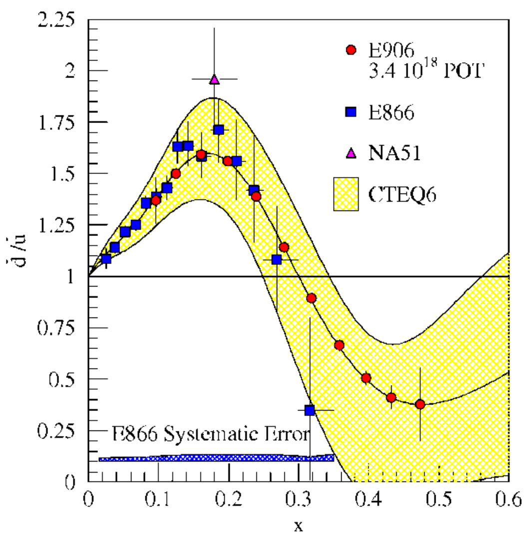
- ➡ Can still measure sign, AND shape of the Sivers function, with 10x less L_{int} !
- ➡ What if the sign changes, BUT $\left| f_{1T}^{\perp} \right|_{DIS} \neq \left| \ldots \right|_{D-}$?

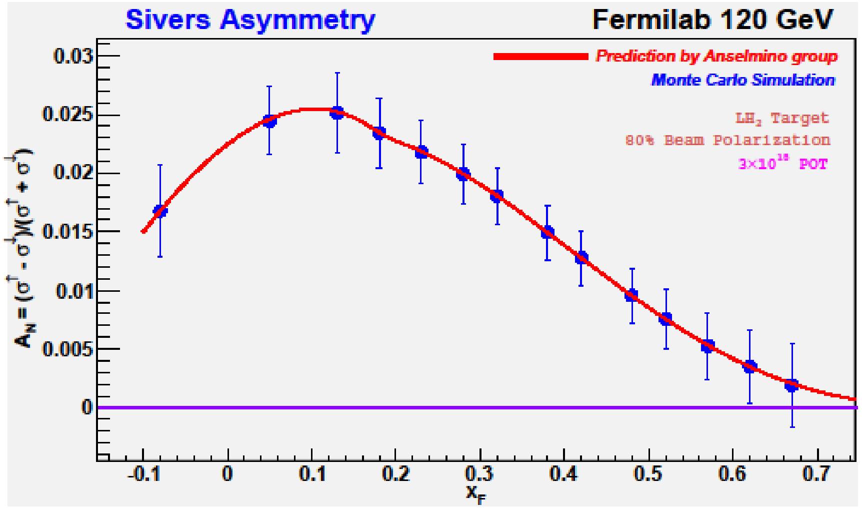
Planned Polarized Drell-Yan Experiments

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 ~ 0.05 (low mass)	2 x 10^{33} cm^{-2} s^{-1}	2014
PAX (GSI)	$p^\uparrow$ + p_{par}	collider $\sqrt{s}$ = 14 GeV	x_1 = 0.1 – 0.9	2 x 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 x 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 x 10^{35} cm^{-2} s^{-1}	>2015 ??
NICA (JINR)	$p^\uparrow$ + p	collider $\sqrt{s}$ = 20 GeV	x_1 = 0.1 – 0.8	1 x 10^{30} cm^{-2} s^{-1}	>2014
PHENIX (RHIC)	$p^\uparrow$ + p	collider $\sqrt{s}$ = 500 GeV	x_1 = 0.05 – 0.1	2 x 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 x 10^{33} 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	6 x 10^{34} cm^{-2} s^{-1}	>2018
A_nDY RHIC (IP-2)	$p^\uparrow$ + p	500 GeV $\sqrt{s}$ = 32 GeV	x_1 = ??	?? cm^{-2} s^{-1}	2013
SeaQuest (unpol.) (FNAL)	p + p	120 GeV $\sqrt{s}$ = 15 GeV	x_1 = 0.3 – 0.9	3.4 x 10^{35} cm^{-2} s^{-1}	2011
pol. SeaQuest (FNAL)	**$p^\uparrow$ + p**	**120 GeV** **$\sqrt{s}$ = 15 GeV**	**x_1 = 0.3 – 0.9**	**1 x 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





Thank you!