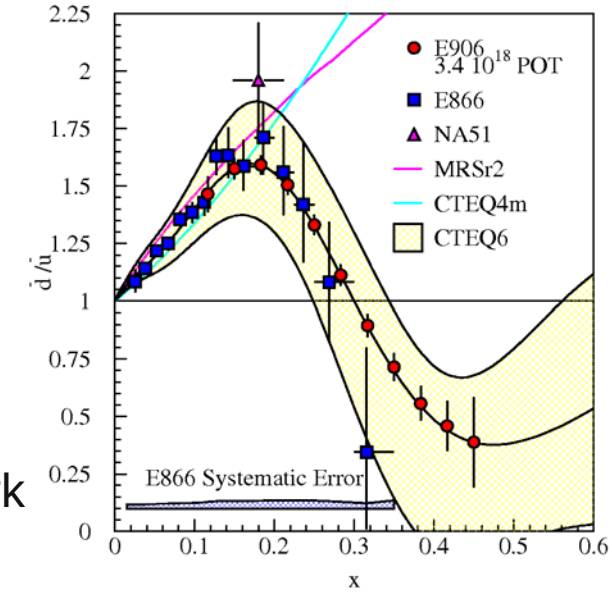
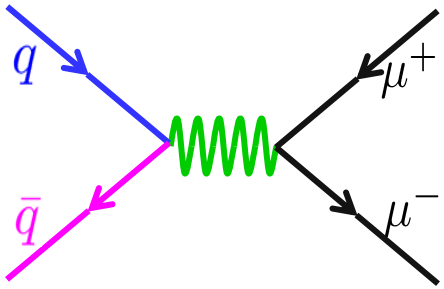
E906 Update: Drell-Yan Measurements of Nucleon and Nuclear Structure with the Fermilab Main Injector

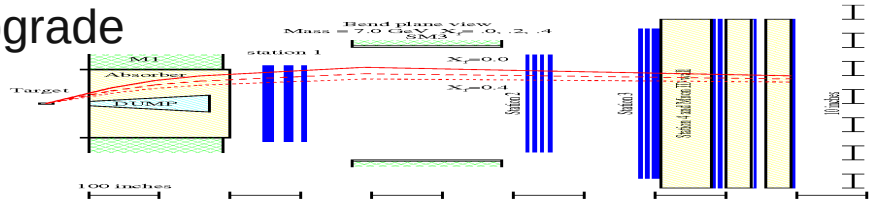
Paul E. Reimer

19 October 2006

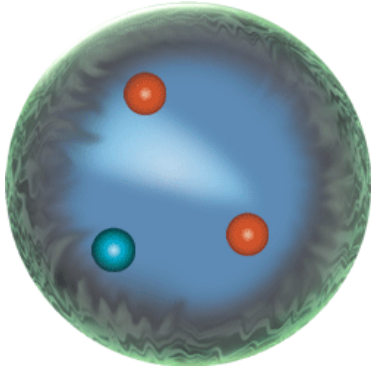


- What will we learn?
  - d-bar/u-bar in the proton
  - Nuclear effects in the sea quark distributions
  - High-*x* valence distributions
  - Partonic energy loss in cold nuclear matter
- What will we measure?
- How will we measure it?
  - Spectrometer upgrade



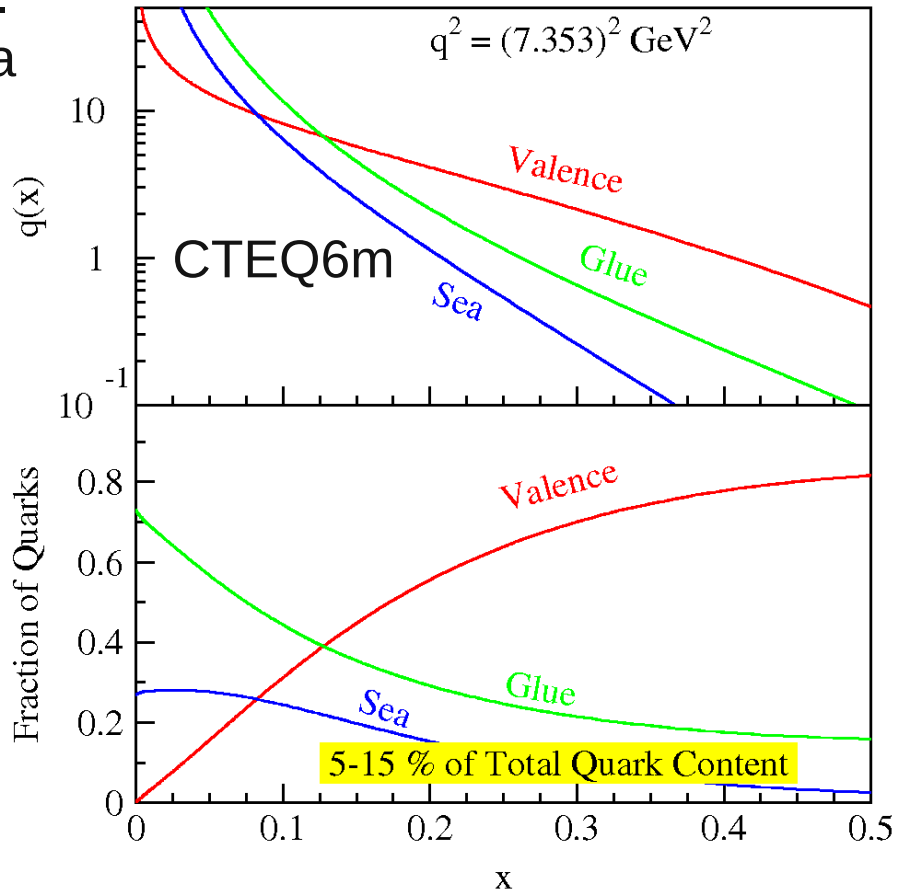


What is the distribution of sea quarks?



In the nucleon:

- Sea and gluons are important:
  - 98% of mass; 60% of momentum at $Q^2 = 2$ GeV^2
- Not just three valence quarks and QCD. Shown by E866/NuSea d-bar/u-bar data
- Significant part of LHC beam.
- What are the origins of the sea?



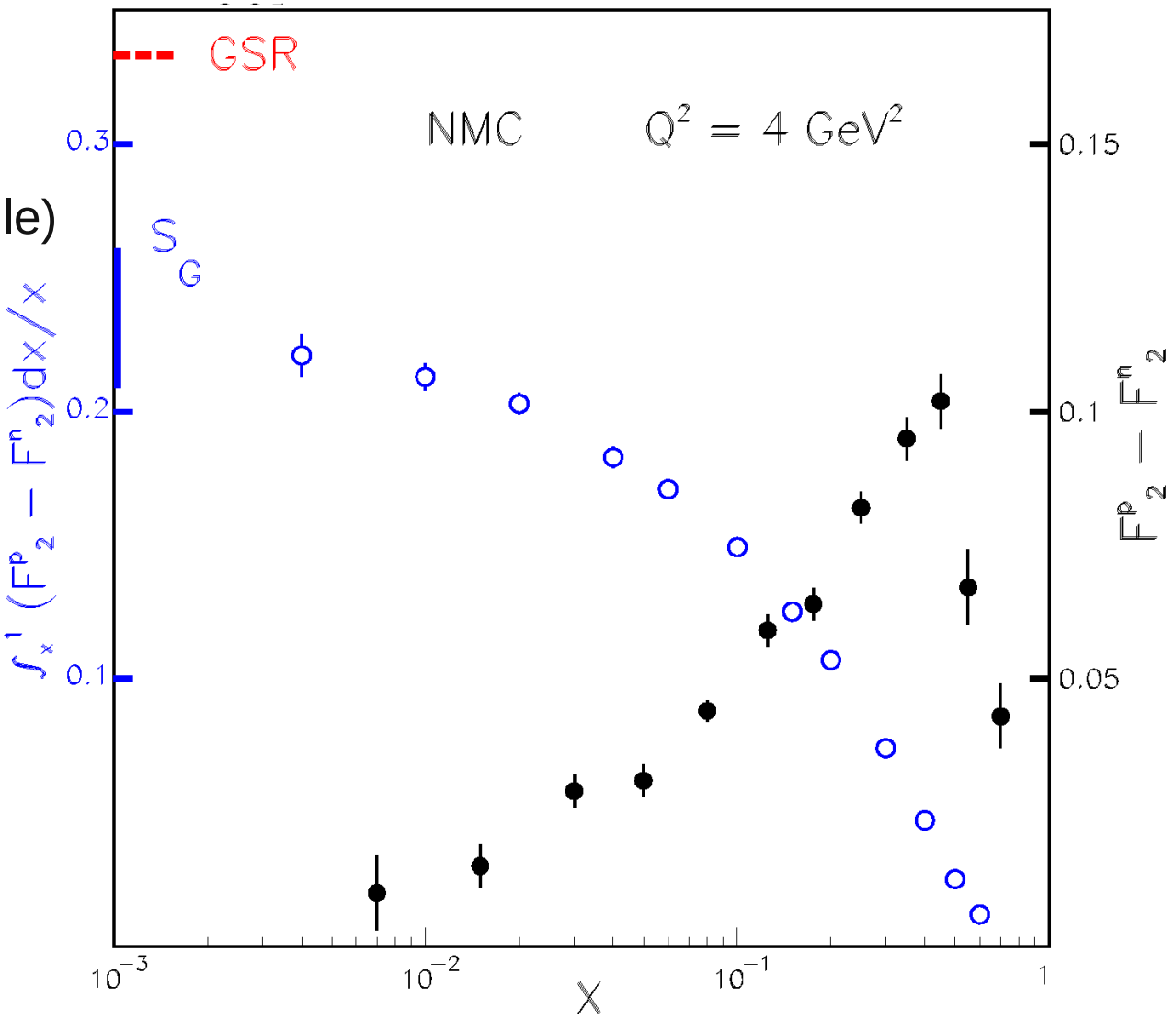
In nuclei:

- The nucleus is not just a sum of protons and neutrons
- What distinguishes this?
  - Bound system
  - Binding via virtual mesons affects antiquarks distributions

Light Antiquark Flavor Asymmetry: Brief History

- Naïve Assumption:
  $\bar{d}(x) = \bar{u}(x)$
- NMC (Gottfried Sum Rule)

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



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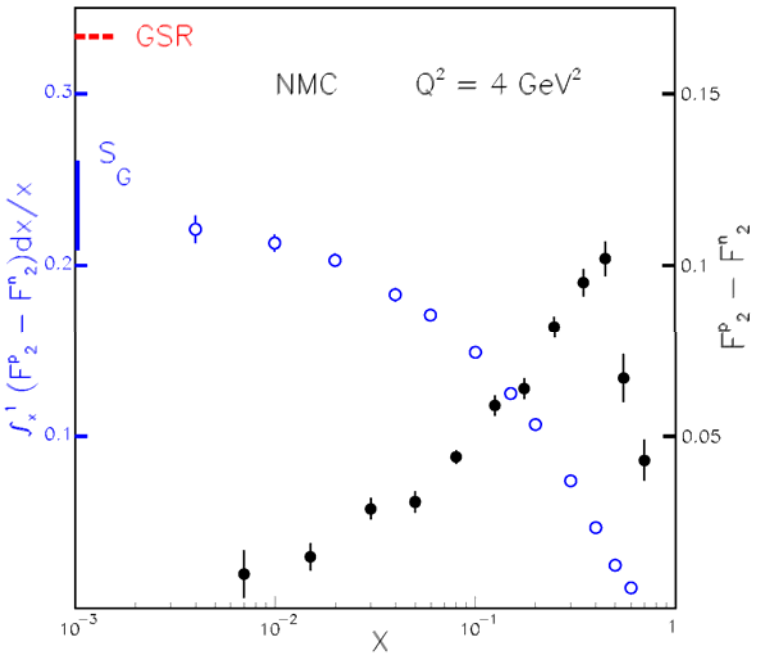
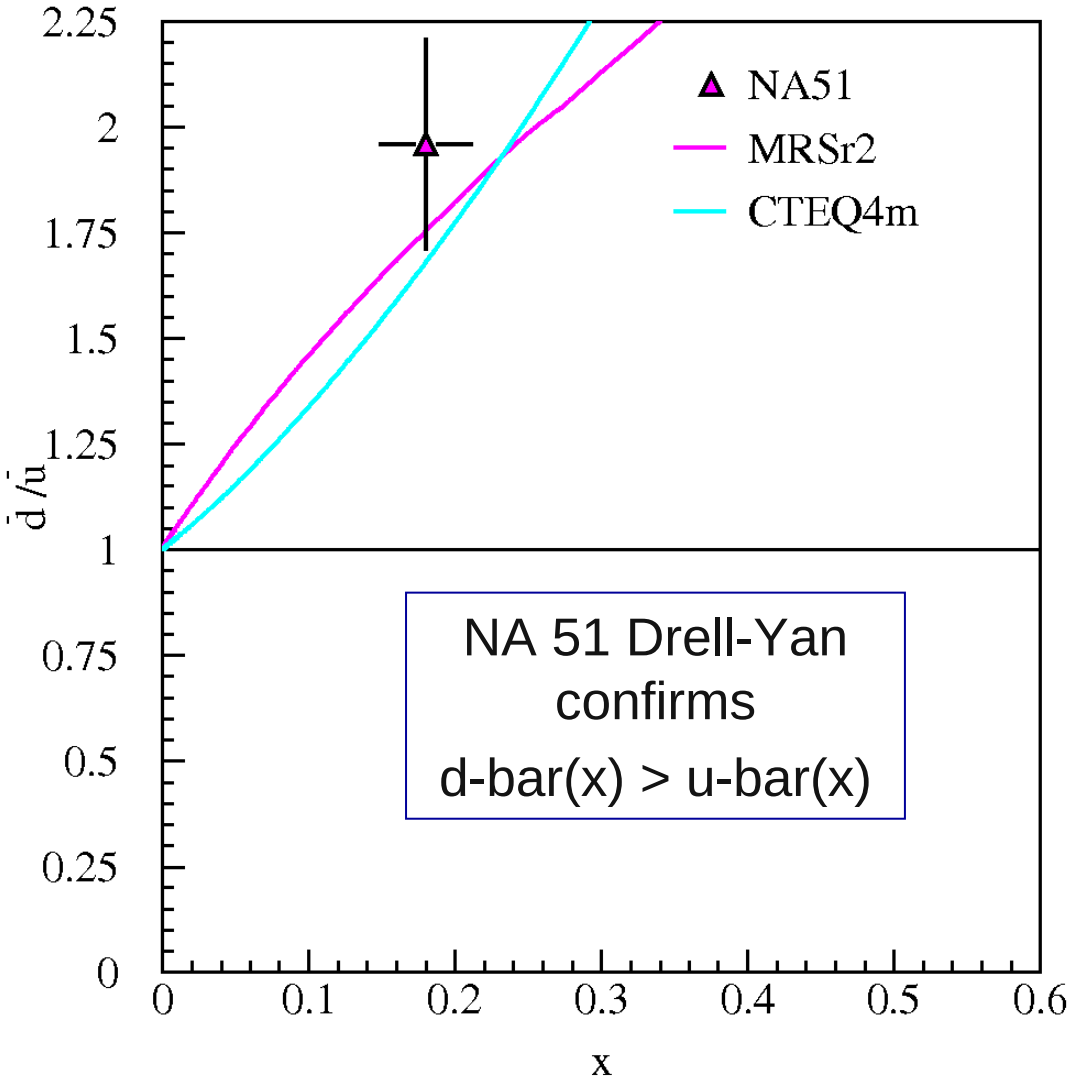
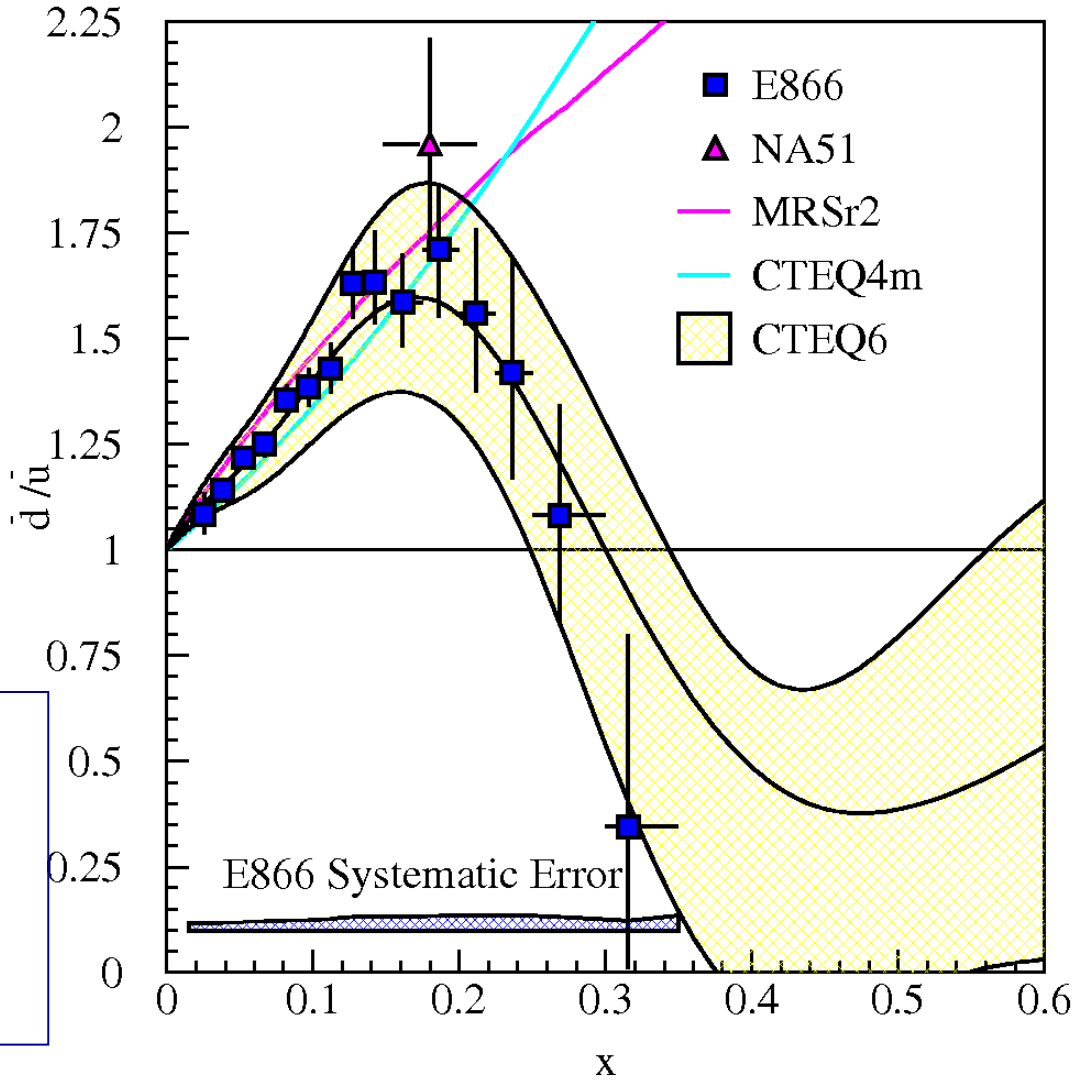




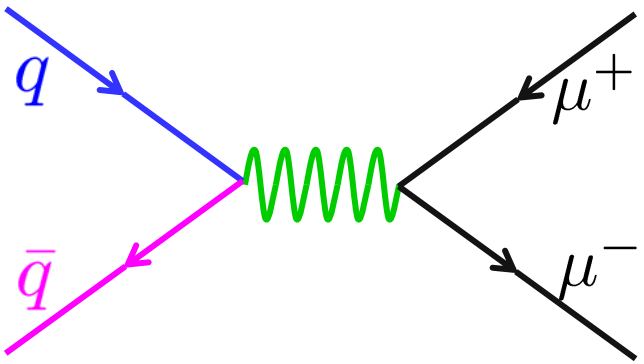
Light Antiquark Flavor Asymmetry: Brief History

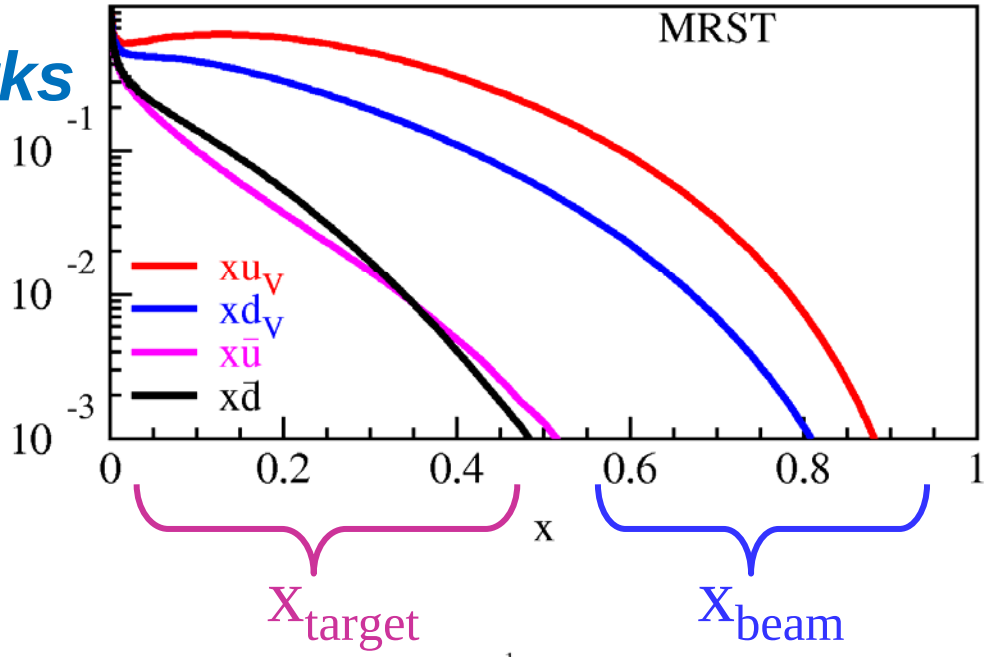
- Naïve Assumption:
  $\bar{d}(x) = \bar{u}(x)$
- NMC (Gottfried Sum Rule)
  $\int_0^1 \left[\bar{d}(x) - \bar{u}(x)\right] dx \neq 0$
- NA51 (Drell-Yan)
  $\bar{d} > \bar{u}$ at $x = 0.18$
- E866/NuSea (Drell-Yan)
  $\bar{d}(x)/\bar{u}(x)$ for $0.015 \leq x \leq 0.35$

- Knowledge of distributions is data driven
  - Sea quark distributions are difficult for Lattice QCD
- **E906 extends this knowledge**



Drell-Yan scattering:
A laboratory for sea quarks

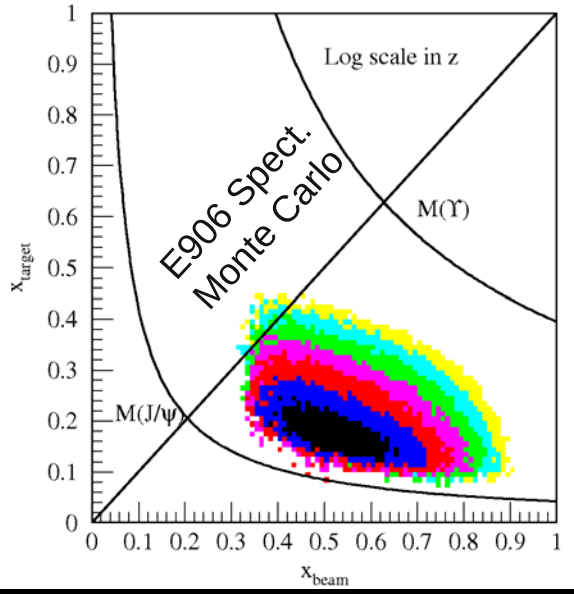




$$\frac{d^2\sigma}{dx_1 dx_2} = \frac{4\pi\alpha^2}{9x_1x_2}\frac{1}{s}\sum e^2\left[\bar{q}_t(x_t)q_b(x_b) + q_t(x_t)\bar{q}_b(x_b)\right]$$

Detector acceptance chooses x_{target} and x_{beam}.

- Fixed target $\Rightarrow$ high $x_F = x_{beam} - x_{target}$
- Valence Beam quarks at high-x.
- Sea Target quarks at low/intermediate-x.



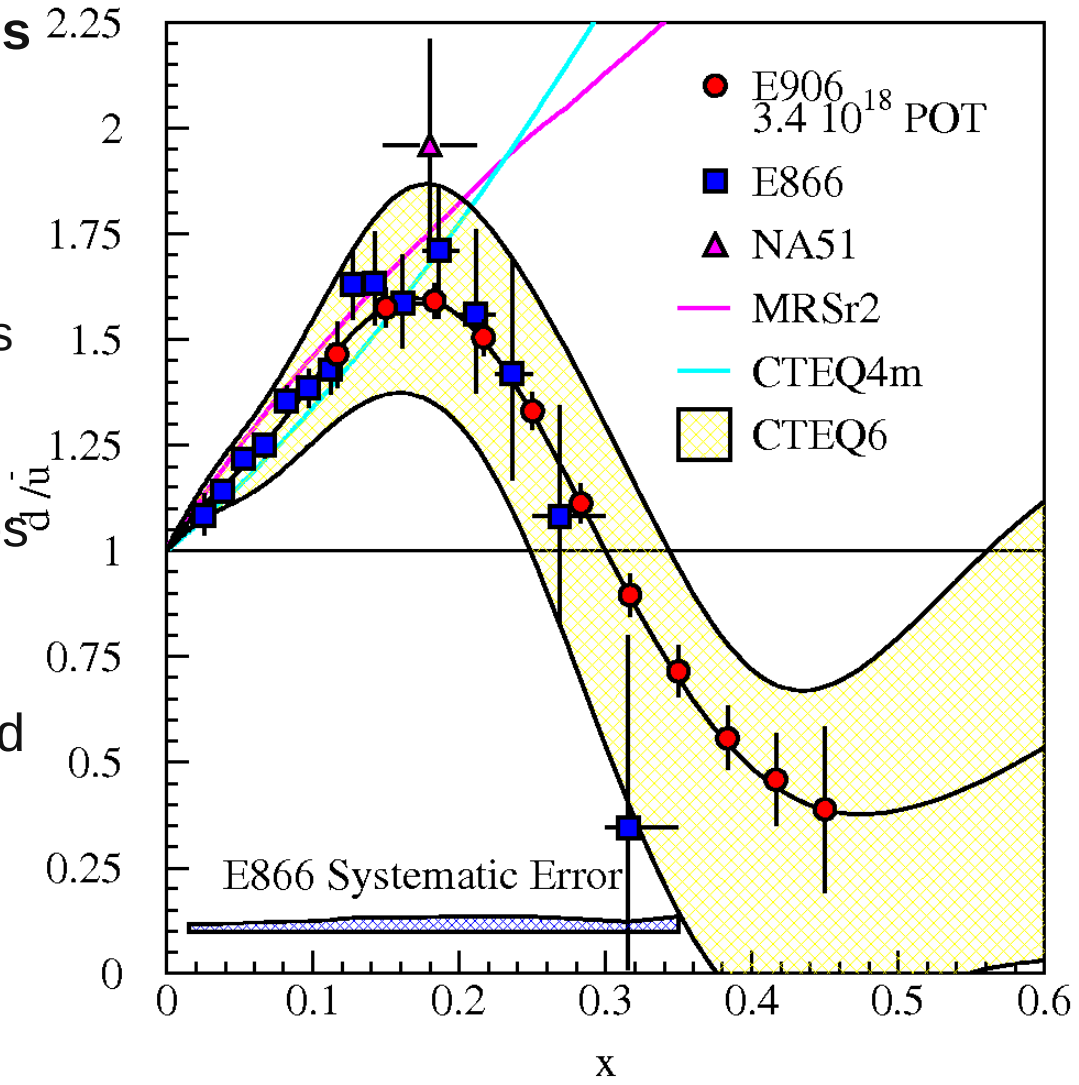
Extracting d-bar/-ubar From Drell-Yan Scattering

Ratio of Drell-Yan cross sections

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

(in leading order—E866 data analysis confirmed in NLO)

- Global NLO PDF fits which include E866 cross section ratios agree with E866 results
- Fermilab E906/Drell-Yan will extend these measurements and reduce statistical uncertainty.
- E906 expects systematic uncertainty to remain at approx. 1% in cross section ratio.



Advantages of 120 GeV Main Injector

The (very successful) past:

Fermilab E866/NuSea

- Data in 1996-1997
- ^{1}H, ^{2}H, and nuclear targets
- 800 GeV proton beam

The future:

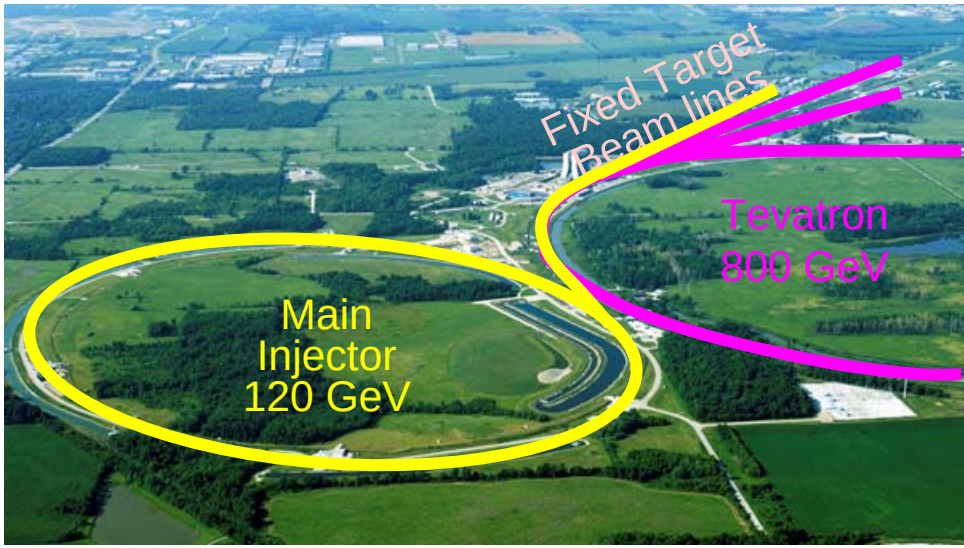
Fermilab E906

- Data in 2009
- ^{1}H, ^{2}H, and nuclear targets
- 120 GeV proton Beam

$$\frac{d^2\sigma}{dx_1 dx_2} = \frac{4\pi\alpha^2}{9x_1x_2}\frac{1}{s} \times \sum_i e_i^2 \left[q_{ti}(x_t)\bar{q}_{bi}(x_b) + \bar{q}_{ti}(x_t)q_{bi}(x_b)\right]$$

- Cross section scales as 1/s
  - *7× that of 800 GeV beam*
- Backgrounds, primarily from J/ψ decays scale as s
  - *7× Luminosity for same detector rate as 800 GeV beam*

50× statistics!!

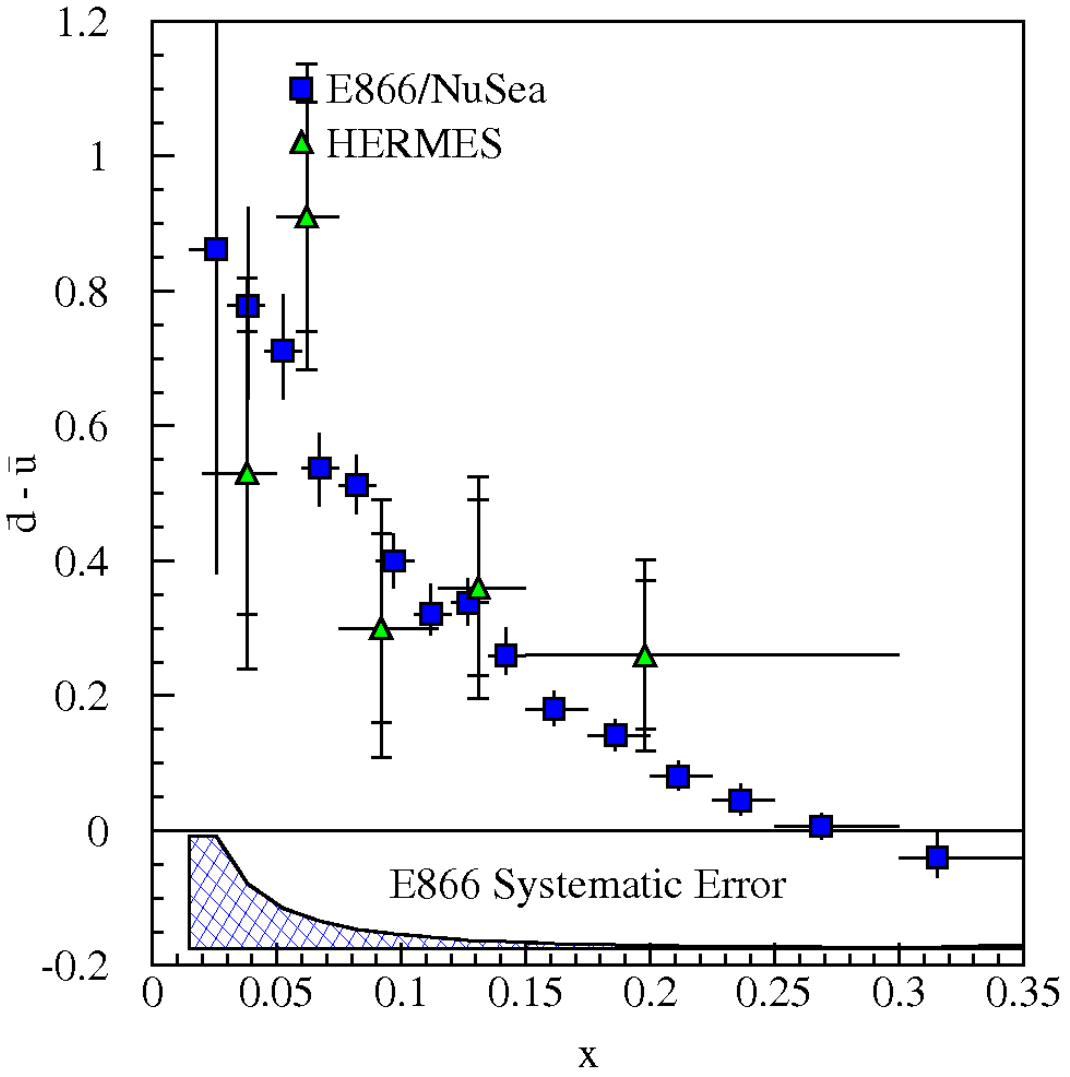


Proton Structure: By What Process Is the Sea Created?

- A proton with 3 valence quarks plus glue **cannot** be right at any scale!!

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

- $\bar{d} - \bar{u}$
  - Symmetric sea via pair production from gluons subtracts off
  - No Gluon contribution at 1st order in α_s
  - Nonperturbative models are motivated by the observed difference



Proton Structure: By What Process Is the Sea Created?

- Meson Cloud in the nucleon

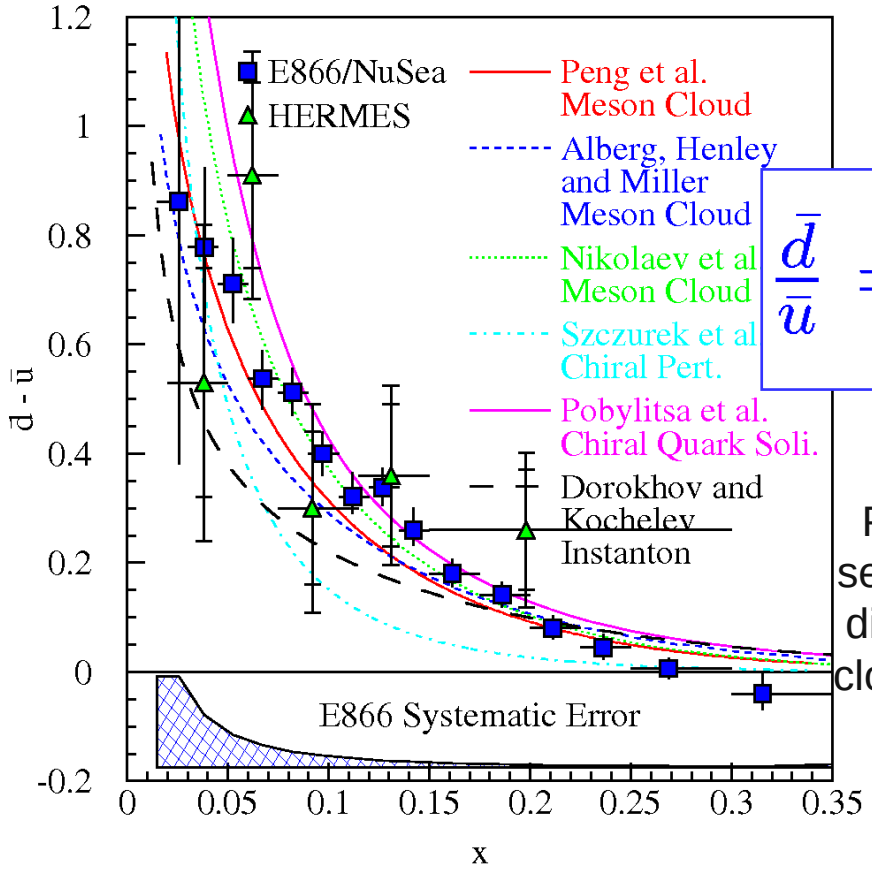
  Sullivan process in DIS

  $|p\rangle = |p_0\rangle + \alpha\,|N\pi\rangle + \beta|\Delta\pi\rangle + \ldots$

- Chiral Models

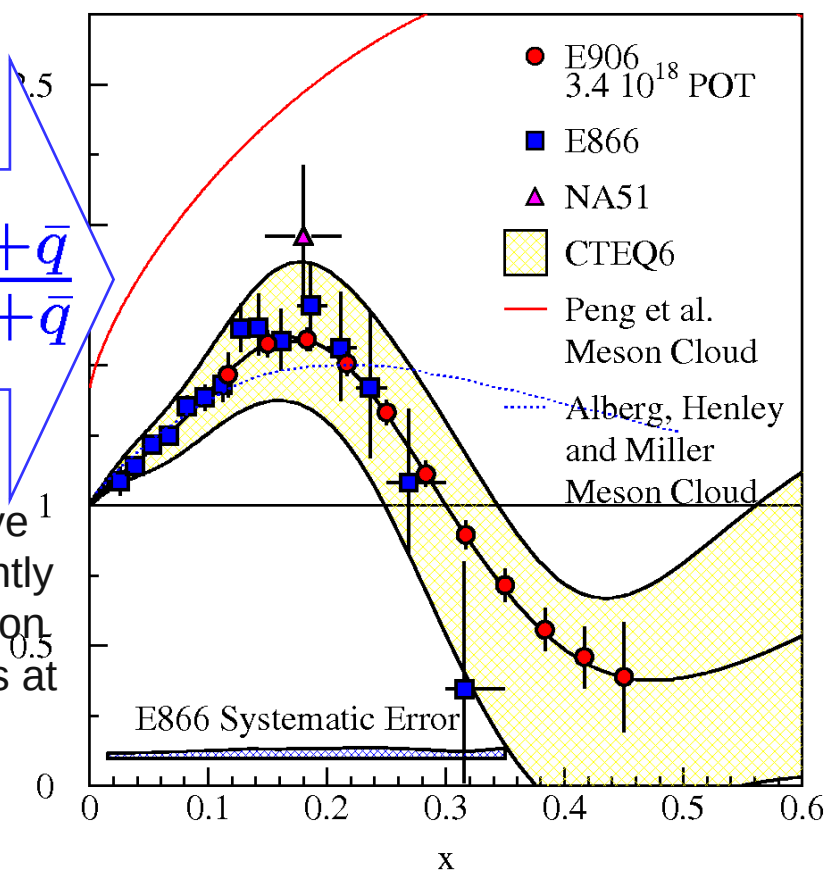
  Interaction between Goldstone Bosons and valence quarks

  $|u\rangle \rightarrow |d\pi^+\rangle$ and $|d\rangle \rightarrow |u\pi^-\rangle$



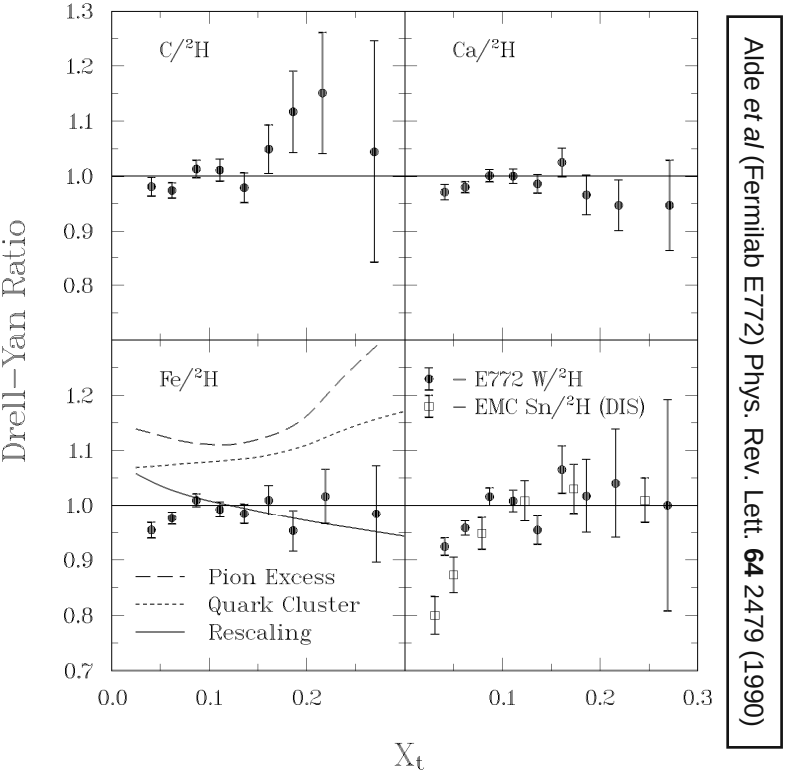
$$\frac{\bar{d}}{\bar{u}} = \frac{\bar{d}^{\pi} + \bar{q}}{\bar{u}^{\pi} + \bar{q}}$$

Perturbative sea apparently dilutes meson cloud effects at large-x

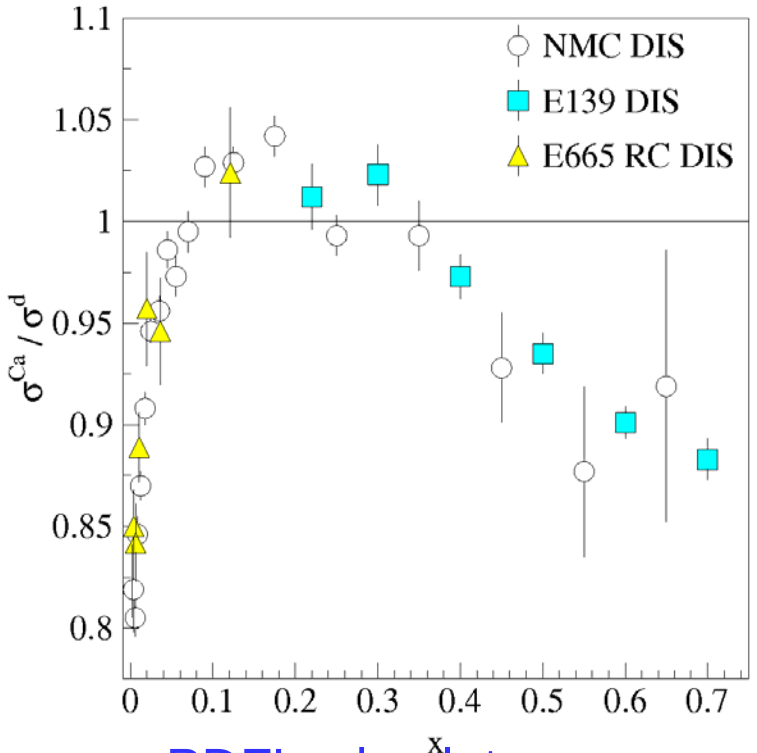


Structure of nucleonic matter: How do sea quark distributions differ in a nucleus?

- EMC: Parton distributions of bound and free nucleons are different.
- Antishadowing not seen in Drell-Yan—Valence only effect



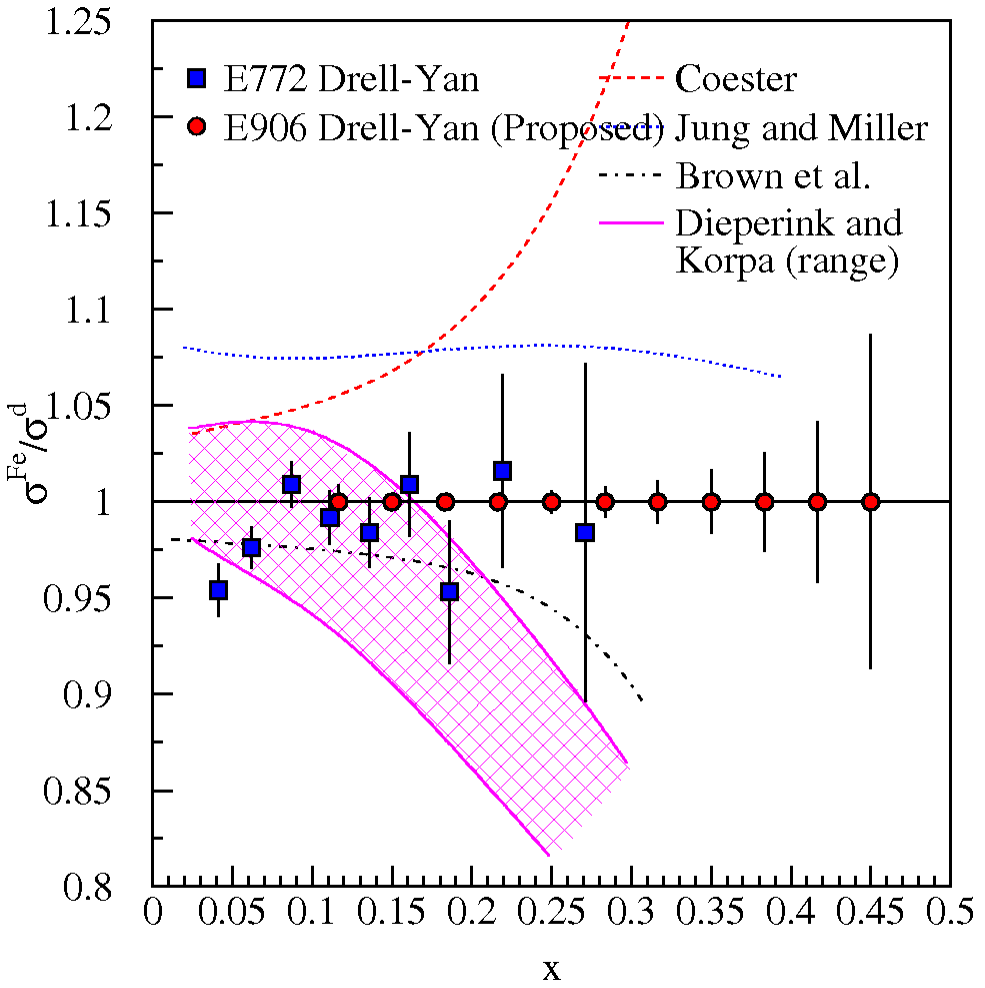
Alde *et al* (Fermilab E772) Phys. Rev. Lett. **64** 2479 (1990)



- Intermediate-*x* *sea* PDF's absolute magnitude set by ν-DIS on iron.
  - Are nuclear effects the same for the sea as for valence?
  - Are nuclear effects with the weak interaction the same as electromagnetic?
- What can the sea parton distributions tell us about the effects of nuclear binding?

Structure of nucleonic matter: Where are the nuclear pions?

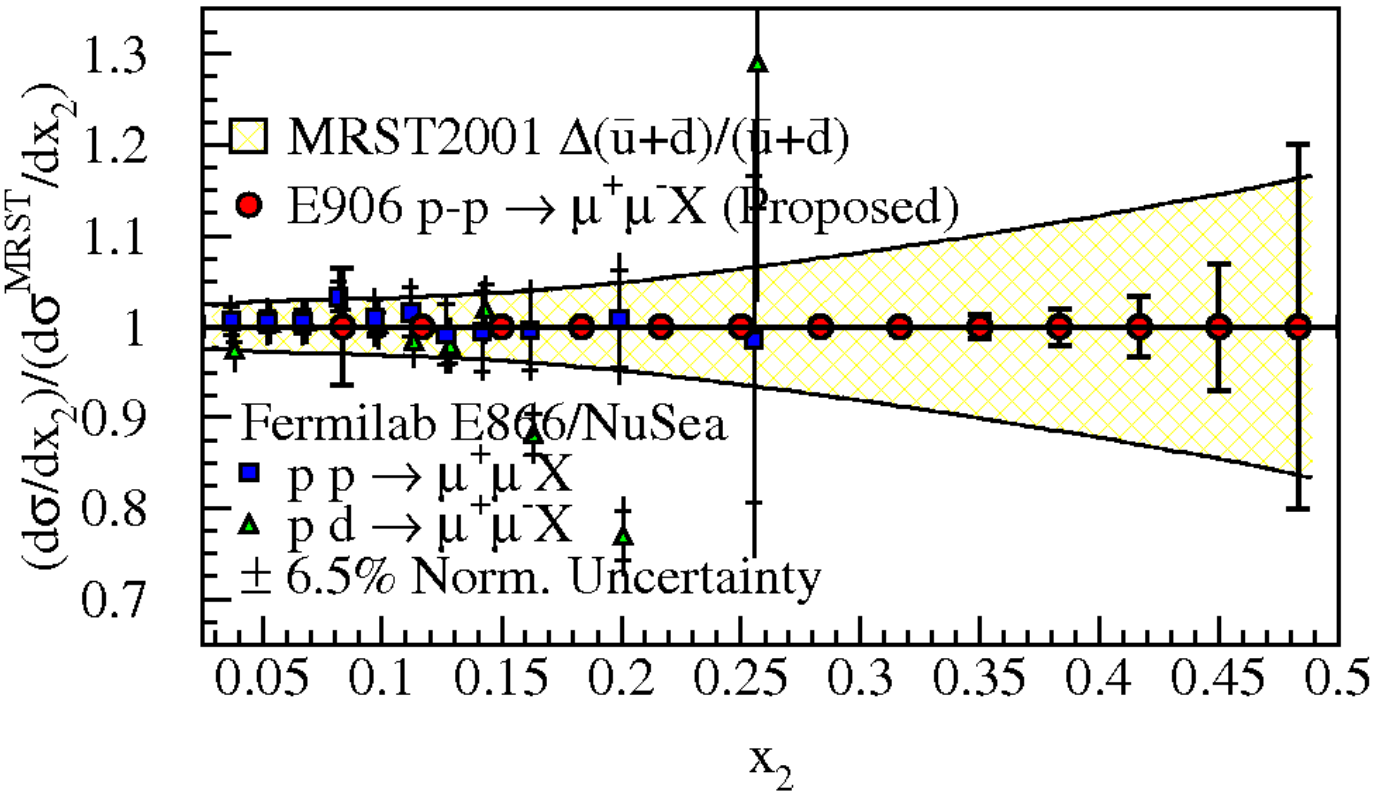
- The binding of nucleons in a nucleus is expected to be governed by the exchange of virtual “Nuclear” mesons.
- No antiquark enhancement seen in Drell-Yan (Fermilab E772) data.
- Contemporary models predict large effects to antiquark distributions as x increases.
- Models must explain both DIS-EMC effect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



Drell-Yan Absolute Cross Sections: x_{target}

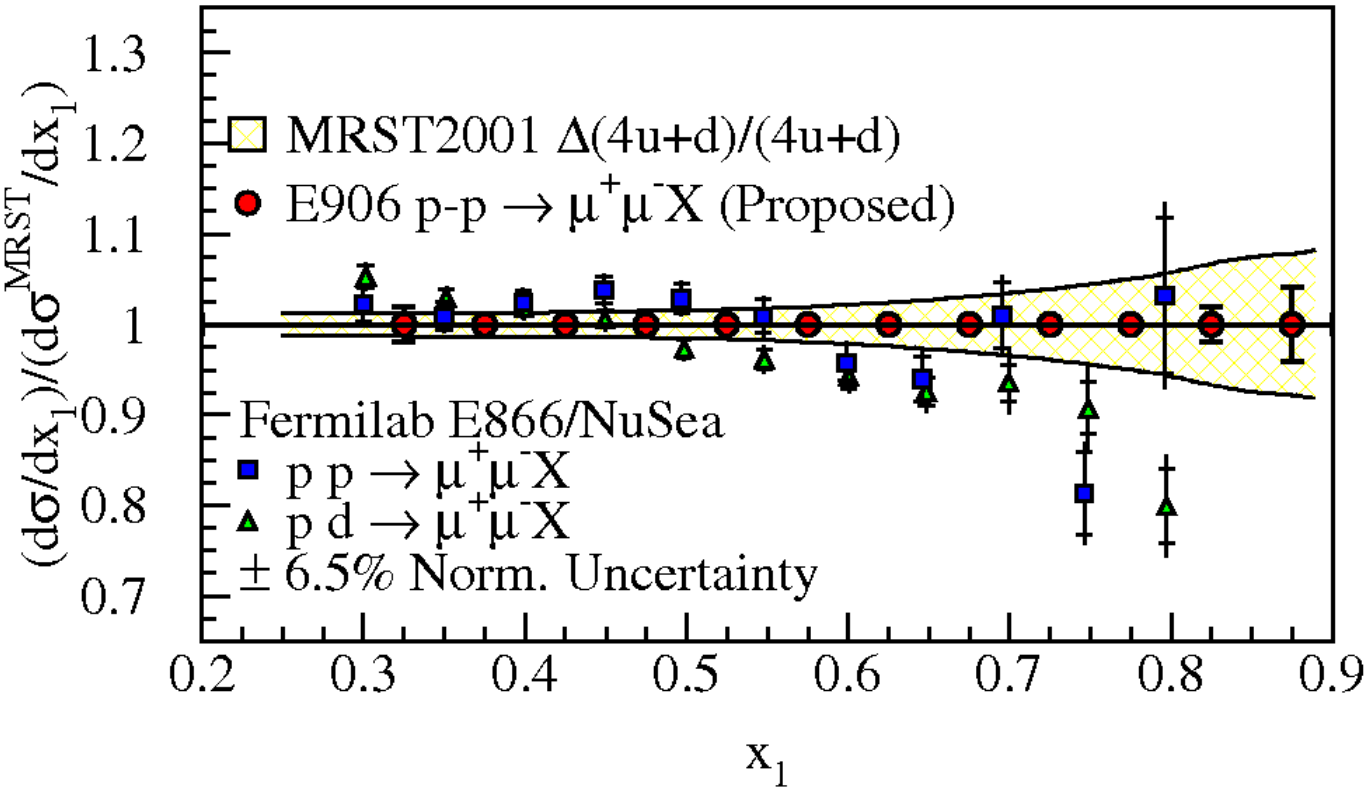
Measures a convolution of beam and target PDF

- absolute magnitude of high-x valence beam distributions
- absolute magnitude of the sea in the target
  - *Currently determined by ν–Fe DIS*



Drell-Yan Absolute Cross Sections: x_{target}

- Reach high-x through *beam proton*—Large $x_F \Rightarrow$ large x_{beam}.
- High-x distributions poorly understood
  - Nuclear corrections are large, even for deuterium
  - Lack of proton data
- Proton-Proton—no nuclear corrections—*4u(x) + d(x)*

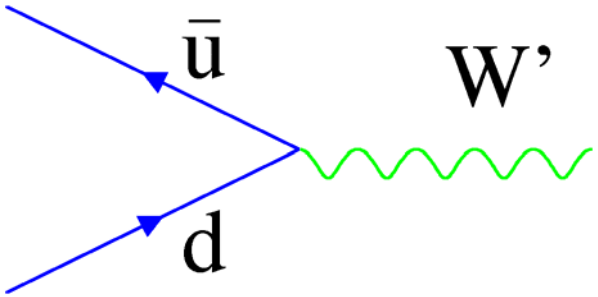


What will these measurement tell us?

- Better knowledge of parton distributions
  - Input to LHC: Consider 5 TeV Vector Boson

$$\bar{u}(x)d(x) \rightarrow W' \text{ with } M^2_{W'} = x_1 x_2 s$$

$x_1 \approx x_2 \approx 0.35 \Rightarrow$ d-bar/u-bar = 1 or 0?



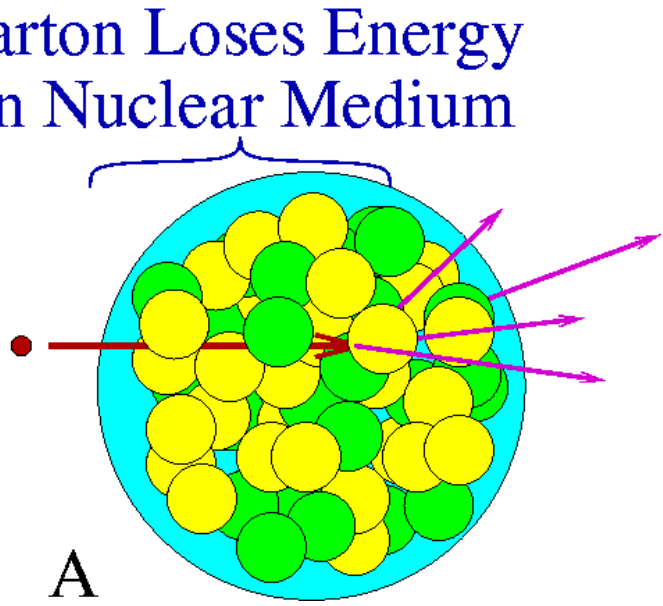
- Gluon distributions form symmetric sea

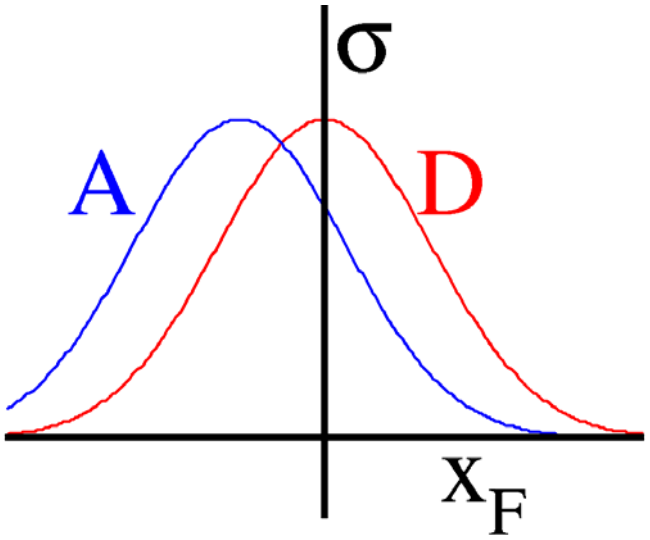
- Absolute magnitude of sea quark distributions
  - Absolute cross sections
  - Nuclear effects in sea quarks relevant interpretation of νDIS data

- Absolute magnitude of high-x distributions

Partonic Energy Loss

- An understanding of partonic energy loss in both cold and hot nuclear matter is paramount to elucidating RHIC data.
- Pre-interaction parton moves through cold nuclear matter and looses energy.
- Apparent (reconstructed) kinematic values (x_1 or x_F) is shifted
- Fit shift in x_1 relative to deuterium

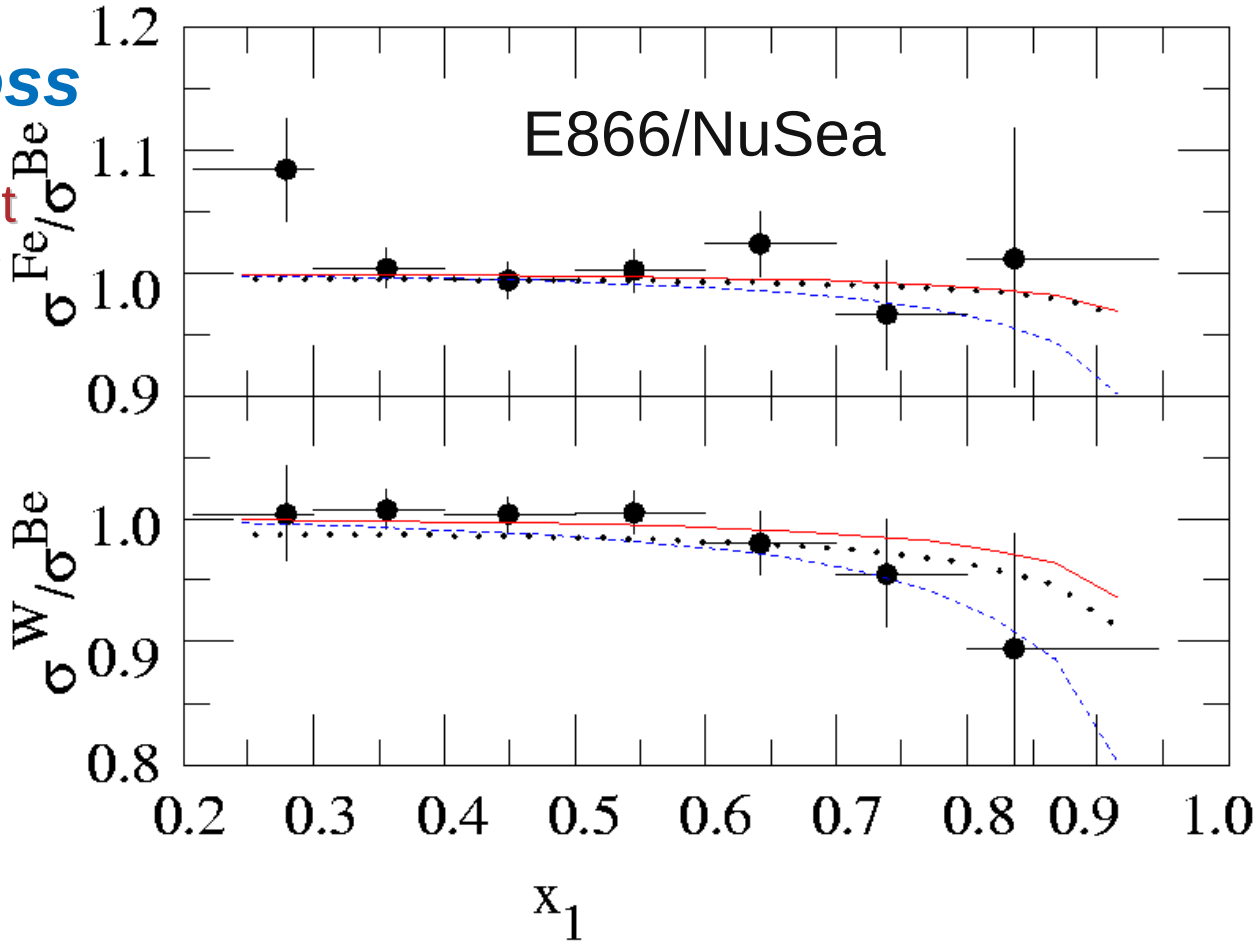




- Models:
  - Galvin and Milana $\Delta x_1 = -\kappa_1 x_1 A^{\frac{1}{3}}$
  - Brodsky and Hoyer $\Delta x_1 = -\frac{\kappa_2}{s} A^{\frac{1}{3}}$
  - Baier *et al.* $\Delta x_1 = -\frac{\kappa_3}{s} A^{\frac{2}{3}}$

Partonic Energy Loss

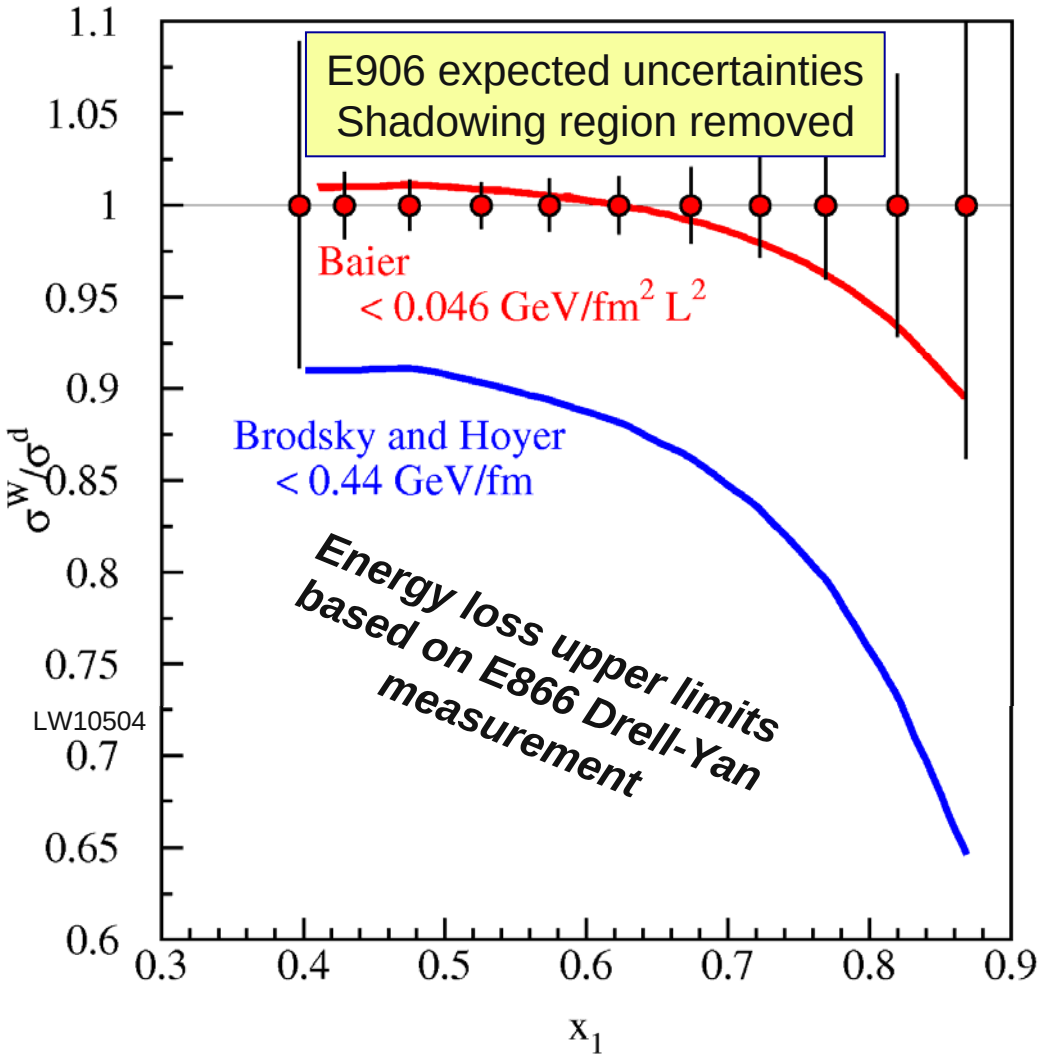
- E866 data are consistent with NO partonic energy loss for all three models
- Caveat: A correction must be made for shadowing because of x_1—x_2 correlations
  - E866 used an empirical correction based on EKS fit do DIS and *Drell-Yan*.



- Treatment of parton propagation length and shadowing are critical
  - Johnson et al. find 2.2 GeV/fm from the same data with different shadowing correction
- **Better data outside of shadowing region are necessary.**

Parton Energy Loss

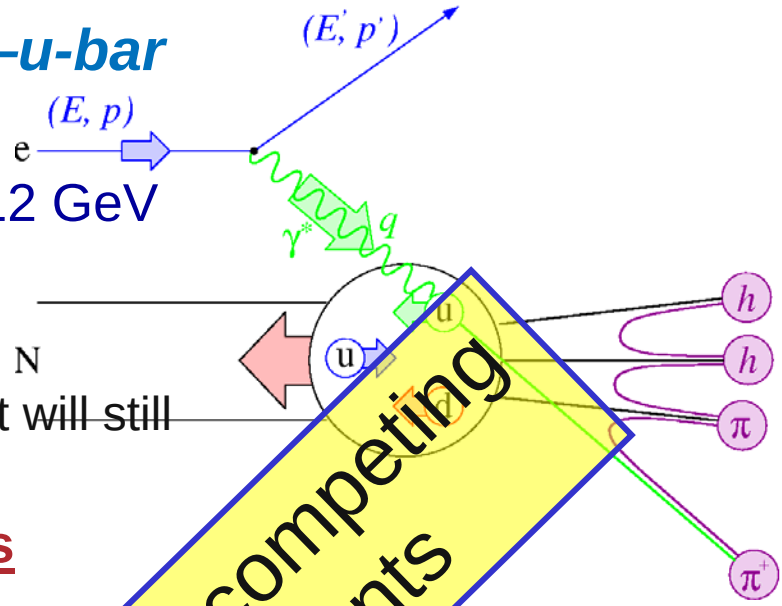
- Energy loss $\propto$ 1/s
  - larger at 120 GeV
- Ability to distinguish between models
- Measurements rather than upper limits



- E906 will have sufficient statistical precision to allow events within the shadowing region, $x_2 < 0.1$, to be removed from the data sample

Other Possible Measurements of d-bar—u-bar asymmetry

- Semi-Inclusive DIS—HERMES, JLab, JLab 12 GeV
  - Tag struck quark through leading hadron
  - Must understand fragmentation
  - HERMES will reduce statistical uncertainty but will still have significant systematic uncertainty
  - **Dominated by systematic uncertainties**
- Drell-Yan—JPARC
  - Initial phase of JPARC is 30 GeV—sufficient only for J/ψ studies, no Drell-Yan (no phase space for events above J/ψ)
  - JPARC Phase II—50 GeV
    - great possibilities for polarized Drell-Yan
    - Berger criteria for nuclear targets—insufficient energy for heavy A
    - No partonic energy loss studies—x_{beam}-x_{target} correlations
    - Experimental issues: p_T acceptance, $\pi^{\pm}$ decay in flight background
  - **Physics Program cannot be reached by 30 GeV machine (physics program strongly endorsed)**



There are no competing measurements

Fermilab E906/Drell-Yan Collaboration

Abilene Christian University
Donald Isenhower, Mike Sadler, Rusty Towell

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

University of Colorado
Ed Kinney

Fermi National Accelerator Laboratory
Chuck Brown

University of Illinois
Naiomi C.R Makins, Jen-Chieh Peng

Los Alamos National Laboratory
Gerry Garvey, Mike Leitch, Pat McGaughey, Joel Moss

Rutgers University
Ron Gilman, Charles Glashausser, Xiaodong Jaing, E. Kuchina, Ron Ransome, Elaine Schulte

Texas A & M University
Carl Gagliardi, Bob Tribble

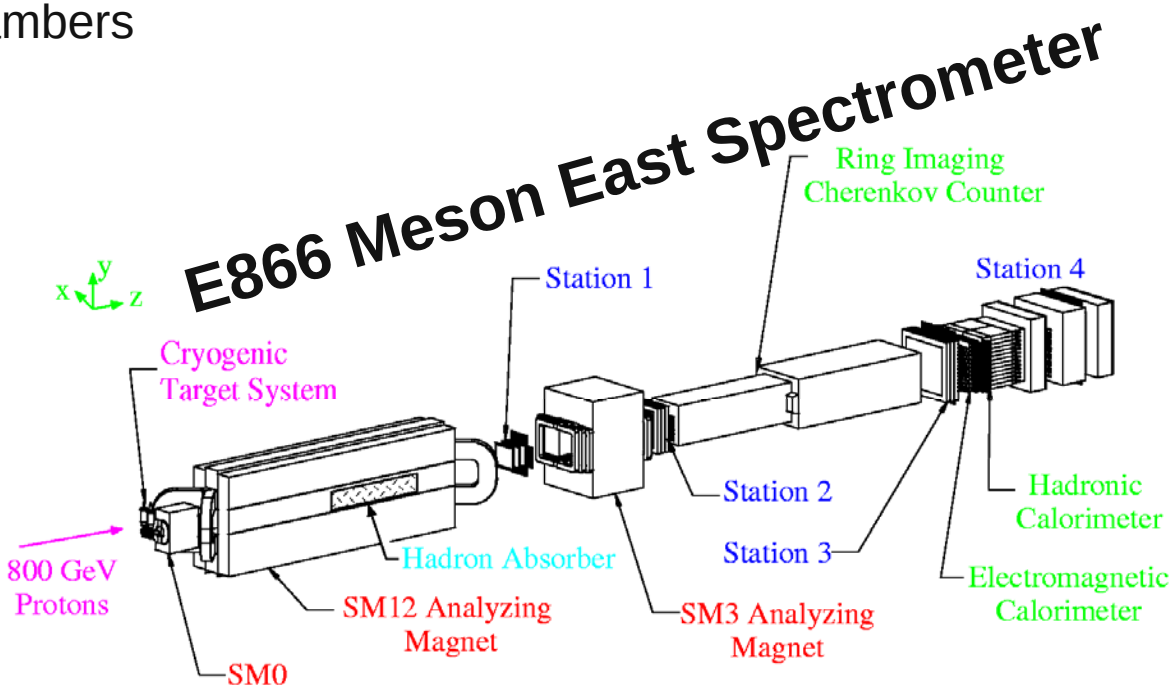
Thomas Jefferson National Accelerator Facility
Dave Gaskell

Valparaiso University
Don Koetke, Jason Webb

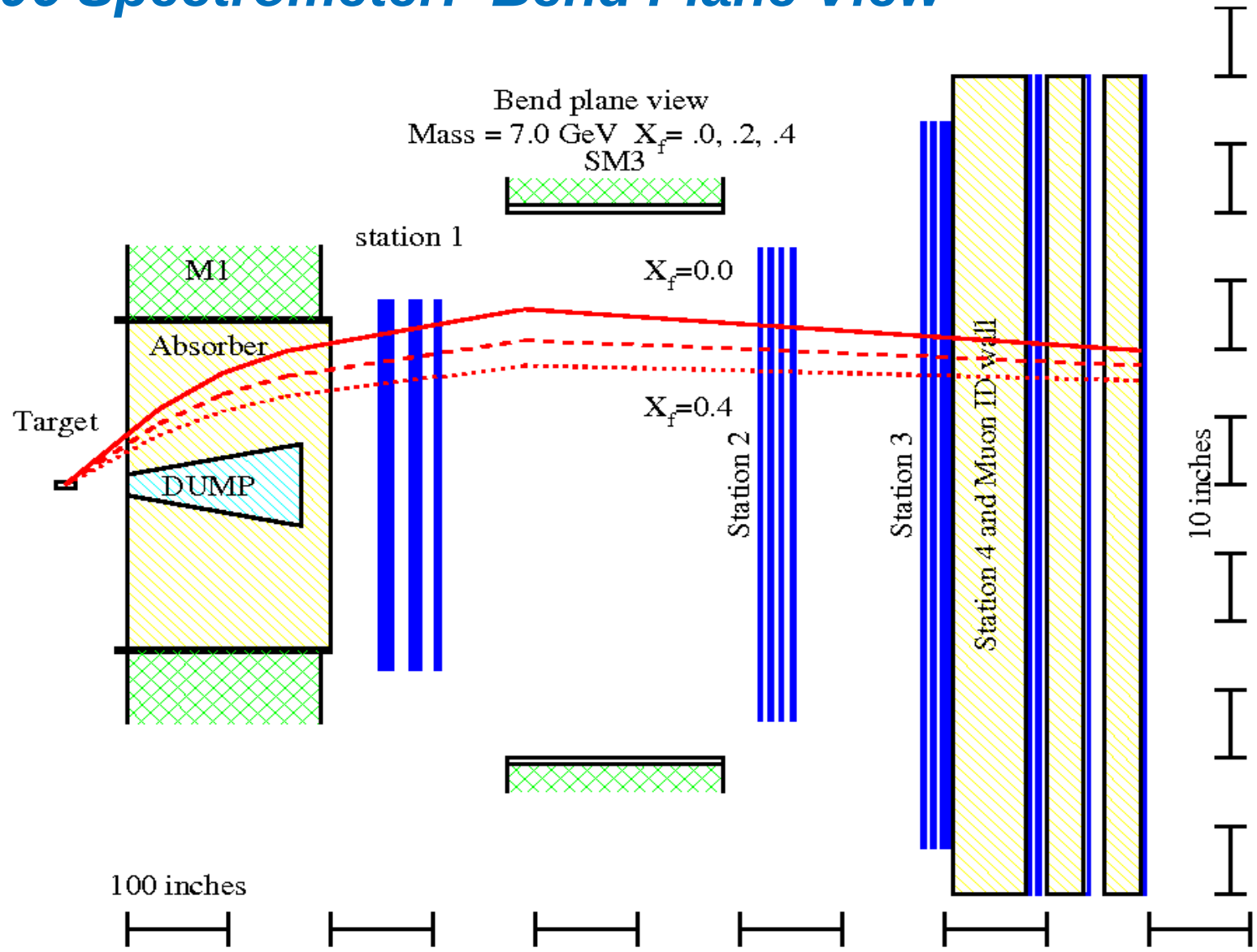
*Co-Spokespersons

Drell-Yan Spectrometer Guiding Principles

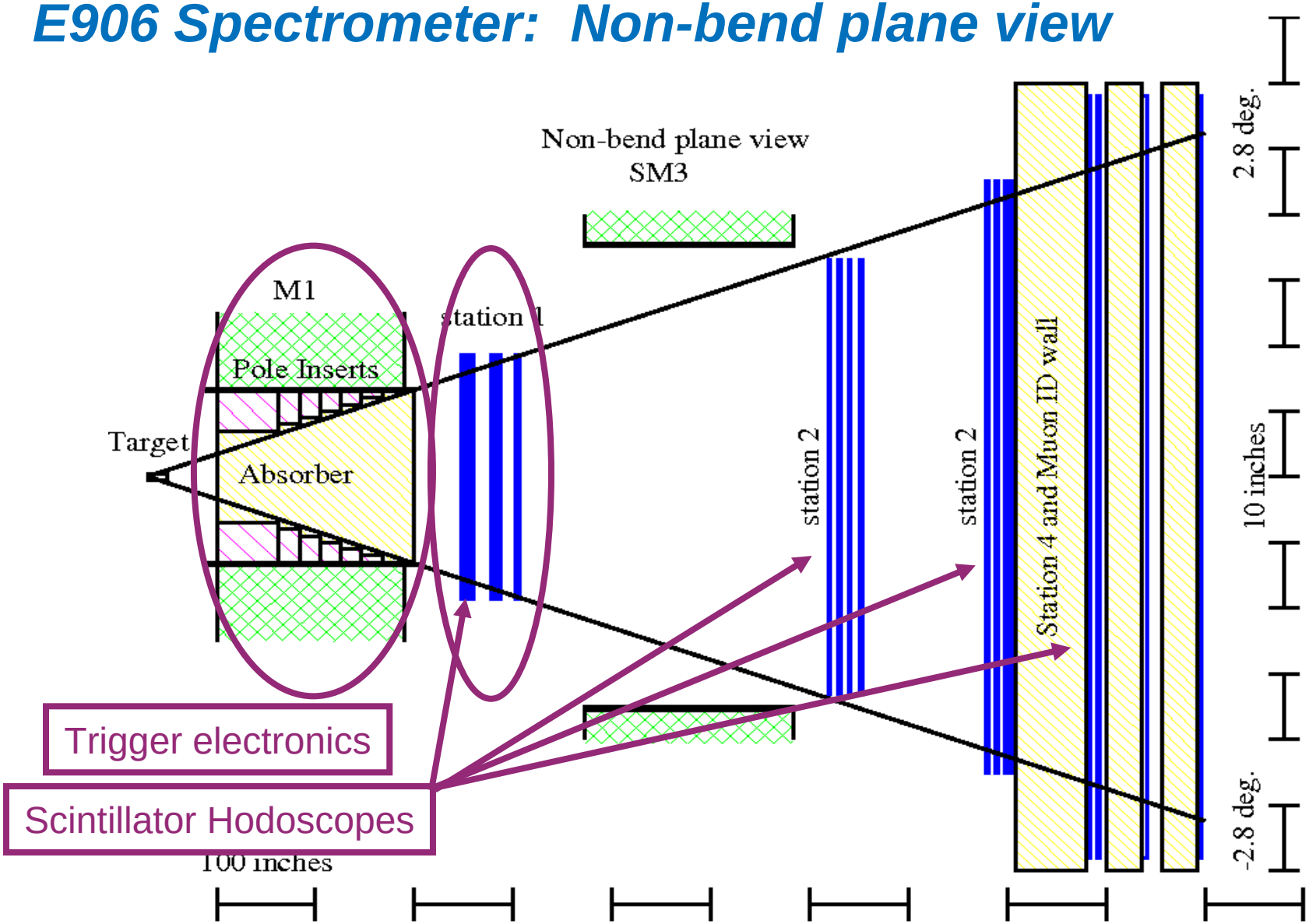
- Follow basic design of MEast spectrometer (don't reinvent the wheel):
  - Two magnet spectrometer
  - Beam dump within first Magnet
  - Hadron absorber within first magnet
  - Muon-ID wall before final elements
- Where possible and practical, reuse elements of the E866 spectrometer.
  - Tracking chamber electronics (and electronics from E871)
  - Hadron absorber, beam dump, muon ID walls
  - Station 2 and 3 tracking chambers
  - Hodoscope array PMT's
  - SM3 Magnet
- New Elements
  - 1st magnet (different boost) Experiment shrinks from 60m to 26m
  - Sta. 1 tracking (rates)
  - Scintillator (age)
  - Trigger (flexibility)



E906 Spectrometer: Bend Plane View



E906 Spectrometer: Non-bend plane view



Spectrometer Upgrade Budget and Schedule

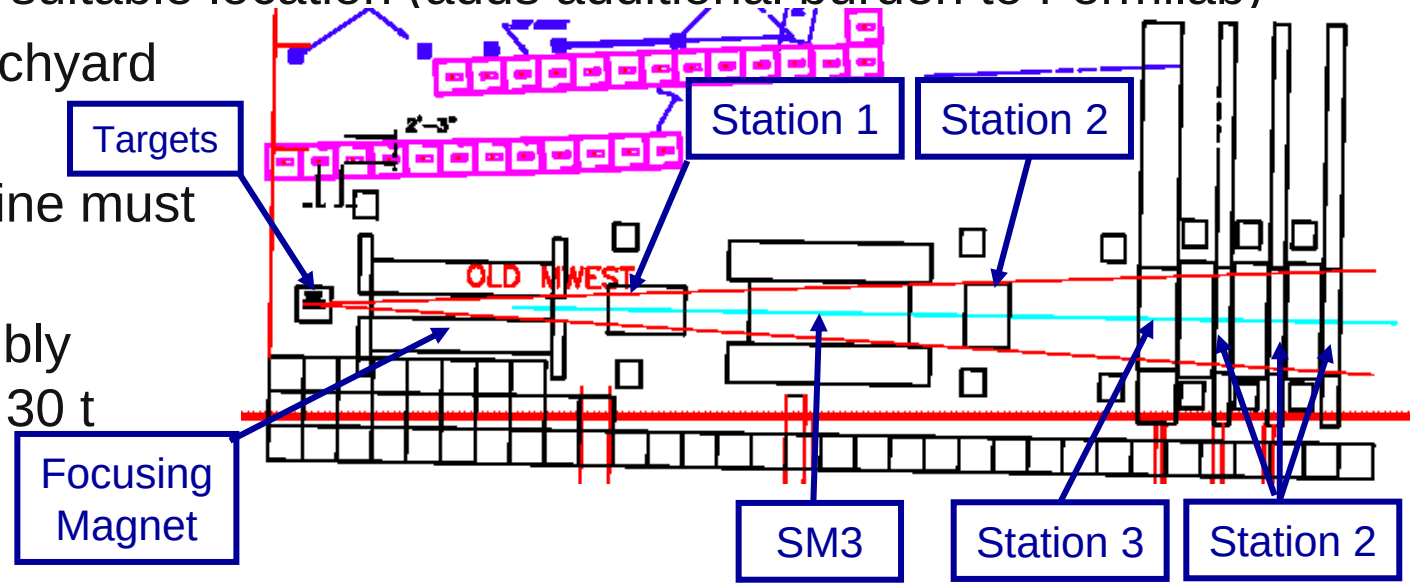
- **Approximate Cost:**
  - Magnet coil fabrication: US$1.4M
  - US$0.8M for Spectrometer upgrades
- **Funding sources**
  - US DOE-Office of Nuclear Physics US$2.0M
  - US NSF US$0.3M
- Two timelines have been proposed to DOE/ONP, both starting FY07—**schedule is funding driven**
  - Realistic: Funds over three years, coil purchase in FY08, spectrometer completion in early FY09
  - Optimistic: Funds over two years, coil purchase in FY07
- DOE/ONP has asked Argonne to hold a cost/schedule review before receiving any funds
  - Tentatively scheduled for December
  - **Need Phase II approval and draft MOU with Fermilab**

Proton Economics

- Total of 5.2×10^{18} protons (over 2 years)
- Maximum instantaneous rate of 2×10^{12} proton/sec
  - Based on E866 experience with target related rate dependence—balance systematic and statistical uncertainties
  - Station 1 chamber rates.
- Possible delivery scenario:
  - 5 sec spill of 1×10^{13} protons each minute
  - Longer spill (5 sec) desirable over 5-1 sec spills

Experimental Location

- Originally proposed MEast was ideal
  - Superconducting Cryo-Module Test Facility (SMTF) now in MEast
- MWest provides a suitable location (adds additional burden to Fermilab)
  - Complete Switchyard 120 Upgrade
  - MWest beam line must be rebuilt
  - Magnet assembly difficult—need 30 t crane



- KTeV's Hall—New possibility being studied

Bottom line:

Experiment has will moved to accommodate Fermilab's space needs, but the move from Meson East increased the impact on Fermilab resources

Request of Fermilab and Impact

Accelerator Division

Provide a slow extracted beam of 120 GeV protons at a rate of no more than 2×10^{12}/s for a total of 5.2×10^{18} protons on target in two years

- Assuming MWest location, the Switchyard 120 upgrade (or another solution to reduce beam losses) must be implemented.
- Spill cycle with 5 sec 1×10^{13} protons each minute will provide desired instantaneous and total luminosity

Provide beam line and instrumentation

- Beam line must be rebuilt

Provide utilities (power and cooling water) for magnets and power supplies

- Minor impact on other operations

Computing Division

Provide PREP electronics, including 1700 channels of multi-hit TDC's

- Collaboration could take on testing of modules as requested by PREP
- Additional solutions (other sources) are being investigated

DAQ and data logging suggestions are reasonable

Request of Fermilab and Impact

Research Division

Assembly of new M1 magnet

- Requires 30-ton crane to for yoke pieces. This was available in MEast, but not in MWest. A crane would need to be rented for assembly.
- Modification of existing yoke on top and bottom, modification of existing copper beam dump
- Additional foundation pits must be excavated for magnets (again these were available in MEast location).

Installation of SM3 in spectrometer location

- Again requires use of 30-ton crane

Provide liquid hydrogen and deuterium targets and drive mechanism

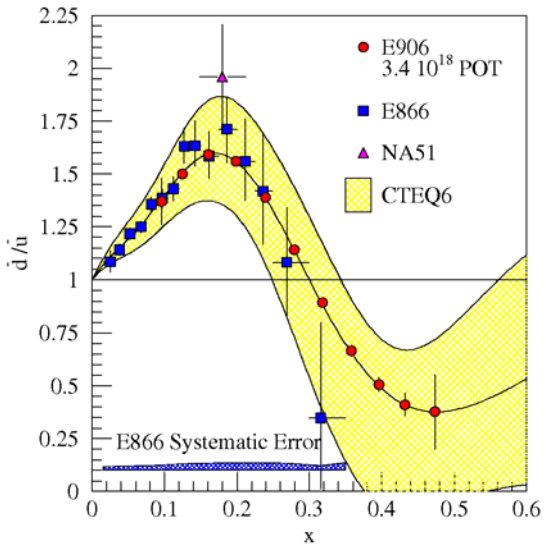
- If still available, reuse e866 target system

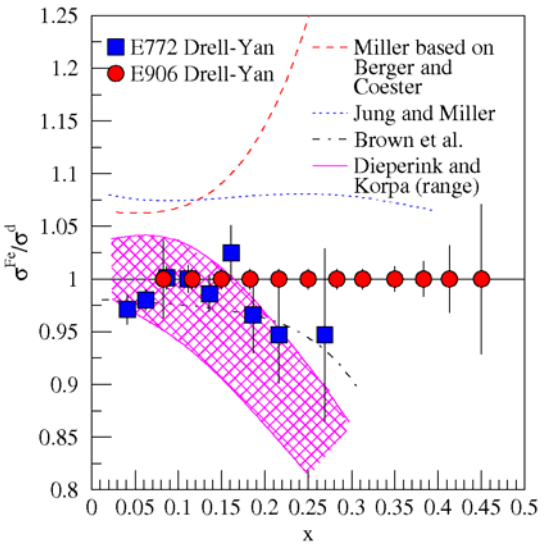
Additional "minor" requests—see appendix of proposal for complete list

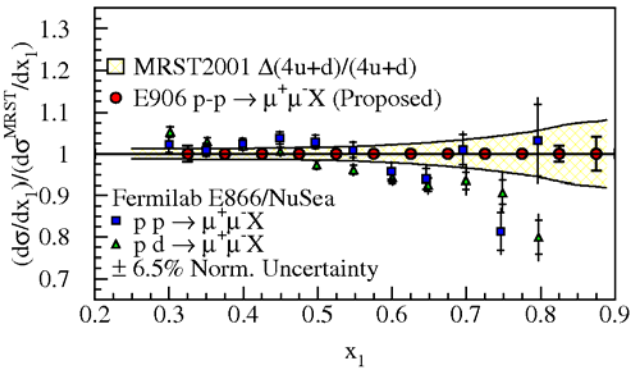
Drell-Yan at Fermilab

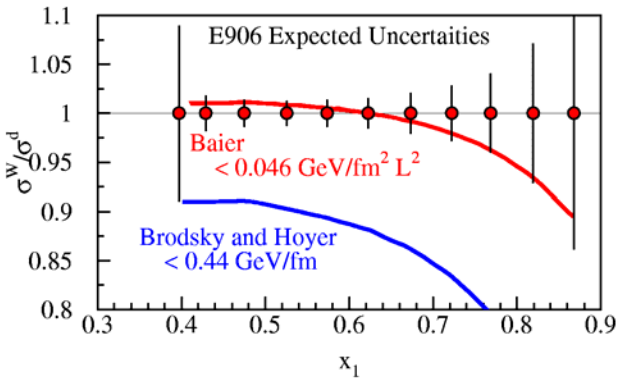
- **What is the structure of the nucleon?**
  - What is d-bar/u-bar?
  - What are the origins of the sea quarks?
  - What is the high-x structure of the proton?
- **What is the structure of nucleonic matter?**
  - Where are the nuclear pions?
  - Is anti-shadowing a valence effect?
- **Do colored partons lose energy in cold nuclear matter?**
- **Answers from Fermilab E906/Drell-Yan**
  - Significant increase in physics reach over previous Drell-Yan experiments
  - DOE/ONP funding of spectrometer likely this year

E906 needs Phase II approval for this to happen



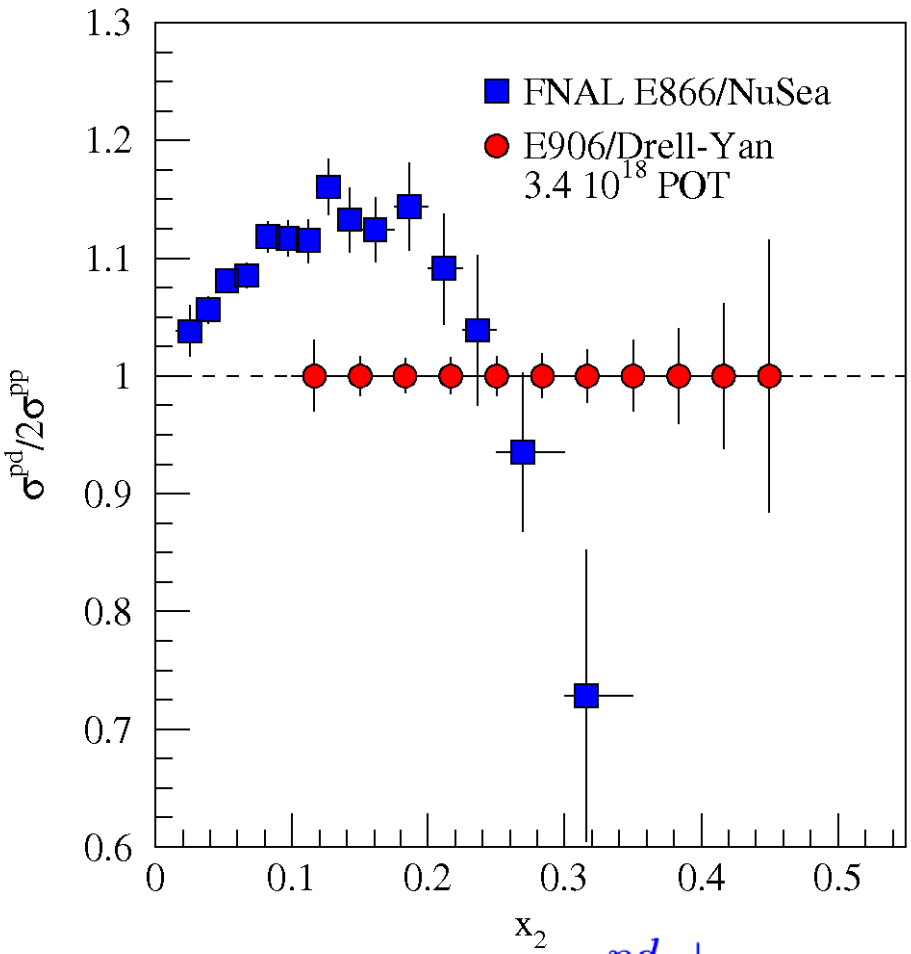


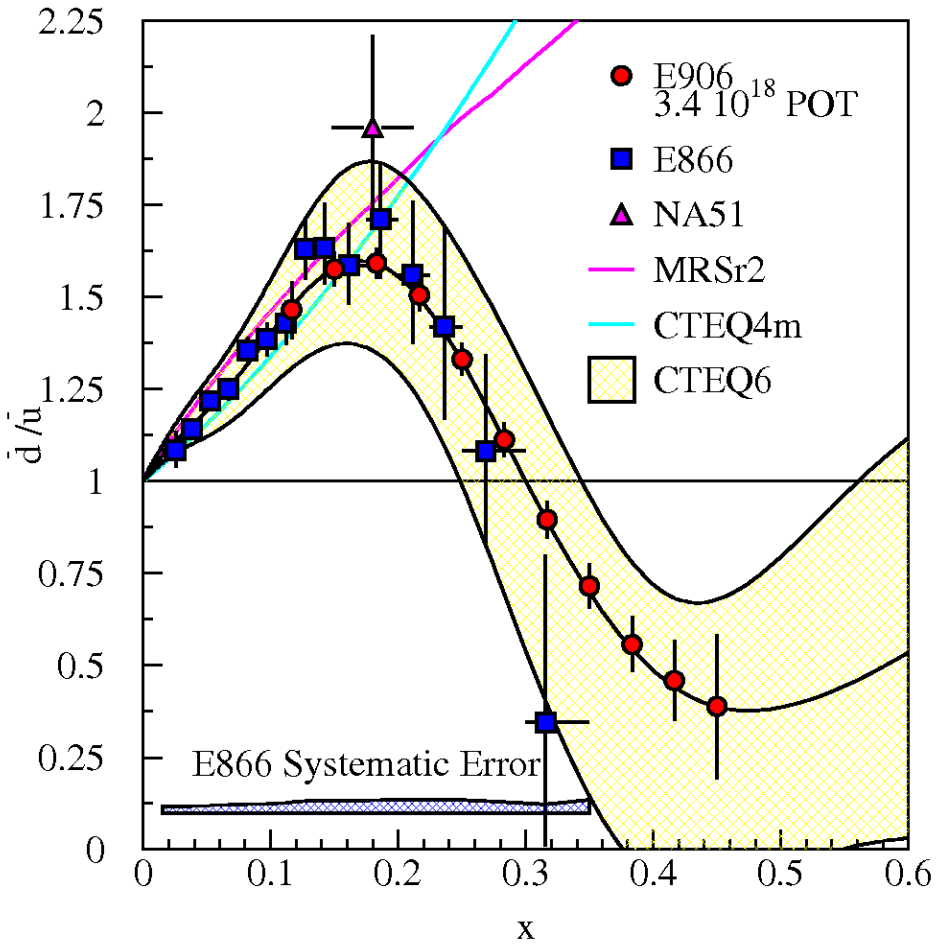




Additional Material

Drell-Yan Cross Section Ratio and d-bar/u-bar

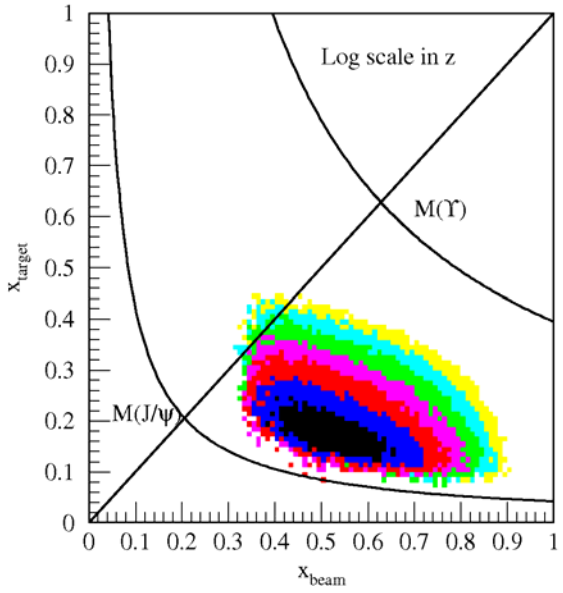


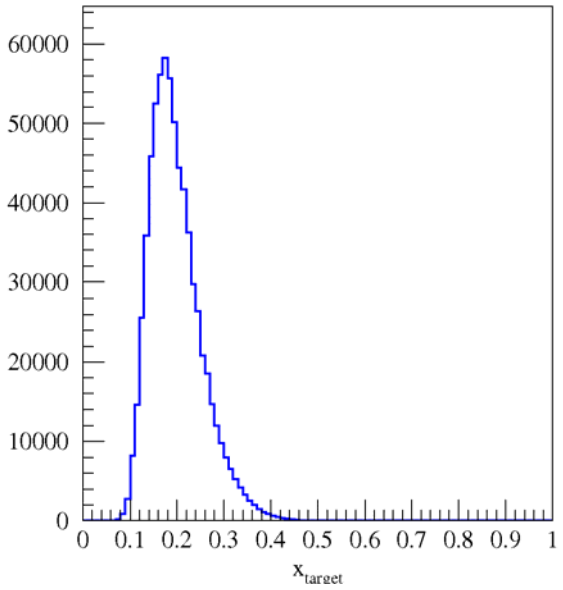


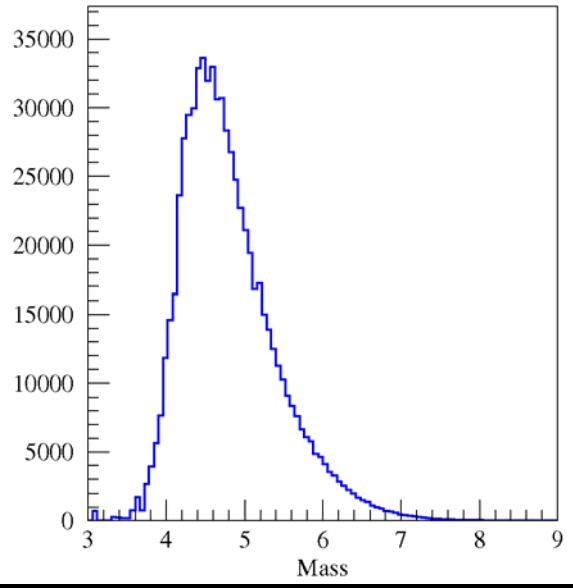
$$\left.\frac{\sigma^{pd}}{2\sigma^{pp}}\right|_{x_b \gg x_t} \approx \frac{1}{2}\left[1 + \frac{\bar{d}(x_t)}{\bar{u}(x_t)}\right]$$

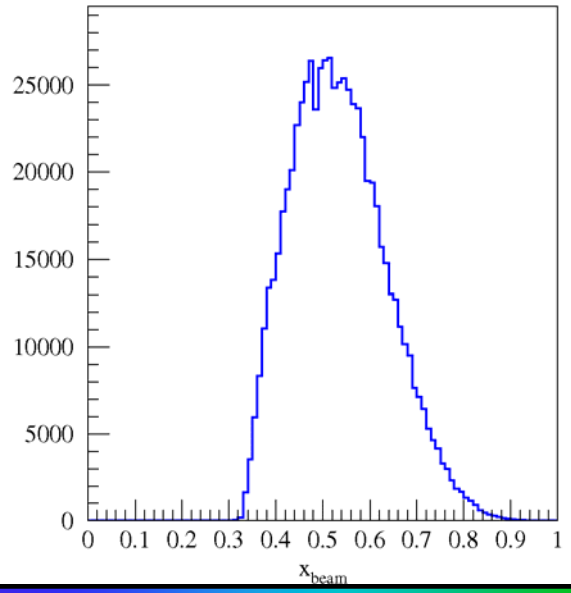
Drell-Yan Acceptance

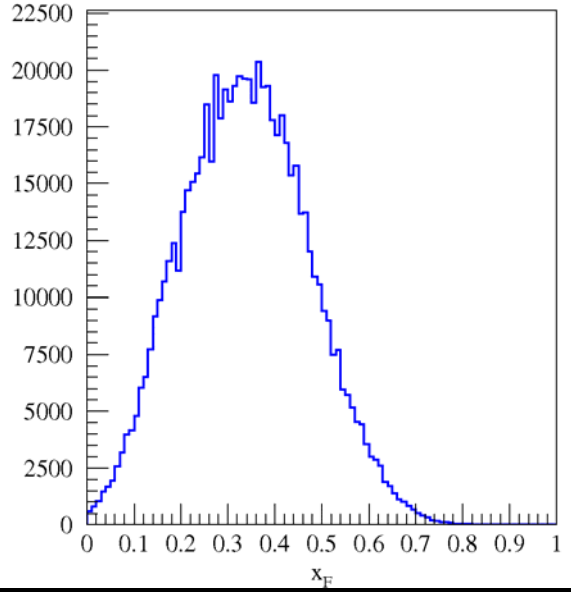
- Programmable trigger removes likely J/ψ events
- Transverse momentum acceptance to above 2 GeV
- Spectrometer could also be used for J/ψ, ψ′ studies



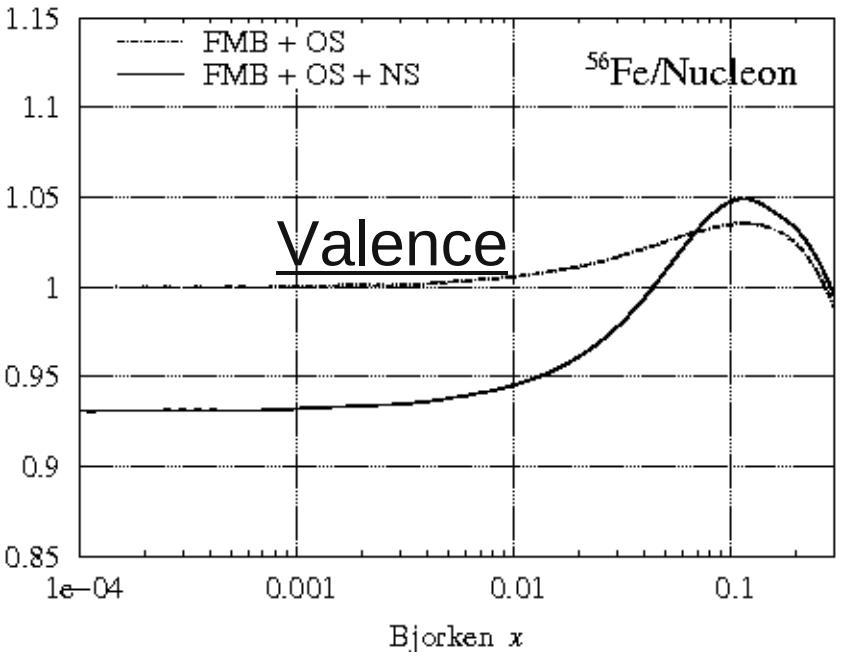


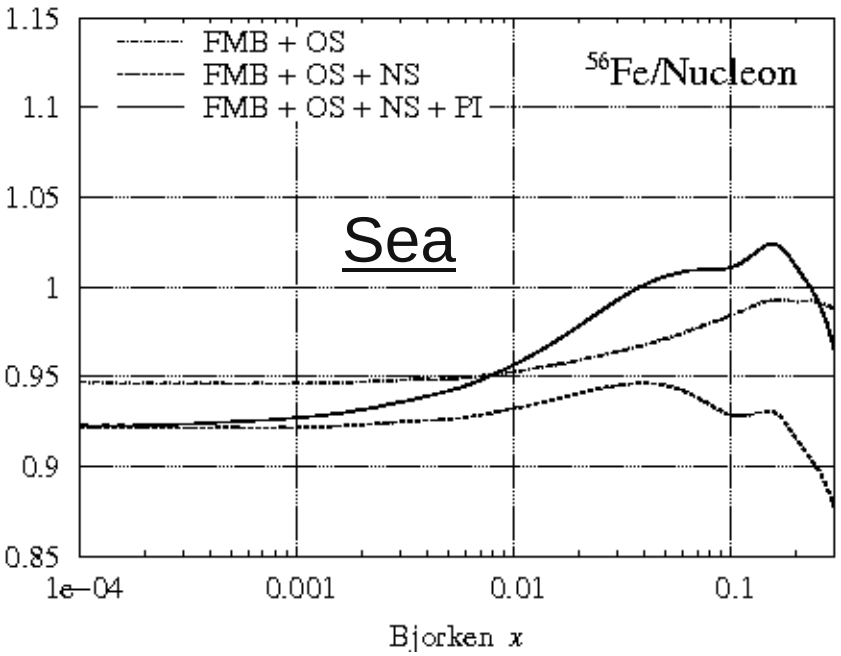






Kulagin and Petti sea vs. valence nuclear effects





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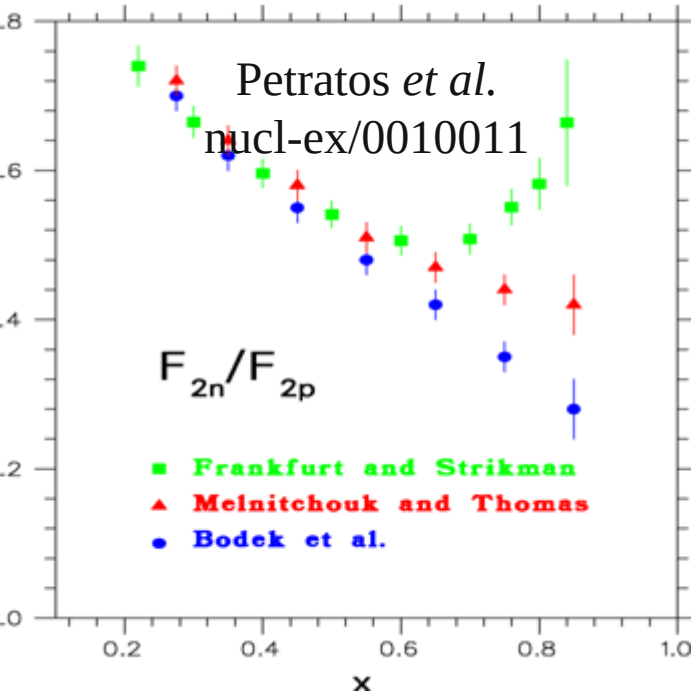
Proton Valence Structure: Unknown as $x \to 1$

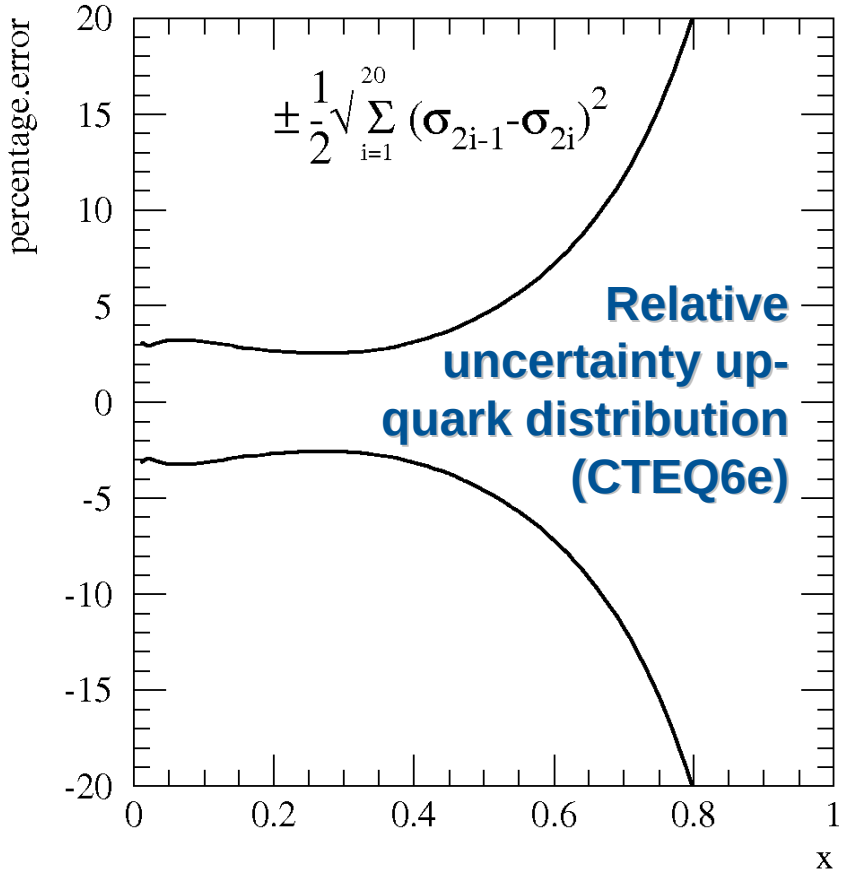
Theory

- Exact SU(6): $d/u \to 1/2$
- Diquark S=0 dom.: $d/u \to 0$
- pQCD: $d/u \to 3/7$

Data

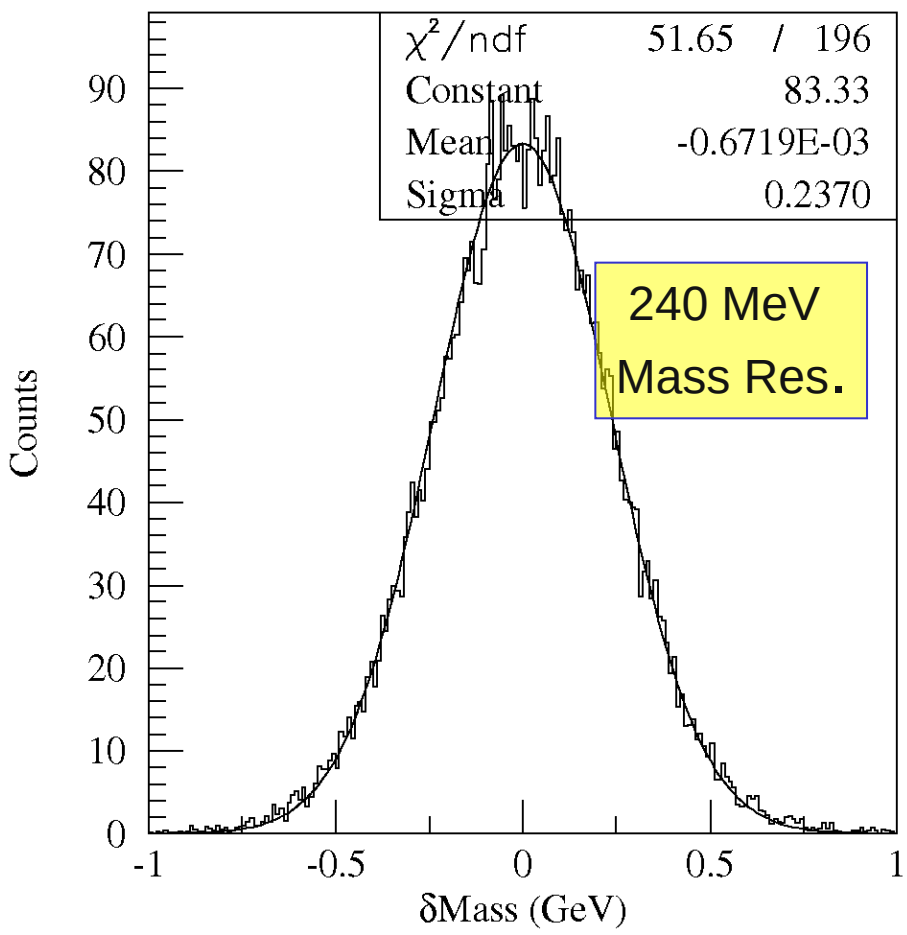
- Binding/Fermi Motion effects in deuterium—choice of treatments.
- ***Proton data is needed.***

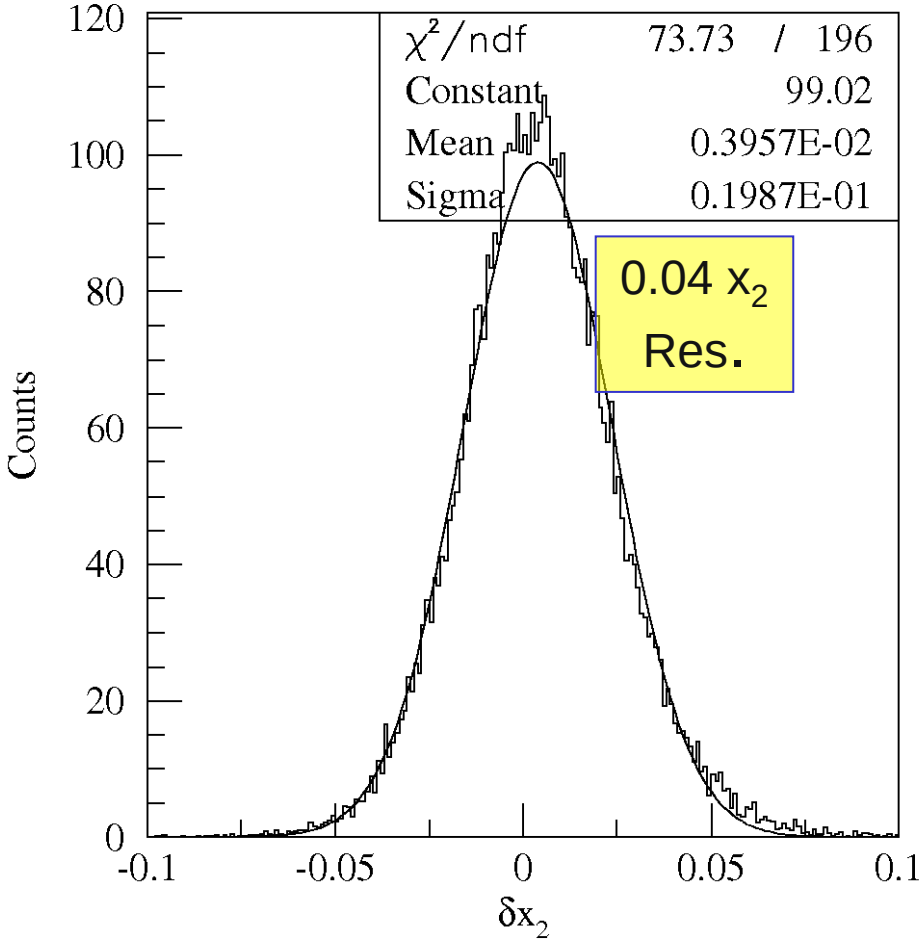




Reality:
We don't even know the u or d quark distributions—there really is very little high-x proton data

Detector Resolution





- Triggered Drell-Yan events

Detector Rates

	LH_2 Target		$LD2$ Target		Copper Beam Dump	
	μ's	Trks.	μ's	Trks.	μ's	Trks.
π^+ decay-in-flight	81 k	12 k	195 k	29 k	153 k	13 k
π^- decay-in-flight	35 k	8 k	84 k	20 k	76 k	20 k
K^+ decay-in-flight	63 k	13 k	151 k	31 k	139 k	20 k
K^- decay-in-flight	6 k	3 k	15 k	6 k	18 k	8 k
Total μ^+	144 k	25 k	346 k	60 k	292 k	33 k
Total μ^-	41 k	11 k	99 k	26 k	94 k	28 k

Expected single muon rates per 2×10^{12} protons from decay-in-flight mesons which pass through the detector (μ's) and satisfy trigger matrix tracking requirements (Trks.) from liquid hydrogen and deuterium targets and the copper beam dump.

Publications of the Fermilab Drell-Yan Program

E866/NuSea

- E.A. Hawker *et al.* *Measurement of the Light Antiquark Flavor Asymmetry in the Nucleon Sea,* Phys. Rev. Lett. **80**, 3715 (1998).
- J.C. Peng *et al.* *d-bar/u-bar Asymmetry and the Origin of the Nucleon Sea,* Phys. Rev. **D58**, 092004 (1998).
- M.A. Vasiliev *et al. Parton energy loss limits and shadowing in Drell-Yan dimuon production,* Phys. Rev. Lett. **83**, 2304 (1999).
- M.J. Leitch *et al.* *Measurement of Differences between J/ψ and ψ' Suppression in p-A Collisions*, Phys. Rev. Lett. **84**, 3256 (2000).
- C.N. Brown *et al.* *Observation of Polarization in Bottomonium Production at sqrt s = 38.8 GeV*, Phys. Rev. Lett. **86**, 2529 (2001).
- R.S. Towell *et al.* *Improved Measurement of the d-bar/u-bar Asymmetry in the Nucleon Sea,* Phys. Rev. **D64**, 052002 (2001).
- T.H. Chang *et al.* *J/ψ polarization in 800-GeV p Cu interactions,* Phys. Rev. Lett. **91** 211801 (2003).
- L.Y. Zhu *et al.* *Measurement of Angular Distributions of Drell-Yan Dimuons in p + d Interaction at 800-GeV/c,* Submitted to Phys. Rev. Lett. arxiv:hep-ex/0609005.

E789 Publications:

- M.S. Kowitt *et al.* *Production of J/ψ at Large x_F in 800 GeV/c p-Copper and p-Beryllium Collisions*, Phys. Rev. Lett. **72**, 1318 (1994).
- M.J. Leitch *et al.* *Nuclear Dependence of Neutral D Production by 800 GeV/c Protons,* Phys. Rev. Lett. **72**, 2542 (1994).
- C.S. Mishra *et al.* *Search for the decay $D^0 \rightarrow \mu^+\mu$,* Phys. Rev. **D50**, 9 (1994).

Publications of the Fermilab Drell-Yan Program

E789 Publications (Cont.):

- D.M. Jansen *et al.* *Measurement of the Bottom-Quark Production Cross Section in 800 GeV/c Proton-Gold Collisions*, Phys. Rev. Lett. **74**, 3118 (1995).
- M.H. Schub *et al.* *Measurement of J/ψ and ψ' Production in 800 GeV/c Proton-Gold Collisions*, Phys. Rev. **D52**, 1307 (1995); Phys. Rev. D53, 570 (1996).
- M.J. Leitch *et al.* *Nuclear Dependence of J/ψ Production by 800 GeV/c Protons near $x_F = 0$*, Phys. Rev. **D52**, 4251 (1995).
- C.N. Brown *et al.* *Nuclear Dependence of Single-Hadron and Dihadron Production in p-A Interactions at sqrt s = 38.8 GeV,* Phys. Rev. **C54**, 3195 (1996).
- D. Pripstein *et al.* *Search for flavor-changing neutral currents and lepton-family-number violation in two-body D_0 decays*, Phys. Rev. **D61**, 032005 (2000).

E772 Publications:

- D.M. Alde *et al.* *Nuclear Dependence of Dimuon Production at 800 GeV,* Phys. Rev. Lett. **64**, 2479 (1990).
- D.M. Alde *et al.* *A Dependence of J/ψ and ψ' Production at 800 GeV/c*, Phys. Rev. Lett. **66**, 133 (1991).
- D.M. Alde *et al.* *Nuclear Dependence of the Production of Upsilon Resonances at 800 GeV*, Phys. Rev. Lett. **66**, 2285 (1991).
- P.L. McGaughey *et al.* *Cross sections for the production of high-mass muon pairs from 800 GeV proton bombardment of ^2H*, Phys. Rev. **D50**, 3038 (1994).
- P.L. McGaughey *et al.* *Limit on the d-bar/u-bar asymmetry of the nucleon sea from Drell-Yan production*, Phys. Rev. Lett. **69**, 1726 (1992).