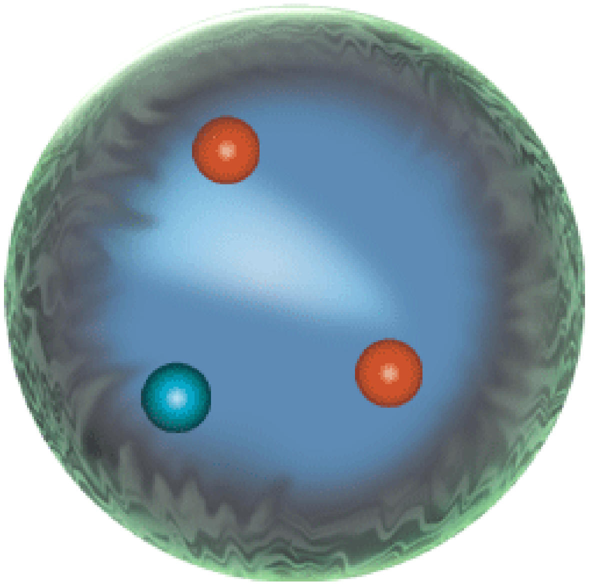
E906 at FNAL:
Measurements of Flavor Asymmetry of Antiquarks in the Nucleon



- Flavor asymmetry of sea quarks
- E866
- E906
- Taiwan group in E906.

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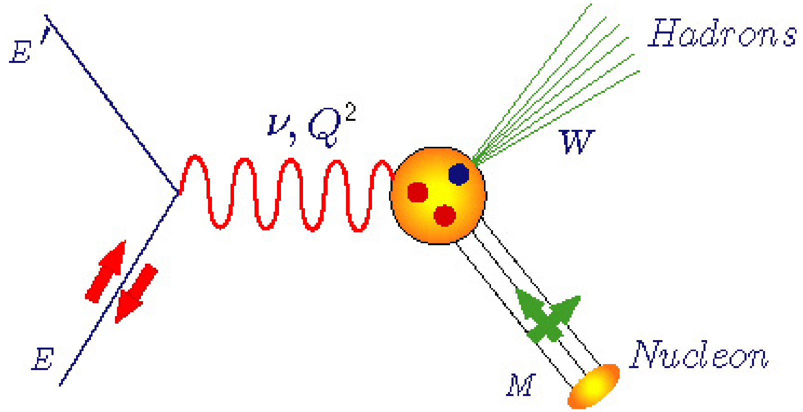
Introduction

Inclusive Electron Scattering – Formalism



Q^2 : Four-momentum transfer
x : Bjorken variable (=$Q^2/2M\nu$)
ν : Energy transfer
M : Nucleon mass
W : Final state hadronic mass

U $$\frac{d^2\sigma}{dE'd\Omega}(\downarrow\Uparrow + \uparrow\Uparrow) = \frac{8\alpha^2\cos^2(\theta/2)}{Q^4}\left[\frac{F_2(x,Q^2)}{\nu} + \frac{2F_1(x,Q^2)}{M}\tan^2(\theta/2)\right]$$

- Unpolarized structure functions $F_1(x,Q^2)$ and $F_2(x,Q^2)$, or $F_T(x,Q^2)$ [=$2xF_1(x,Q^2)$] and $F_L(x,Q^2)$, to separate by measuring $R = \sigma_L/\sigma_T$

L
- Polarized structure functions $g_1(x,Q^2)$ and $g_2(x,Q^2)$

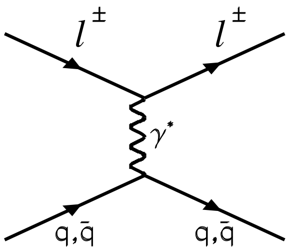
$$\frac{d^2\sigma}{dE'd\Omega}(\downarrow\Uparrow - \uparrow\Uparrow) = \frac{4\alpha^2}{MQ^2}\frac{E'}{\nu E}\left[(E + E'\cos\theta)g_1(x,Q^2) - \frac{Q^2}{\nu}g_2(x,Q^2)\right]$$

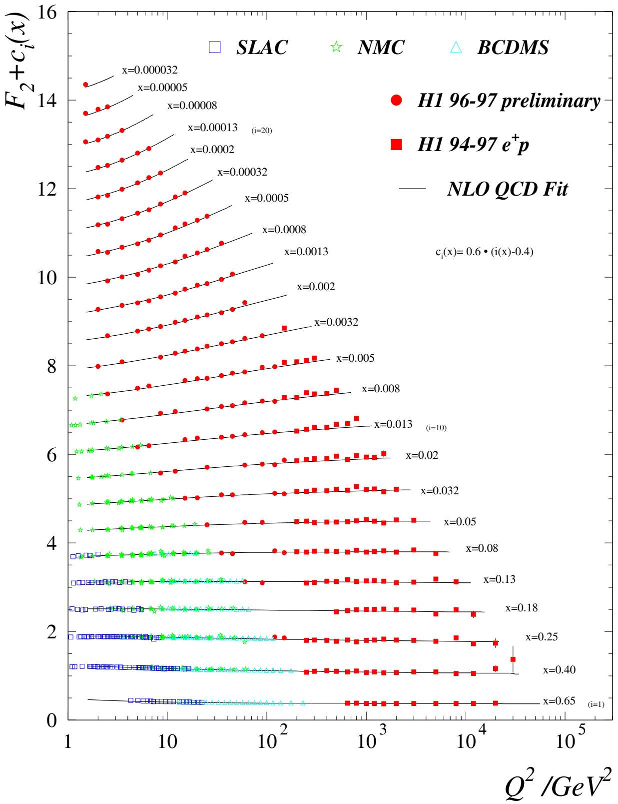
T
$$\frac{d^2\sigma}{dE'd\Omega}(\downarrow\Rightarrow - \uparrow\Rightarrow) = \frac{4\alpha^2\sin\theta}{MQ^2}\frac{E'^2}{\nu^2 E}\left[\nu g_1(x,Q^2) + 2Eg_2(x,Q^2)\right]$$

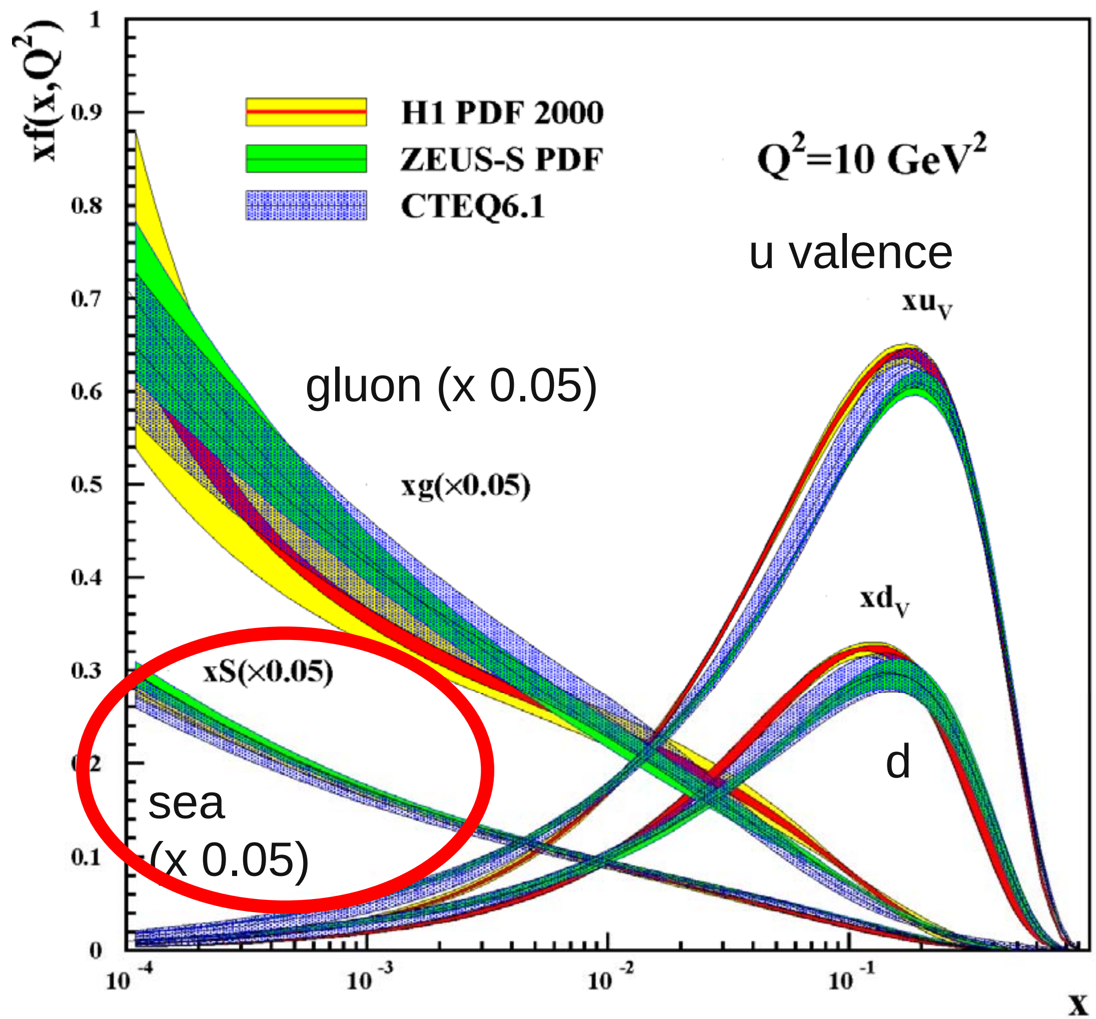
Unpolarized Parton Distributions (CTEQ6)

- After 40 years DIS experiments, unpolarized structure of the nucleon reasonably well understood.
- High *x* → valence quark dominating

$$F_2(x,Q^2) = \sum_i e_i^2 x[q_i(x,Q^2) + \bar{q}_i(x,Q^2)]$$







Is $\bar{u} = \bar{d}$ in the proton?

$$F_2^p(x,Q^2) - F_2^n(x,Q^2) = \frac{1}{3}x[u_v(x,Q^2) - d_v(x,Q^2)] + \frac{2}{3}x[\bar{u}(x,Q^2) - \bar{d}(x,Q^2)]$$

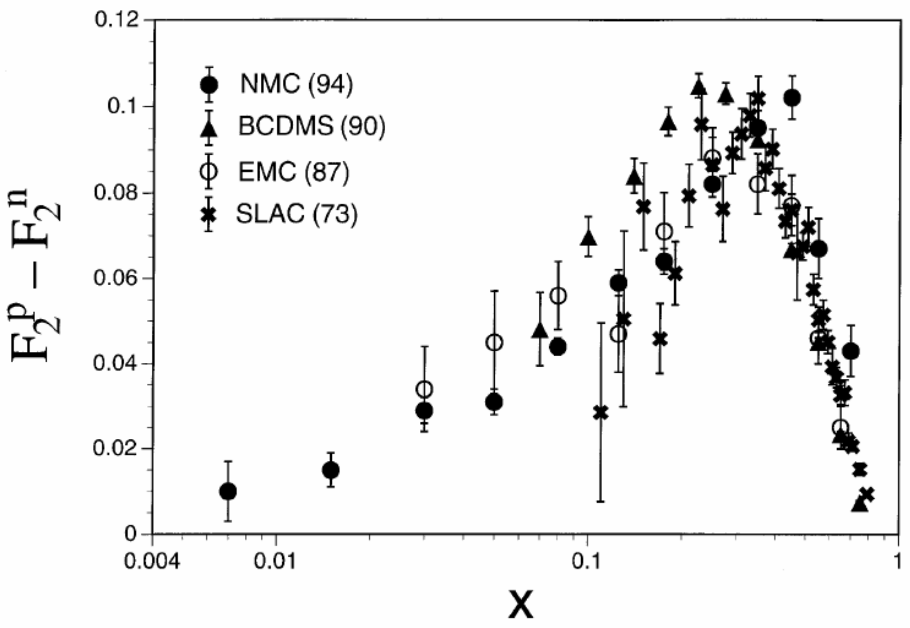
Test of the Gottfried Sum Rule

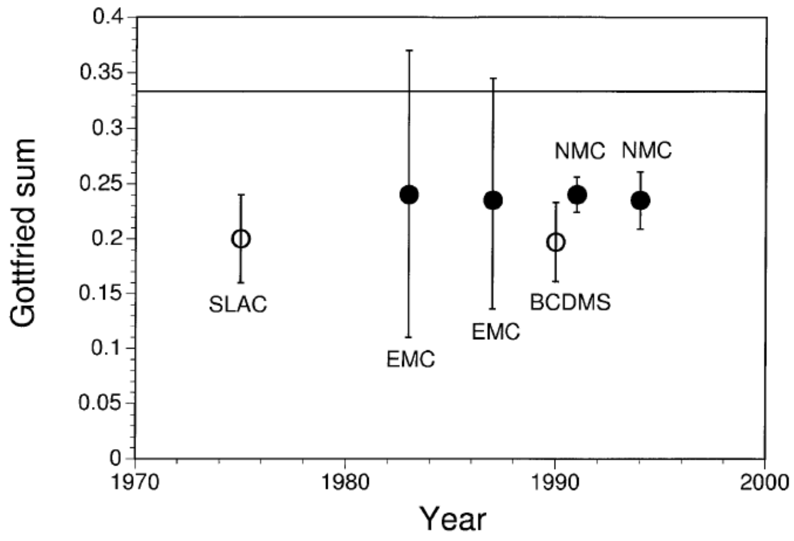
$$S_G = \int_0^1 [(F_2^p(x) - F_2^n(x))/x]\,dx$$

$$= \frac{1}{3} + \frac{2}{3}\int_0^1 (\bar{u}_p(x) - \bar{d}_p(x))\,dx$$

$$= \frac{1}{3} \quad (if\ \bar{u}_p = \bar{d}_p)$$

Experimental Measurement of Gottfried Sum





New Muon Collaboration (NMC), Phys. Rev. D50 (1994) R1

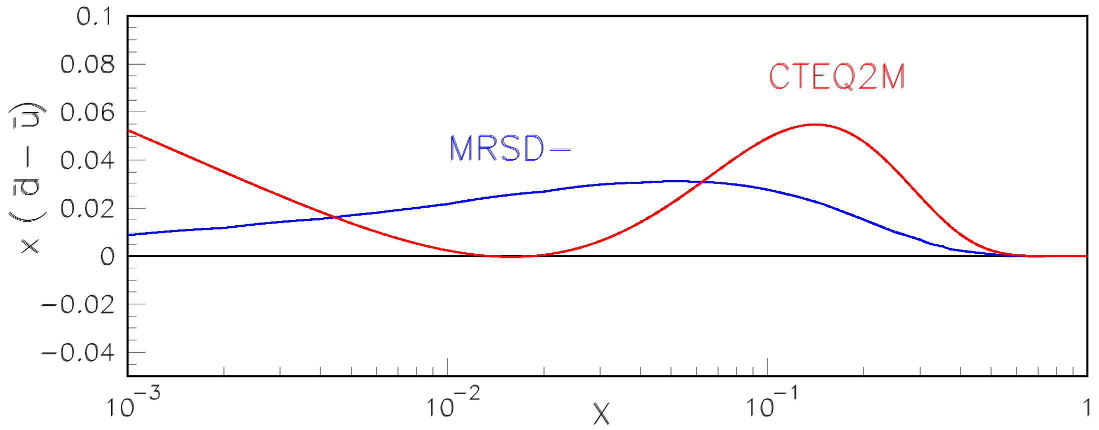
$S_G = 0.235 \pm 0.026$

(Significantly lower than 1/3 !)

Explanations for the NMC result:

- Uncertain extrapolation for 0.0 < x < 0.004
- Charge symmetry violation $(\bar{u}_n \neq \bar{d}_p, \; \bar{d}_n \neq \bar{u}_p)$
- $\bar{u}(x) \neq \bar{d}(x)$ in the proton

$$\int_0^1 (\bar{d}(x) - \bar{u}(x))\, dx = 0.148 \pm 0.04$$



Need independent methods to check the $\bar{d} - \bar{u}$ asymmetry, and to measure its x-dependence !

Light Antiquark Flavor Asymmetry: Brief History

- Naïve Assumption:

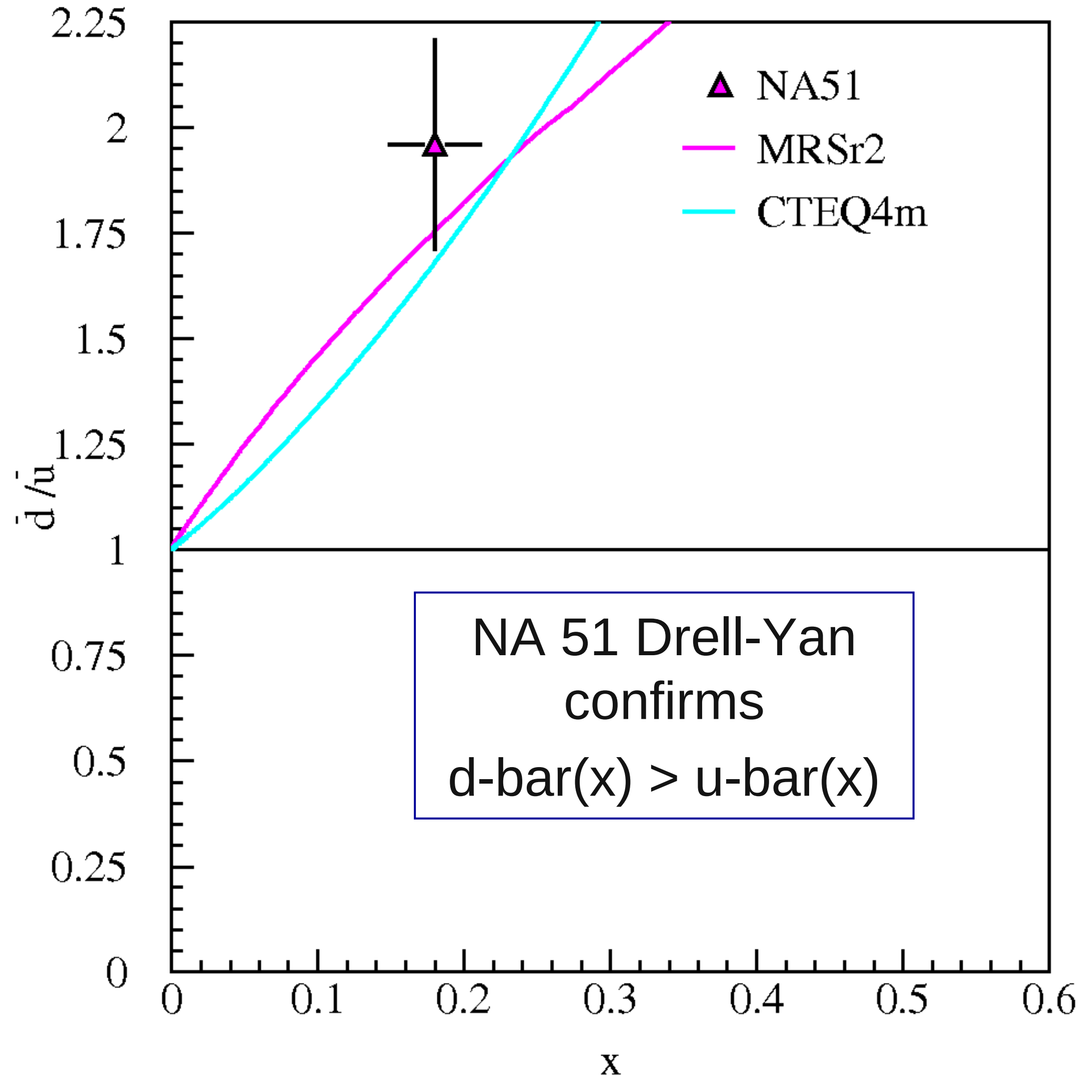
$$\bar{d}(x) = \bar{u}(x)$$

- NMC (Gottfried Sum Rule)

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

- NA51 (Drell-Yan, 1994)

$$\bar{d} > \bar{u} \text{ at } x = 0.18$$



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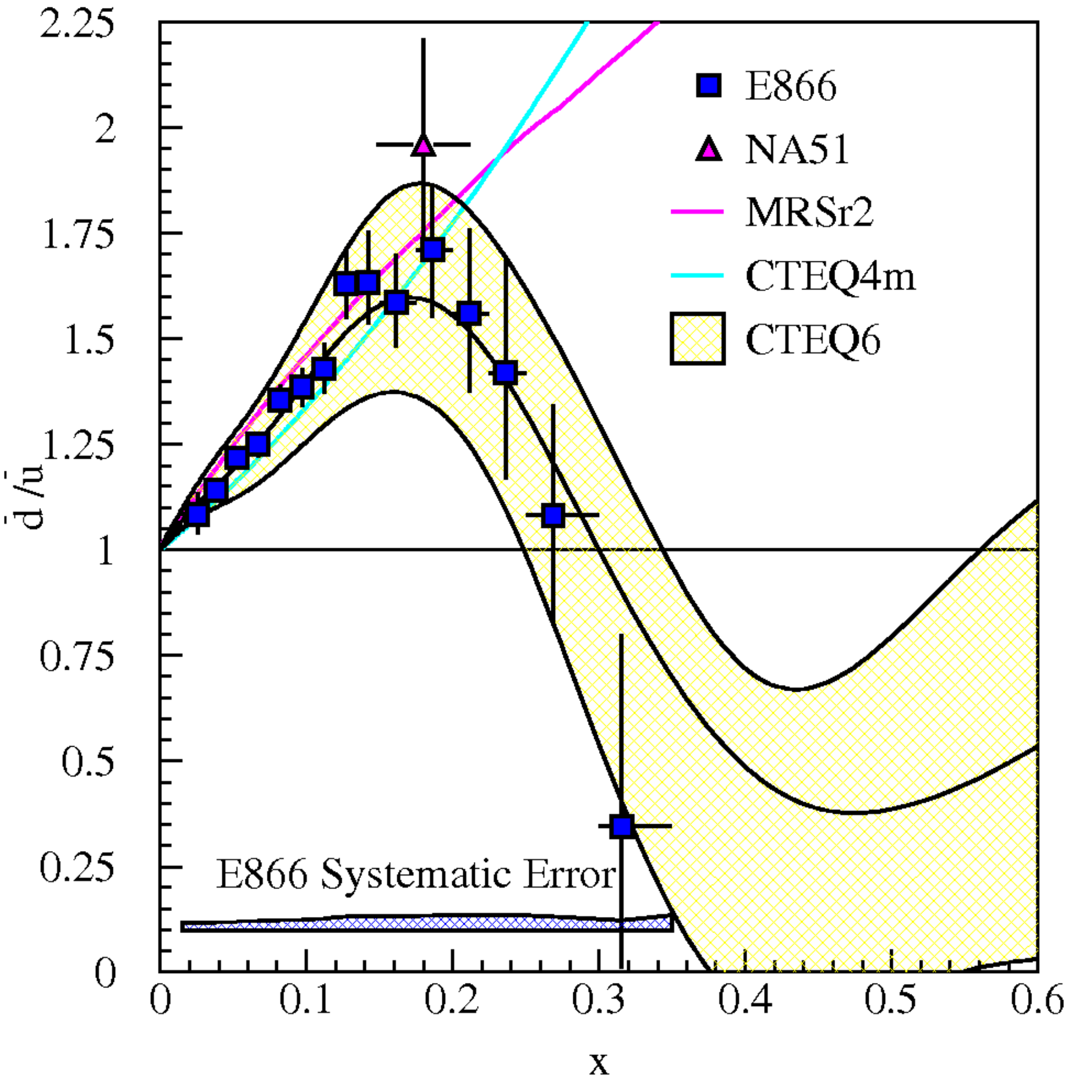
  $\bar{d} > \bar{u}$ at $x = 0.18$

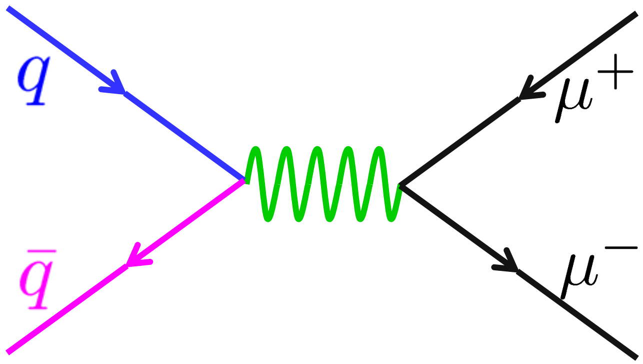
- E866/NuSea (Drell-Yan, 1998)

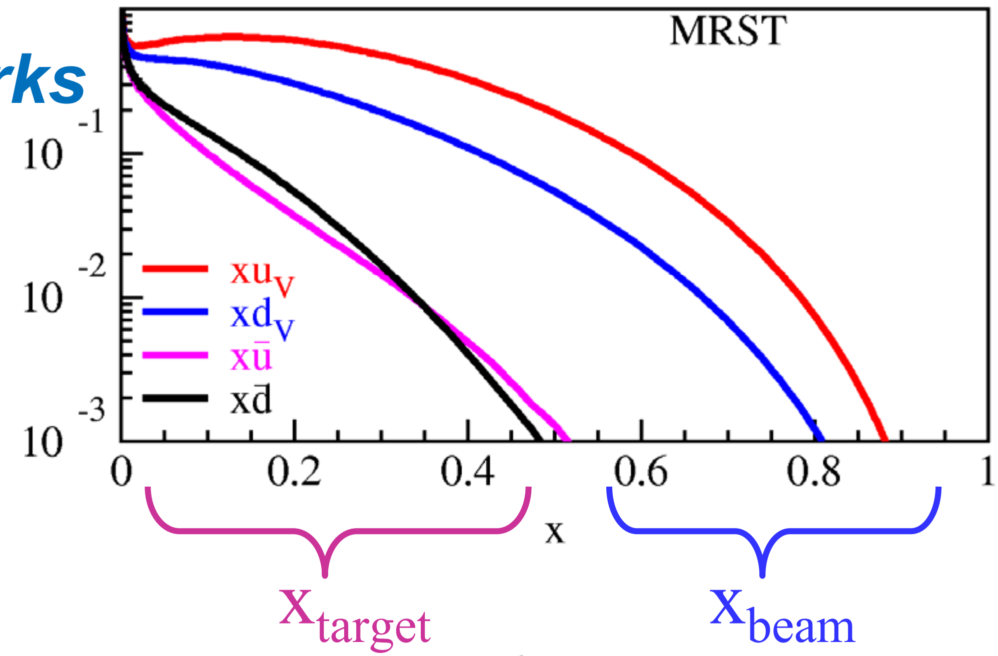
  $\bar{d}(x)/\bar{u}(x)$ for $0.015 \leq x \leq 0.35$



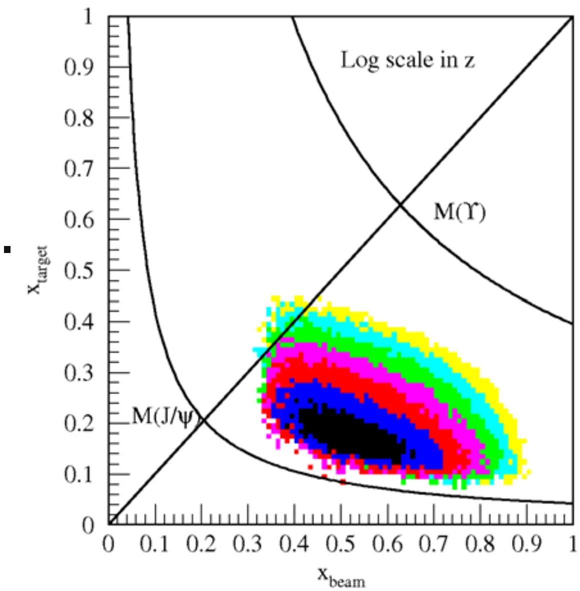
E866

Drell-Yan scattering:
A laboratory for sea quarks





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

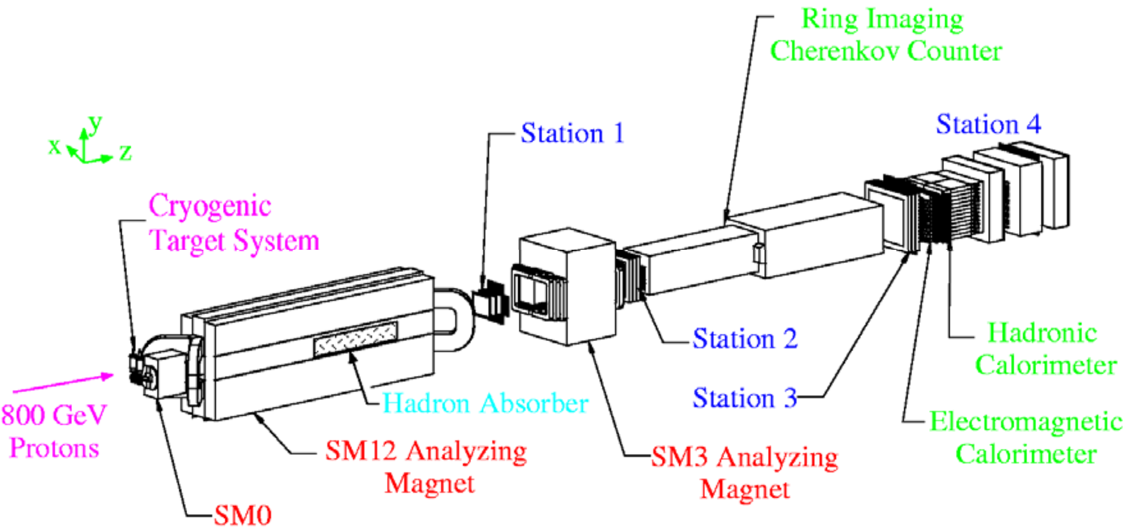


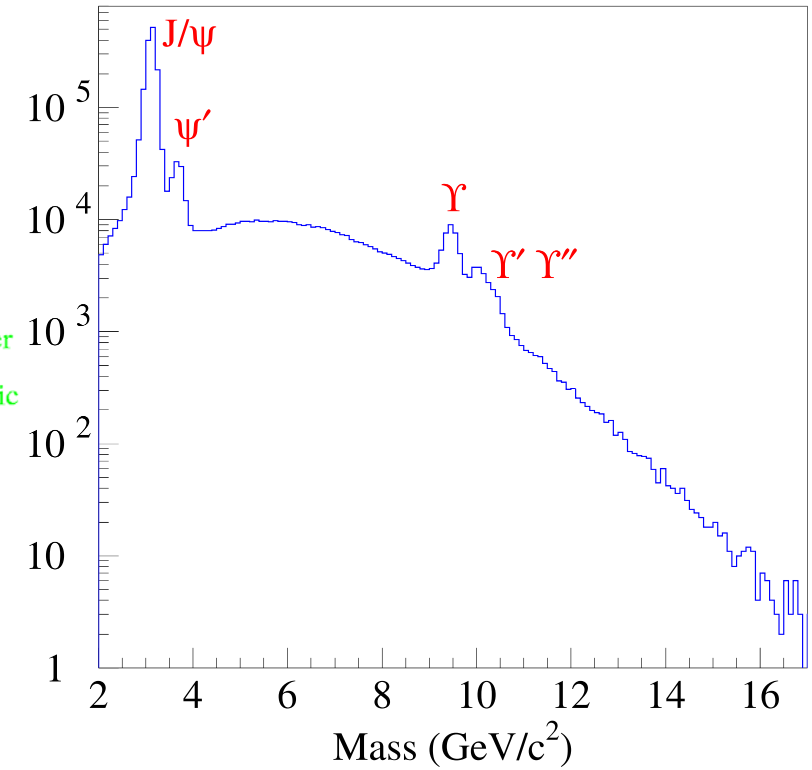
Detector acceptance chooses x_{target} and x_{beam}.

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

Fermilab E866 Measurements

$$800\ GeV\ \sigma(p+d \rightarrow \mu^+ \mu^- X)/\sigma(p+p \rightarrow \mu^+ \mu^- X)$$





$$\left.\frac{\sigma^{pd}}{2\sigma^{pp}}\right|_{x_1 \gg x_2} \approx \frac{1}{2}\left[\frac{1+\frac{d(x_1)}{4u(x_1)}}{1+\frac{d(x_1)}{4u(x_1)}\frac{\bar{d}(x_2)}{\bar{u}(x_2)}}\right]\left[1+\frac{\bar{d}(x_2)}{\bar{u}(x_2)}\right]$$

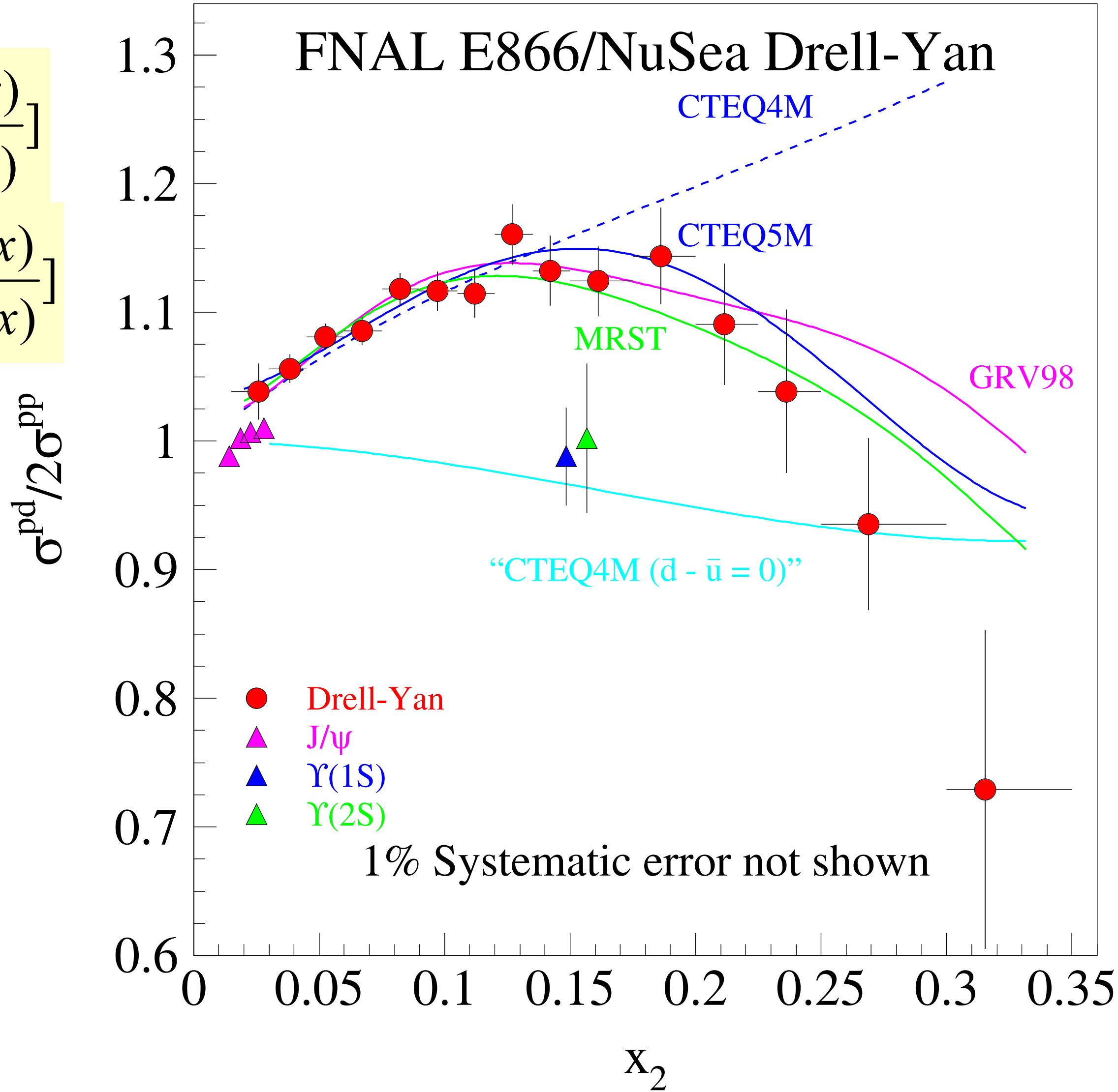
$$\left.\frac{\sigma^{pd}}{2\sigma^{pp}}\right|_{x_1 \gg x_2} \approx \frac{1}{2}\left[1+\frac{\bar{d}(x_2)}{\bar{u}(x_2)}\right]$$

Fermilab E866 Measurements

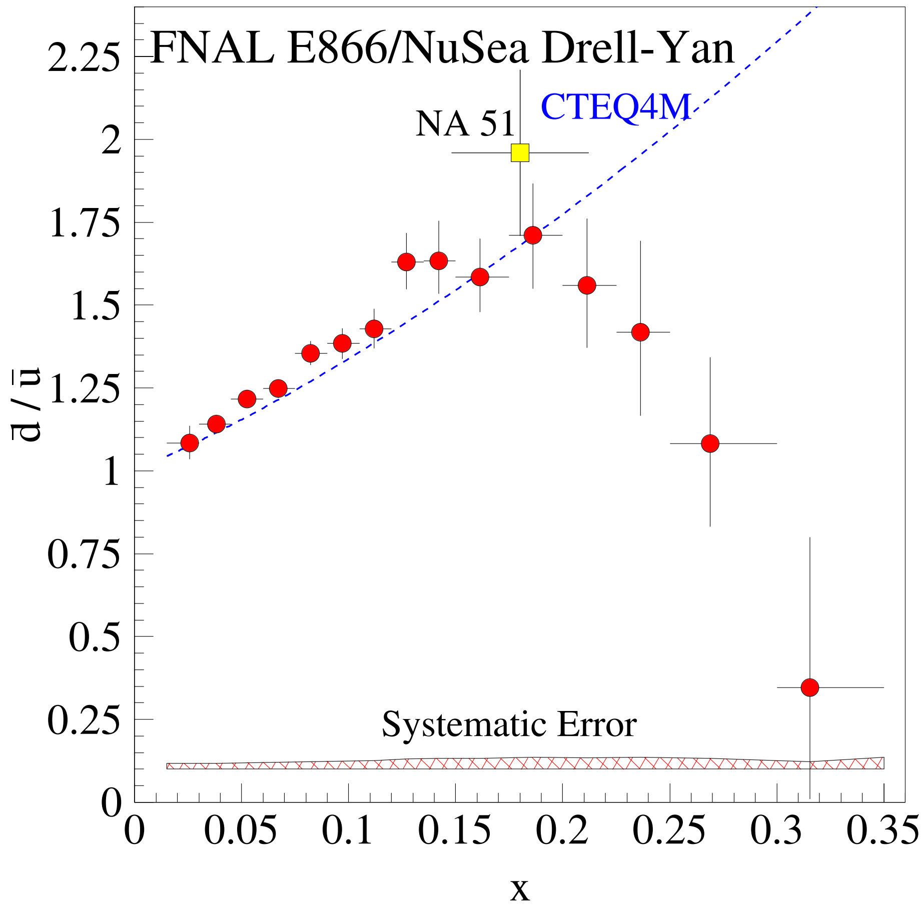
$$800\ GeV\ \sigma(p+d \to \mu^+ \mu^- X)/\sigma(p+p \to \mu^+ \mu^- X)$$

$$\text{Drell-Yan}: \frac{\sigma^{pd}}{2\sigma^{pp}} \approx \frac{1}{2}[1+\frac{\bar{d}(x)}{\bar{u}(x)}]$$

$$J/\psi, \gamma \quad : \frac{\sigma^{pd}}{2\sigma^{pp}} \approx \frac{1}{2}[1+\frac{g_n(x)}{g_p(x)}]$$



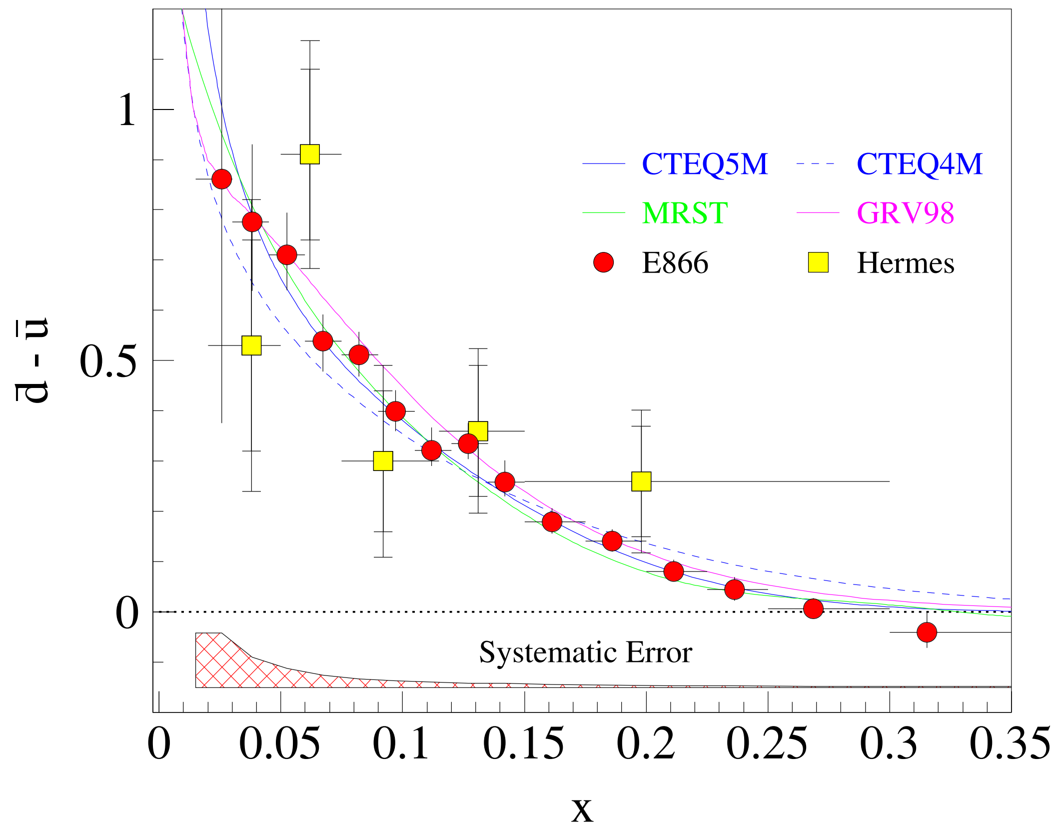
Extraction of $\bar{d}/\bar{u}$ Extraction of $\bar{d} / \bar{u}$



- For $x < 0.15$ $\bar{d}/\bar{u}$ follows parameterizations
- For $x > 0.2$ approaches $\bar{d} = \bar{u}$

$\bar{d}-\bar{u}$ Comparison with Hermes

Extraction of $\bar{d}-\bar{u}$



$$\int_0^1 [\bar{d}(x)-\bar{u}(x)] = 0.118 \pm 0.011\ (E866)$$

$$\int_0^1 [\bar{d}(x)-\bar{u}(x)] = 0.16 \pm 0.03\ (HERMES)$$

$$\int_0^1 [\bar{d}(x)-\bar{u}(x)] = 0.147 \pm 0.039\ (NMC)$$

- Semi-inclusive Deep-Inelastic scattering
- HERMES Collaboration, K. Ackerstaff *et al.*, Phys. Rev. Lett. **81** 5519 (1998)

HERMES: Semi-Inclusive DIS

$E866: \ <Q^2> = 54\, GeV^2; \quad HERMES: \ <Q^2> = 2.3\, GeV^2$

Origins of $\bar{u}(x) \neq \bar{d}(x)$?

- Pauli blocking by the valence quarks

  $g \to \bar{u}u$ is more suppressed than $g \to \bar{d}d$ in the proton since

  $p = uud$ (Field and Feynman 1977)

  (pQCD calculations by Ross and Sachrajda)

  (Bag model calculation by Signal, Thomas, Schreiber)

- Chiral quark-soliton model

  Quark spectrum includes a bound state plus the

  polarized negative and positive Dirac continuum

  (Diakonov, Pobylitsa, Polyakov, Wakamatsu, Kubota)

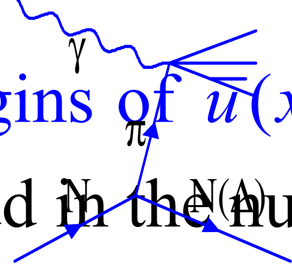
- Instanton model

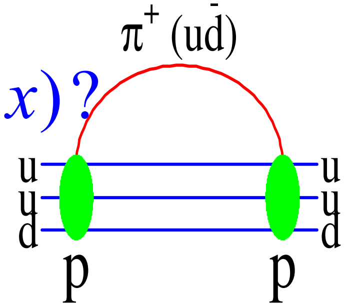
  $u_L \to u_R d_R \bar{d}_L, \ d_L \to d_R u_R \bar{u}_L,$ etc. (Dorokhov, Kochelev)

- Statistical model (Bourrely, Buccella, Soffer)

The valence quarks affect the Dirac vacuum and the quark-antiquark sea

Origins of $\bar{u}(x) \neq \bar{d}(x)$?





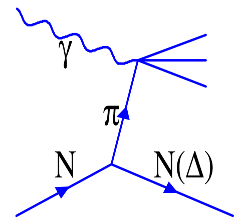
- Meson cloud in the nucleons

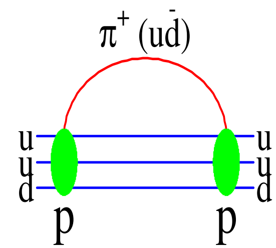
  Sullivan Processed in DIS

  $\Rightarrow \; |p> = |p_0> + a|\pi N> + b|\pi\Delta>$

  $\Rightarrow \; p \rightarrow \pi^+(u\bar{d}) + n$

  $\Rightarrow \; p \rightarrow \pi^+(u\bar{d}) + \Delta^0$



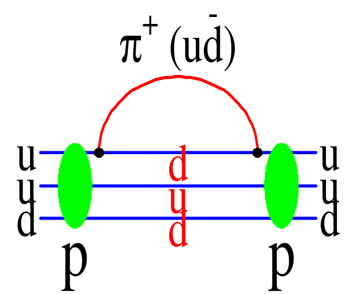


- Chiral quark model

  Goldstone bosons couple to valence quarks

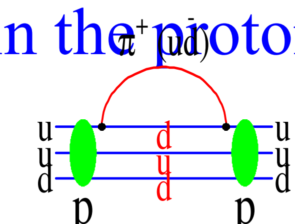
  $\Rightarrow \; u \rightarrow \pi^+ + d$

  $\Rightarrow \; u \rightarrow K^+ + s$



The pion cloud is a source for antiquarks in the proton,

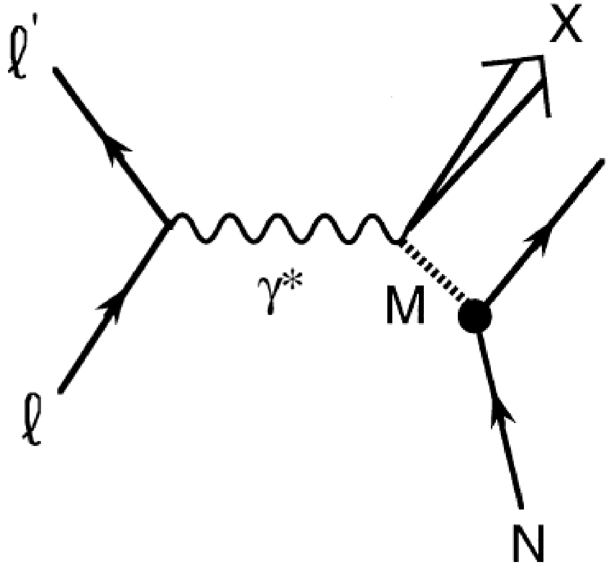
and it leads to $\bar{d} > \bar{u}$

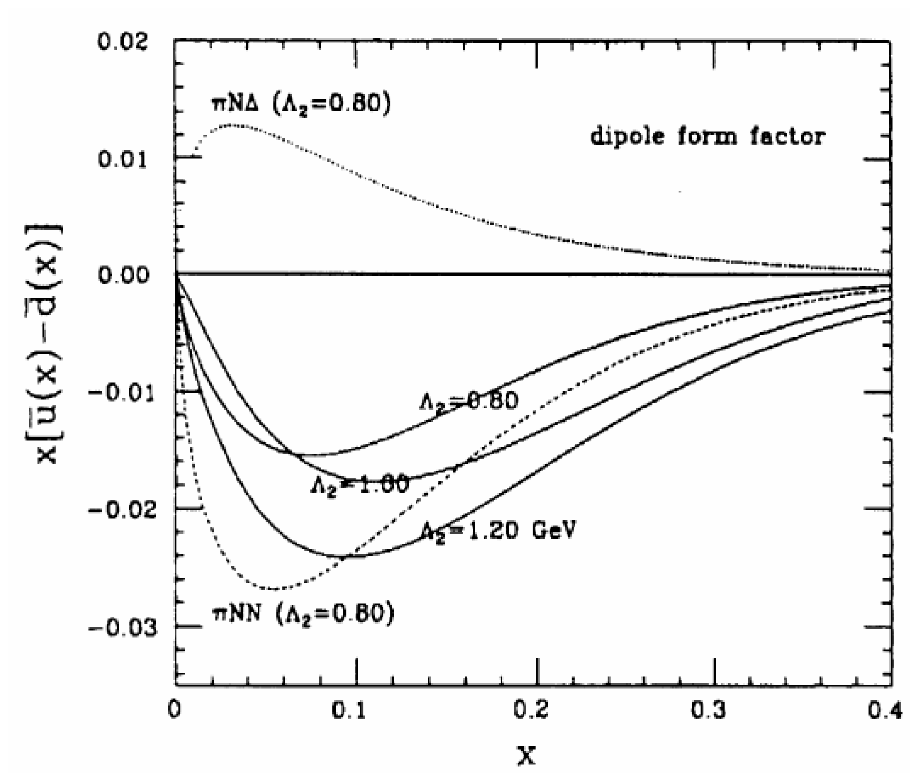


Meson Cloud Model

- Virtual π is emitted by the proton and the intermediate state is π + Baryon.

$$|p\rangle \to \sqrt{1-a-b}|p_0\rangle + \sqrt{a}\left(-\sqrt{\frac{1}{3}}|p_0\pi^0\rangle + \sqrt{\frac{2}{3}}|n_0\pi^+\rangle\right) + \sqrt{b}\left(\sqrt{\frac{1}{2}}|\Delta_0^{++}\pi^-\rangle - \sqrt{\frac{1}{3}}|\Delta_0^+\pi^0\rangle + \sqrt{\frac{1}{6}}|\Delta_0^0\pi^+\rangle\right).$$





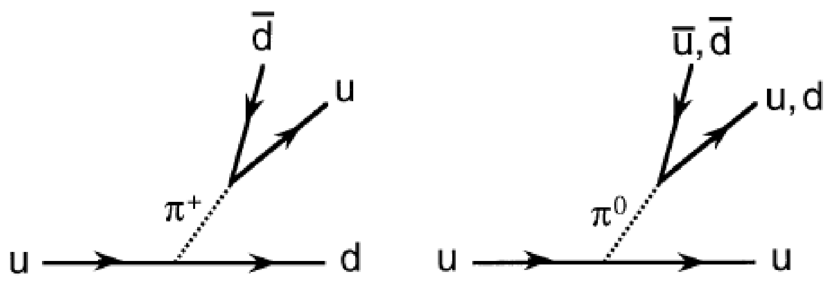
$$p \to N\pi\,,\ \pi^+ : \pi^0 : \pi^- = 2:1:0$$

$$\sum_\pi |\vec{\phi}_\pi^* \cdot \vec{\tau}|(\bar{u}-\bar{d})_\pi = -2V\pi \qquad \text{for the } \pi NN \text{ process},$$

$$\sum_\pi |\vec{\phi}_\pi^* \cdot \vec{T}|(\bar{u}-\bar{d})_\pi = +2V\pi \qquad \text{for the } \pi N\Delta,$$

Chiral Quark Model

- Virtual π is emitted by the constituent quark.



$$q \to q\pi\ ,\ \pi^{+} : \pi^{0} : \pi^{-} = 4:3:2$$

$$u \to a\pi^{+} + ad + \tfrac{1}{2}a\pi^{0} + \tfrac{1}{2}au = \tfrac{7}{4}au + \tfrac{5}{4}ad + \tfrac{1}{4}a\bar{u} + \tfrac{5}{4}a\bar{d}\ .$$

$$d \to a\pi^{-} + au + \tfrac{1}{2}a\pi^{0} + \tfrac{1}{2}ad = \tfrac{5}{4}au + \tfrac{7}{4}ad + \tfrac{5}{4}a\bar{u} + \tfrac{1}{4}a\bar{d}\ .$$

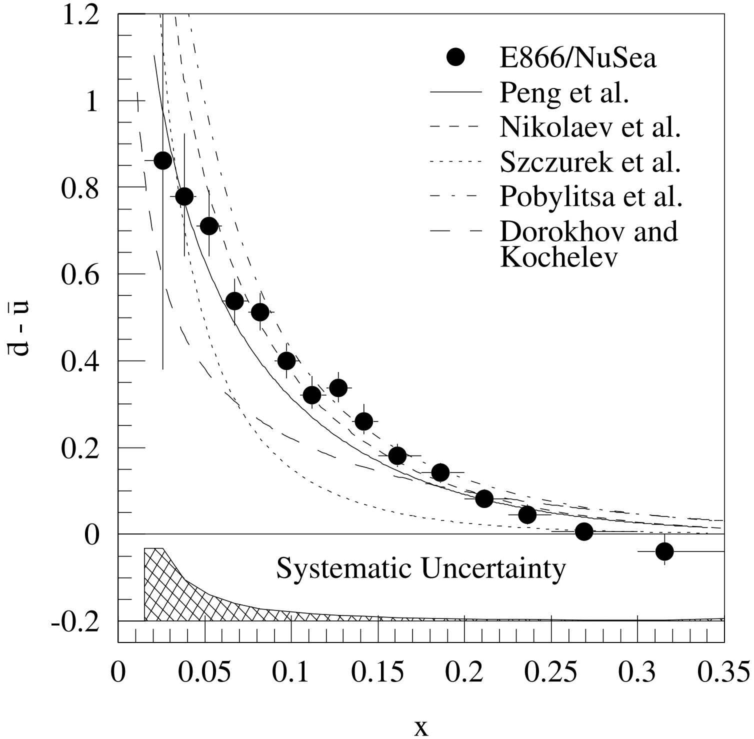
$$\Delta I_{\mathrm{G}} = \tfrac{2}{3}(\bar{u} - \bar{d}) = -\tfrac{2}{3}a\ .$$

$$a = \frac{g_A^2\ m_u^2}{8\pi^2\ f^2}\int_0^1 \mathrm{d}z\ \theta(\Lambda^2 - \tau(z))z\left\{\ln\left[\frac{\Lambda^2 + M_\pi^2}{\tau(z) + M_\pi^2}\right] + M_\pi^2\left[\frac{1}{\Lambda^2 + M_\pi^2} - \frac{1}{\tau(z) + M_\pi^2}\right]\right\}, \qquad (4.28)$$

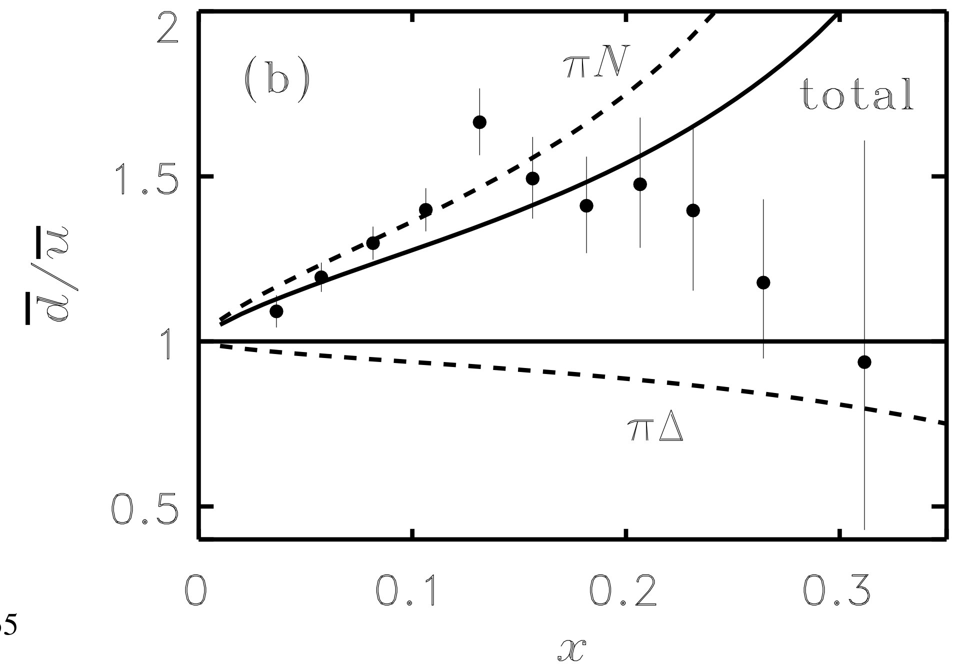
where $\tau(z) = m_u^2 z^2/(1 - z)$ and $\theta(x)$ is a cutoff function defined by $\theta(x) = 1$ for $x > 0$ and 0 for $x < 0$.

Comparison with models

$\bar{d} - \bar{u}$



$\bar{d} / \bar{u}$



Most models can explain $\bar{d} - \bar{u}$

No model can describe $\bar{d} / \bar{u}$ at large x !

$$x(\overline{d}-\overline{u})$$

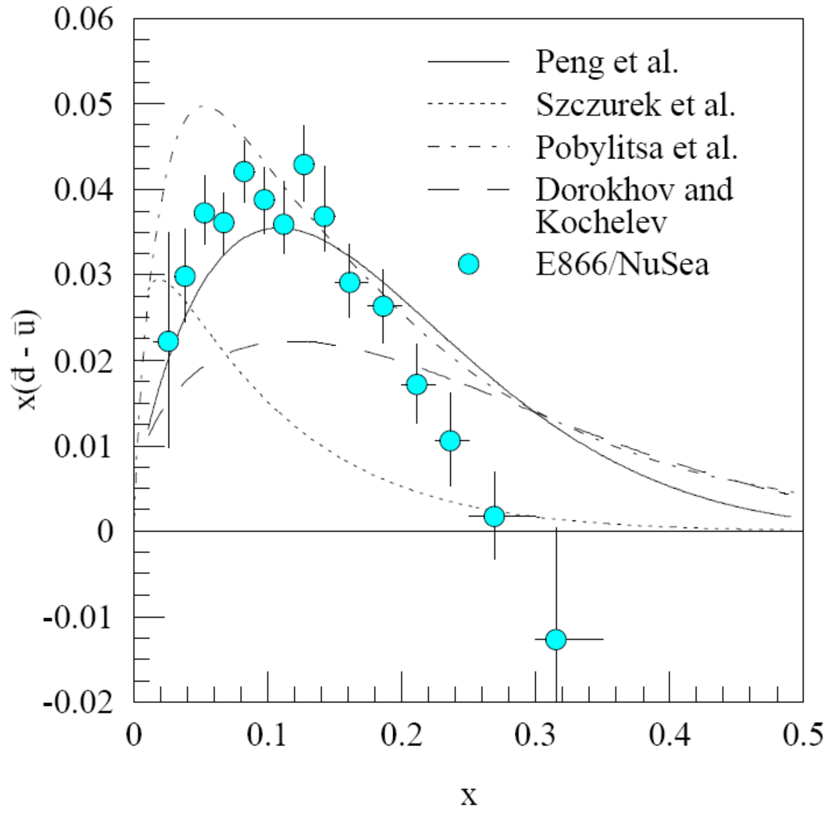


FIG. 3: Fermilab E866/NuSea results [8–10] for $x\left[\bar{d}(x)-\bar{u}(x)\right]$ at a mass scale of 7.35 GeV. The curves represent four model calculations of $x\left[\bar{d}(x)-\bar{u}(x)\right]$. The solid curve is a meson-cloud model calculation including nucleons, deltas and pions [9]. The dotted and dot-dashed curves are a chiral quark models [22, 23] and the long-dashed curve is an instanton inspired parameterization [24].

E906

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:

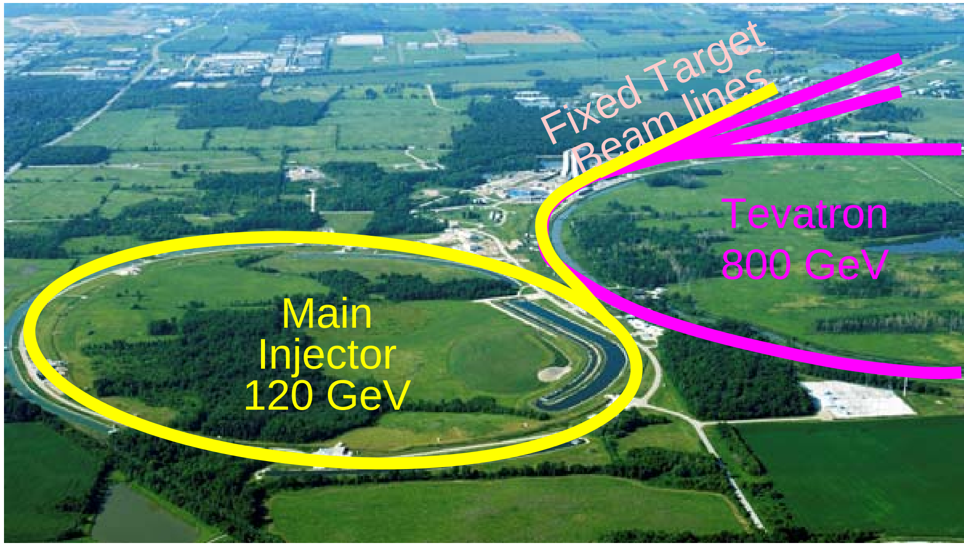
Fermilab E906

- Data taking planned in 2010
- ^{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
  - *7x that of 800 GeV beam*
- Backgrounds, primarily from J/ψ decays scale as s
  - *7x Luminosity for same detector rate as 800 GeV beam*

50x statistics!!



Fermilab E906/Drell-Yan Collaboration

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Thomas Jefferson National Accelerator Facility
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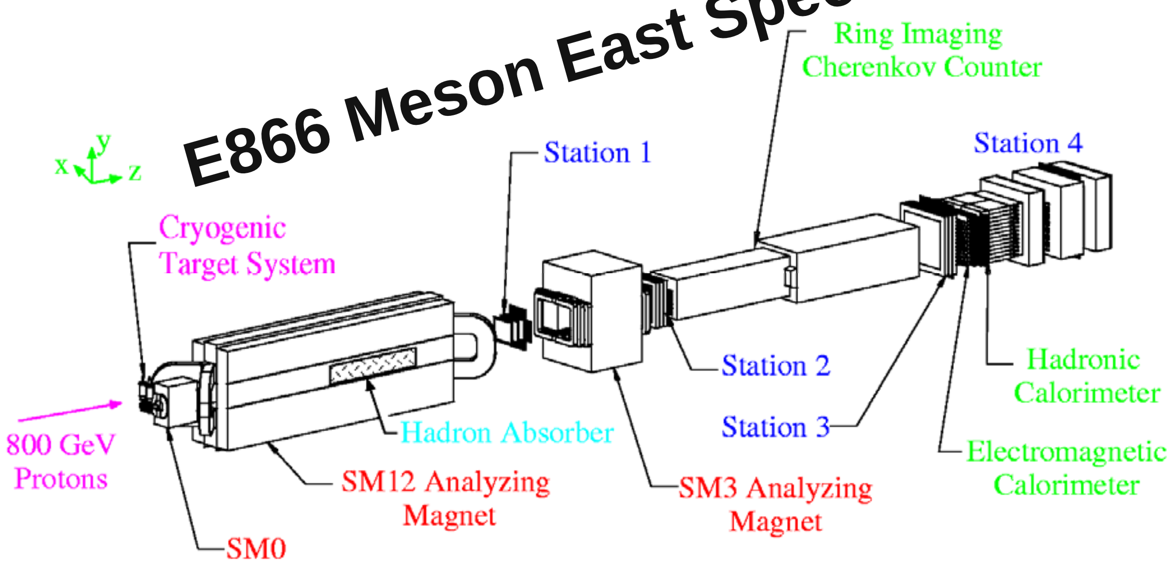
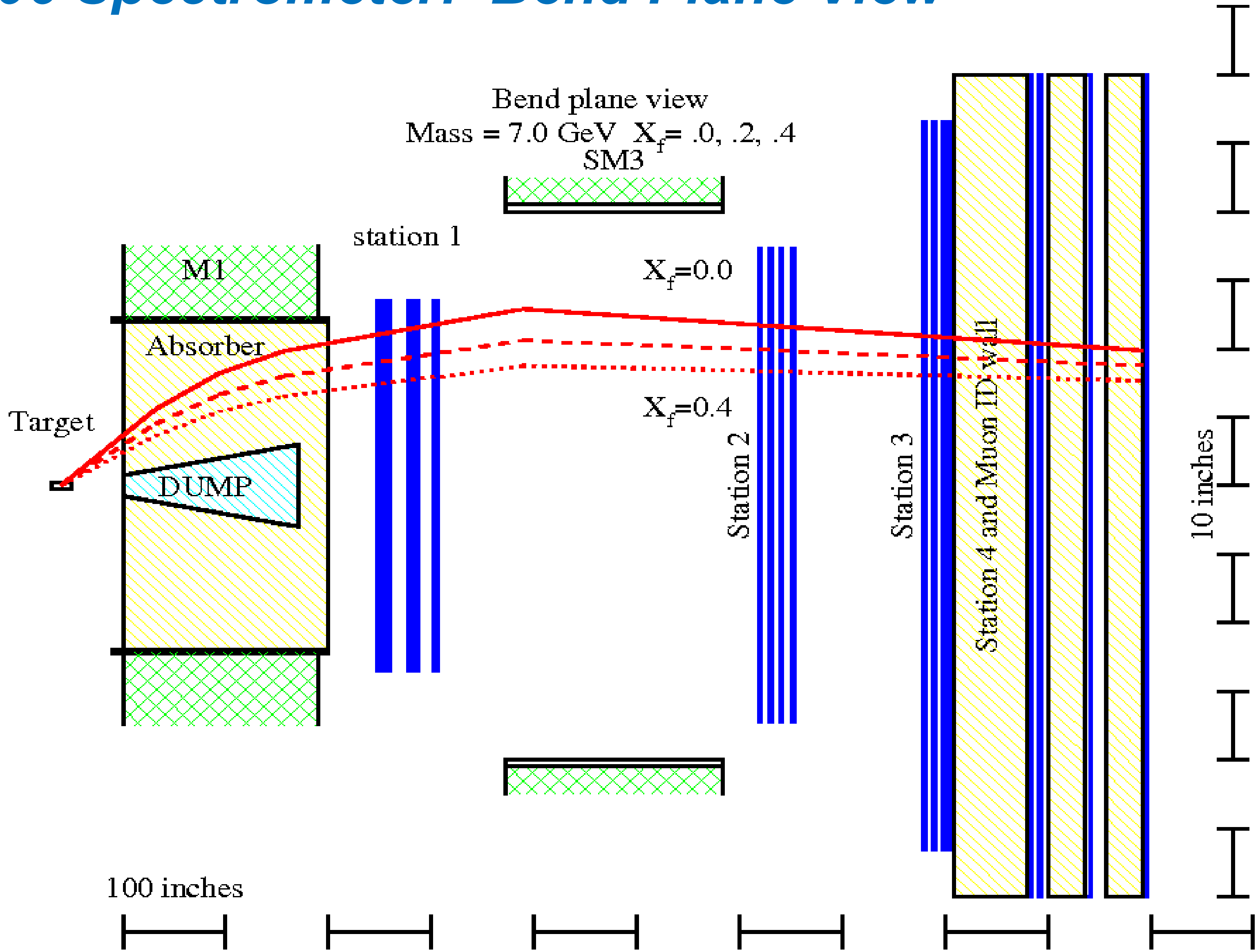
Drell-Yan Spectrometer Guiding Principles

- 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)

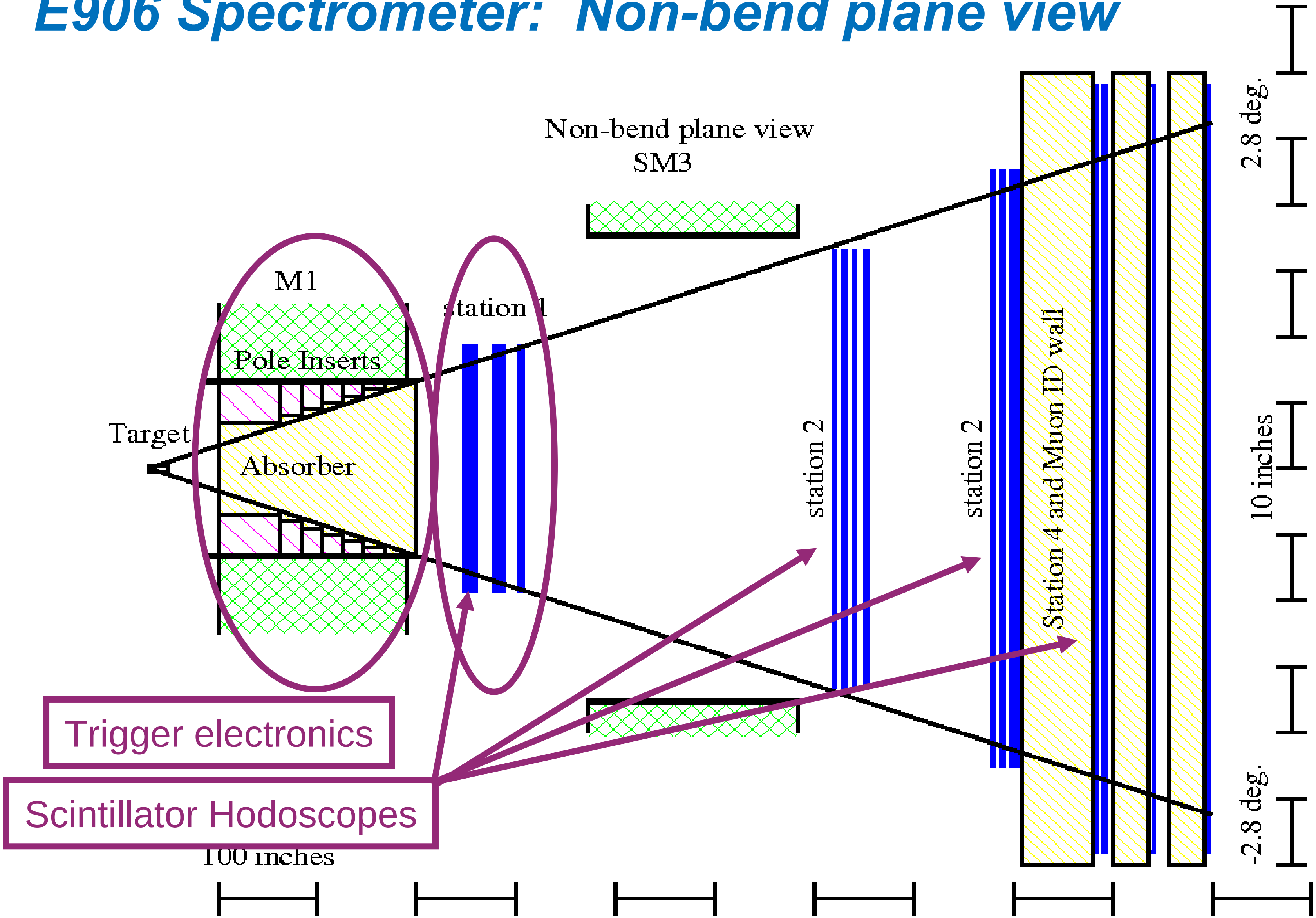
E866 Meson East Spectrometer



E906 Spectrometer: Bend Plane View



E906 Spectrometer: Non-bend plane view



Experimental Challenge

- Higher probability of muonic decay for the produced hadrons.
- Larger multiple scattering for the muon traveling through hadron absorber and solid magnet.
- Worse duty factor for beam structure.
- Higher singles rates.

TABLE II: Wire Chamber Specifications and Singles Rates

Station	Type	x size (cm)	y size (cm)	wire spacing (mm)	wire orientations	Number of Channels	Expected Singles Rates (MHz)
1	MWPC	94	137.2	2.0	Y,Y',U,U',V,V'	5500	80
2	DC	137.7	149.9	10.2	Y,Y',U,U',V,V'	1000	20
3	DC	203.0	162.4	20.3	Y,Y',U,U',V,V'	700	4
4	Prop. Tubes	250.0	250.0	50.8	Y, Y', X, X'	400	8

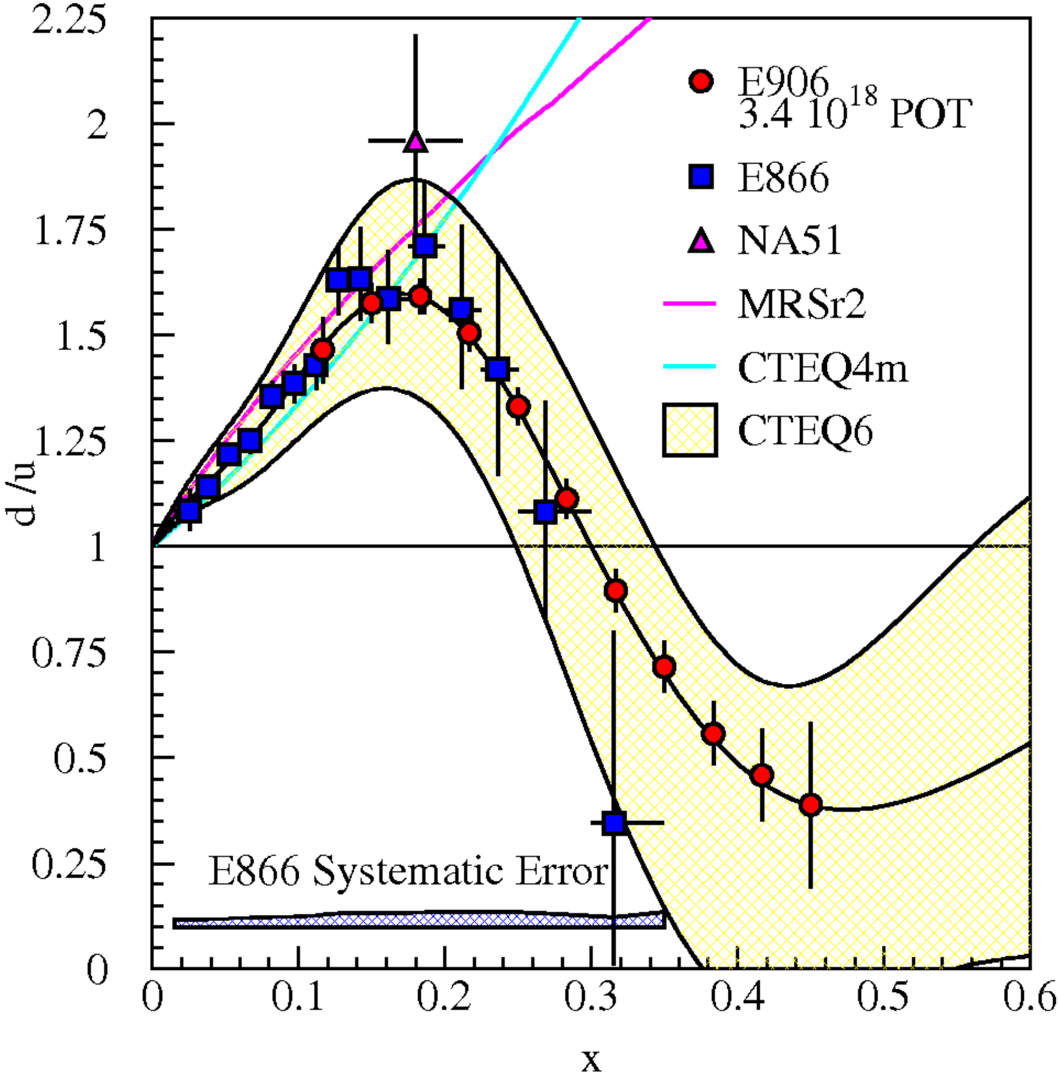
Extracting d-bar/-ubar From Drell-Yan Scattering

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)

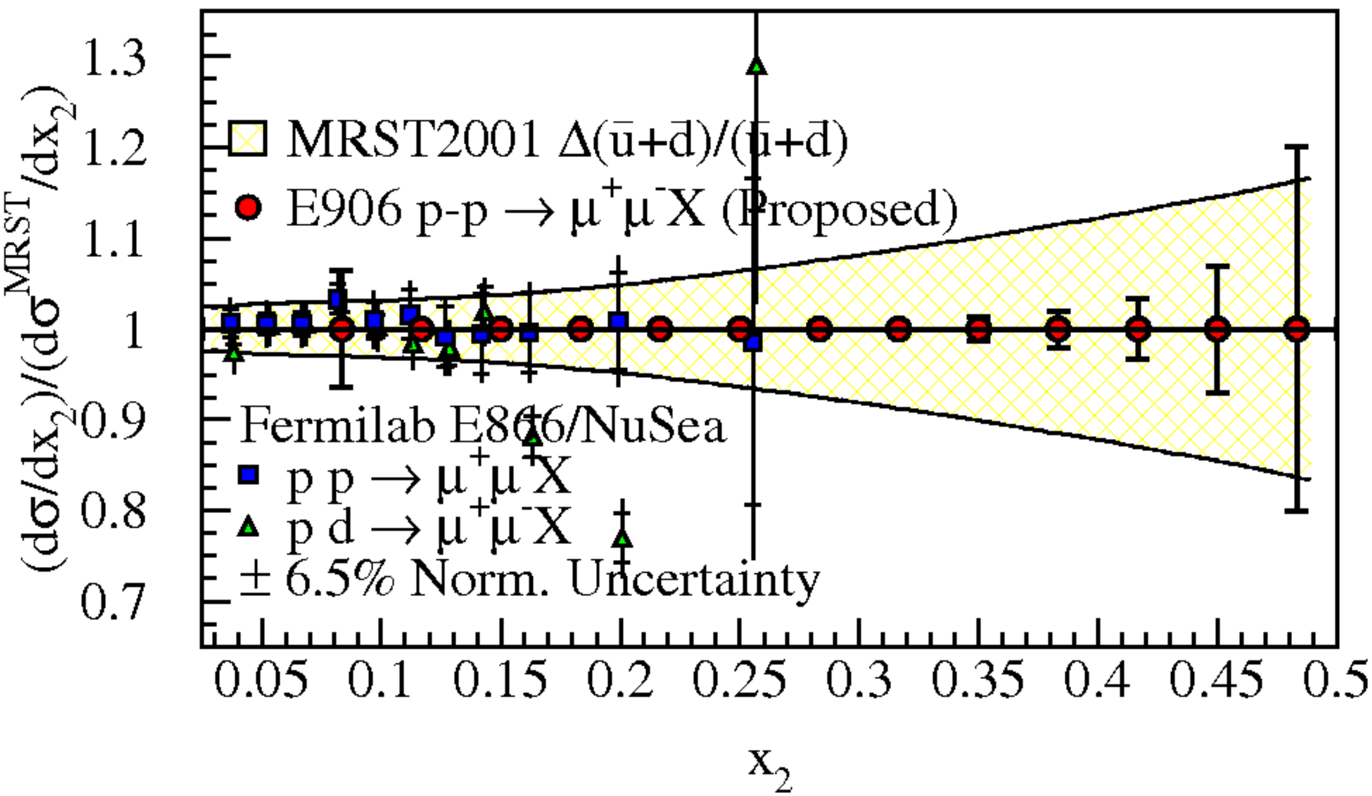
- Global NLO PDF fits which include E866 cross section ratios agree with E866 results
- Fermilab E906/Drell-Yan will extend these measurements and reduce statistical uncertainty.
- E906 expects systematic uncertainty to remain at approx. 1% in cross section ratio.



Drell-Yan Absolute Cross Sections: x_{target}

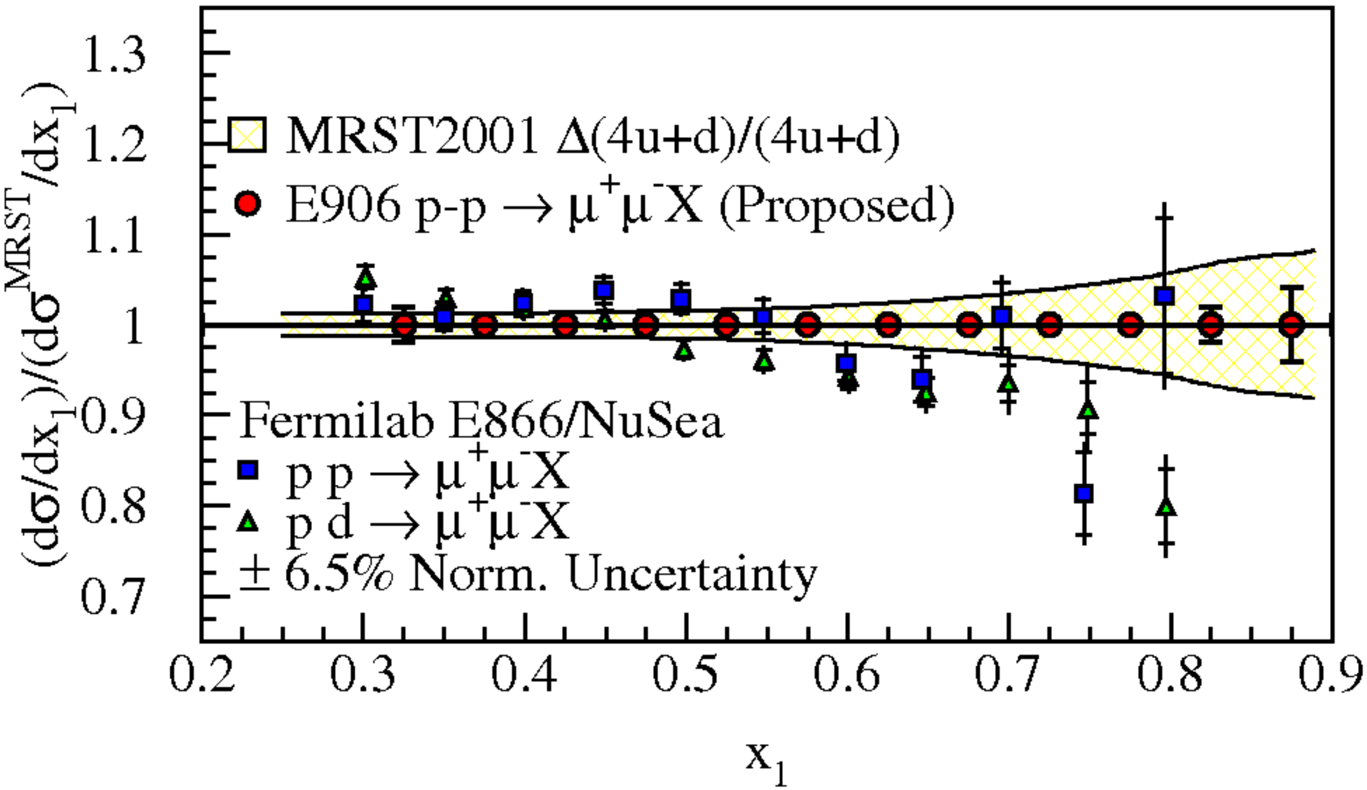
Measures a convolution of beam and target PDF

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



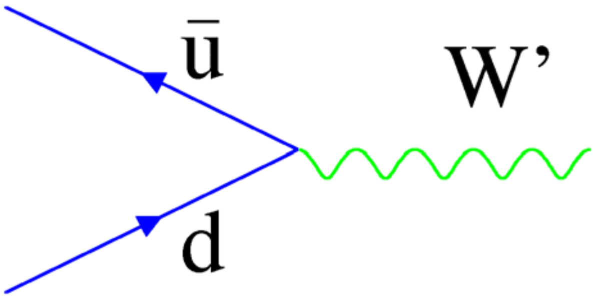
Drell-Yan Absolute Cross Sections: x_{beam}

- 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



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

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

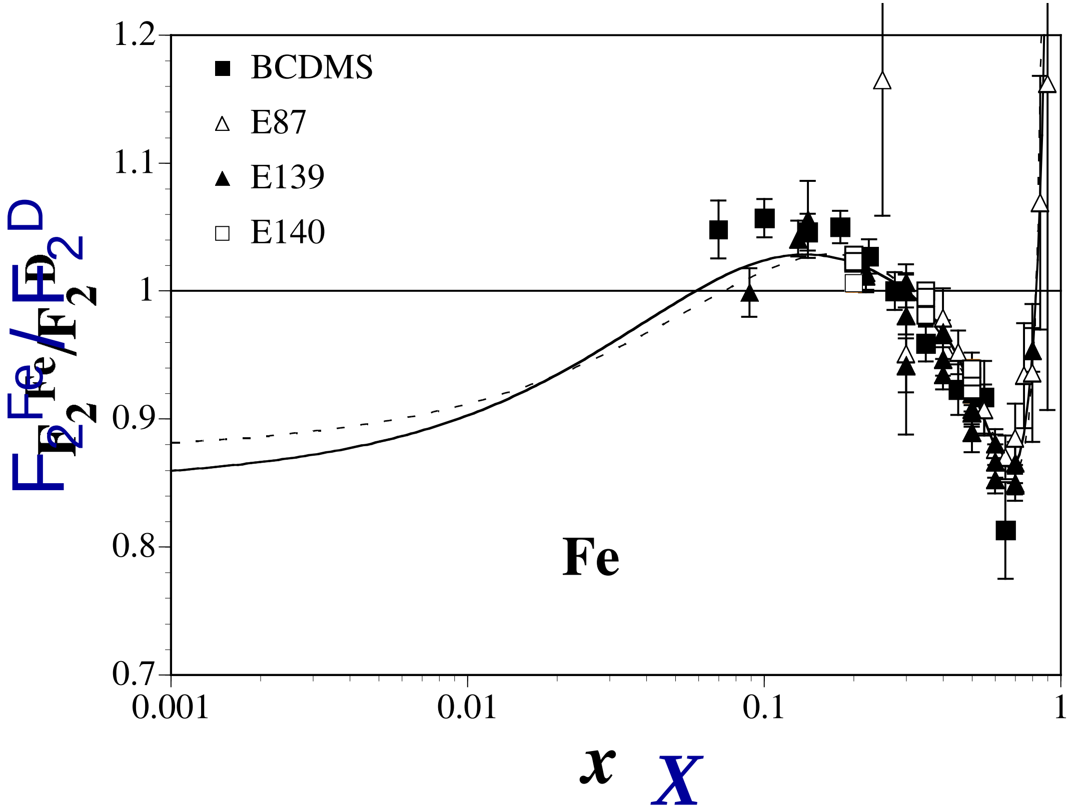
- Gluon distributions form symmetric sea

- 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

Modification of Parton Distributions in Nuclei

EMC effect observed in DIS

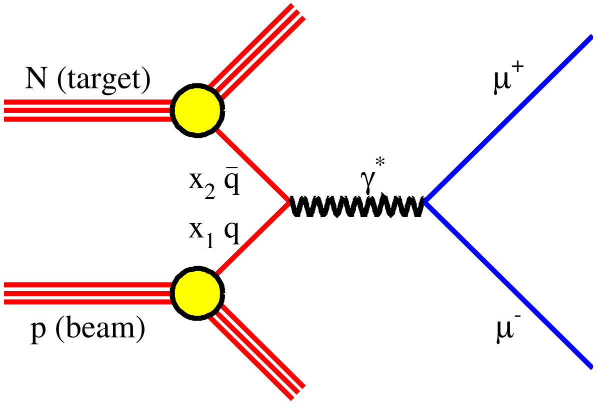


F_2 contains contributions from quarks and antiquarks

How are the antiquark distributions modified in nuclei?

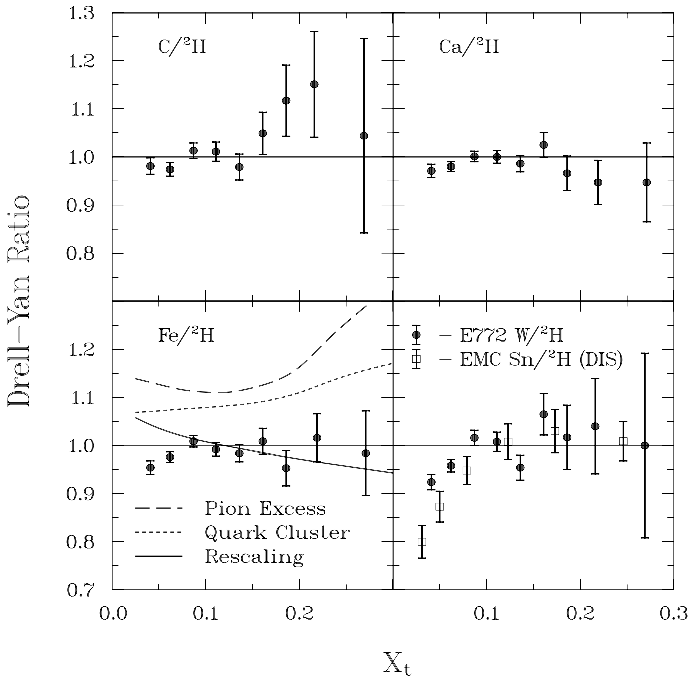
The Drell-Yan Process:

$$pA \rightarrow \mu^+ \mu^- X$$



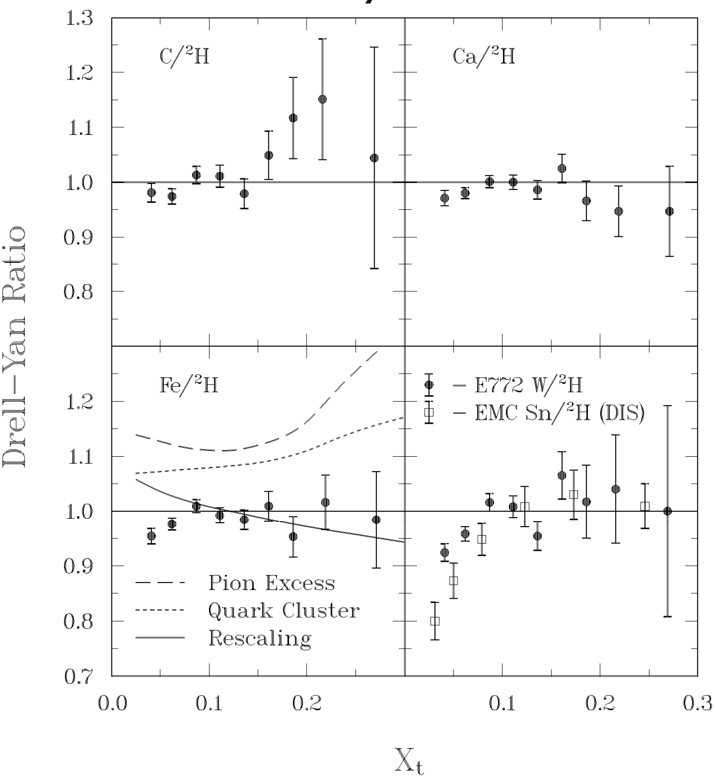
$$\frac{\sigma^{pA}}{\sigma^{pd}} \approx \frac{\bar{u}_A(x)}{\bar{u}_N(x)}$$

The x-dependence of $\bar{u}_A(x)/\bar{u}_N(x)$ can be directly measured

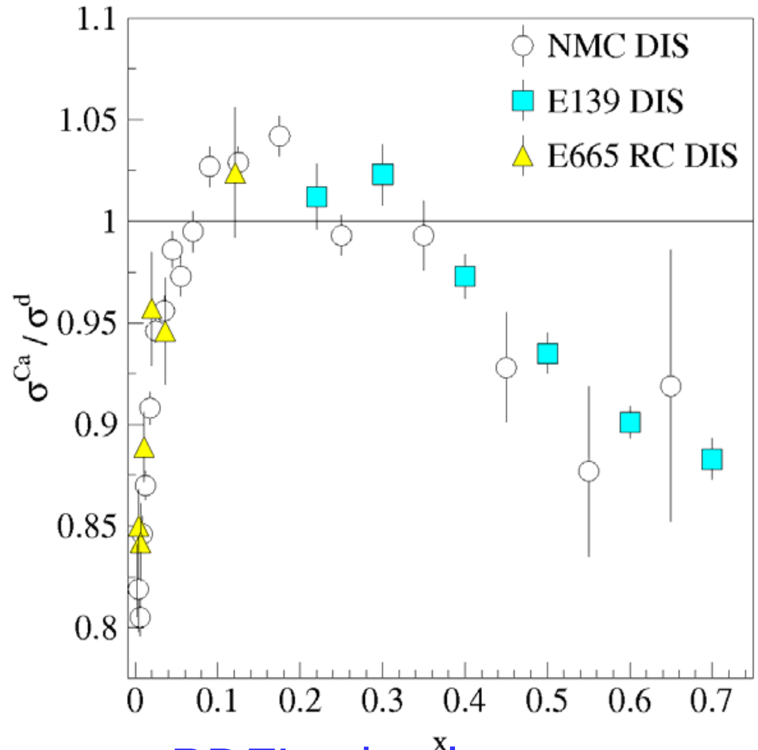


Structure of nucleonic matter: How do sea quark distributions differ in a nucleus?

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



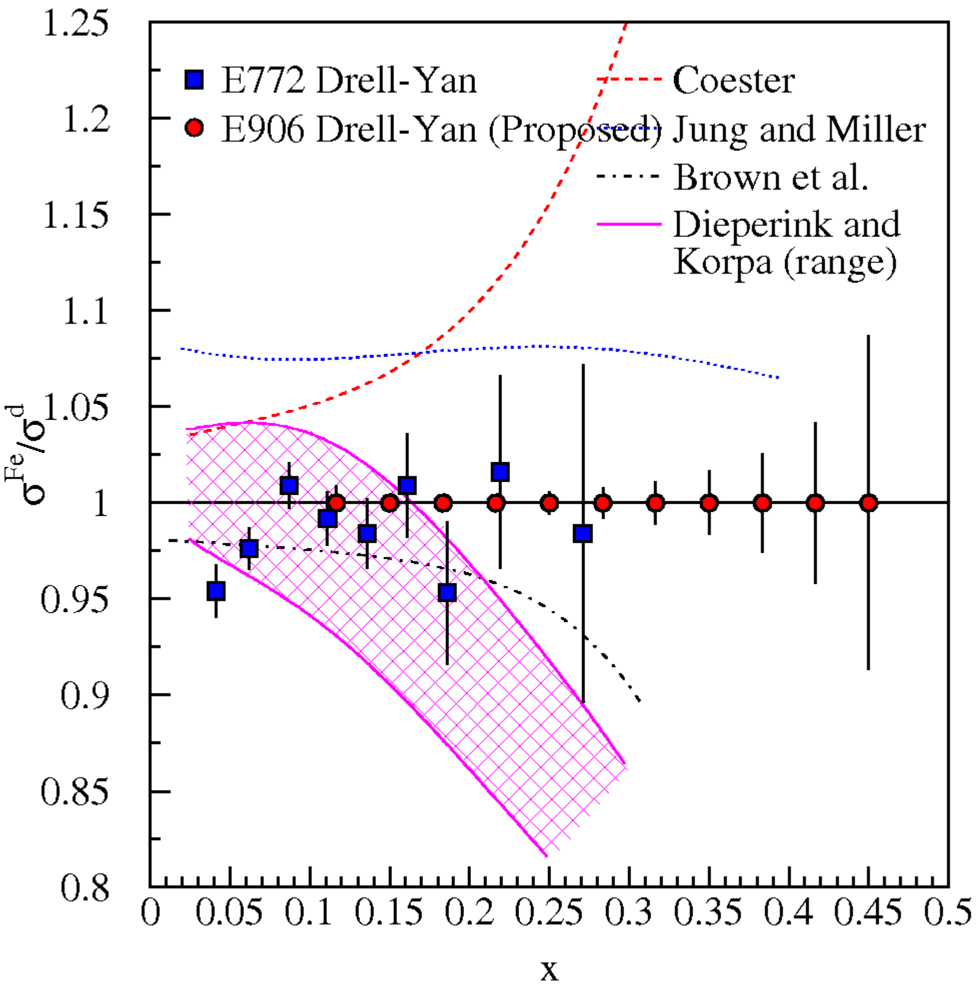
Alde *et al* (Fermilab E772) Phys. Rev. Lett. **64** 2479 (1990)



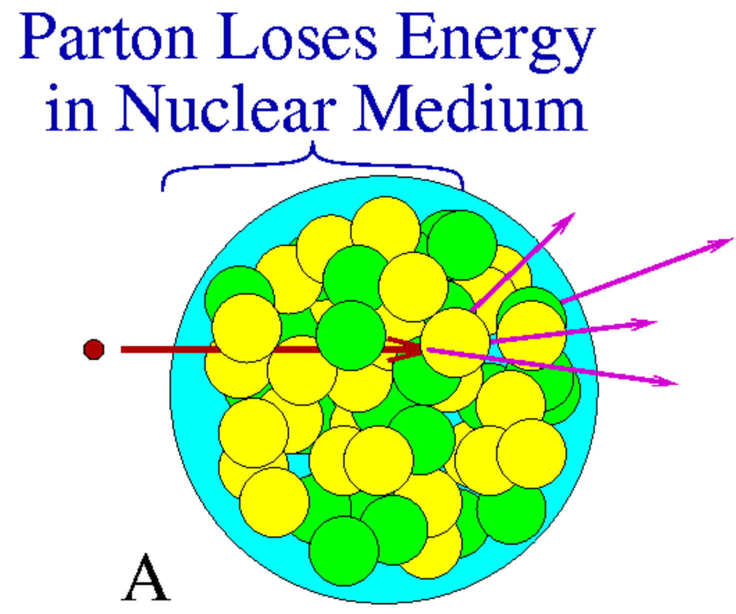
- Intermediate-*x* *sea* PDF's absolute magnitude set by ν-DIS on iron.
  - Are nuclear effects the same for the sea as for valence?
  - Are nuclear effects with the weak interaction the same as electromagnetic?
- What can the sea parton distributions tell us about the effects of nuclear binding?

Structure of nucleonic matter: Where are the nuclear pions?

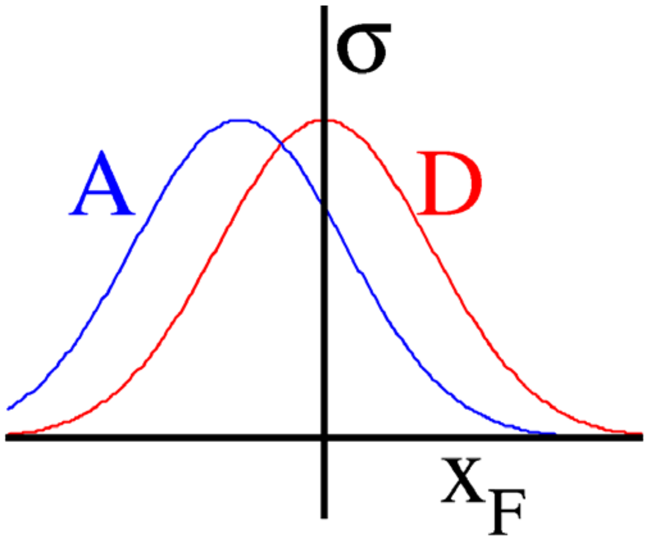
- The binding of nucleons in a nucleus is expected to be governed by the exchange of virtual "Nuclear" mesons.
- No antiquark enhancement seen in Drell-Yan (Fermilab E772) data.
- Contemporary models predict large effects to antiquark distributions as x increases.
- Models must explain both DIS-EMC effect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



Partonic Energy Loss



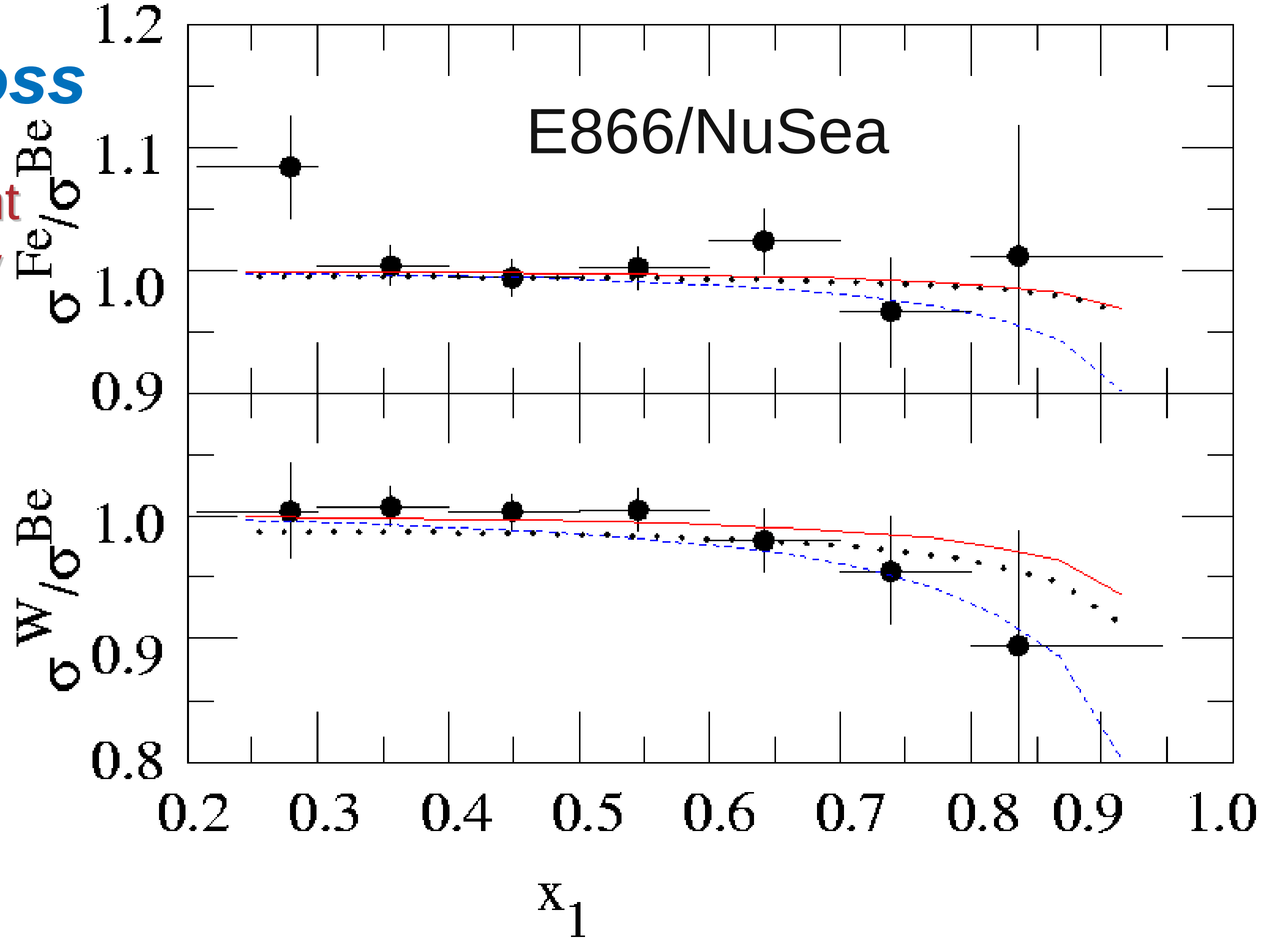
- An understanding of partonic energy loss in both cold and hot nuclear matter is paramount to elucidating RHIC data.
- Pre-interaction parton moves through cold nuclear matter and looses energy.
- Apparent (reconstructed) kinematic values (x_1 or x_F) is shifted
- Fit shift in x_1 relative to deuterium



- 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

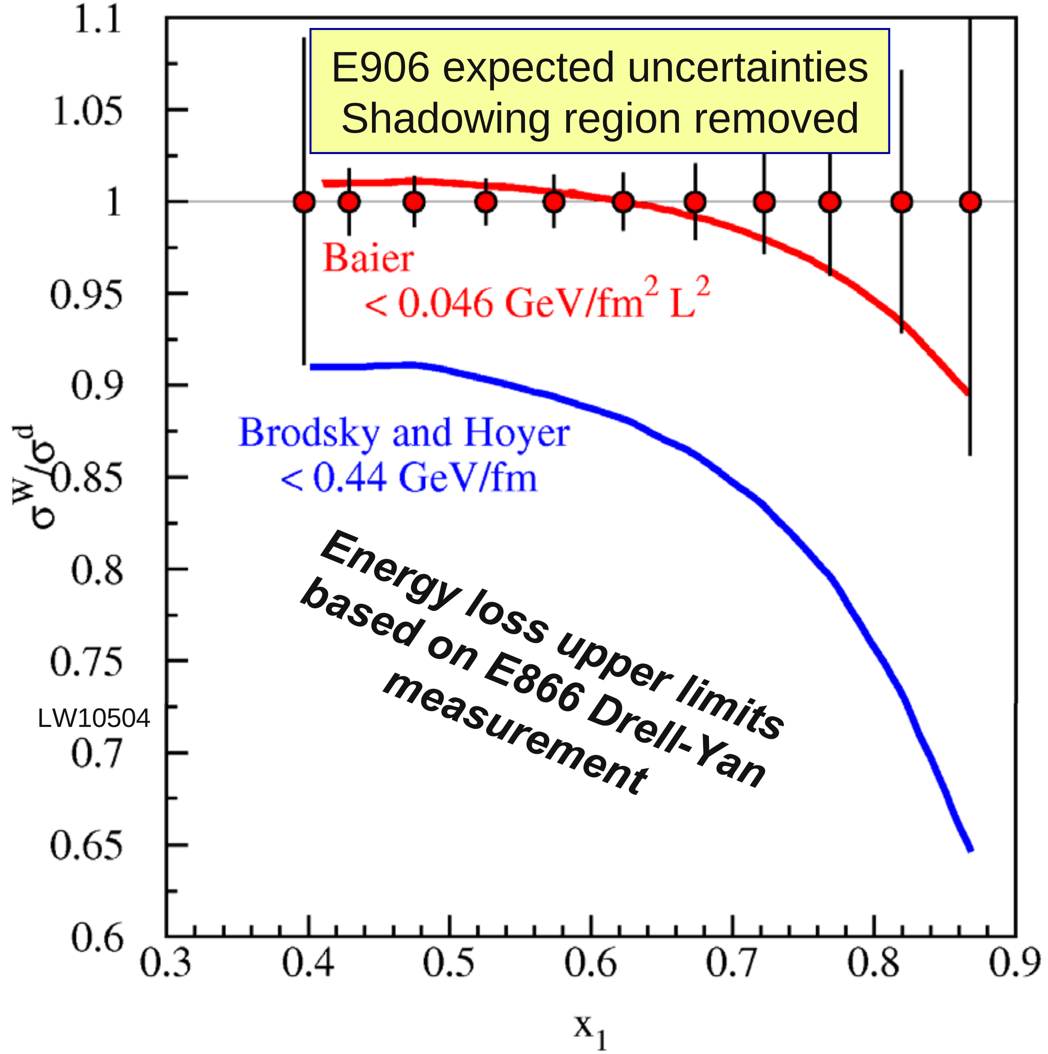
- E866 data are consistent with NO partonic energy loss for all three models
- Caveat: A correction must be made for shadowing because of x_1—x_2 correlations
  - E866 used an empirical correction based on EKS fit do DIS and *Drell-Yan*.



- 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.**

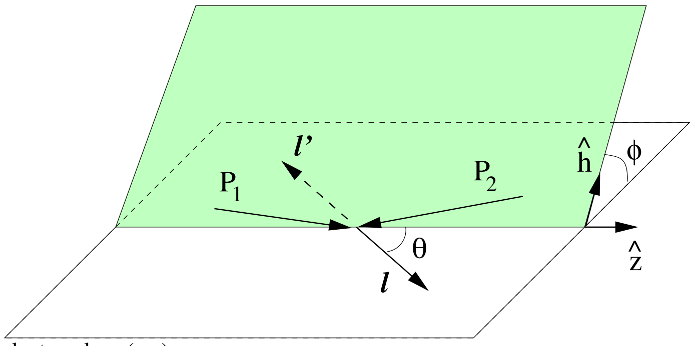
Parton Energy Loss

- Energy loss / 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

Drell-Yan decay angular distributions



$$h_1 + h_2 \to \gamma^* + x \to l^+ + l^- + x \quad (q + \overline{q} \to \gamma^*)$$

Θ and Φ are the decay polar and azimuthal angles of the μ^+ in the dilepton rest-frame

Collins-Soper frame

A general expression for Drell-Yan decay angular distributions:

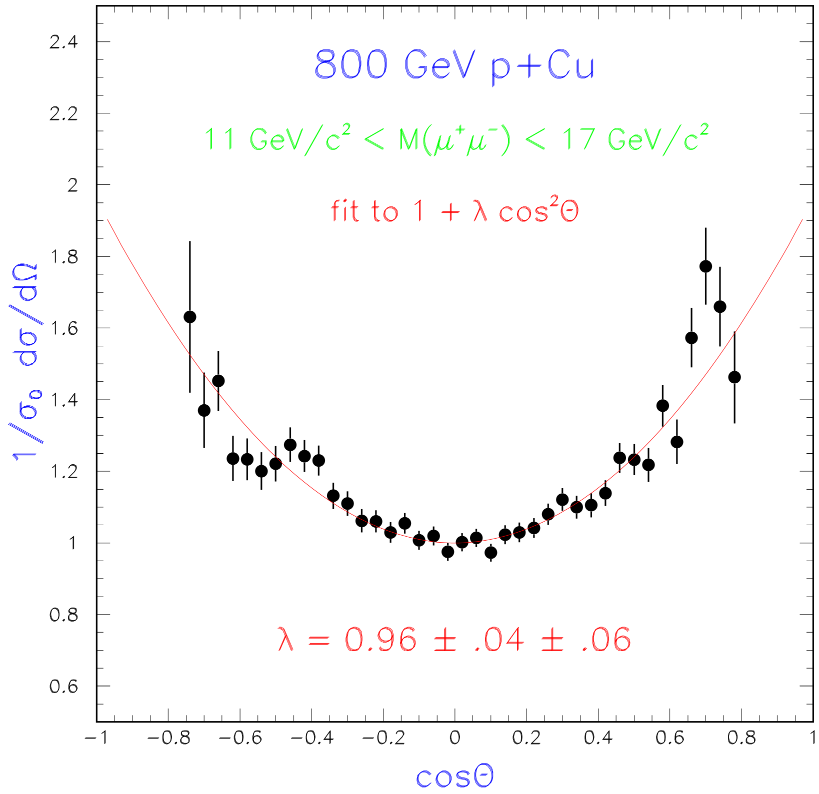
$$\left(\frac{1}{\sigma}\right)\left(\frac{d\sigma}{d\Omega}\right) = \left[\frac{3}{4\pi}\right]\left[1 + \lambda \cos^2\theta + \mu \sin 2\theta \cos\phi + \frac{\nu}{2}\sin^2\theta \cos 2\phi\right]$$

"Naive" Drell-Yan (transversely polarized γ^*, no transverse momentum) $\to \lambda = 1,\ \mu = 0,\ \nu = 0$

In general : $\lambda \neq 1,\ \mu \neq 0,\ \nu \neq 0$

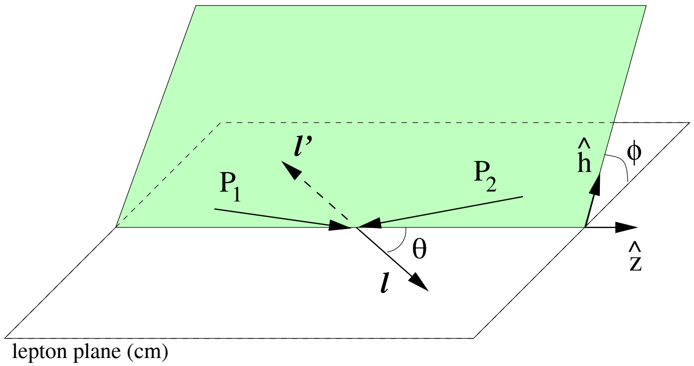
Decay Angular Distribution of Drell-Yan

$$\text{Prediction:} \quad \frac{d\sigma}{d\Omega} = \sigma_0 (1 + \cos^2 \theta)$$



Data from Fermilab E772

McGaughey, Moss, Peng; Annu. Rev. Nucl. Part. Sci. 49 (1999) 217 (hep/ph-9905409)



Θ and Φ are the decay polar and azimuthal angles of the μ^+ in the dilepton rest-frame

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Lam-Tung relation: $1-\lambda=2\nu$

– Reflect the spin-1/2 nature of quarks (analog of the Callan-Gross relation in DIS)

– Insensitive to QCD - corrections

Decay angular distributions in pion-induced Drell-Yan

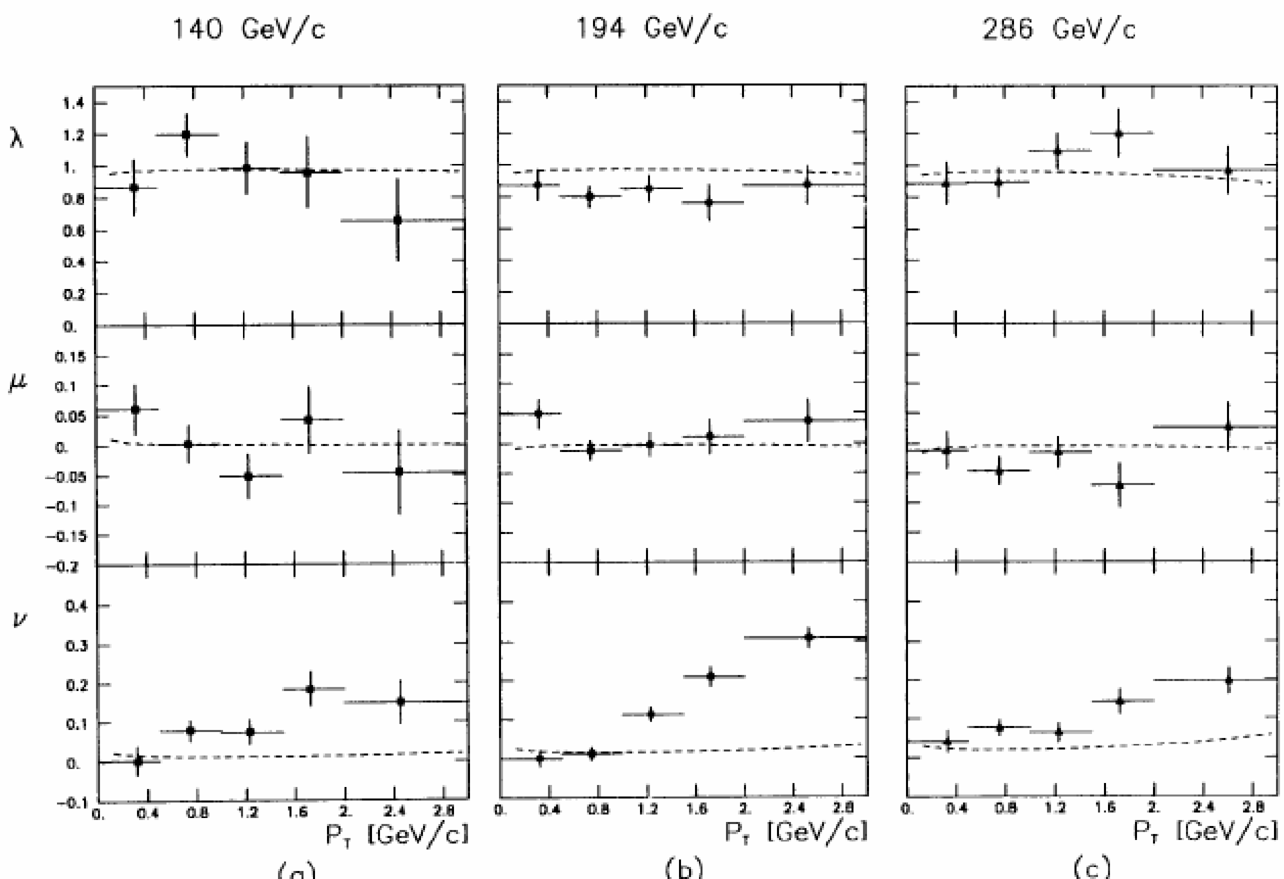


Fig. 3a–c. Parameters λ, μ, and ν as a function of P_T in the CS frame. a 140 GeV/c; b 194 GeV/c; c 286 GeV/c. The error bars correspond to the statistical uncertainties only. The horizontal bars give the size of each interval. The dashed curves are the predictions of perturbative QCD [3]

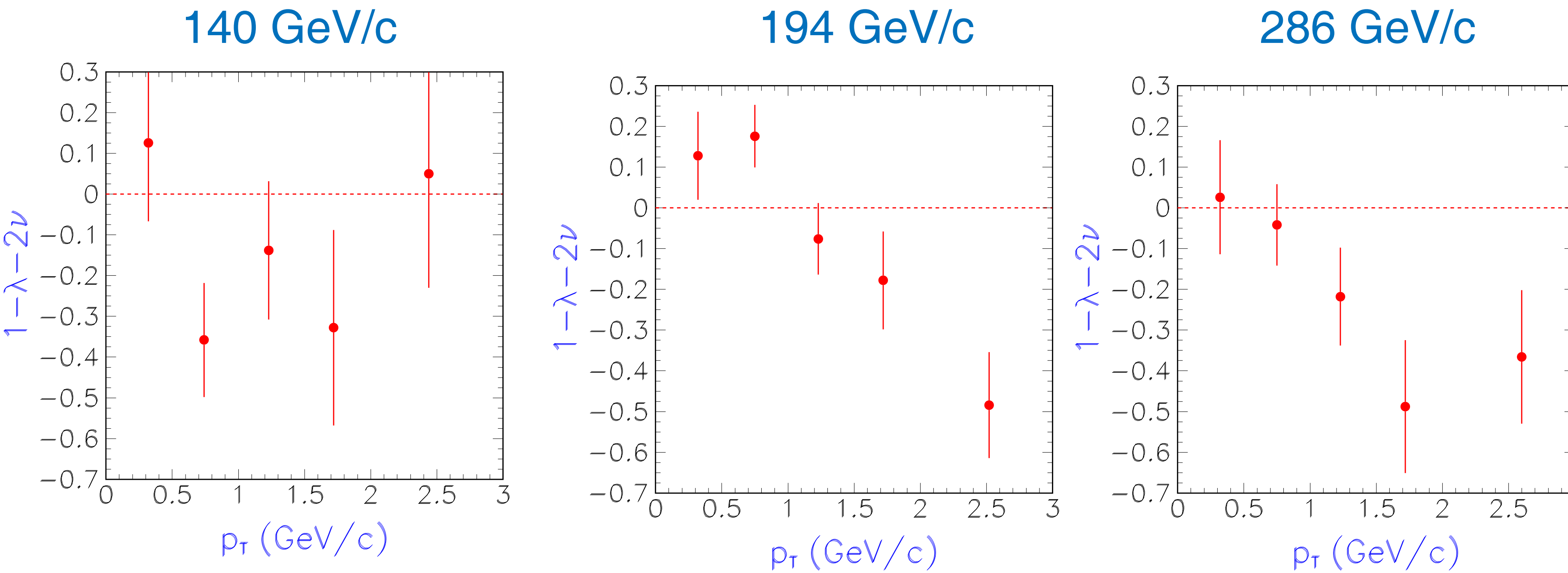
NA10 π^- +W

Z. Phys. 37 (1988) 545

Dashed curves are from pQCD calculations

$\nu \neq 0$ and ν increases with p_T

Is the Lam-Tung relation violated?



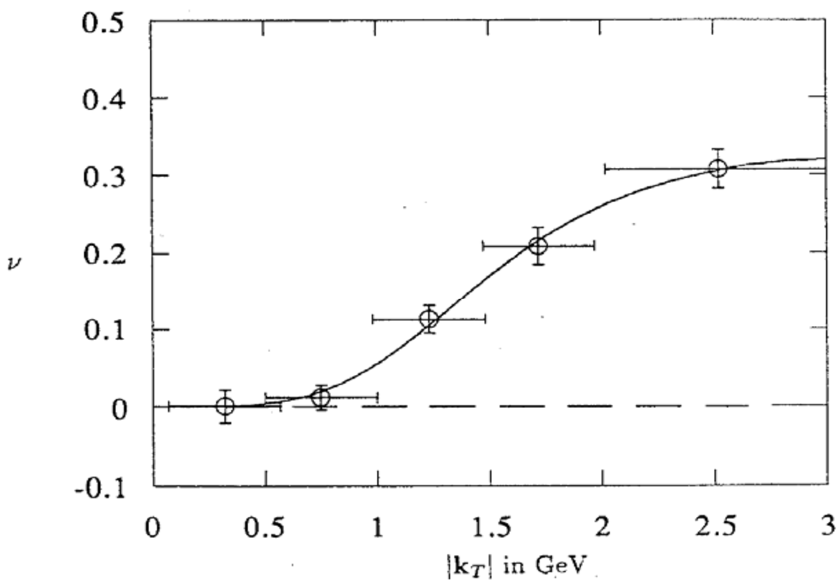
Data from NA10 (Z. Phys. 37 (1988) 545)

Violation of the Lam-Tung relation suggests non-perturbative origin

QCD vacuum effects

Brandenburg, Nachtmann & Mirkes, Z. Phy. C60,697(1993)

•Nontrivial QCD vacuum may lead to correlation between the transverse spins of the quark (in nucleon) and the antiquark (in pion).



$q\bar{q}$ spin density matrix contains terms:

$H_{ij}(\vec{\sigma}\cdot\vec{e}_i)(\vec{\sigma}\cdot\vec{e}_j)$ and

$$\nu \,\square\, \frac{2(H_{22}-H_{11})}{1+H_{33}}$$

$$\nu \approx 2\kappa = 2\kappa_0 \frac{p_T^4}{p_T^4 + m_T^4}$$

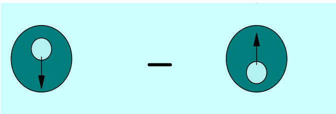
$$\lambda \approx 1; \mu \approx 0$$

κ_0=0.17, m_T=1.5

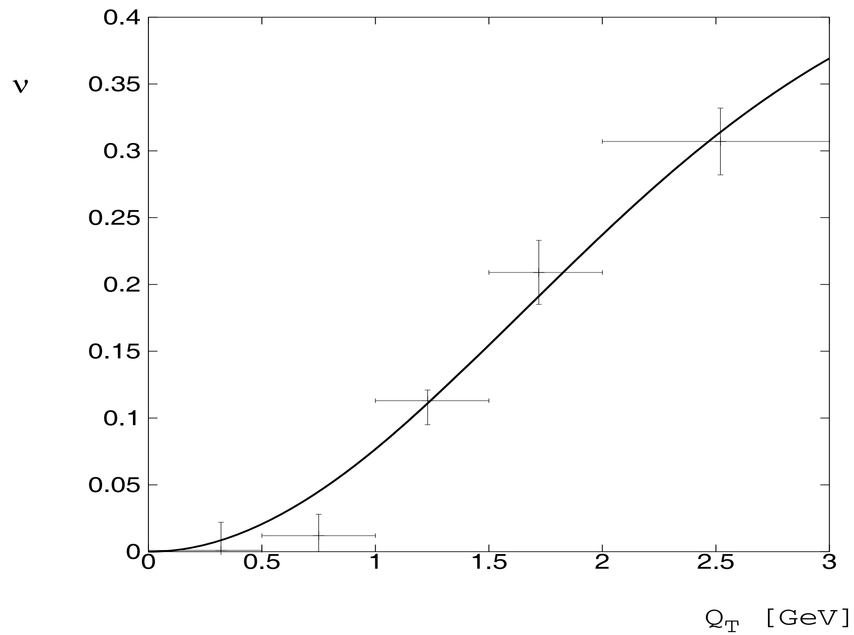
•The helicity flip in the instanton-induced contribution may lead to nontrivial vacuum.

Boer,Brandenburg,Nachtmann&Utermann, EPC40,55(2005).

Boer-Mulders function $h_1^{\perp}$



- $h_1^{\perp}$ represents a correlation between quark's k_T and transverse spin in an unpolarized hadron
- $h_1^{\perp}$ is a time-reversal odd, k_T – dependent parton distribution
- $h_1^{\perp}$ can lead to an azimuthal dependence with $\nu \propto \left(\frac{h_1^{\perp}}{f_1}\right)\left(\frac{\overline{h}_1^{\perp}}{\overline{f}_1}\right)$



$$h_1^{\perp}(x, k_T^2) = \frac{\alpha_T}{\pi} c_H \frac{M_C M_H}{k_T^2 + M_C^2} e^{-\alpha_T k_T^2} f_1(x)$$

$$\nu = 16\kappa_1 \frac{Q_T^2 M_C^2}{(Q_T^2 + 4M_C^2)^2}$$

κ_1=0.47, M_C=2.3 GeV

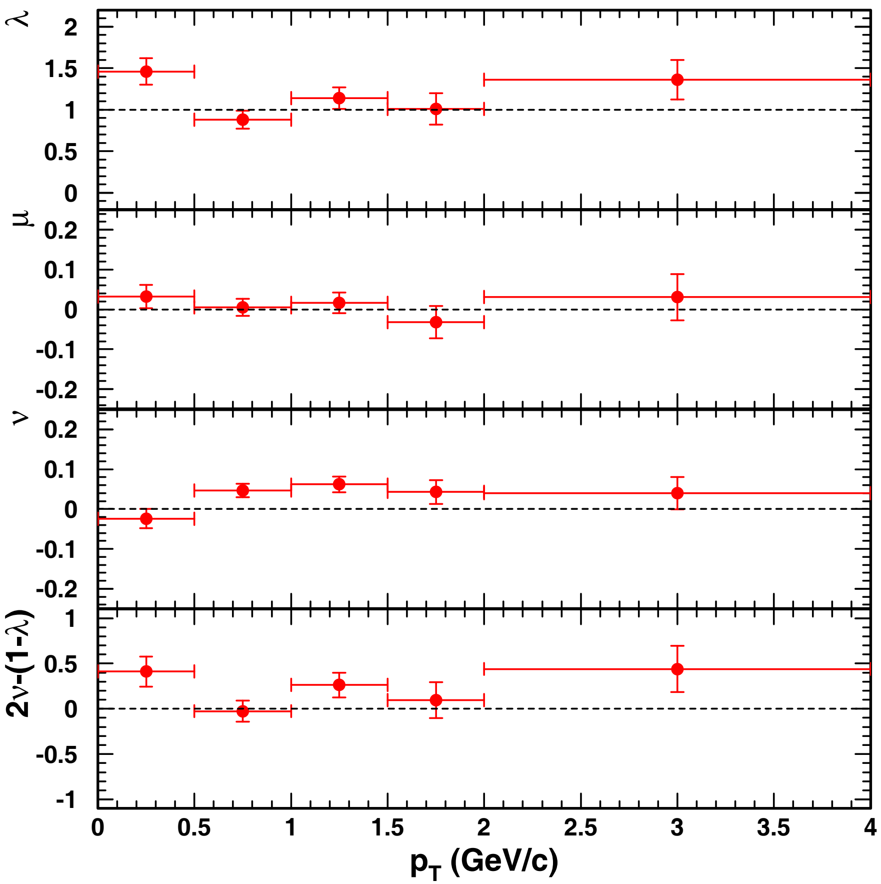
Boer, PRD 60 (1999) 014012

Motivation for measuring decay angular distributions in p+p and p+d Drell-Yan

- No proton-induced Drell-Yan azimuthal decay angular distribution data
- Provide constraints on models explaining the pion-induced Drell-Yan data. ($h_1^\perp$ is expected to be small for sea quarks. The vacuum effects should be similar for p+N and **π+N**)
- Test of the Lam-Tung relation in proton-induced Drell-Yan
- Compare the decay angular distribution of p+p versus p+d

Decay angular distributions for p+d Drell-Yan at 800 GeV/c

$$\left(\frac{1}{\sigma}\right)\left(\frac{d\sigma}{d\Omega}\right)=\left[\frac{3}{4\pi}\right]\left[1+\lambda\cos^2\theta+\mu\sin2\theta\cos\phi+\frac{\nu}{2}\sin^2\theta\cos2\phi\right]$$



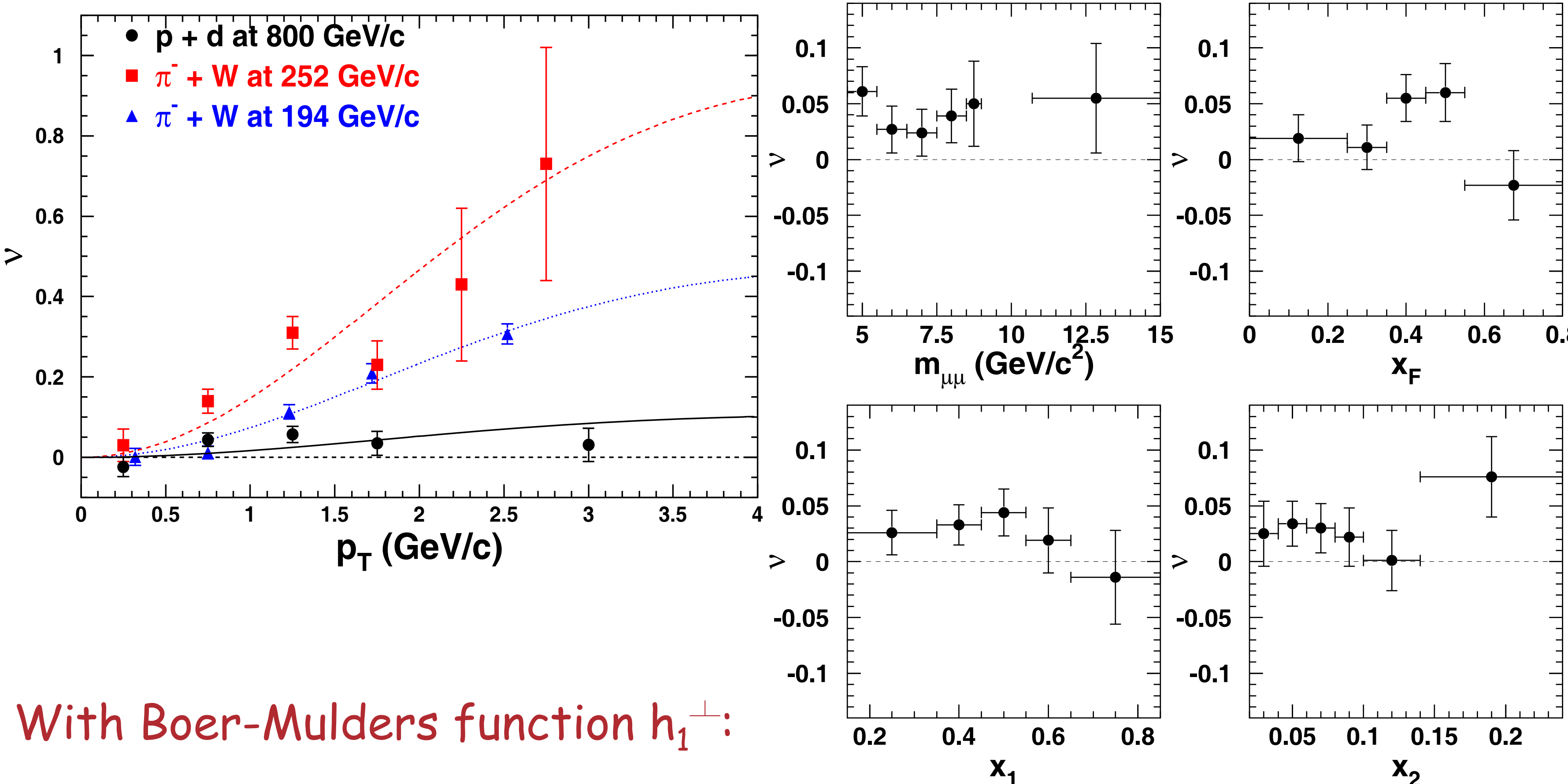
p+d at 800 GeV/c

$<\lambda>$	1.07±0.07
$<\mu>$	0.04±0.013
$<\nu>$	0.03±0.01
<2ν-1+λ>	-0.13±0.07

No significant azimuthal asymmetry in p+d Drell-Yan!

Azimuthal cos2Φ Distribution in p+d Drell-Yan

L.Y. Zhu, J.C. Peng, P. Reimer et al., PRL 99 (2007) 082301



With Boer-Mulders function $h_1^{\perp}$:

$\nu(\pi^- W \rightarrow \mu^+\mu^- X) \sim$ valence $h_1^{\perp}(\pi)$ * valence $h_1^{\perp}(p)$

$\nu(pd \rightarrow \mu^+\mu^- X) \sim$ valence $h_1^{\perp}(p)$ * sea $h_1^{\perp}(p)$

What does this mean?

- These results suggest that the Boer-Mulders functions $h_1^{\perp}$ for sea quarks are significantly smaller than for valence quarks.
- These results also suggest that the non-trivial vacuum correlation between the sea-quark transverse spin (in one hadron) and the valence-quark transverse spin (in another hadron) is small.

Timeline of E906

- 2002: E906 Approved by Fermilab PAC
- 2006: E906 funded by DOE Nuclear Physics
- **2008, Dec: Stage-II approval by Fermilab Director and MOU between Fermilab and E906 Collaboration finalized.**

Final Signatures on MOU 16 Dec 2008

Memorandum of Understanding
between
Fermi National Accelerator Laboratory
and the
E-906 Drell-Yan Experiment

December 12, 2008
Version 1.01

Contents

SIGNATURES

P. Reimer – E-906 Co-spokesperson	12 Dec 08 Date
D. Geesaman – E-906 Co-spokesperson	12 Dec 08 Date
R. Dixon – Accelerator Division Head	12-16-08 Date
G. Bock – Acting Particle Physics Division Head	12/16/08 Date
V. White – Computing Division Head	12/16/08 Date
R. Ortgiesen – FESS Head	12-16-08 Date
N. Grossman – ES&H Director	15-Dec-08 Date
S. Holmes – Associate Director for Accelerators	12/16/08 Date
Y-K. Kim – Deputy Director	12/16/08 Date
P. Oddone – Director	12/16/08 Date

2008 Christmas Gift to E906 from Pier Oddone

Fermilab

Fermi National Accelerator Laboratory
P.O. Box 500 • Batavia, Il. • 60510-0500
630-840-3211 FAX 630-840-2900

Director's Office

December 24, 2008

Dr. Paul Reimer
Dr. Donald Geesaman
Physics Division, Building 203
Argonne National Laboratory
9700 S. Cass Avenue
Argonne IL 60439

Dear Paul and Don,

We would like to congratulate you on the progress you made in refining plans, adding new collaborators, and securing additional funding sources for the E-906 Drell-Yan experiment. These efforts have made it possible to develop the plans embodied in the Memorandum of Understanding that has just been signed by you and the Laboratory. Given all this progress, it is appropriate to grant Stage II approval for the experiment, and I am happy to do so now.

Best of luck as you proceed with construction of the E-906/Drell-Yan experiment.

Sincerely,

Piermaria Oddone

cc: Y. Kim

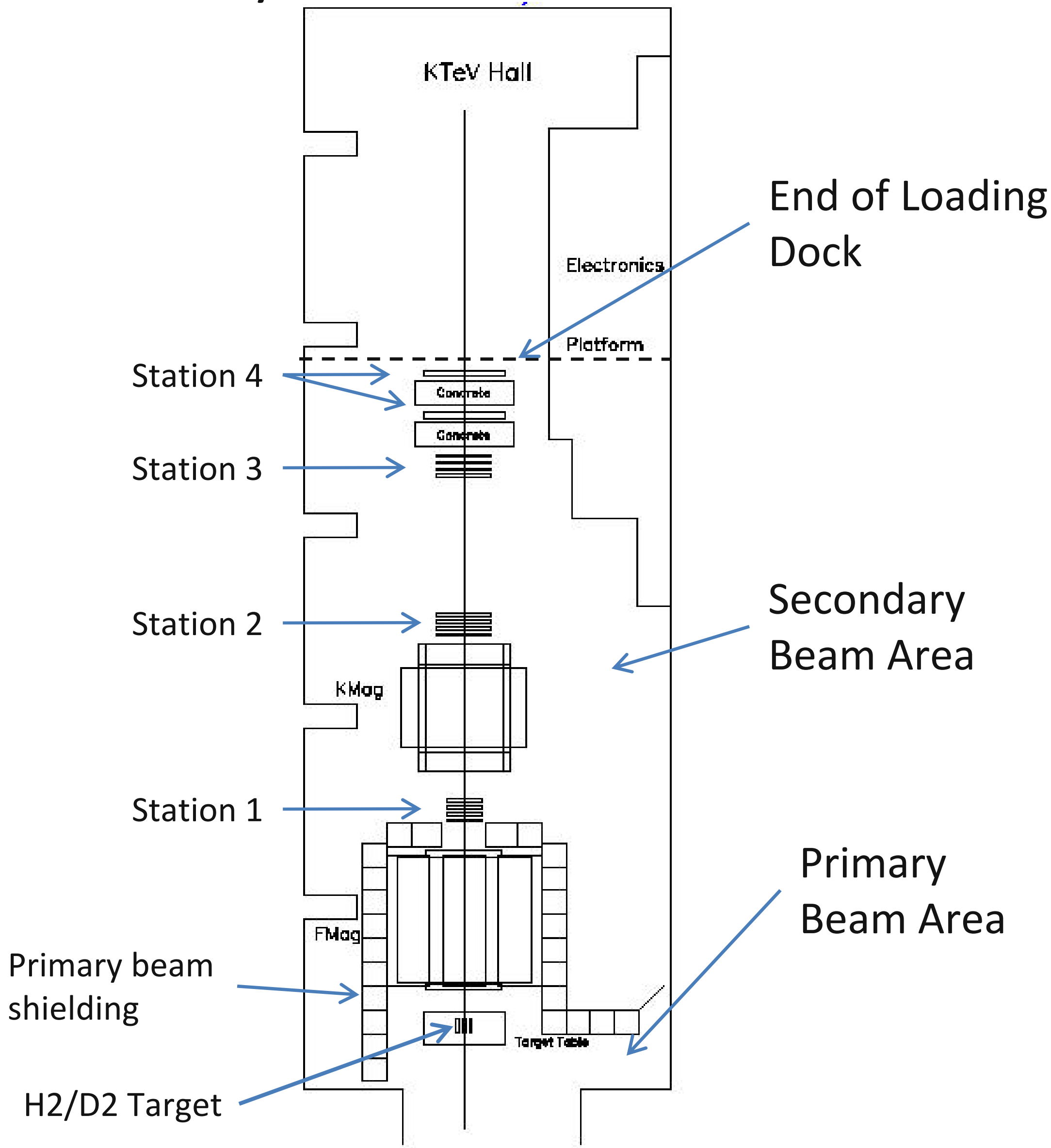
Proton Economics

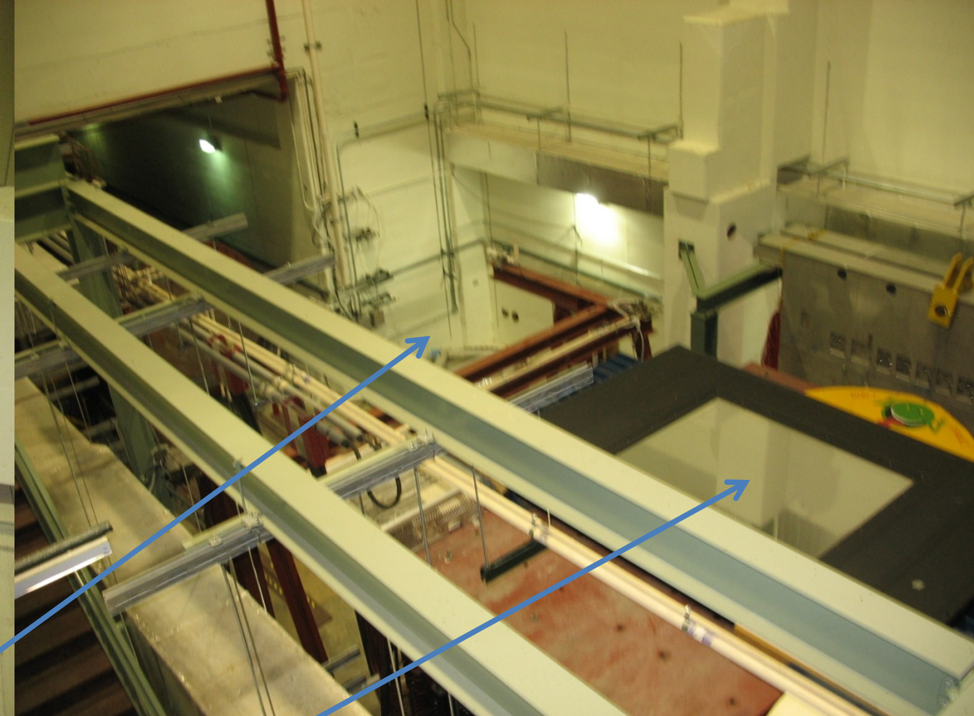
- Location: KTeV's Hall
- Beam Request: Total of 5.2×10^{18} protons (over 2 years)

- 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

Layout of E906 in KTeV Hall





KTeV Hall looking toward incoming beam

Area upstream of KTeV magnet

KTeV magnet

Assembly area downstream of KTeV magnet

South end of
counting room

North end of
counting room

Taiwan Group

Members:

- Institute of Physics, Academia Sinica中研院物理所: Wen-Chen Chang 章文箴, Ping-Kun Teng 鄧炳坤, Yen-Chu Chen 陳彥竹, Da-Shung Su 蘇大順(engineer), Bo-Ru Lin 林伯儒 (research assistant), Shiuan-Hal Shiu 許軒豪 (Ph.D. student from Central Univ.)
- Ling-Tung University嶺東科技大學: Ting-Hua Chang 張定華

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- Ling-Tung University嶺東科技大學: Ting-Hua Chang 張定華

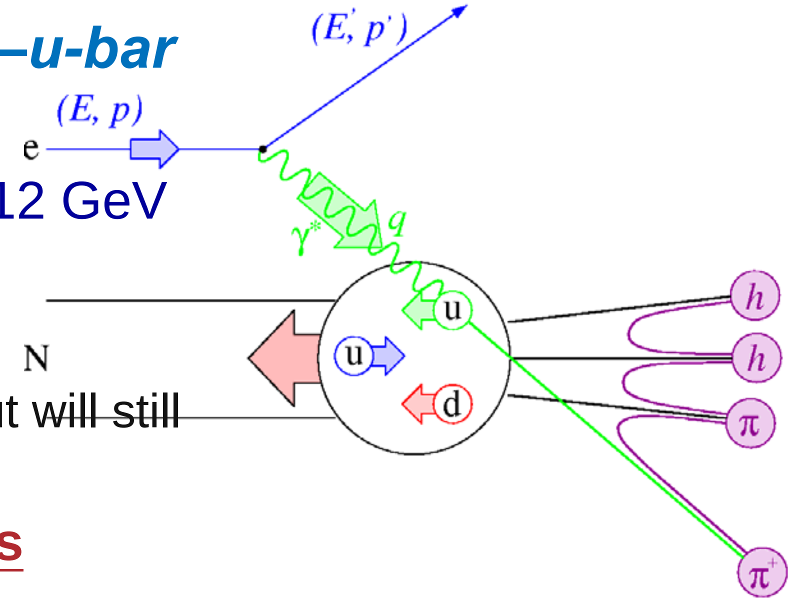
Committed responsibility:

- Build 400 preamplifier-discriminators cards (6400 channels in total) for 5500 tracking channels in Station 1 MWPC and for 400 channels Proportional tubes in Station 4.
- Build the readout system for Coincidence Registers (CR), which consists of 110 CR modules (7040 channels in total) for 5500 tracking channels in Station 1 MWPC, for 400 channels Proportional tubes in Station 4, and for 320 channels of the hodoscope planes in all stations.
- Participate in the LVL2-Trigger project – two CEAN V1495 FPGA logic units purchased and one Ph.D. student will be available in the early summer to work on this project.

Timeline of E906

- 2002: E906 Approved by Fermilab PAC
- 2006: E906 funded by DOE Nuclear Physics
- **2008, Dec: Stage-II approval by Fermilab Director and MOU between Fermilab and E906 Collaboration finalized.**
- Construction and installation of spectrometer and readout electronics to be done in 2009 and upper half of 2010.
- First beam expected in the fall of 2010!

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, $\pi^{\S}$ decay in flight background

Timeline of E906

- 2002: E906 Approved by Fermilab PAC
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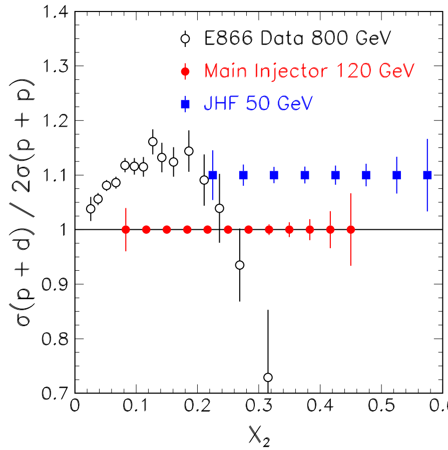
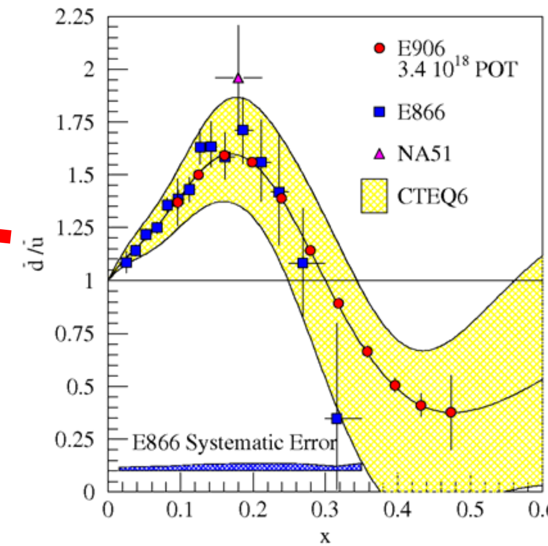
- Spectrometer construction and installation in 2009 and upper half of 2010.
- **First beam expected in the fall of 2010!**
- *Post Fermilab run, most of hardware may be moved to JPARC, Japan, for further measurements: 50 GeV proton beam to explore $x \rightarrow 1$ and polarized Drell-Yan process.*

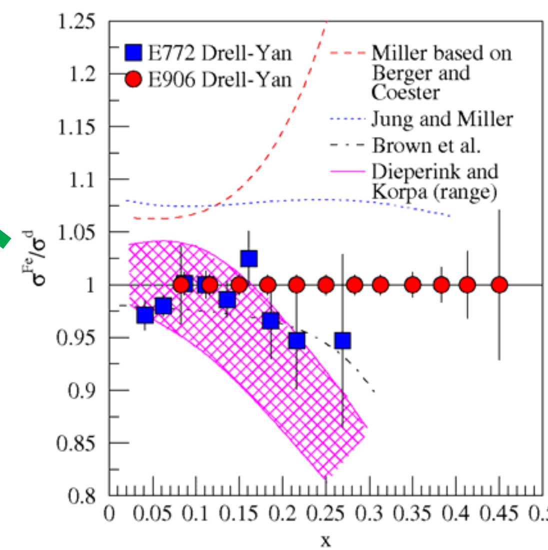


Conclusion: Expected Impact from E906/Drell-Yan

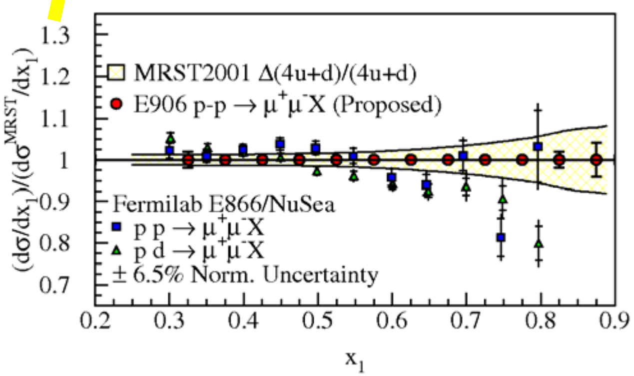
- **What is the structure of the nucleon?**
  - What is d-bar/u-bar?
  - What are the origins of the sea quarks?
  - What is the high-x structure of the proton?

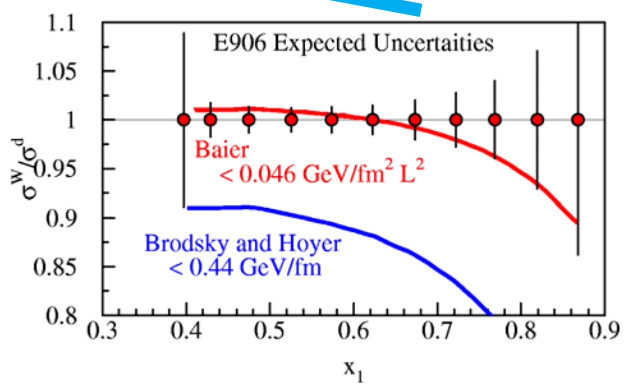


- **What is the structure of nucleonic matter?**
  - Where are the nuclear pions?
  - Is anti-shadowing a valence effect?



- **Do colored partons lose energy in cold nuclear matter?**





END