Flavor Structure of the Nucleon & Semi-Inclusive Deep Inelastic Scattering

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Outline of the Lectures

- Historical Overview
- Experimental Tools for Probing the Parton Distributions
- Flavor Structure of the Nucleon Sea
- Other Symmetries of the Parton Distribution and Fragmentation Functions
- Future Prospects at Jefferson Lab and Other Facilities

Evidences for sub-structure in the nucleons

- Anomalous magnetic moments for proton and neutron
- Finite size of proton deduced from electron-proton elastic scattering
- Excited states of the nucleon
- Quark model description of the nucleons
- Deep-Inelastic Scattering (elastic scattering of electrons off charged quarks)

Magnetic Moments of Leptons and Nucleons

Magnetic moments for leptons

$$\mu = \frac{g}{2}\mu_B \qquad \mu_B = \frac{e\hbar}{2m_l}$$

e	μ	τ	ν
$g = 2.002319304374$	$g = 2.002331832$	$1.896 < g < 2.116$	$\mu_\nu < 1.5 \times 10^{-10}\ \mu_B$

Magnetic moments for nucleons

$$\mu = \frac{g}{2}\mu_N \qquad \mu_N = \frac{e\hbar}{2m_p}$$

p	n
$g = 5.58569467$ (expect $g = 2$)	$g = -3.826085$ (expect $g = 0$)

Measurements of nucleon magnetic moments

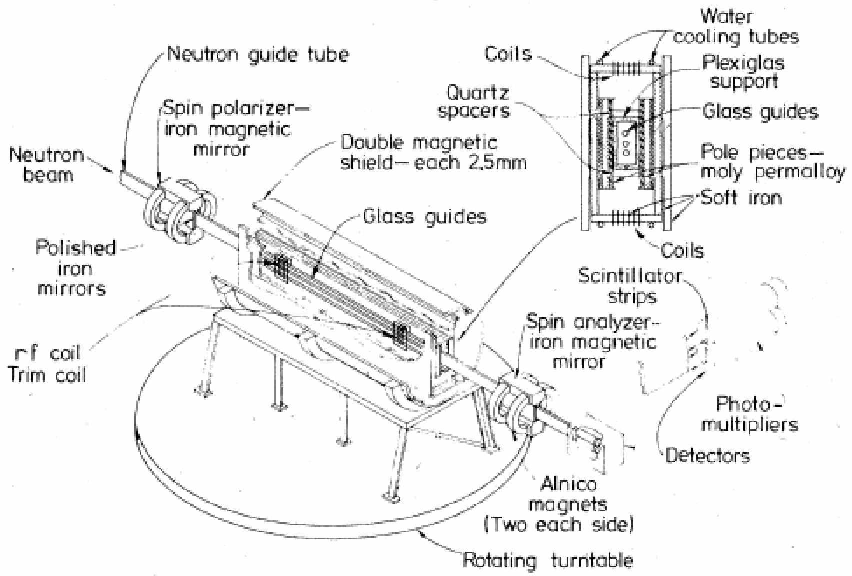


FIG. 1. Schematic view of spectrometer with detail of neutron polarization and detection equipment.

Neutron magnetic moment

Separated-oscillatory-field magnetic resonance technique (Ramsey)

Cold neutron beam from ILL (Grenoble)

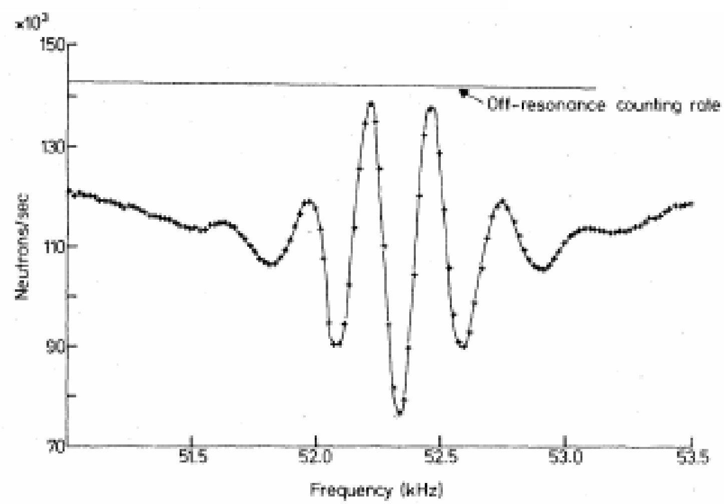
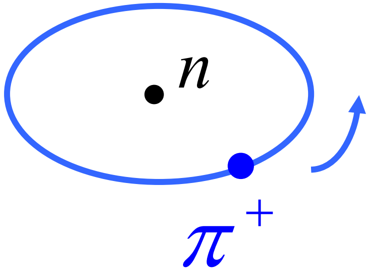


FIG. 3. Typical neutron resonance.

Early explanation of nucleon anomalous magnetic moments

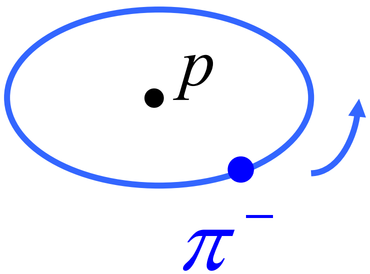
Meson cloud is responsible for the anomalous part ?

$$p \rightarrow n \text{ (point-like)} + \pi^{+}$$



g_p = 5.59 = 2 + 3.59

$$n \rightarrow p \text{ (point-like)} + \pi^{-}$$



g_n = -3.83 = 0 - 3.83

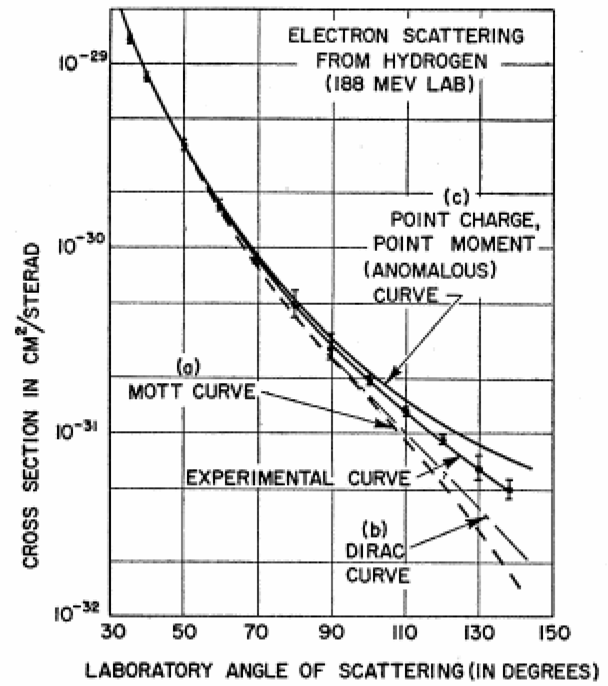
Electron-proton elastic scattering

PHYSICAL REVIEW VOLUME 102, NUMBER 3 MAY 1, 1956

Elastic Scattering of 188-Mev Electrons from the Proton and the Alpha Particle*†‡§‖¶

R. W. McAllister and R. Hofstadter
Department of Physics and High-Energy Physics Laboratory, Stanford University, Stanford, California

(Received January 25, 1956)



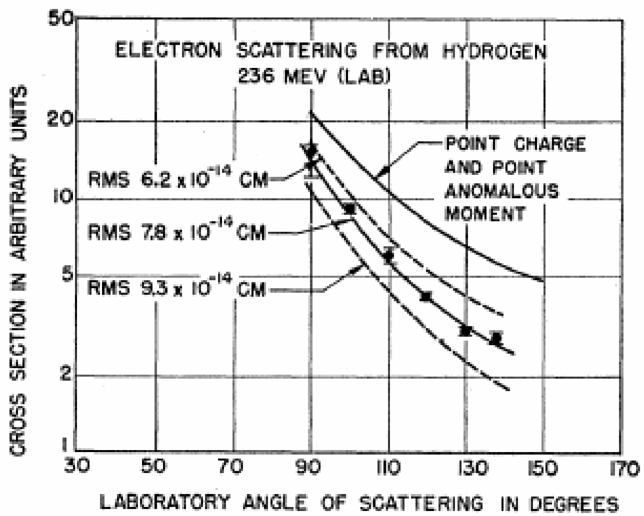
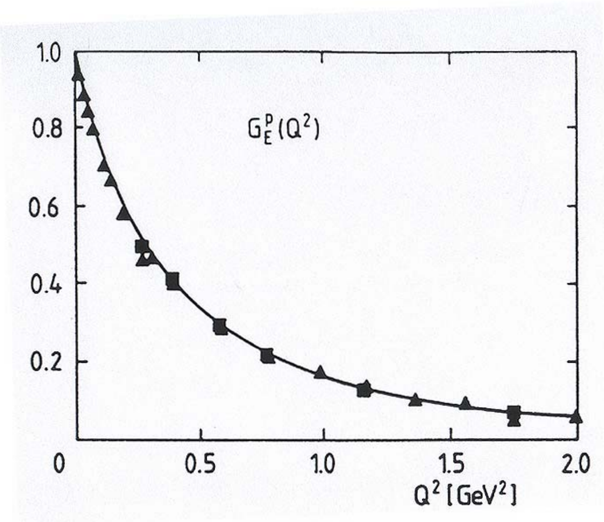
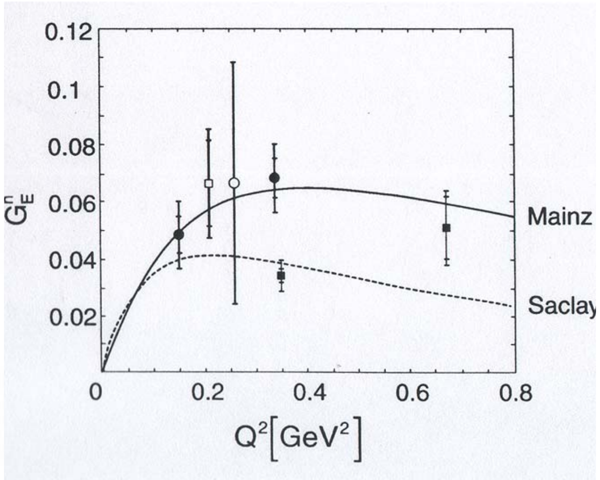
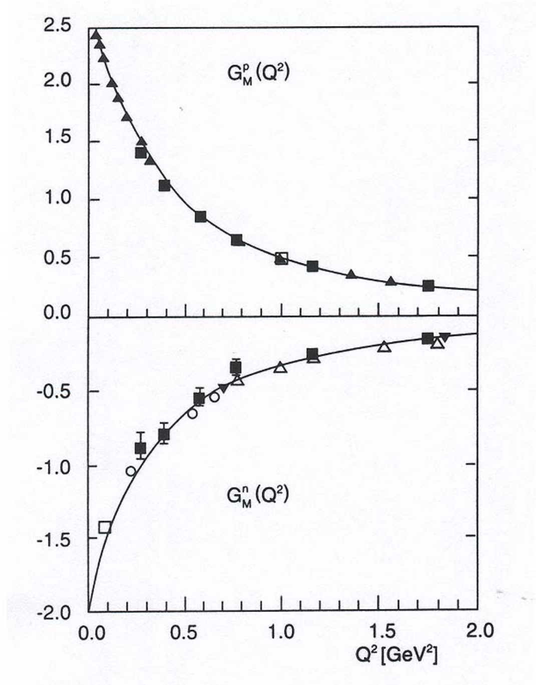


Fig. 6. This figure shows the experimental points at 236 Mev and the attempts to fit the shape of the experimental curve. The best fit lies near 0.78×10^{-13} cm.

Nucleon electric and magnetic form factors







$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{Mott} \left\{ \frac{G_E^2(Q^2) + \frac{Q^2}{4M^2} G_M^2(Q^2)}{1 + \frac{Q^2}{4M^2}} + \frac{Q^2}{2M^2} G_M^2(Q^2) \tan^2 \frac{\theta}{2} \right\}$$

$G_E^p(0) = 1;\quad G_E^n(0) = 0;\qquad G_M^p(0) = \mu_p = 2.793;\ G_M^n(0) = \mu_n = -1.913$

$$< r^2 >= \frac{-6}{G(0)} \frac{dG(Q^2)}{dQ^2} \Big|_{Q^2=0}$$

Naïve Quark Model

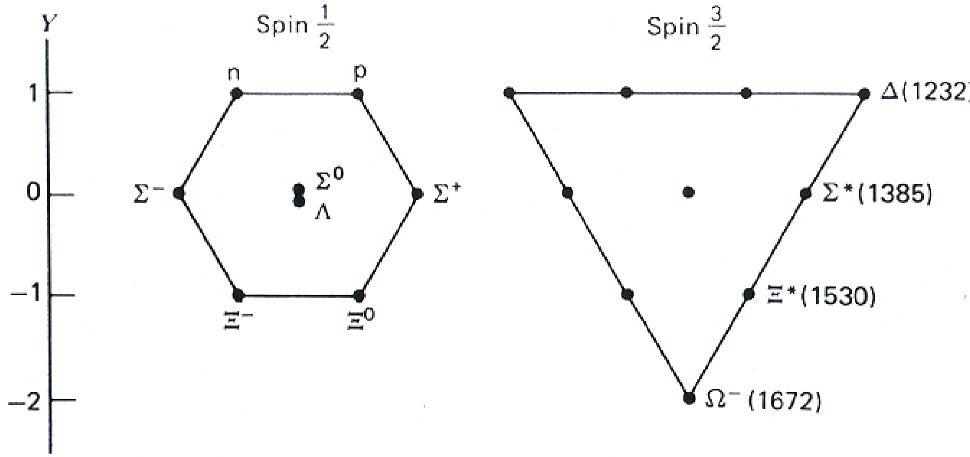


Fig. 2.8 Ground-state baryons: (8, 2) + (10, 4).

$$p\uparrow = \frac{1}{\sqrt{18}}\left\{\left[2u\uparrow u\uparrow d\downarrow - u\uparrow u\downarrow d\uparrow - u\downarrow u\uparrow d\uparrow\right] + permutations\right\}$$

$(uu \text{ pair has spin} = 1)$

$$n\uparrow = \frac{1}{\sqrt{18}}\left\{\left[2d\uparrow d\uparrow u\downarrow - d\uparrow d\downarrow u\uparrow - d\downarrow d\uparrow u\uparrow\right] + permutations\right\}$$

$$\Sigma^{+}\uparrow = \frac{1}{\sqrt{18}}\left\{\left[2u\uparrow u\uparrow s\downarrow - u\uparrow u\downarrow s\uparrow - u\downarrow u\uparrow s\uparrow\right] + permutations\right\}$$

Baryon Magnetic moments from Quark Model

$$\mu_p = \langle p\uparrow | \sum_{i=1}^{3} \mu_i (\sigma_z)_i | p\uparrow \rangle$$

$$\mu_u = \frac{(2/3)e\hbar}{2m_u} = \frac{e\hbar}{3m_u} \qquad \mu_d = \frac{(-1/3)e\hbar}{2m_d} = \frac{-e\hbar}{6m_d} \qquad \mu_u = -2\mu_d \ (if\ m_u = m_d)$$

$$\mu_p = \frac{1}{3}(4\mu_u - \mu_d) \qquad \mu_n = \frac{1}{3}(4\mu_d - \mu_u) \qquad \mu_n / \mu_p = -\frac{2}{3} \ \text{(exp value} = -0.685)$$

Baryon	μ/μ_N (Experiment)		Quark model:	μ/μ_N
p	+2.792 847 386	± 0.000 000 063	$(4\mu_u - \mu_d)/3$	—
n	−1.913 042 75	± 0.000 000 45	$(4\mu_d - \mu_u)/3$	—
Λ^0	−0.613	± 0.004	μ_s	—
Σ^+	+2.458	± 0.010	$(4\mu_u - \mu_s)/3$	+2.67
Σ^0			$(2\mu_u + 2\mu_d - \mu_s)/3$	+0.79
$\Sigma^0 \to \Lambda^0$	−1.61	± 0.08	$(\mu_d - \mu_u)/\sqrt{3}$	−1.63
Σ^-	−1.160	± 0.025	$(4\mu_d - \mu_s)/3$	−1.09
Ξ^0	−1.250	± 0.014	$(4\mu_s - \mu_u)/3$	−1.43
Ξ^-	−0.650 7	± 0.002 5	$(4\mu_s - \mu_d)/3$	−0.49
Ω^-	−2.02	± 0.05	$3\mu_s$	−1.84

Baryon Magnetic moments from Quark Model

If there were no color degree of freedom, then the nucleon wave-functions become

$$p\uparrow = \frac{1}{\sqrt{6}}\left\{\left[u\downarrow u\uparrow d\uparrow - u\uparrow u\downarrow d\uparrow\right] + permutations\right\}$$

$(uu$ pair has spin $= 0)$

$$n\uparrow = \frac{1}{\sqrt{6}}\left\{\left[d\downarrow d\uparrow u\uparrow - d\uparrow d\downarrow u\uparrow\right] + permutations\right\}$$

$$\mu_p = \mu_d \qquad \mu_n = \mu_u \qquad \mu_n / \mu_p = -2 \quad (\text{exp value} = -0.685)$$

Mass 3 neuclei

$$^3He\uparrow = \frac{1}{\sqrt{6}}\left\{\left[p\downarrow p\uparrow n\uparrow - p\uparrow p\downarrow n\uparrow\right] + permutations\right\}$$

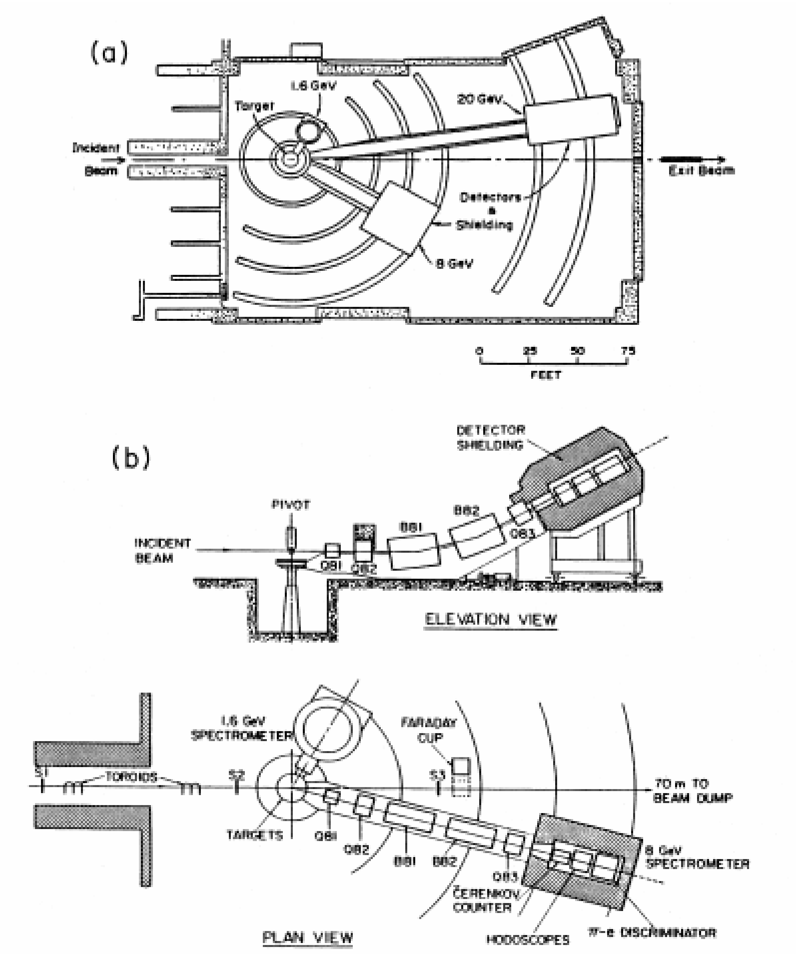
$$^3H\uparrow = \frac{1}{\sqrt{6}}\left\{\left[n\downarrow n\uparrow p\uparrow - n\uparrow n\downarrow p\uparrow\right] + permutations\right\}$$

$$\mu_{^3He} = \mu_n = -1.91\mu_N \qquad \mu_{^3H} = \mu_p = 2.79\mu_N$$

$$\text{exp}: \mu_{^3He} = -2.13\mu_N \qquad \mu_{^3H} = 2.98\mu_N$$

Observation of Scaling Behavior in Deep-Inelastic Scattering

SLAC

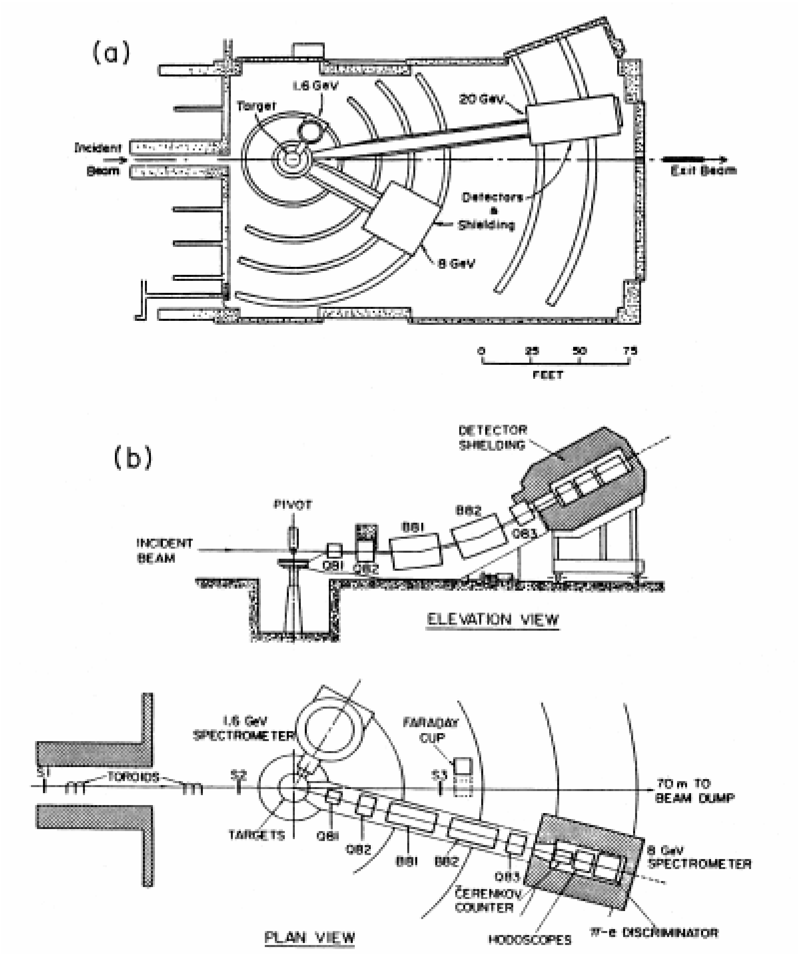


e p → e' X

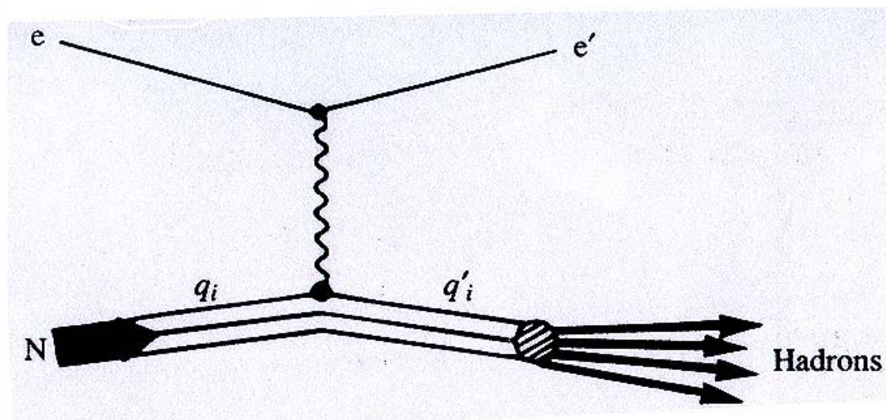
- 20 GeV electron beam
- Original goal was to study higher-mass nucleon resonances

Observation of Scaling Behavior in Deep-Inelastic Scattering

SLAC

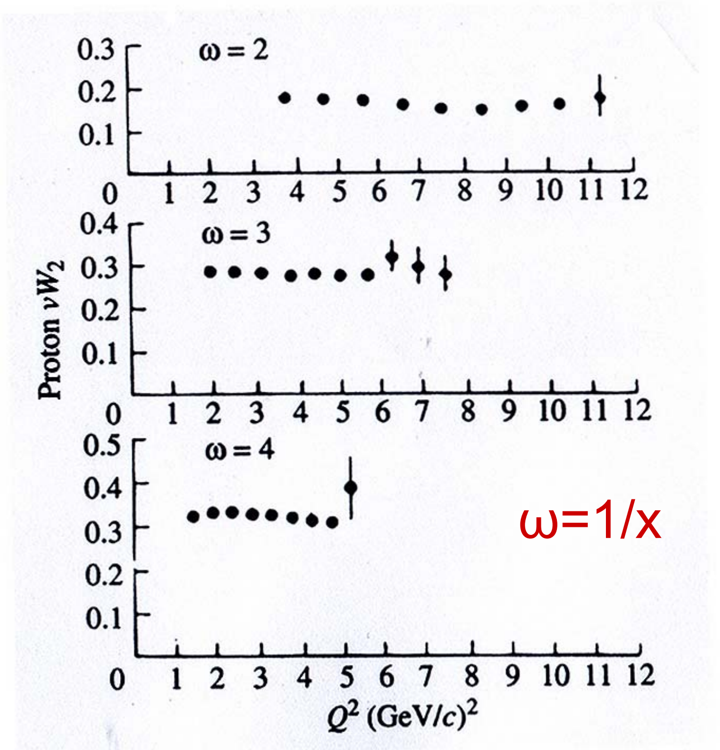


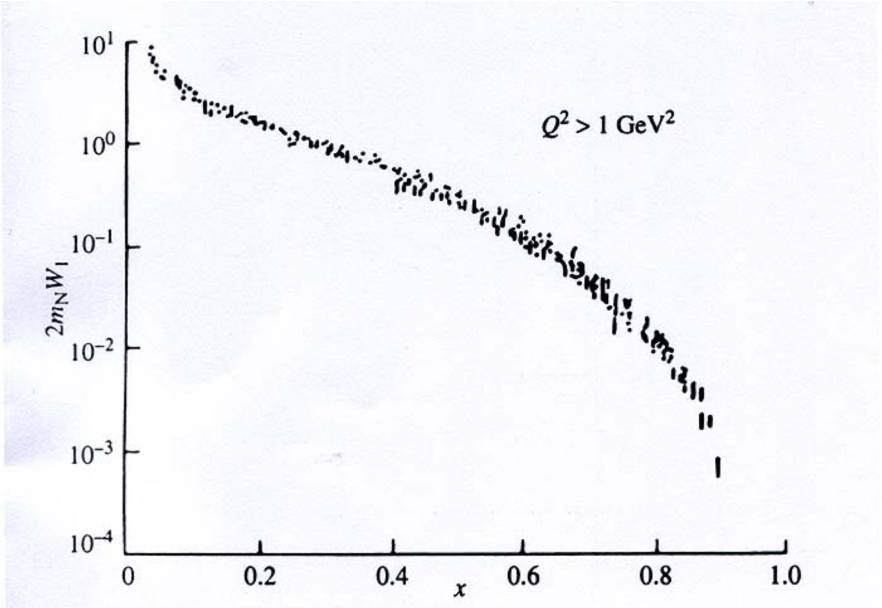
e p → e' X



- 20 GeV electron beam
- Original goal was to study higher-mass nucleon resonances

Observation of Scaling Behavior in Deep-Inelastic Scattering

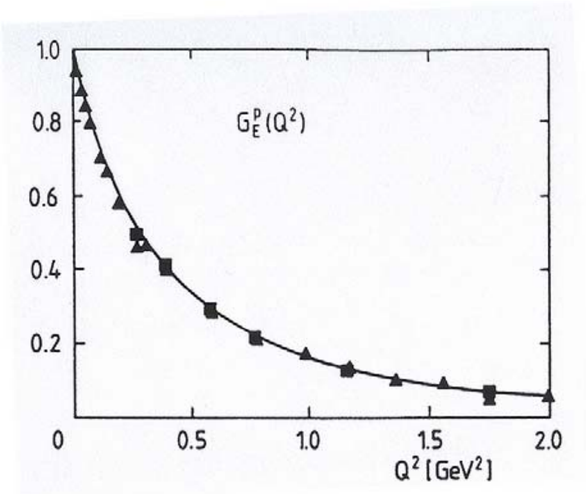




W_1 and W_2 are generalization of the elastic form factors for the inelastic case

Structure functions W_1 and W_2 are functions of x ($x=Q^2/2m\nu$), but independent of Q^2

Connection between Q^2-scaling and point-like particles

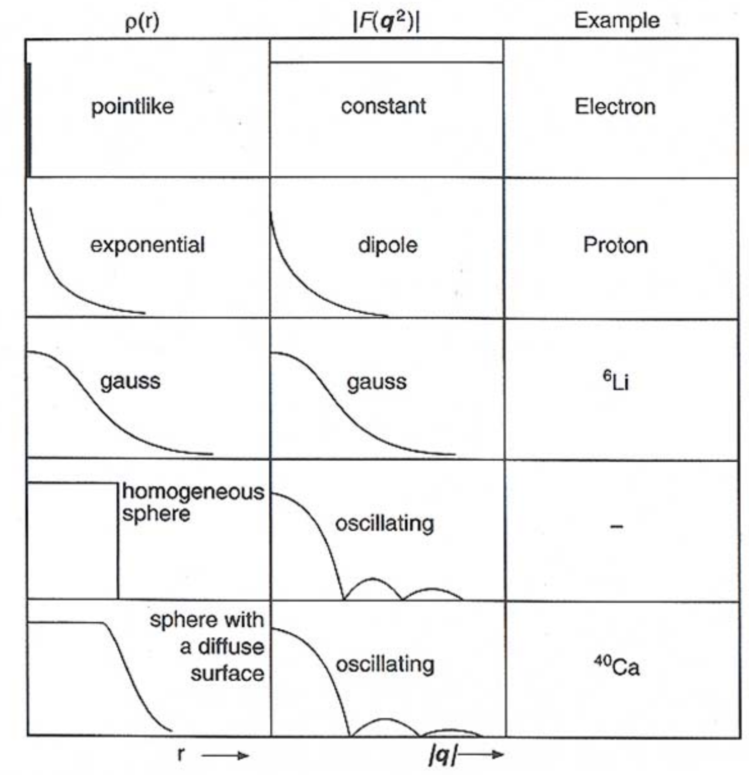


$$G_E^p(Q^2) = [1 + Q^2/(0.71\,\mathrm{GeV}^2)]^{-2}$$

$$f(r) = \frac{1}{(2\pi)^3} \int F(q^2) e^{-i\vec{q}\cdot\vec{r}/\hbar} d^3q$$

Charge distribution $f(r)$		Form Factor $F(q^2)$	
point	$\delta(r)/4\pi$	1	constant
exponential	$(a^3/8\pi) \cdot \exp(-ar)$	$(1 + q^2/a^2\hbar^2)^{-2}$	dipole
Gaussian	$(a^2/2\pi)^{3/2} \cdot \exp(-a^2r^2/2)$	$\exp(-q^2/2a^2\hbar^2)$	Gaussian
homogeneous sphere	$\begin{cases} 3/4\pi R^3 & \text{for } r \le R \\ 0 & \text{for } r > R \end{cases}$	$3\,\alpha^{-3}(\sin\alpha - \alpha\cos\alpha)$ with $\alpha = \lvert q\rvert R/\hbar$	oscillating

Connection between Q^2-scaling and point-like particles



A Q^2-independent structure function implies a scattering off a point particle

What are those point-like particles?

Are they spin-1/2 or spin-0 particles?

Spin-0 (Mott Scattering)

$$\frac{d\sigma}{d\Omega} = \left(\frac{\alpha^2}{4E^2 \sin^4 \frac{\theta}{2}} \right) \frac{E'}{E} \cos^2 \frac{\theta}{2}$$

Spin-1/2 (Dirac Scattering)

$$\frac{d\sigma}{d\Omega} = \left(\frac{\alpha^2}{4E^2 \sin^4 \frac{\theta}{2}} \right) \frac{E'}{E} \left\{ \cos^2 \frac{\theta}{2} - \frac{q^2}{2M^2} \sin^2 \frac{\theta}{2} \right\}$$

ep Deep Inelastic Scattering

$$\frac{d\sigma}{d\Omega dE'} = \left(\frac{\alpha^2}{4E^2 \sin^4 \frac{\theta}{2}} \right) \left\{ W_2(\nu, q^2) \cos^2 \frac{\theta}{2} - 2W_1(\nu, q^2) \sin^2 \frac{\theta}{2} \right\}$$

$$\text{If spin} = 0 \;\Rightarrow\; W_1 = 0$$

$$\text{If spin} = 1/2 \;\Rightarrow\; 2W_1 = \frac{Q^2}{2M^2} W_2$$

Quark-parton model

$$\text{If spin} = 1/2 \quad \Rightarrow \quad 2W_1 = \frac{Q^2}{2M^2} W_2$$

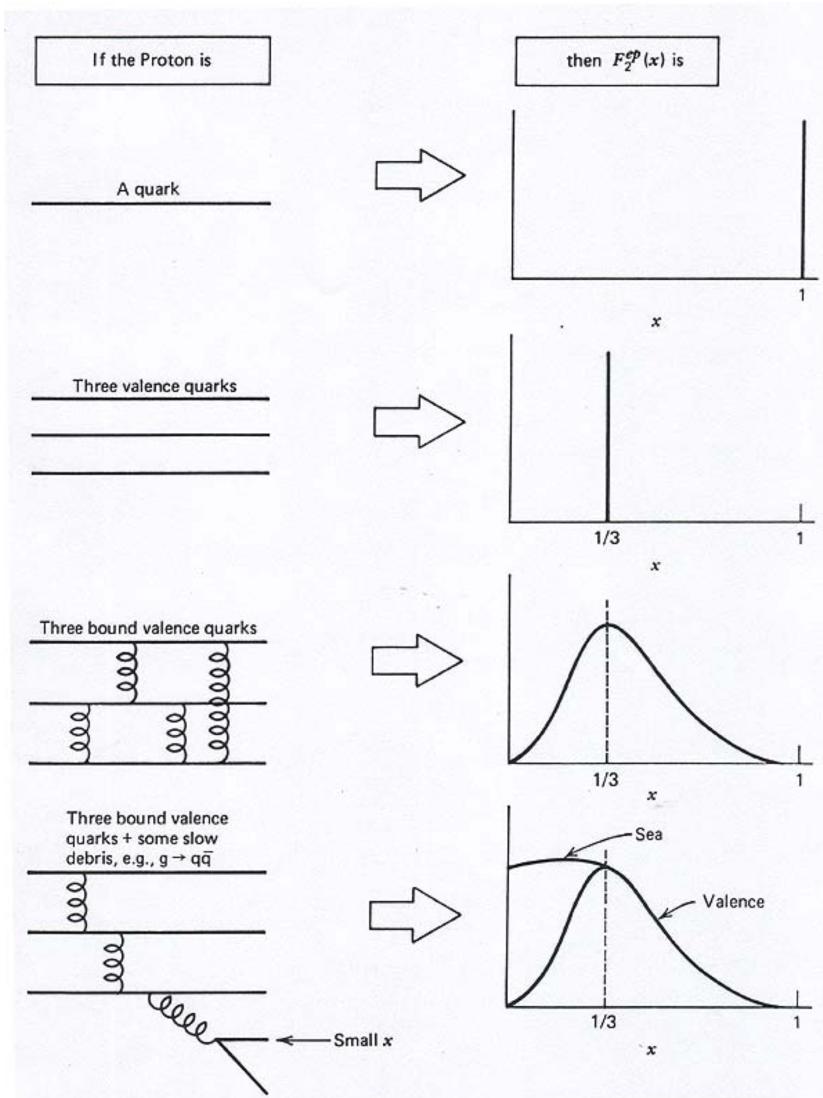
(consistent with experiment)

$$\nu W_2(\nu, Q^2) \rightarrow F_2(x) = \sum_i e_i^2 x f_i(x)$$

$$M W_1(\nu, Q^2) \rightarrow F_1(x) = \frac{1}{2x} F_2(x) = \frac{1}{2} \sum_i e_i^2 f_i(x)$$

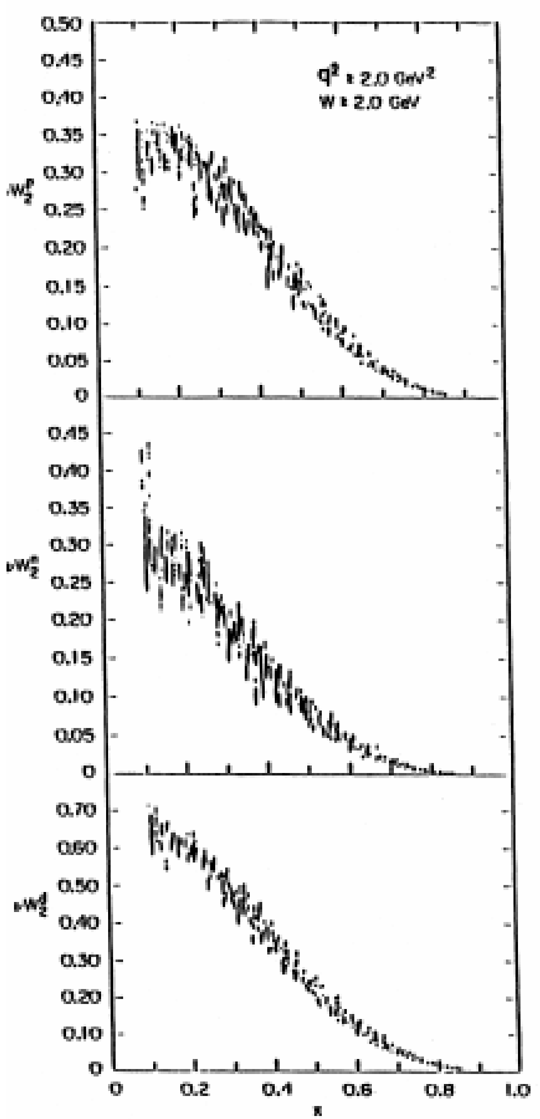
$f_i(x)$ is the momentum distribution of spin $-1/2$ parton i

$F_2(x)$ Structure Function

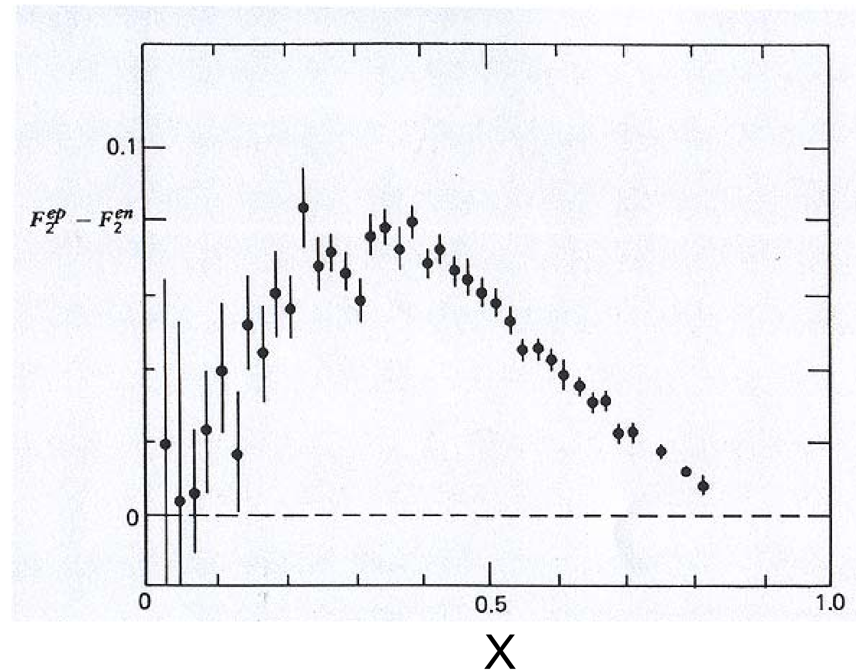


Sea-quarks and valence quarks

Sea-quarks at small-x



Valence-quark from $F_2^p(x)$-$F_2^n(x)$



$$F_2^p(x)/x \approx \frac{4}{9}u(x)+\frac{1}{9}d(x)+\frac{4}{9}\bar{u}(x)+\frac{1}{9}\bar{d}(x)$$

$$F_2^n(x)/x \approx \frac{4}{9}d(x)+\frac{1}{9}u(x)+\frac{4}{9}\bar{d}(x)+\frac{1}{9}\bar{u}(x)$$

$$[F_2^p(x)-F_2^n(x)]/x \approx \frac{1}{3}u_V(x)-\frac{1}{3}d_V(x)$$

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

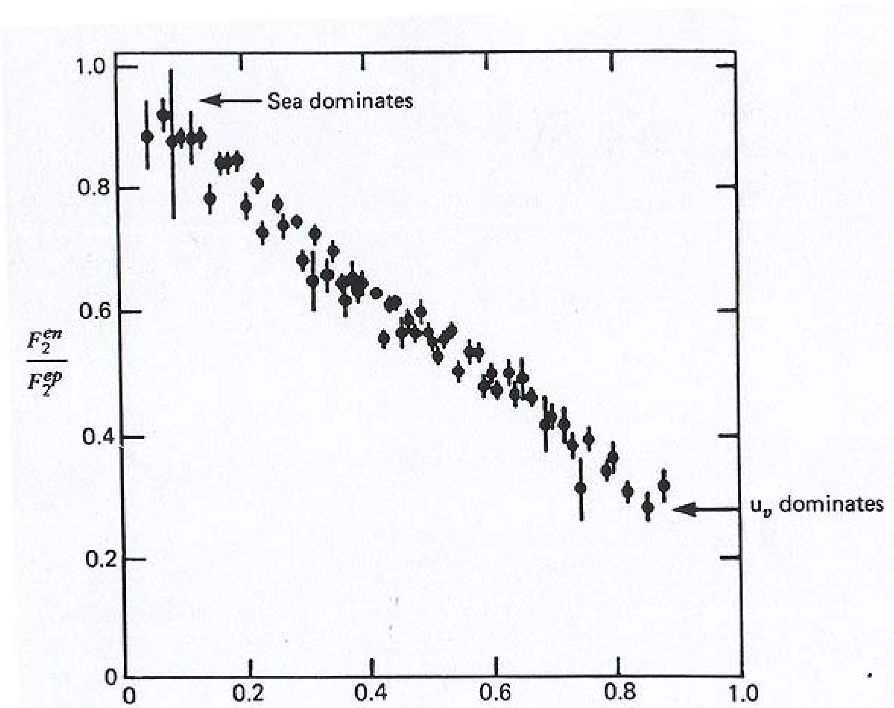
Flavor structure of the parton distributions in the proton

Questions

- *Is* $u_V(x) = 2d_V(x)?$
- *Is* $\bar{u}(x) = \bar{d}(x)?$
- *Is* $\bar{s}(x) = \bar{u}(x)?$
- *Is* $\bar{s}(x) = s(x)?$
- *Is* $u_p(x) = d_n(x)?$
- *Is* $\bar{u}_p(x) = \bar{d}_n(x)?$

Is $u_V(x) = 2d_V(x)$?

F_2^n / F_2^p



X

$$F_2^p(x)/x \approx \frac{1}{9}[4u_V(x) + d_V(x)] + \frac{4}{3}S(x)$$

$$F_2^n(x)/x \approx \frac{1}{9}[u_V(x) + 4d_V(x)] + \frac{4}{3}S(x)$$

$$F_2^n(x)/F_2^p(x) \underset{x\to 0}{\longrightarrow} 1$$

$$F_2^n(x)/F_2^p(x) \underset{x\to 1}{\longrightarrow} \frac{u_V + 4d_V}{4u_V + d_V}$$

$$F_2^n(x)/F_2^p(x) \underset{x\to 1}{\longrightarrow} 0.2 \Rightarrow d_V / u_V \to 0\ !$$

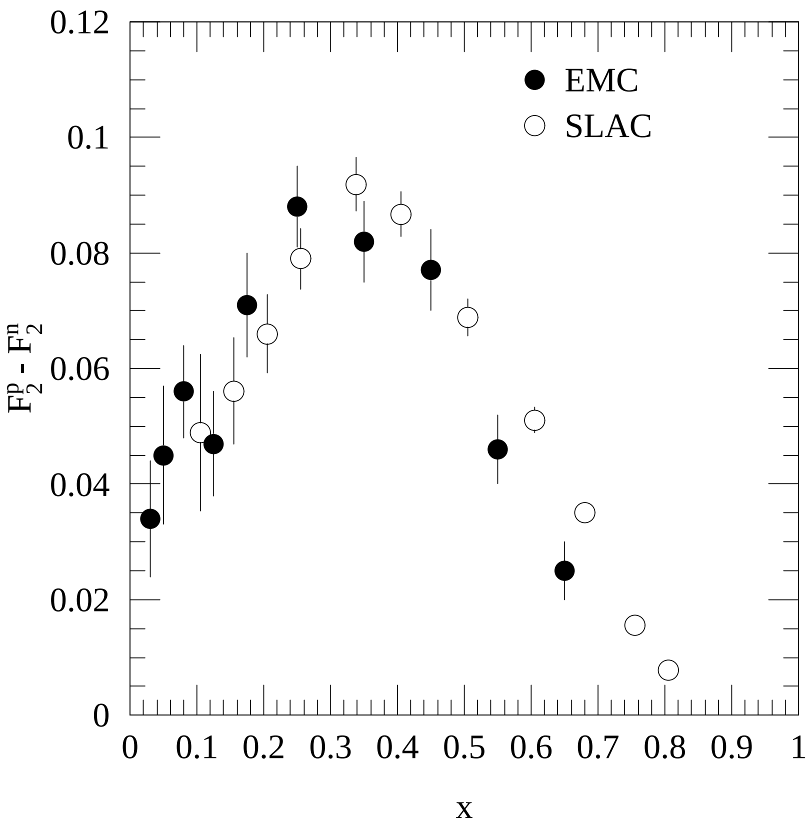
Is $\bar{u}(x) = \bar{d}(x)$?

Gottfried Sum-Rule

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

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

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



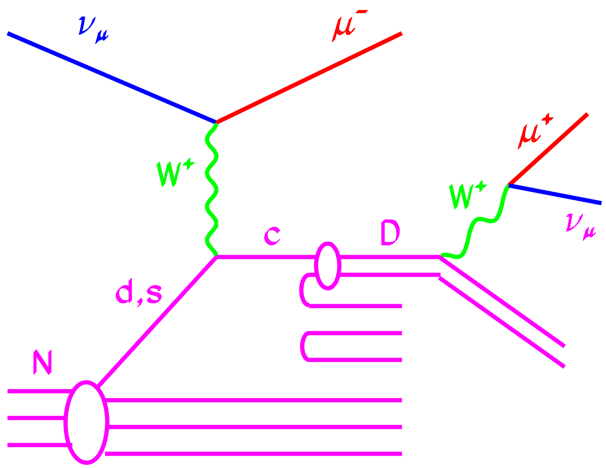
$S_G = 0.28$ (SLAC), $S_G = 0.235$(EMC) !

$$\overline{s}(x) = \overline{u}(x)\ ?$$

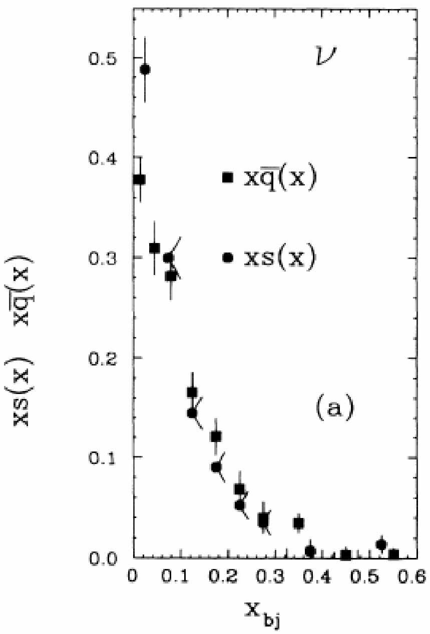
Dimuon production in neutrino DIS from CCFR and NuTeV

$$\nu + s \to \mu^- + c$$

$$c \to \mu^+ + X$$



Results from CCFR



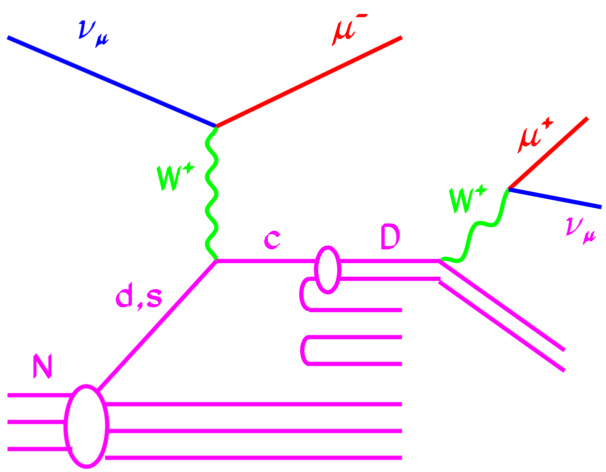
$$\kappa = 2\overline{s}/(\overline{u} + \overline{d}) = 0.44 \pm 0.10$$

$s(x) = \bar{s}(x)$?

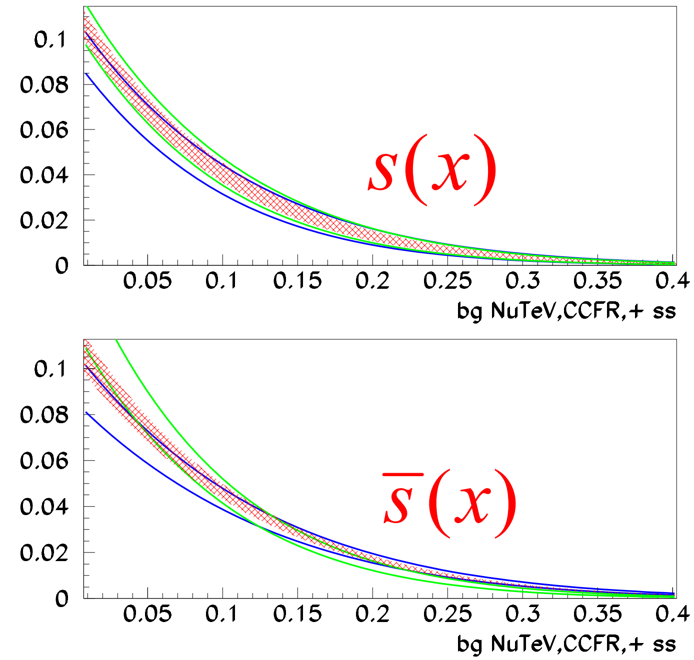
Dimuon production in neutrino DIS from CCFR and NuTeV

$$\nu + s \rightarrow \mu^- + c$$

$$\bar{\nu} + \bar{s} \rightarrow \mu^+ + \bar{c}$$



Results from NuTeV/CCFR

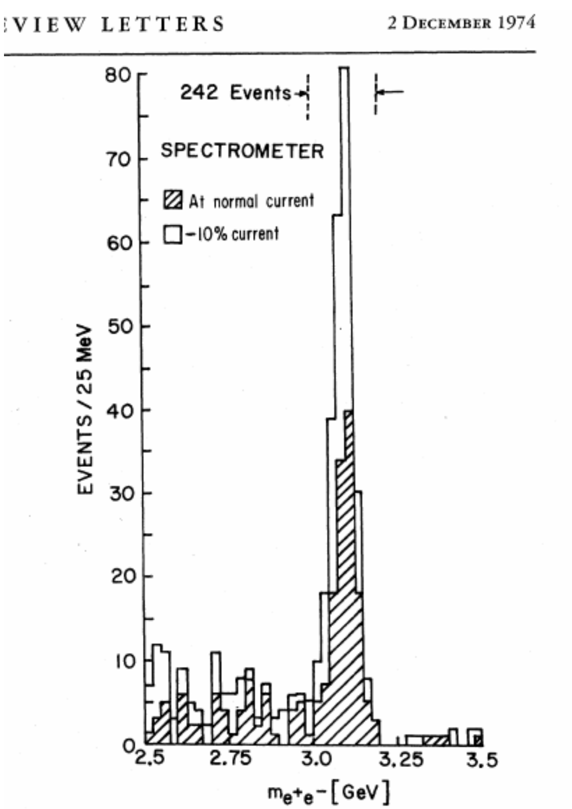


$$s(x) = 0.352\,\frac{\bar{u}(x)+\bar{d}(x)}{2}(1-x)^{-0.77} \qquad \bar{s}(x) = 0.405\,\frac{\bar{u}(x)+\bar{d}(x)}{2}(1-x)^{-2.04}$$

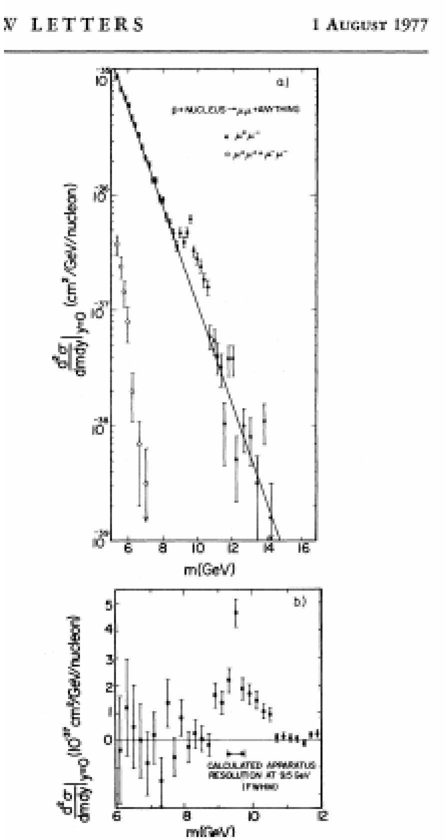
Parity-violating electron scattering is also sensitive to $s/\bar{s}$ asymmetry

There are heavy quarks too!

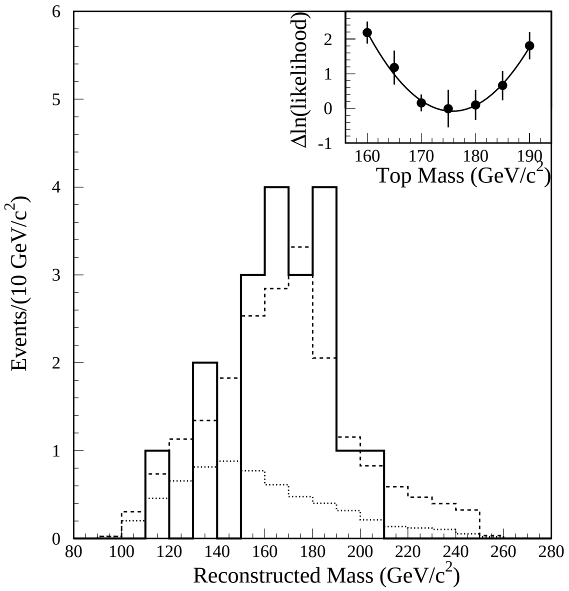
Charm quark



Bottom quark



Top quark



There are gluons too!

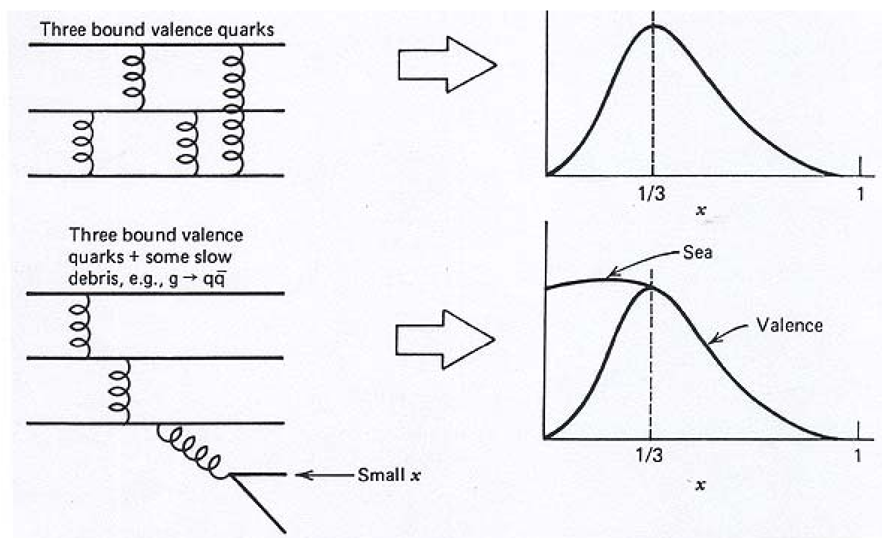
$$\int_0^1 (xp)\,dx\,(u(x)+\overline{u}(x)+d(x)+\overline{d}(x)+s(x)+\overline{s}(x)+c(x)+\overline{c}(x)) = p?$$

$$\int_0^1 x\,dx\,(u(x)+\overline{u}(x)+d(x)+\overline{d}(x)+s(x)+\overline{s}(x)+c(x)+\overline{c}(x)) = 1?$$

$$\int_0^1 dx\,[F_2^p(x)+F_2^n(x)] = \frac{5}{9}\int_0^1 x\,dx\,[u(x)+\overline{u}(x)+d(x)+\overline{d}(x)] \approx 0.30$$

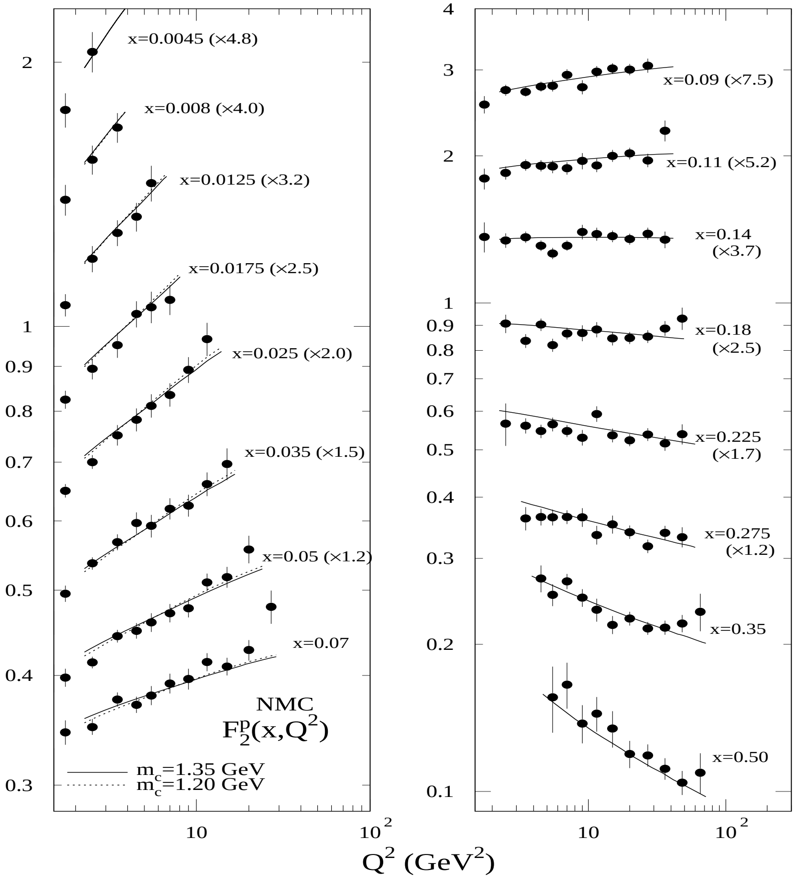
$$\Rightarrow \int_0^1 x\,dx\,[u(x)+\overline{u}(x)+d(x)+\overline{d}(x)] \approx 0.54$$

~ 50% of the proton's momentum is missing!

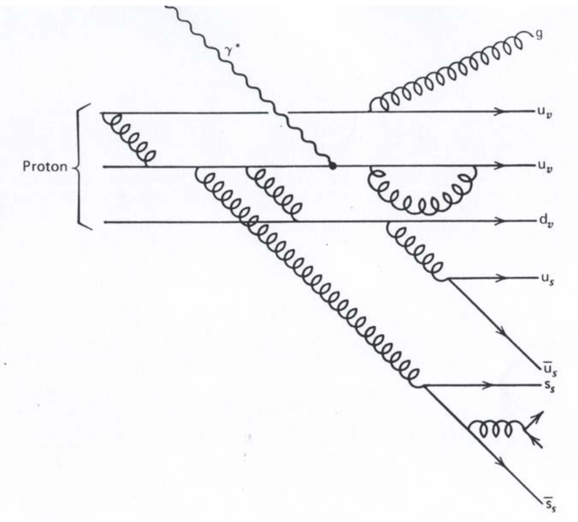


Gluons are not directly probed in DIS

How to extract gluon distributions?



Scaling-violation in DIS

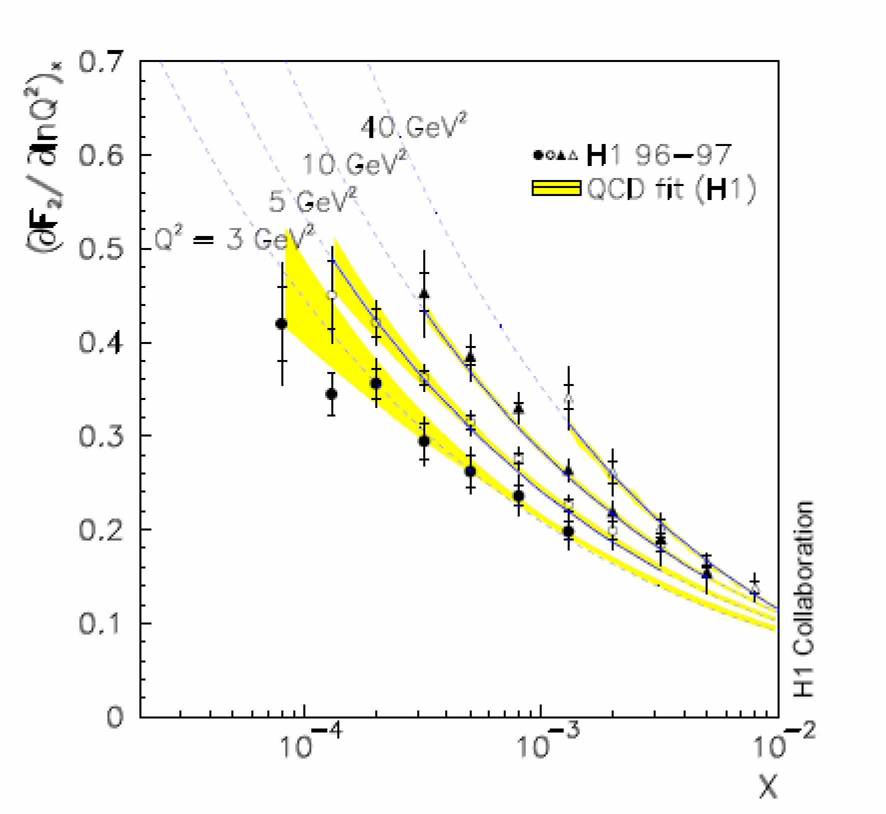


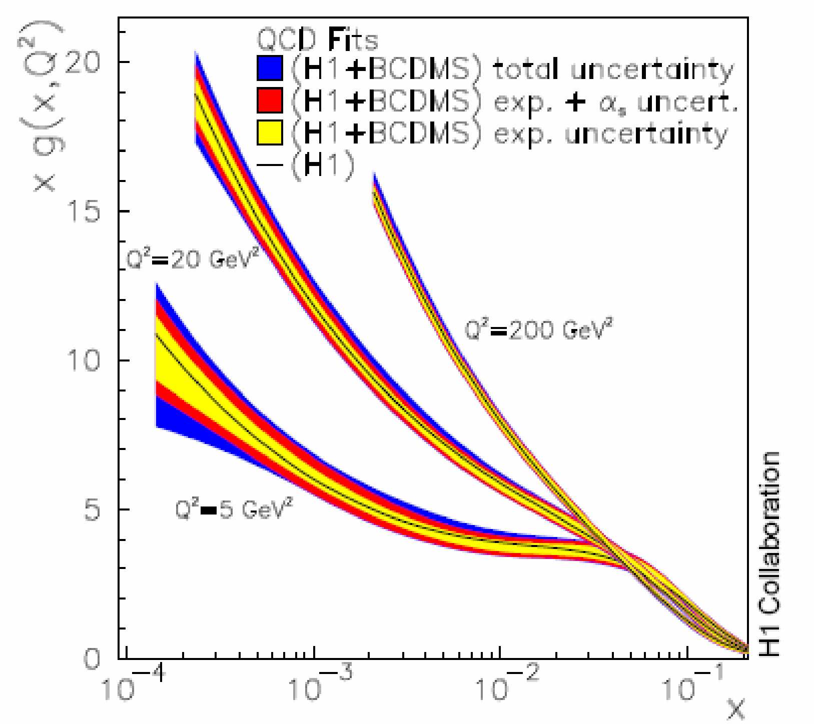
$$\frac{dq_i(x,Q^2)}{d\log Q^2} = \frac{\alpha_s}{2\pi}\int_x^1 \frac{dy}{y}\left(q_i(y,Q^2)P_{qq}(\frac{x}{y}) + g(y,Q^2)P_{qg}(\frac{x}{y})\right)$$

$P_{qq}(z)$ and $P_{qg}(z)$ are the splitting functions

Deduce gluon distribution from scaling violation

How to extract gluon distributions (1) ?





Gluon distribution at very small x deduced from scaling violation in e-p collision at HERA

How to extract gluon distributions (2) ?

Gluon-gluon interaction and gluon-quark interaction in hadron-hadron collisions

- *dijet production*

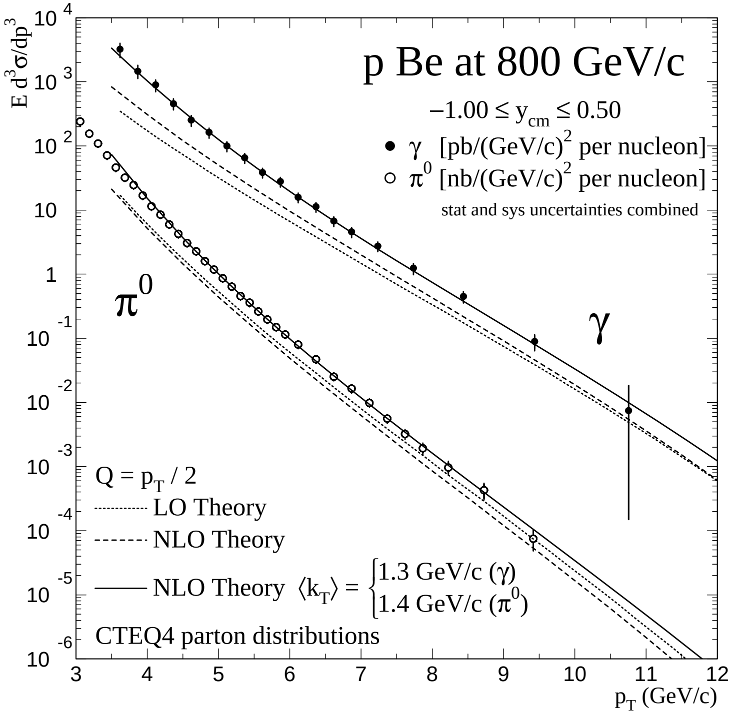
$$gg \to gg \qquad qg \to qg$$

- *heavy quark production*

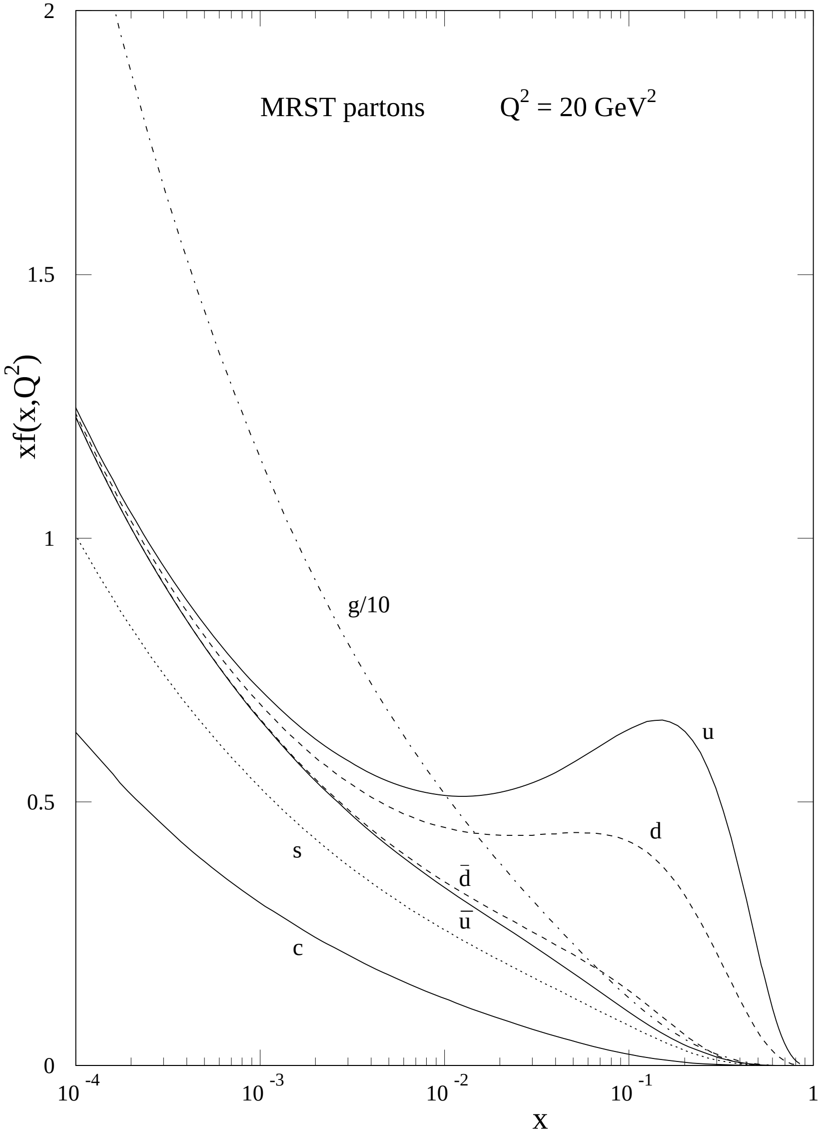
$$gg \to Q\bar{Q}$$

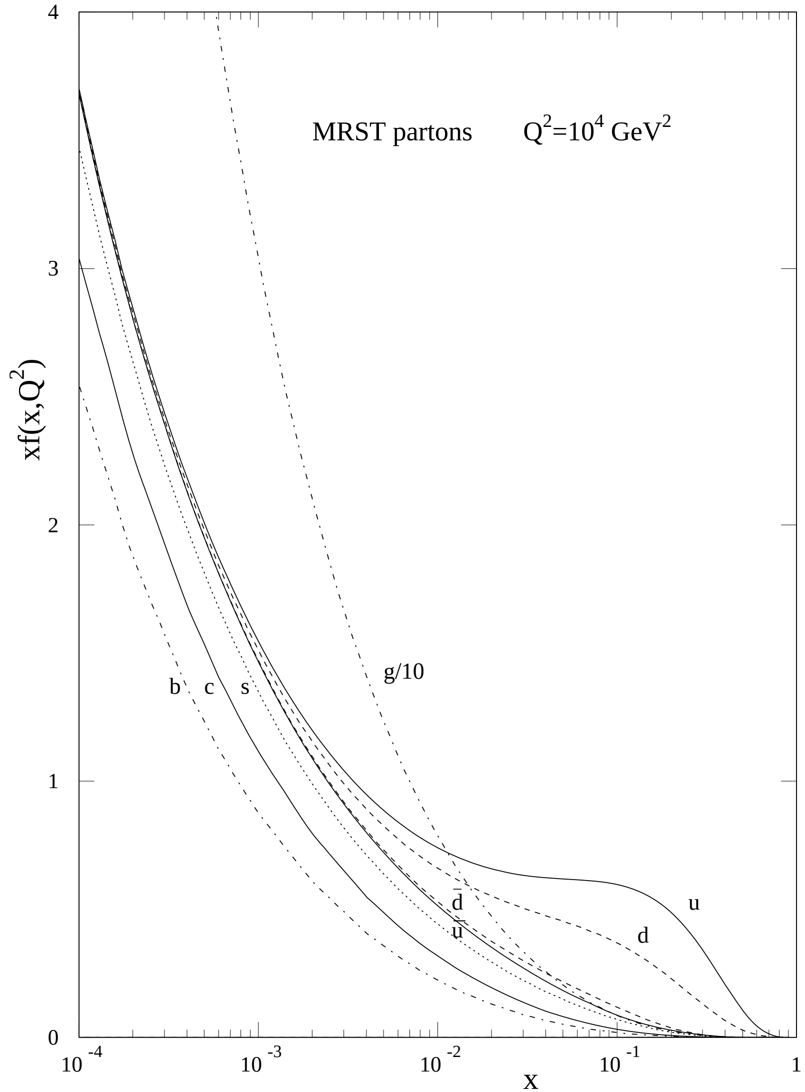
- *direct – photon production*

$$qg \to q\gamma$$

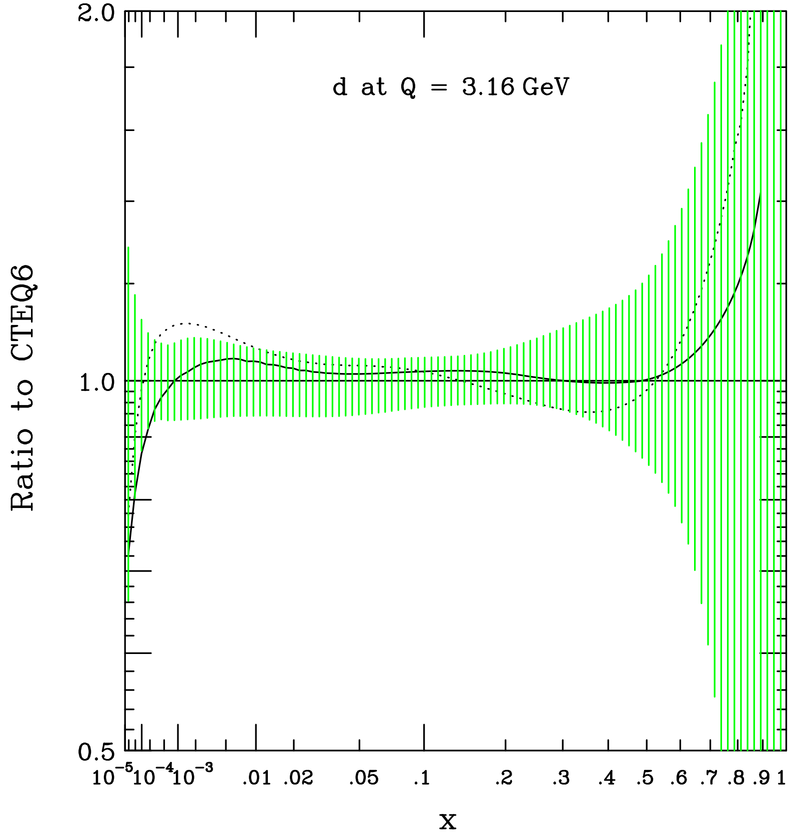


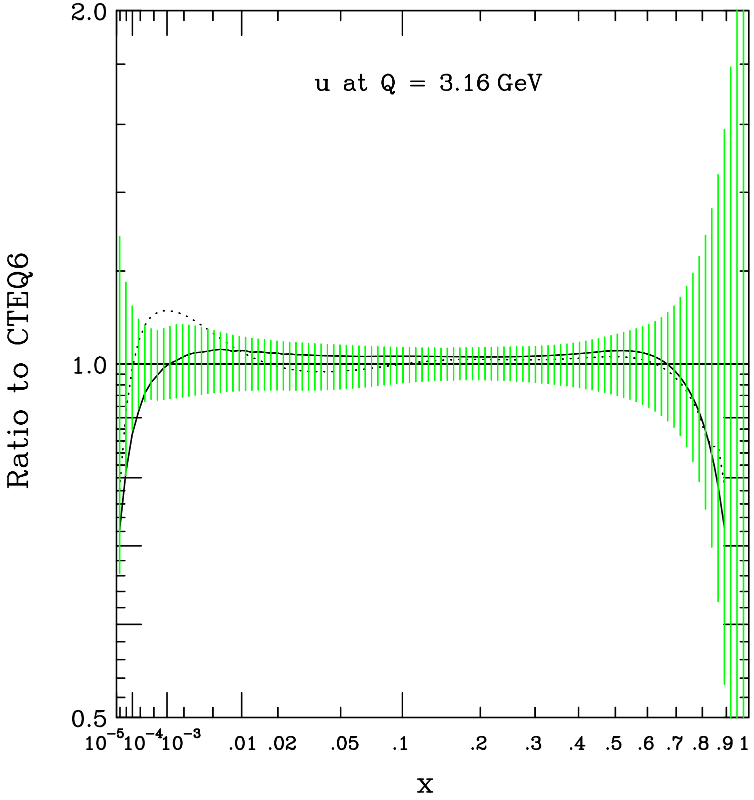
Parton Distribution Functions Parametrizations





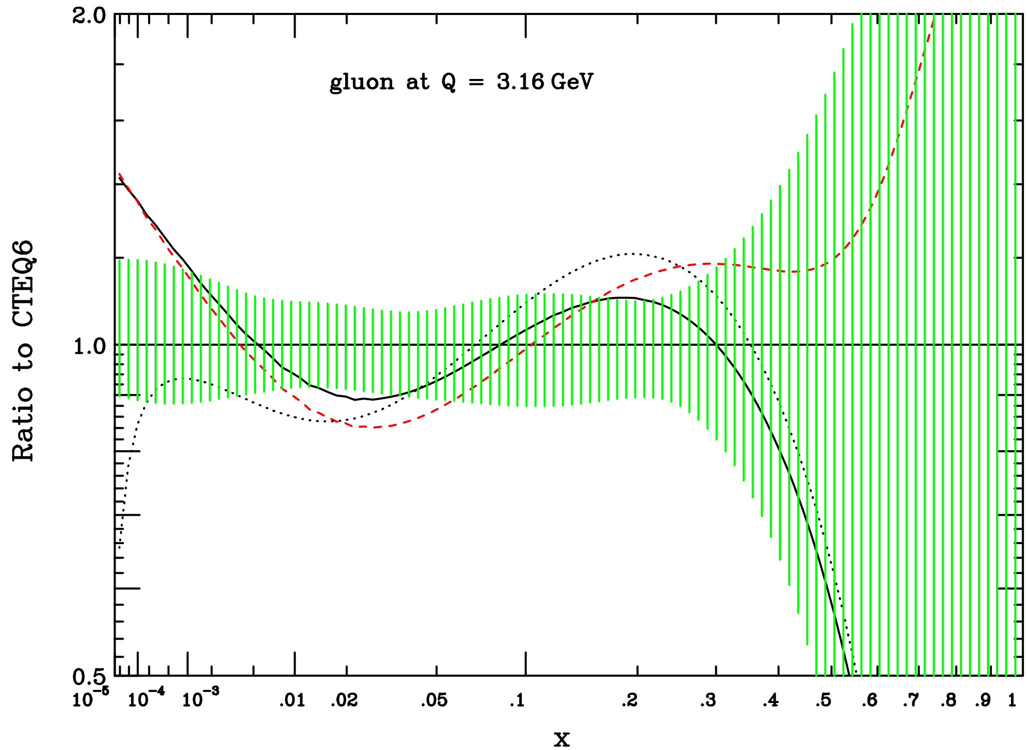
Parton Distribution Functions Parametrization Uncertainties





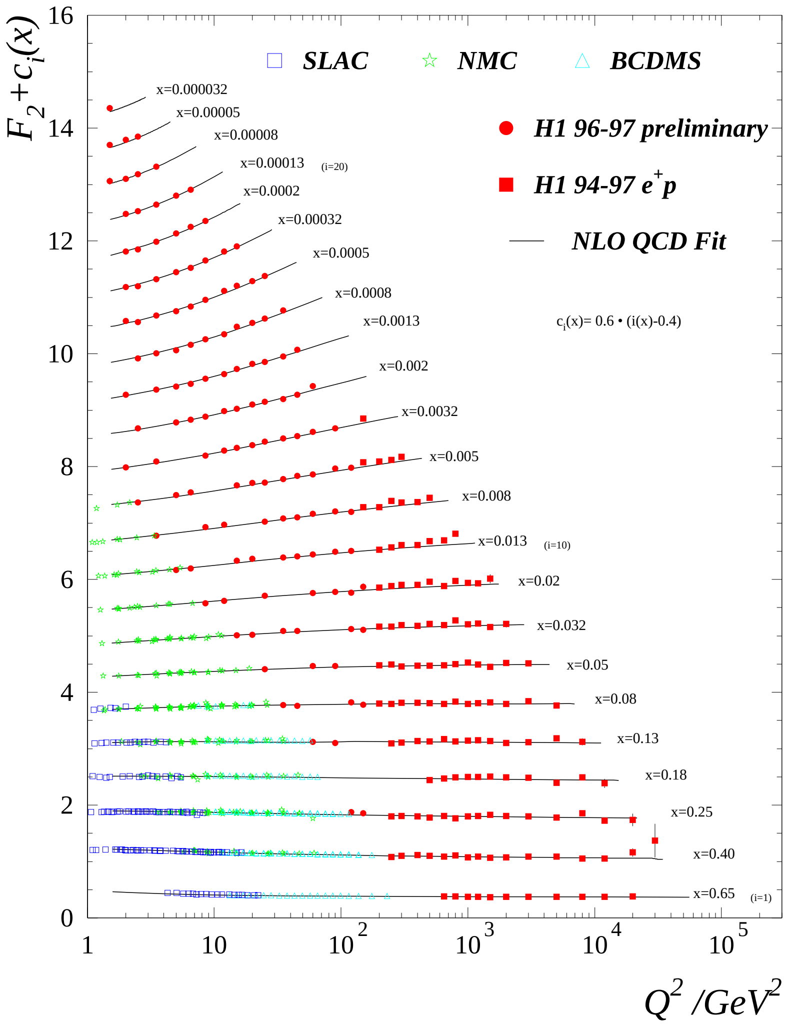
Large uncertainties at large and small x regions

Parton Distribution Functions Parametrizations Unceratinties



Gluon distribution is poorly known

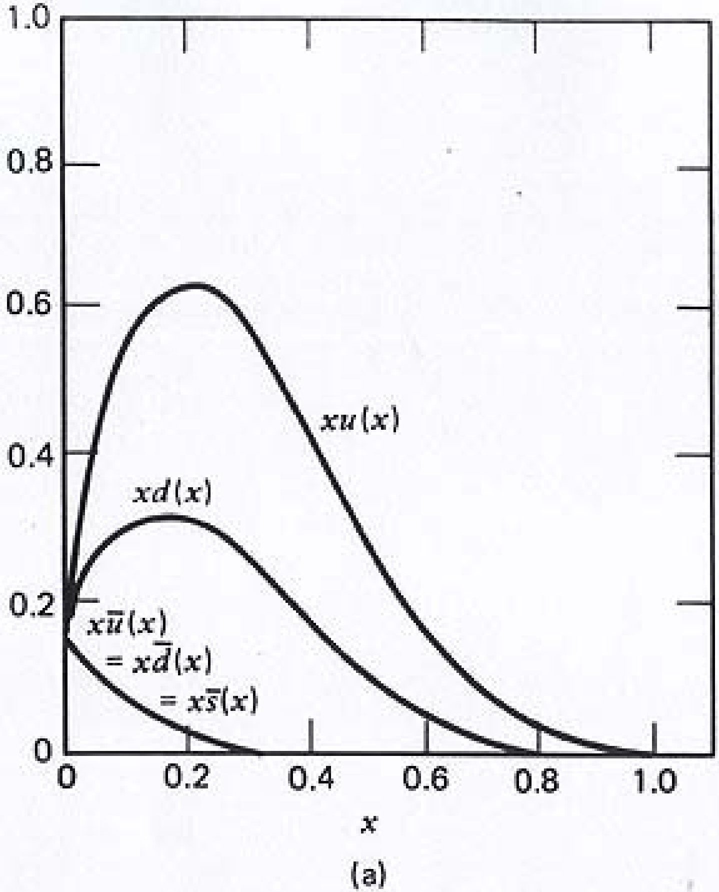
Structure Function: Why Bother?



- Important features:
  - Perturbative and non-perturbative QCD
  - Essential input for all hard processes
- Challenges:
  - Spin and flavor structure
  - Small and large *x* behavior
  - Transition from high-Q^2 to low-Q^2
  - New types of structure functions and fragmentation functions
  - Models and lattice calculations for PDFs

A Case Study of the Nucleon Flavor Structure

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



- neutrino-induced DIS shows that $\bar{s} \neq \bar{u}$
- early experiments suggest $\bar{u} \neq \bar{d}$
- $g \to \bar{u}u$ and $g \to \bar{d}d$ should give very similar $\bar{d}, \bar{u}$ distributions

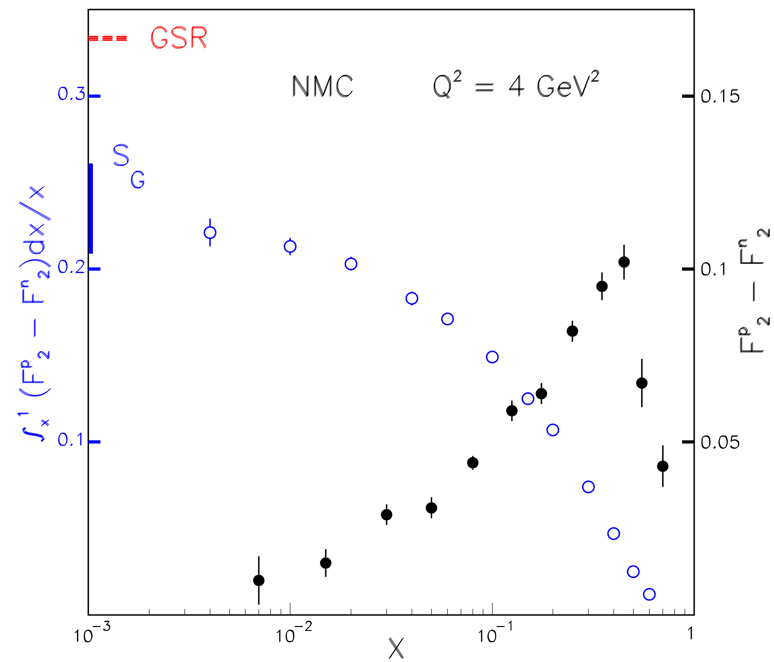
Is $\bar{u} = \bar{d}$ in the proton?

Test of the Gottfried Sum Rule

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

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

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



New Muon Collaboration (NMC) obtains

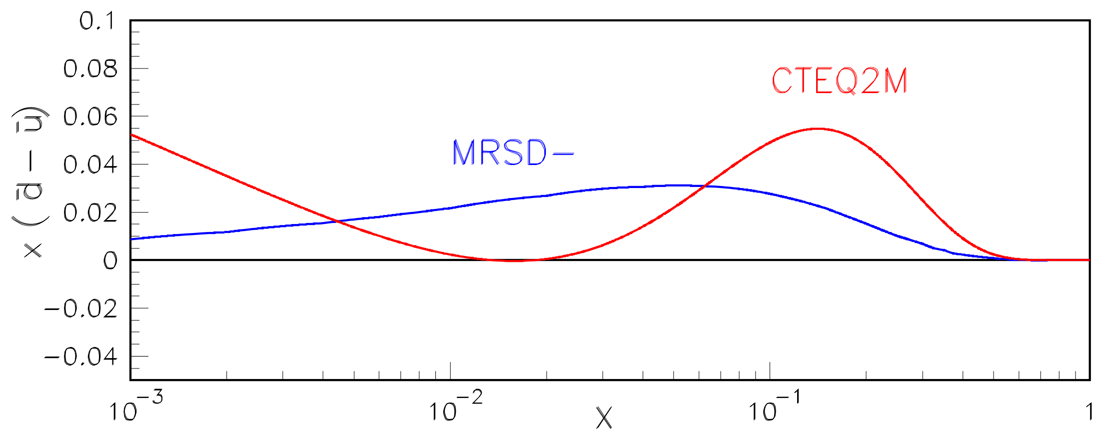
S_G = 0.235 ± 0.026

(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

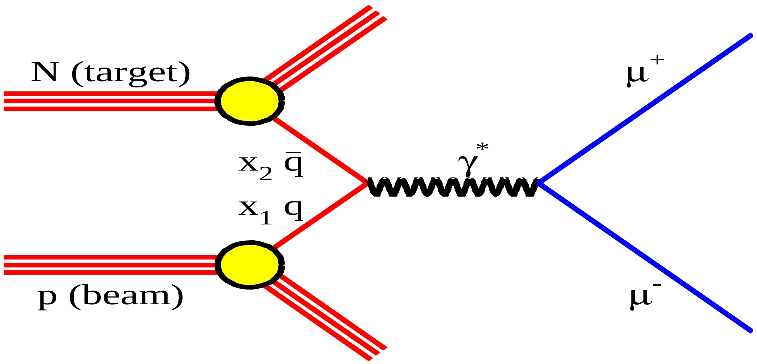
$$\int_0^1 (\bar{d}(x) - \bar{u}(x))\, dx = 0.148 \pm 0.04$$



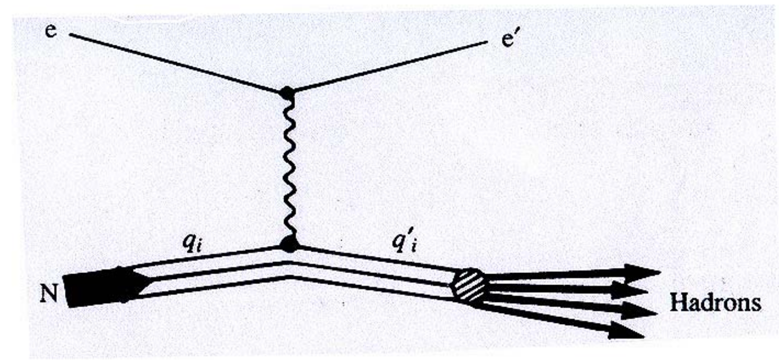
Need independent methods to check the $\bar{d} - \bar{u}$ asymmetry, and to measure its x-dependence !

The Drell-Yan Process: $pN \to \mu^+ \mu^- X$

Drell-Yan Pocess



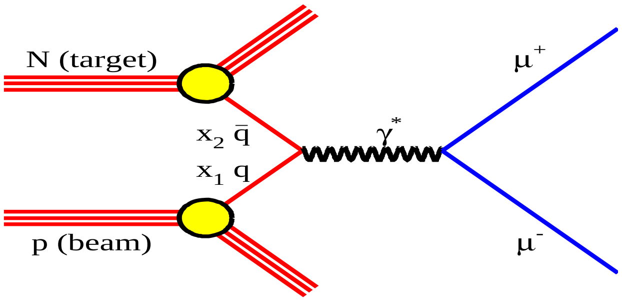
Deep-Inelastic Scattering



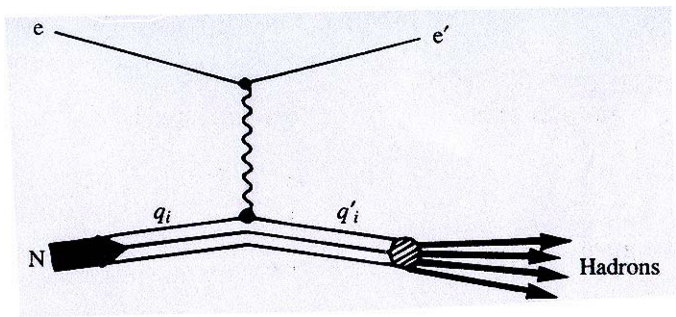
Drell-Yan Pocess	Deep-Inelastic Scattering
Electromagnetic process	Electromagnetic process
Time-like photon	Space-like photon
Two hadrons are involved	One hadron is involved
Two leptons are detected	One lepton is detected
Measure invariant mass (M) and Feynman-x of the di-lepton	Measure Q^2 and Bjorken-x

The Drell-Yan Process: $pN \to \mu^+ \mu^- X$

Drell-Yan Pocess



Deep-Inelastic Scattering



DIS:

$$x = Q^2 / 2m_N \nu \qquad y = \nu / E \qquad \nu = E - E'$$

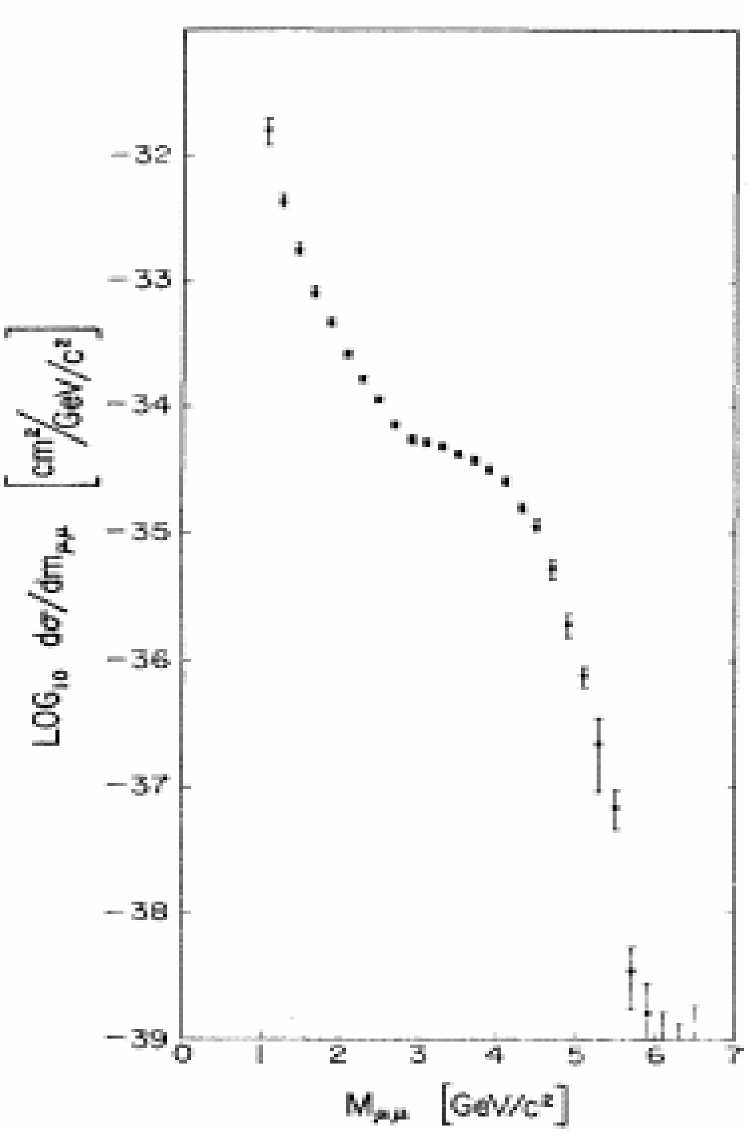
$$\frac{d\sigma}{dxdy} = \frac{2\pi\alpha^2}{Q^4} s\left[1 + (1-y)^2\right] \sum_i e_i^2 x[q_i(x) + \bar{q}_i(x)]$$

Drell-Yan:

$$M^2 = x_1 x_2 s \qquad x_F = x_1 - x_2$$

$$\frac{d\sigma}{dM^2 dx_F} = \frac{4\pi\alpha^2}{9M^2 s} \frac{1}{x_1 + x_2} \sum_i e_i^2 \left[q_i(x_1)\bar{q}_i(x_2) + \bar{q}_i(x_1) q_i(x_2)\right]$$

First Drell-Yan experiment



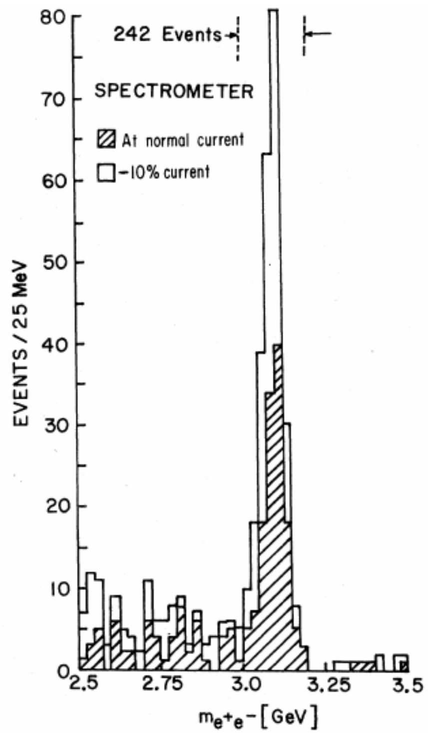
$p+U \rightarrow \mu^+ + \mu^- + X$ 29 GeV proton

Lederman et al. PRL 25 (1970) 1523

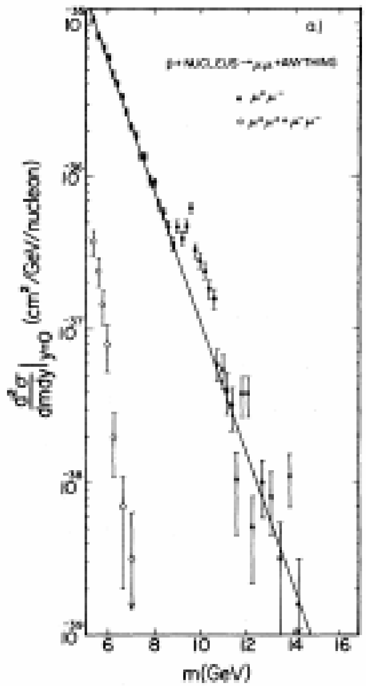
- Experiment originally designed to search for neutral weak boson (Z^0)
- Miss the J/Ψ signal !

Lepton-pair production is a powerful tool for finding new quarks/particles

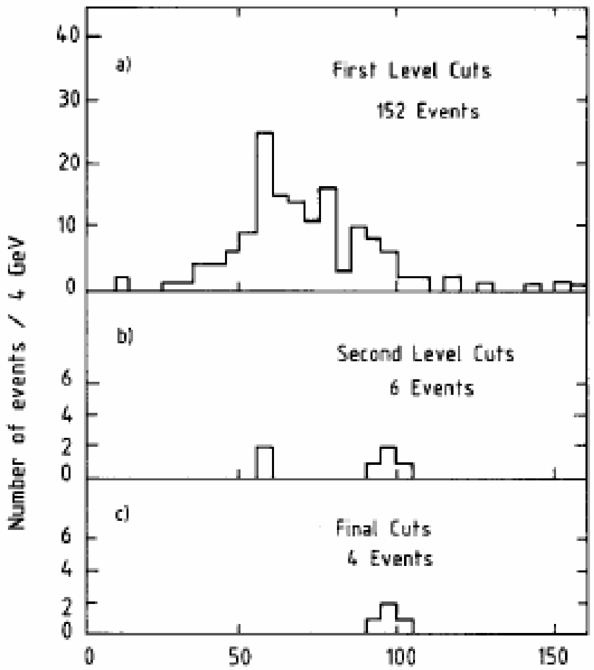
$J/\Psi \to e^+e^-$



$\Upsilon \to \mu^+\mu^-$

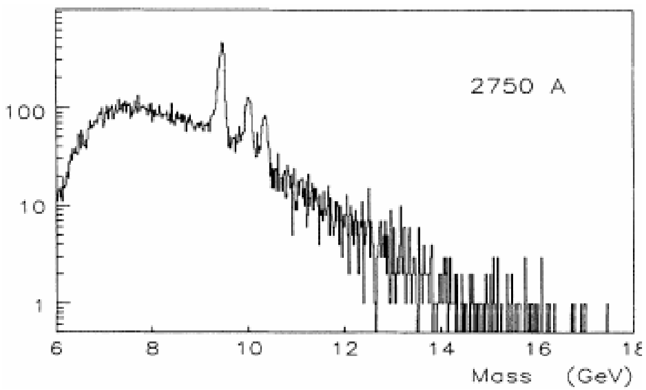


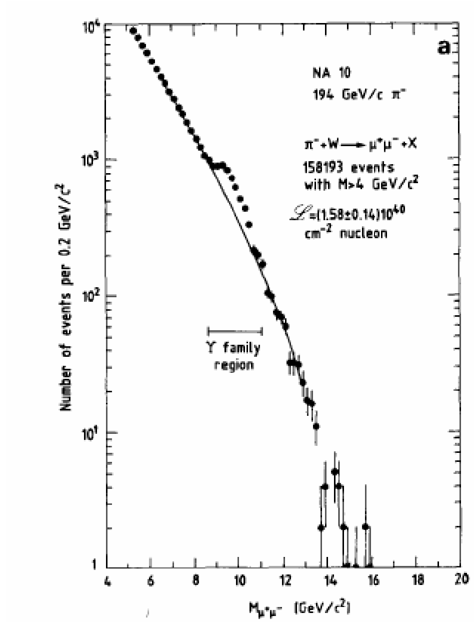
$Z^0 \to e^+e^-$

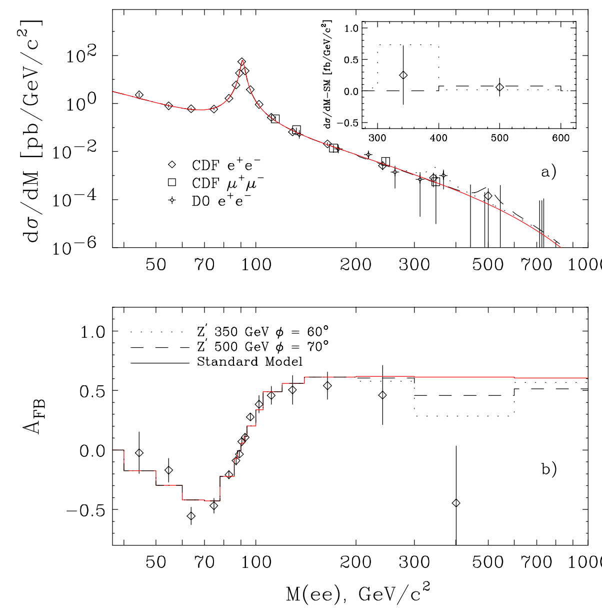


Lepton-pair production also provides unique information on parton distributions

$p+W \rightarrow \mu^+\mu^- X$	$\pi^- + W \rightarrow \mu^+\mu^- X$	$\bar{p}+p \rightarrow l^+l^- X$
800 GeV/c	194 GeV/c	1.8 TeV







Probe antiquark in nucleon

Probe antiquark in pion

Probe antiquark in antiproton

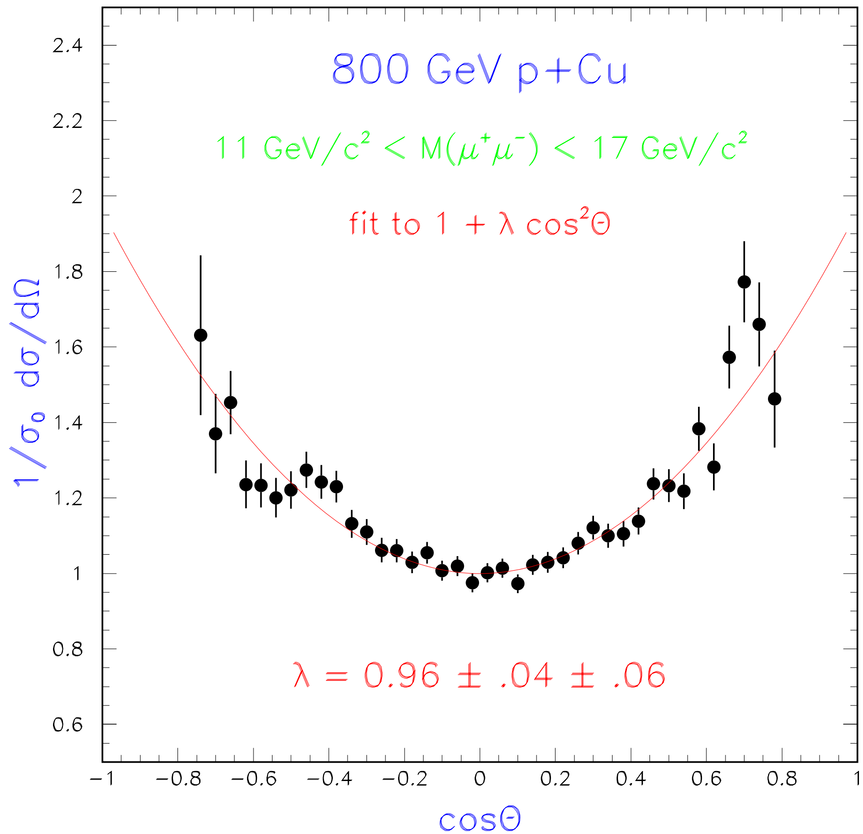
Is Drell-Yan process well understood ?

Decay Angular Distribution of Drell-Yan

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

Annu. Rev. Nucl. Part. Sci. 49 (1999)217

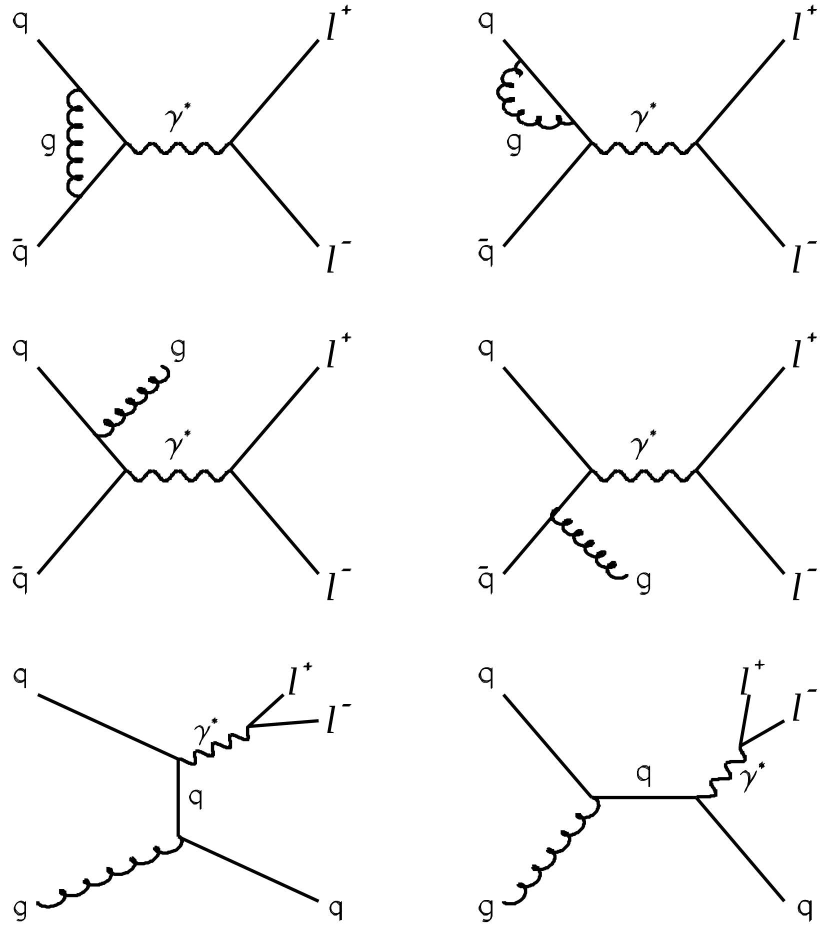
(hep/ph-9905409)



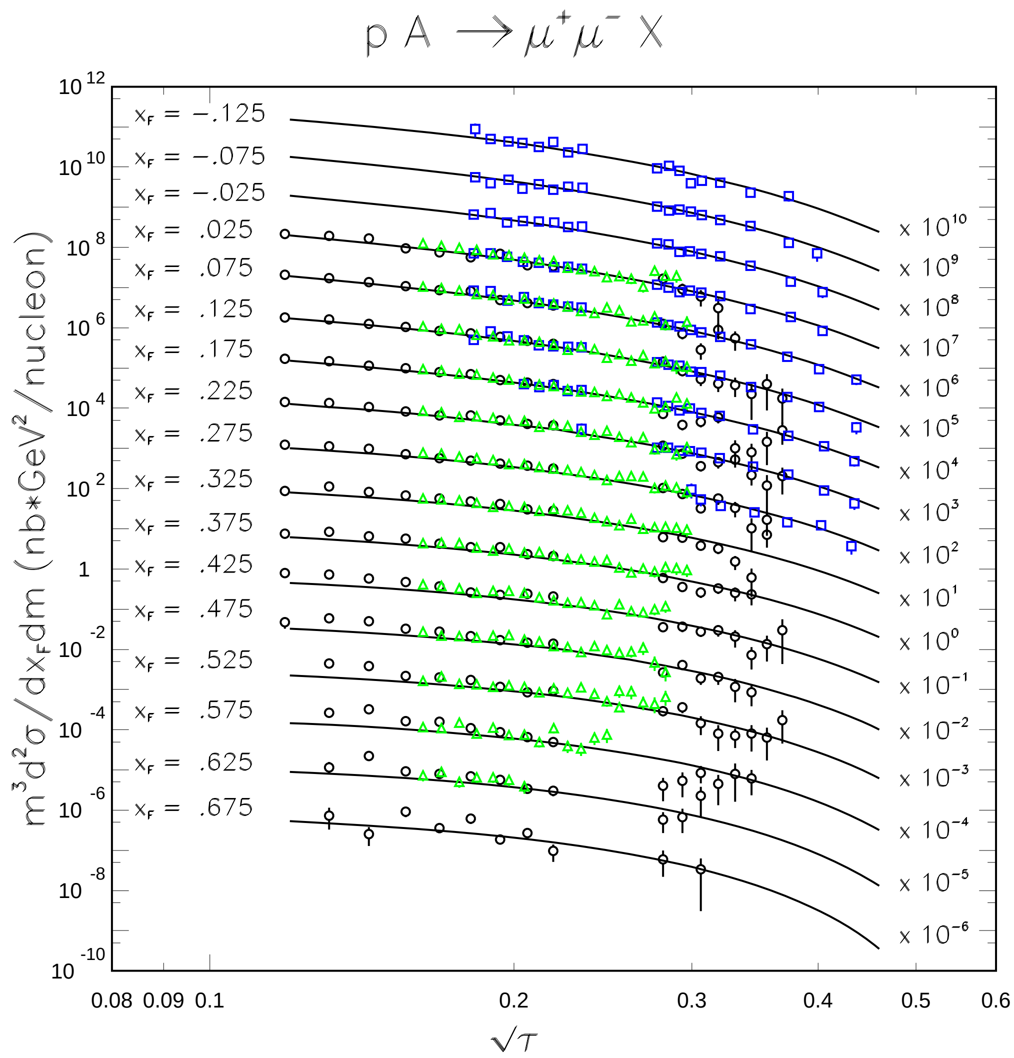
Data from Fermilab E772

Higher-order diagrams for Drell-Yan

(involve gluon line)



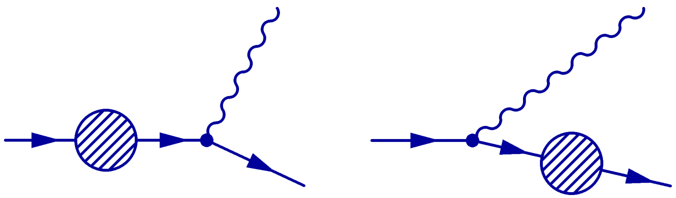
Fits to data from Next-to-Leading-Order calculations



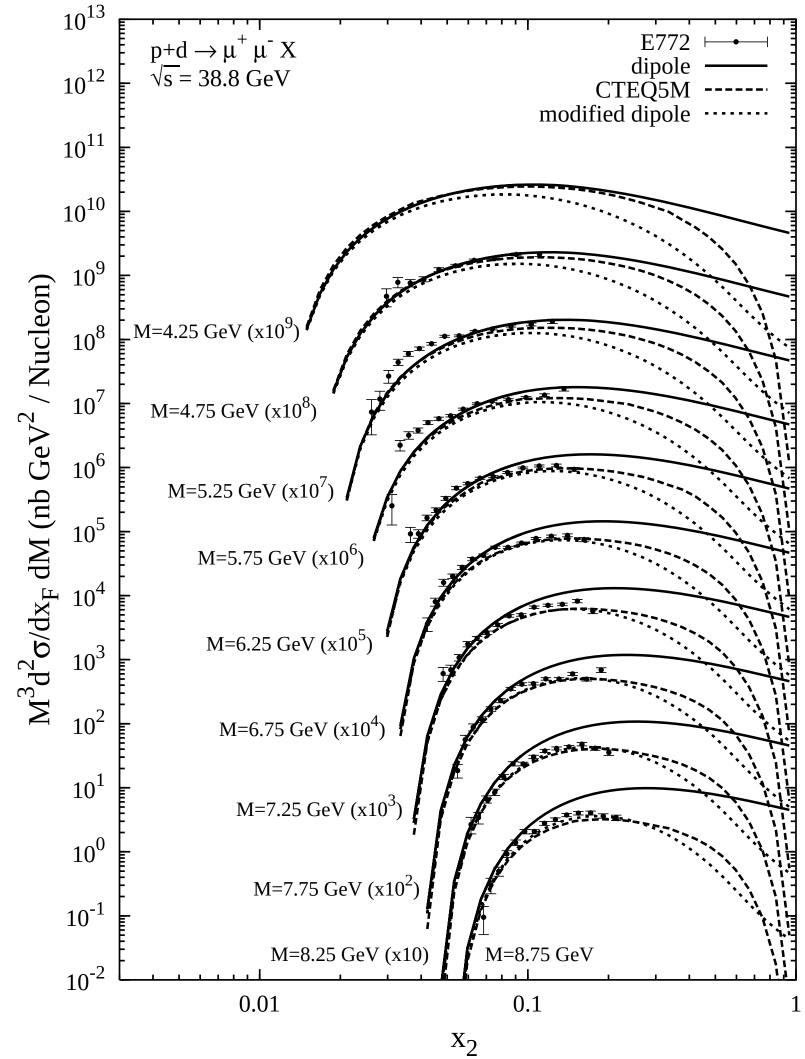
Data are well described by Next – to - Leading order calculations

A Dipole Approach to Drell-Yan

An alternative target-frame approach to Drell-Yan

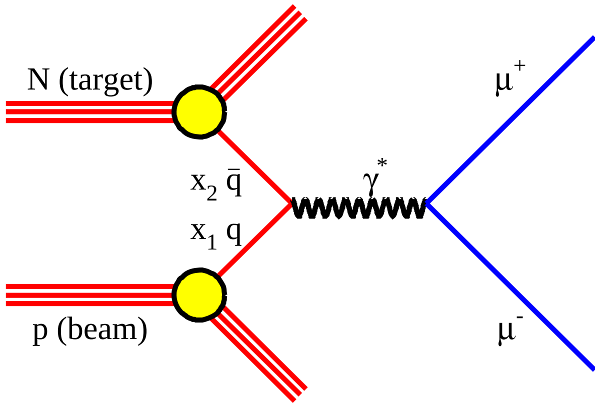


Raufeissen and Peng (hep-ph/0204095)



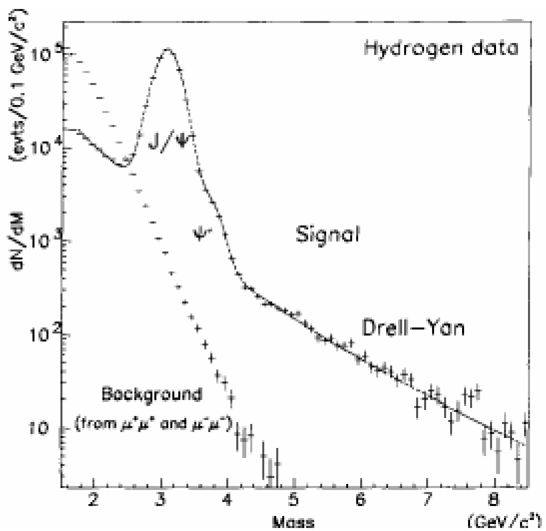
j1

The Drell-Yan Process: $pN \to \mu^+ \mu^- X$



$$\frac{\sigma^{pd}}{2\sigma^{pp}} \approx \frac{1}{2}\left[1 + \frac{\bar{d}(x)}{\bar{u}(x)}\right]$$

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



NA51 observed a large $\bar{d}/\bar{u}$

at $x = 0.18$ ($\bar{d}/\bar{u} = 2.0!!$)

Slide 47

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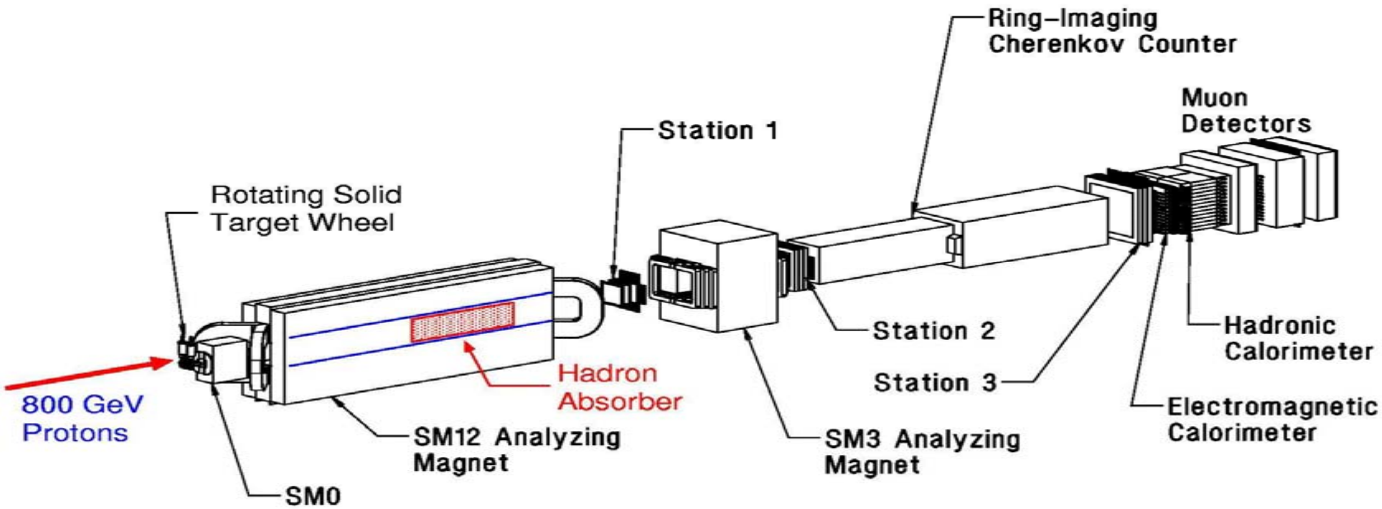
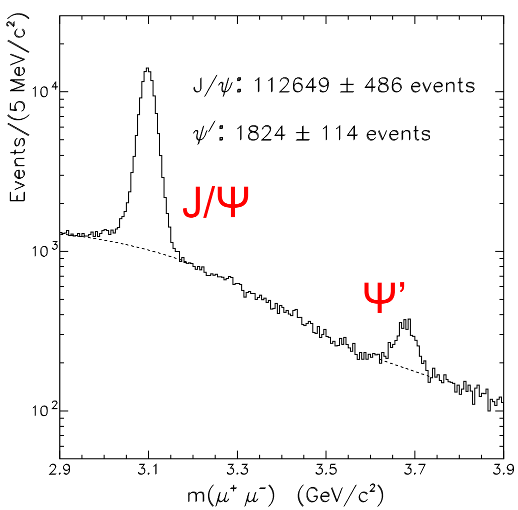
j1 jcpeng, 6/7/2005

Meson East Spectrometer

(E605/772/789/866)

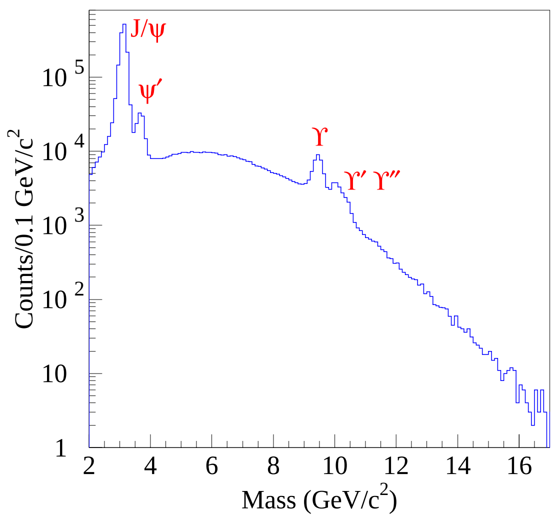


Open-aperture



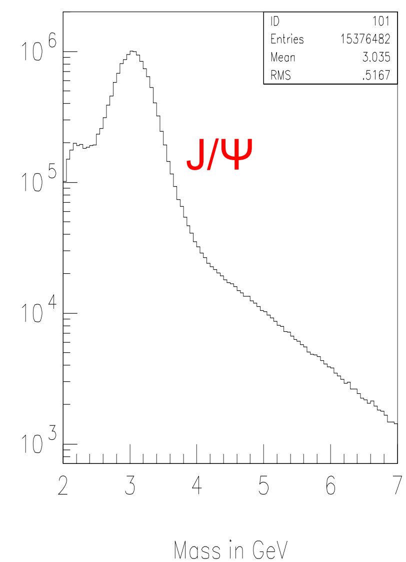
σ(J/ψ) ~ 15 MeV

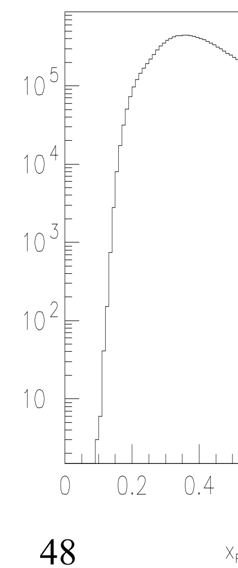
Closed-aperture



σ(J/ψ) ~ 150 MeV

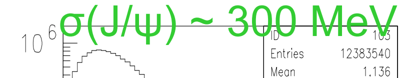
Beam-dump (Cu)





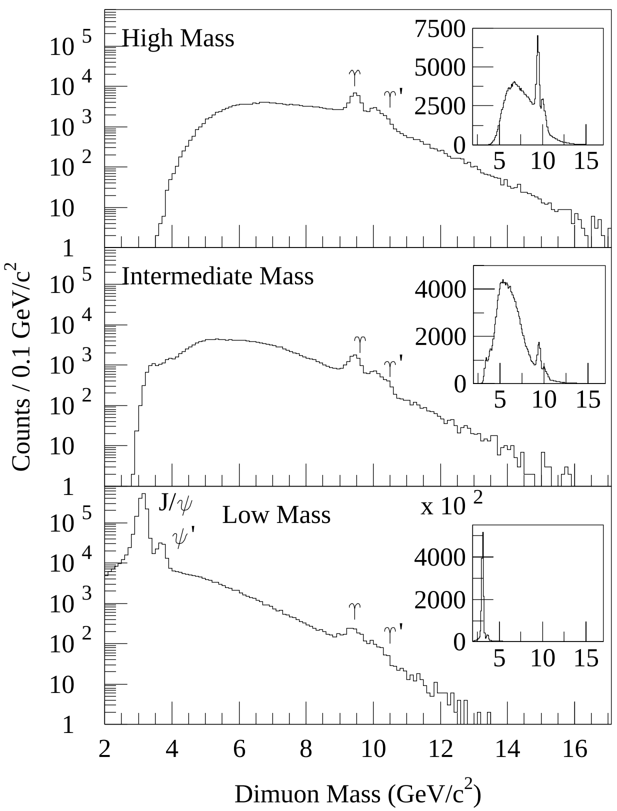
48

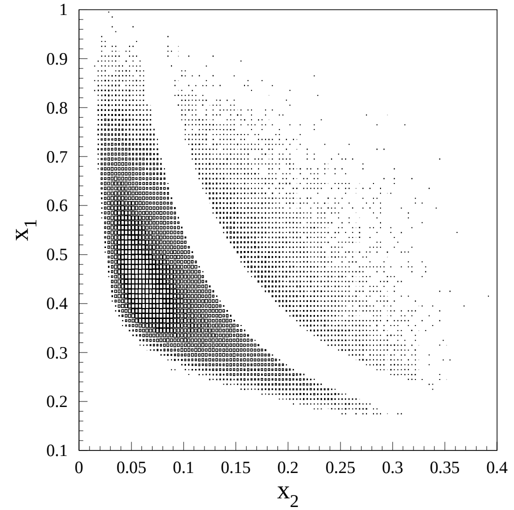
σ(J/ψ) ~ 300 MeV

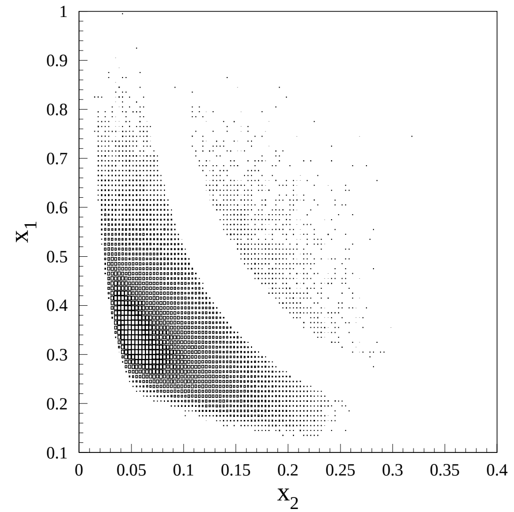


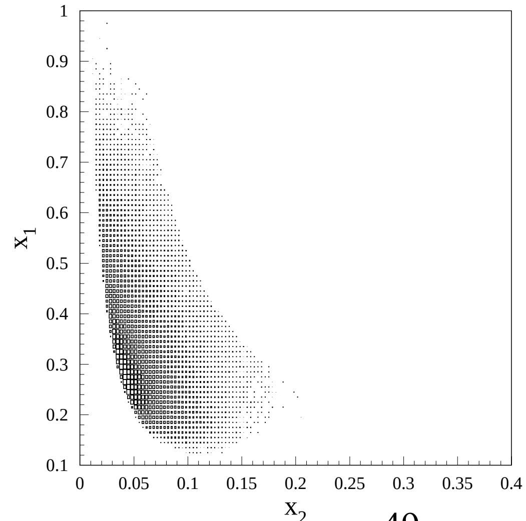
Fermilab E866 Measurements

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



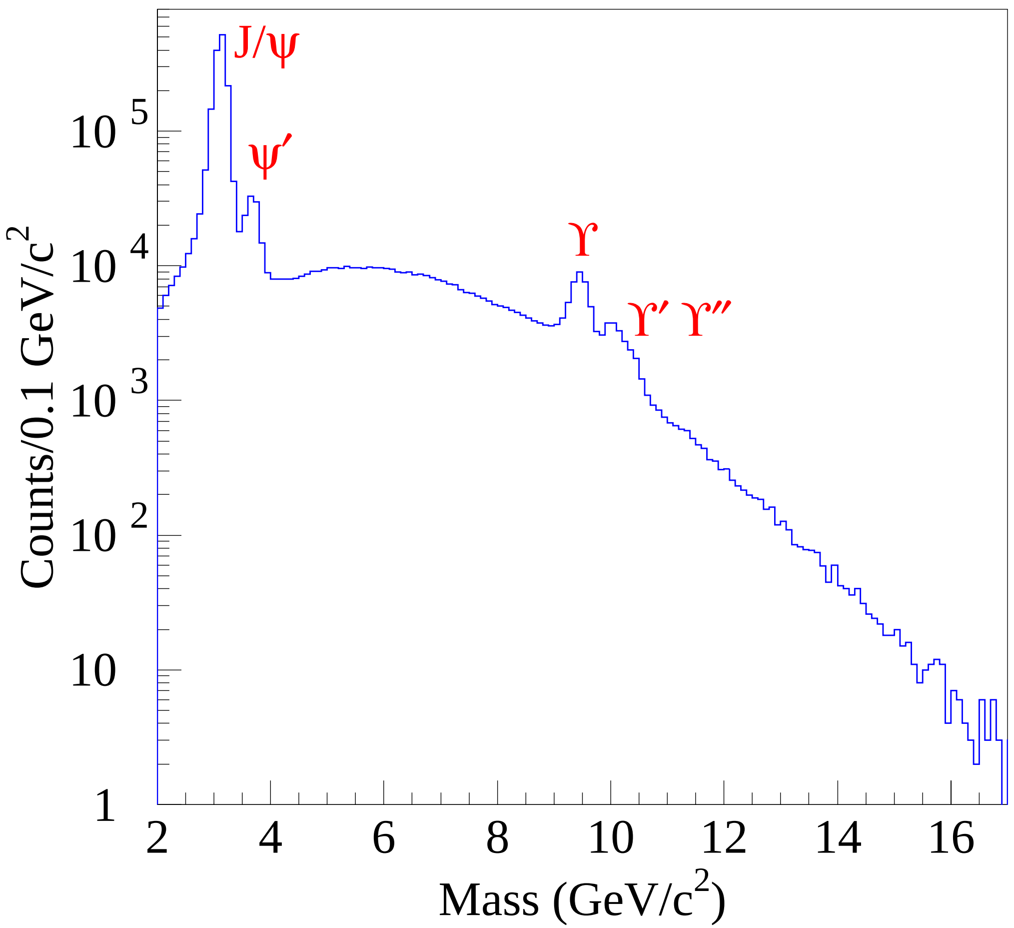






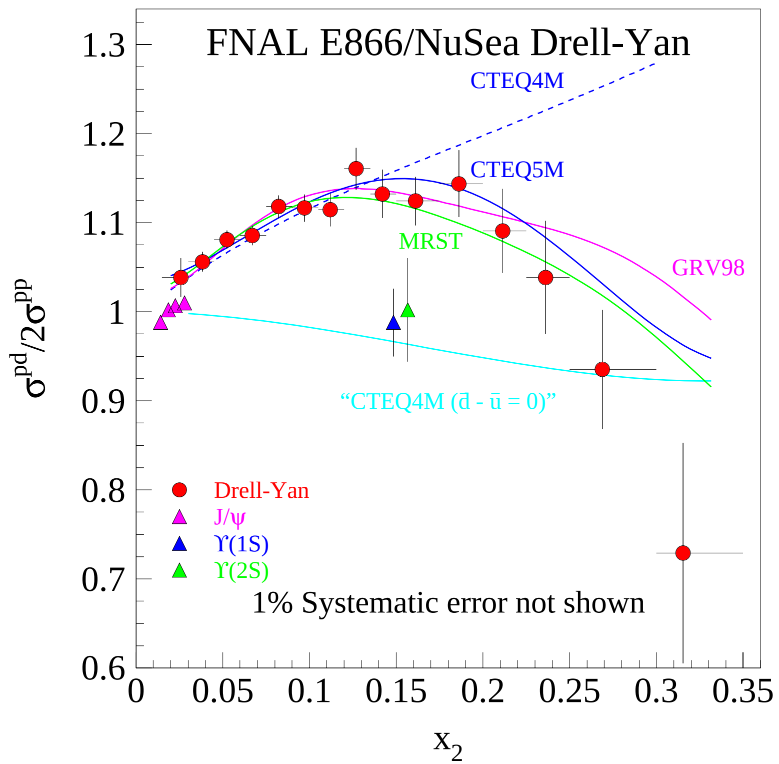
Fermilab E866 Measurements

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



Fermilab E866 Measurements

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

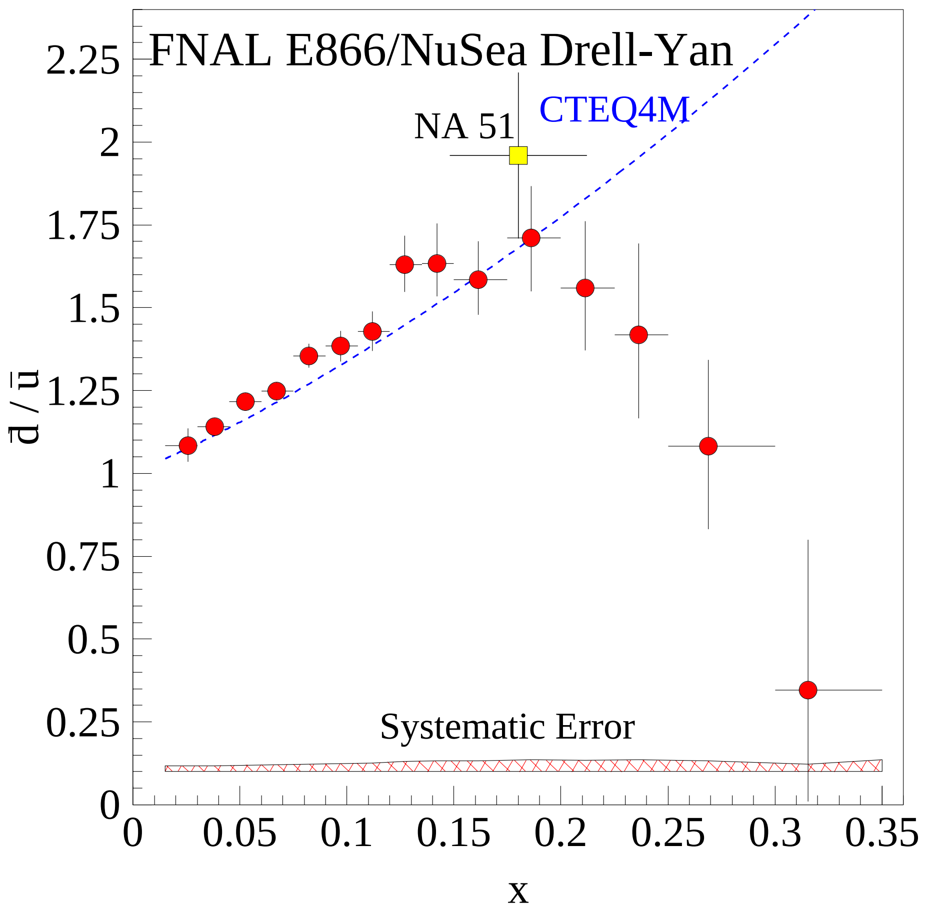


$$Drell-Yan: \quad \sigma^{pd}/2\sigma^{pp} \approx \frac{1}{2}[1+\bar{d}(x)/\bar{u}(x)]$$

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

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

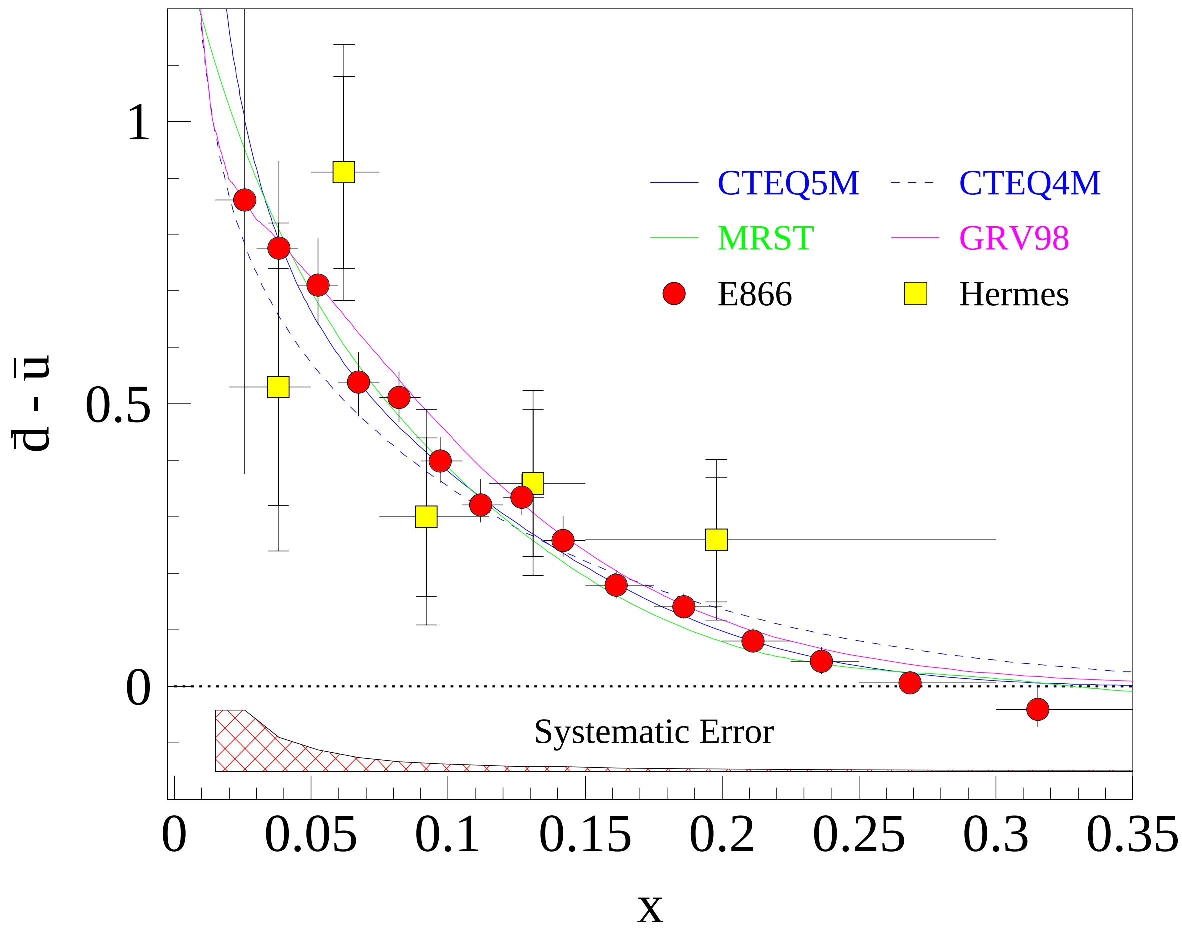
Extraction of $\bar{d}\,/\,\bar{u}$



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

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

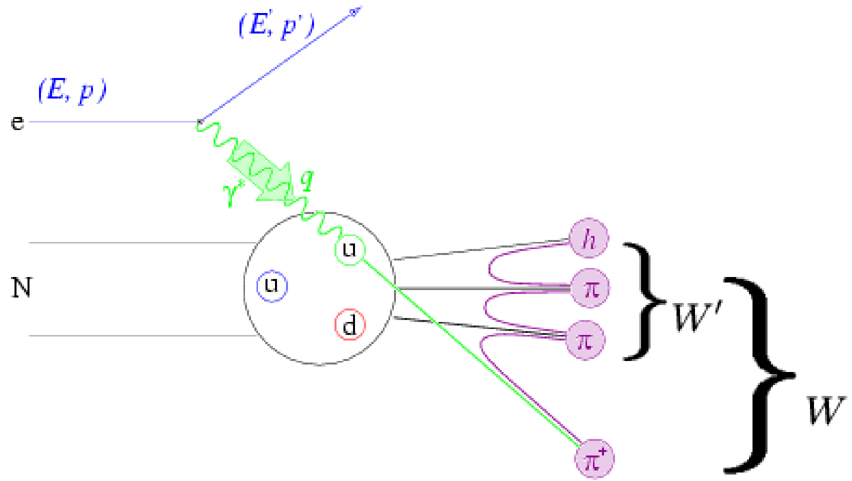
$\bar{d} - \bar{u}$ Comparison with Hermes



HERMES: Semi-Inclusive DIS

- Semi-inclusive Deep-inelastic scattering

Semi-Inclusive DIS



$z = E_\pi / \nu$

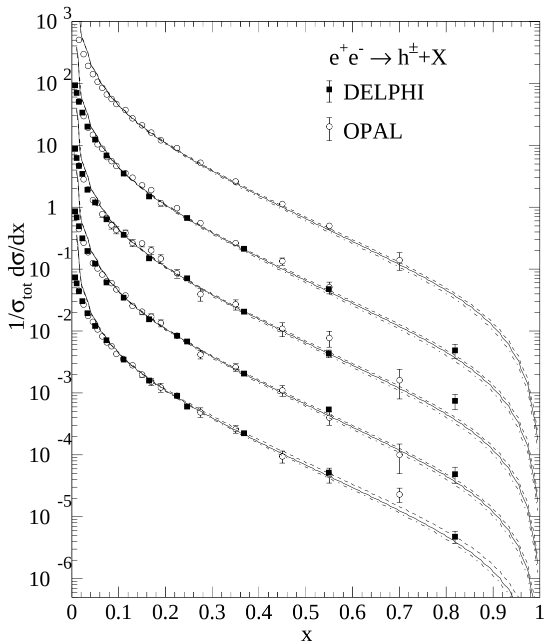
$$\frac{1}{\sigma}\frac{d\sigma}{dz}(ep \to hX) = \frac{\sum_q e_q^2 f_q(x) D_q^h(z)}{\sum_q e_q^2 f_q(x)}$$

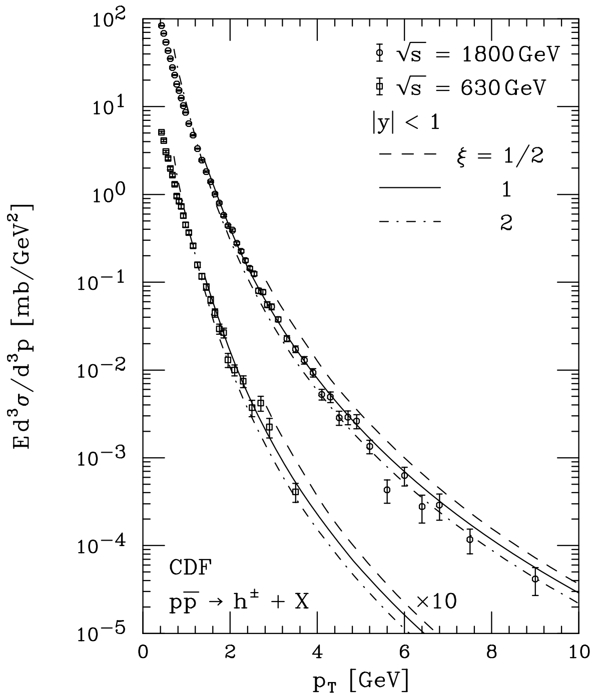
$f_q(x)$: parton distribution function

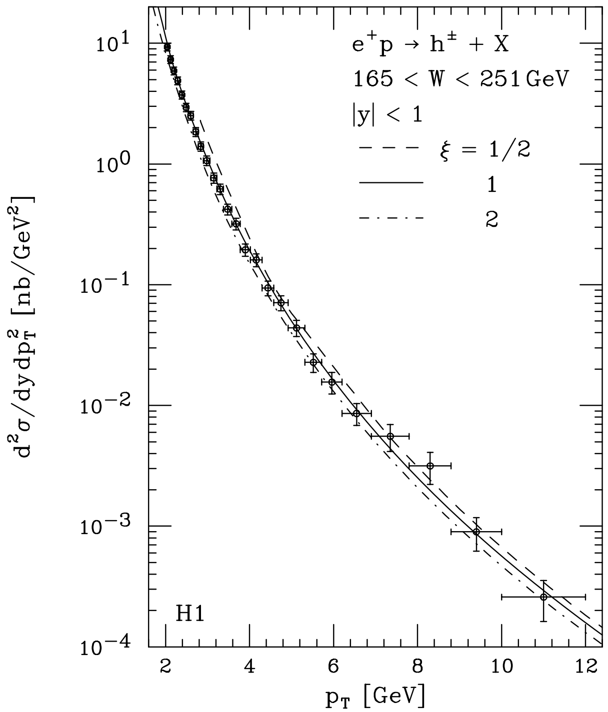
$D_q^h(z)$: fragmentation function

Universality of fragmentation functions

$e^+e^- \to h^\pm + X$ $\qquad p\bar{p} \to h^\pm + X$ $\qquad e^+p \to e^+ + h^\pm + X$







Flavor structure of sea-quark distribution via SIDIS

$$\frac{\bar{d}(x)-\bar{u}(x)}{u(x)-d(x)}=\frac{J(z)[1-r(x,z)]-[1+r(x,z)]}{J(z)[1-r(x,z)]+[1+r(x,z)]}$$

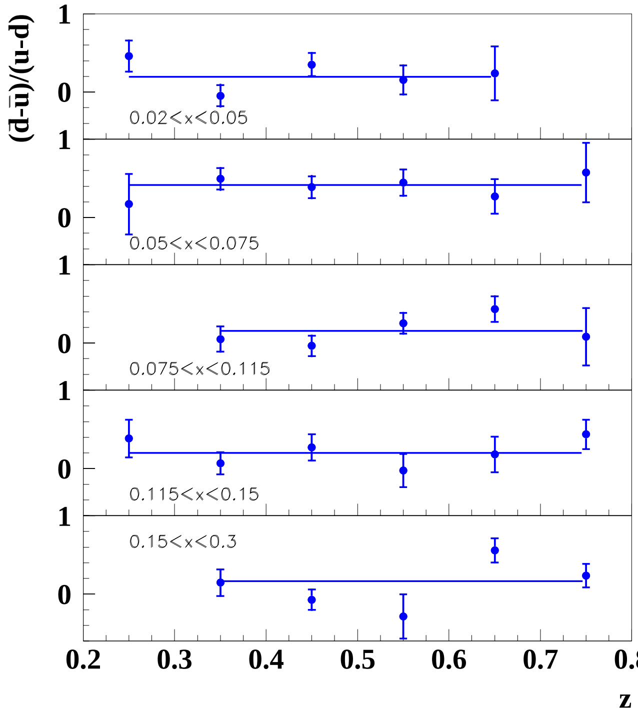
$$r(x,z)=\frac{Y_p^{\pi^-}(x,z)-Y_n^{\pi^-}(x,z)}{Y_p^{\pi^+}(x,z)-Y_n^{\pi^+}(x,z)}$$

$$J(z)=\frac{3}{5}\left(\frac{1+D'(z)}{1-D'(z)}\right); \qquad D'(z)=D_u^{\pi^-}(z)/D_u^{\pi^+}(z)$$

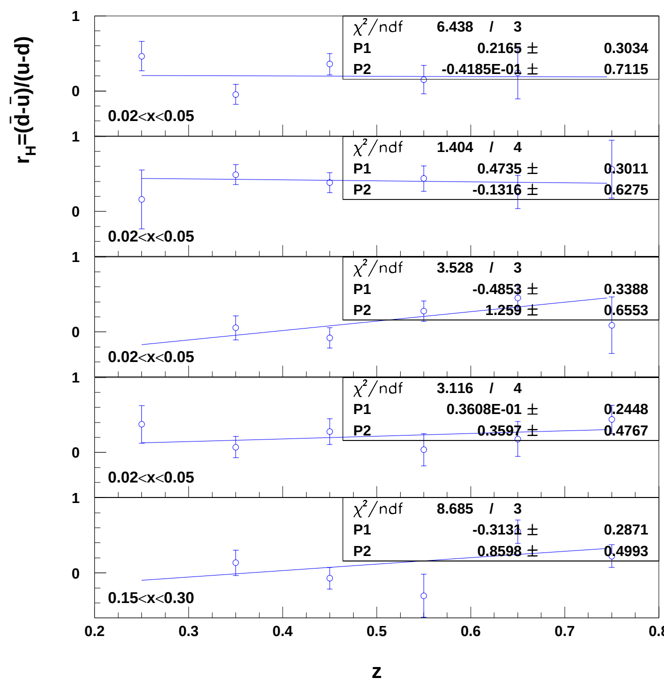
- Assuming factorization is valid
- Require knowledge on the fragmentation function *D'(z)*

Is factorization valid?

HERMES data consistent with no z-dependence

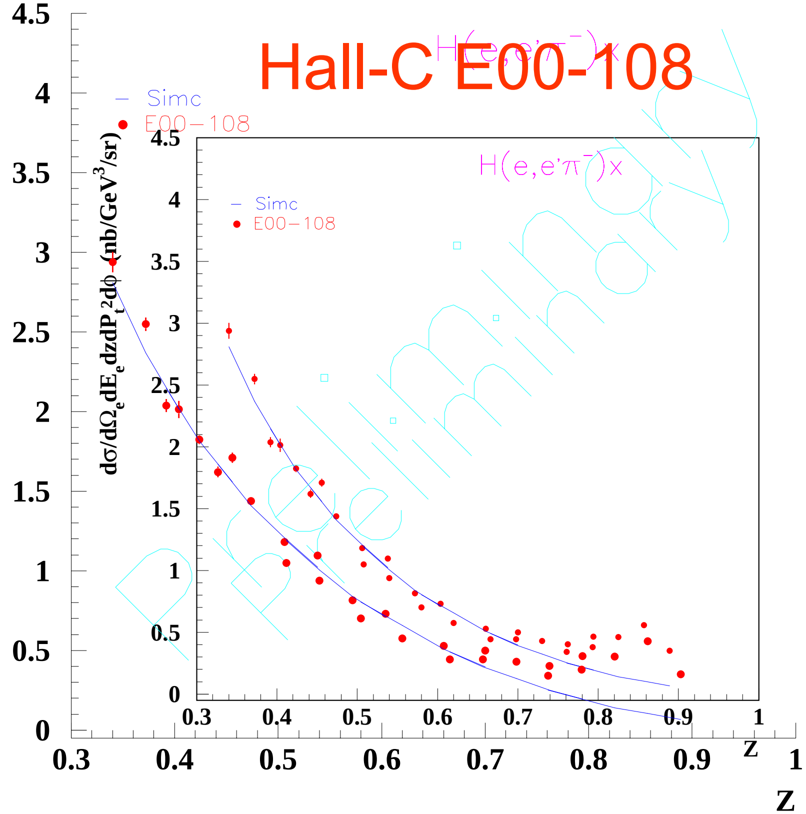


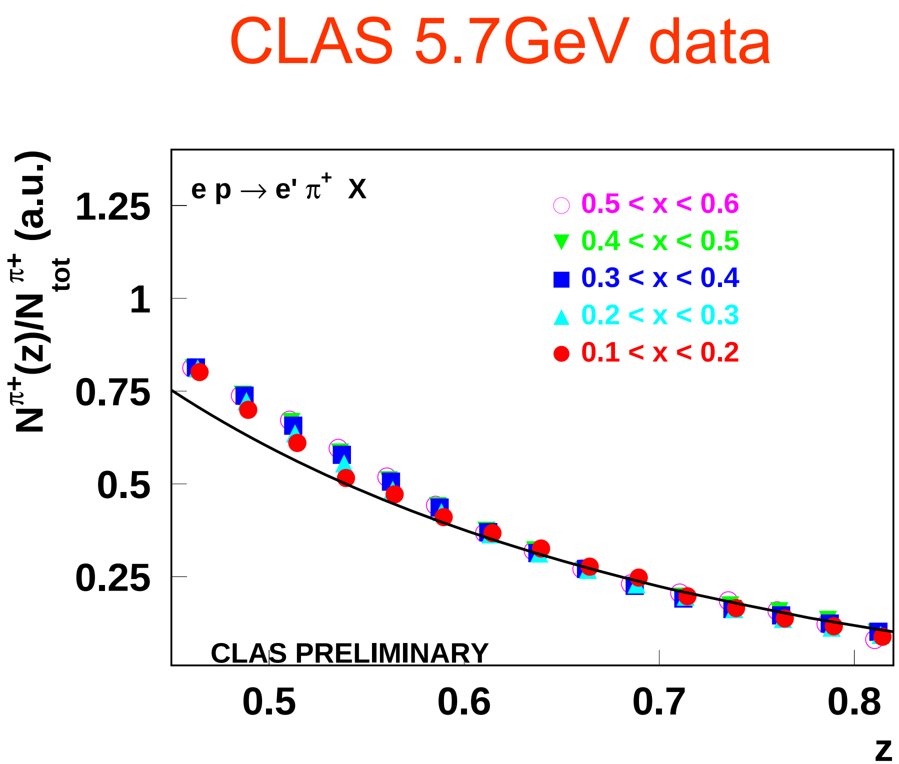
"Best fit" allows some z-dependence



Additional data would test the factorization

Preliminary results from Hall-C E00-108 and CLAS on semi-inclusive pion production



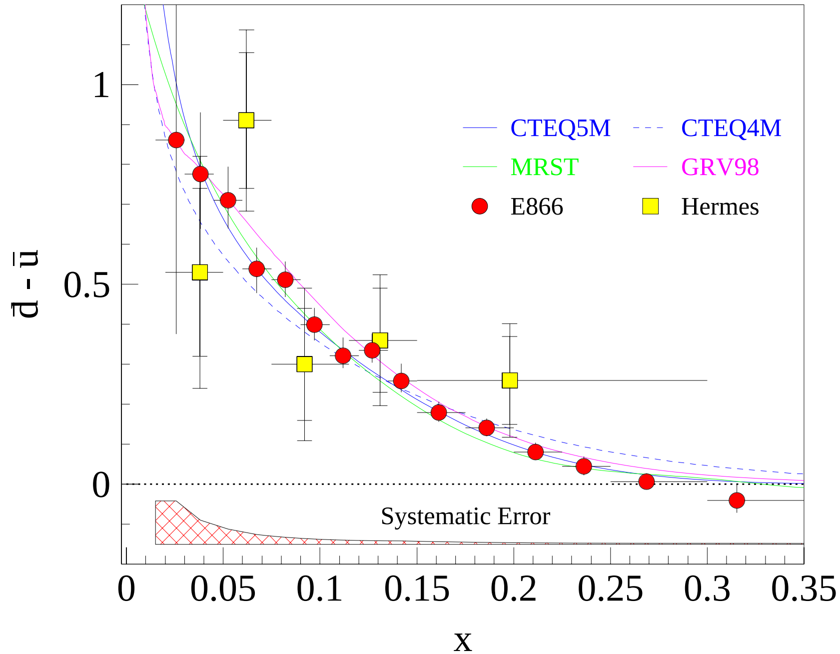


Data are well described by calculations assuming factorization

Similar z-dependence for different x-bins

Recent theory work on SIDIS factorization (hep-ph0404183)

$\bar{d} - \bar{u}$ from D-Y and from SIDIS



HERMES: Semi-Inclusive DIS

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

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

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

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

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)

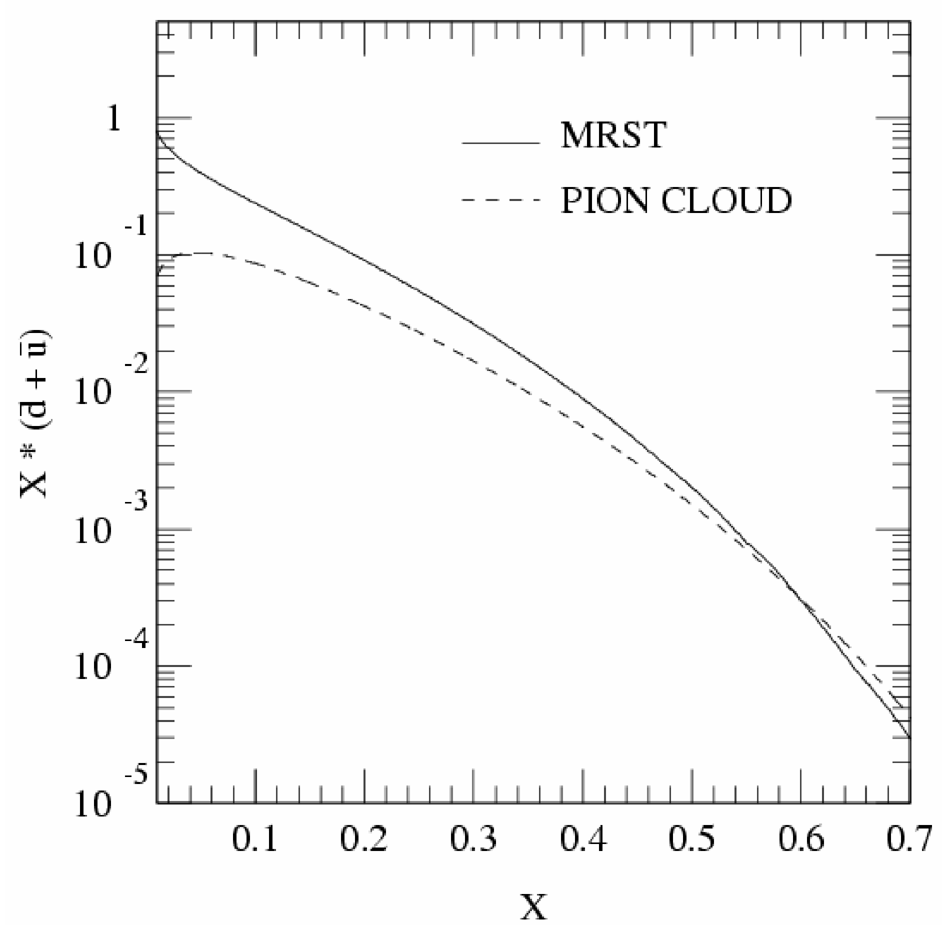
- Instanton model

  $u_L \to u_R d_R \bar{d}_L, \; d_L \to d_R u_R \bar{u}_L,$ etc.

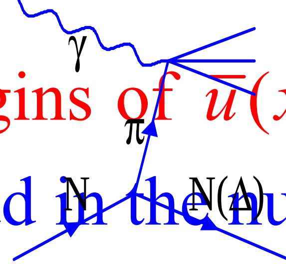
  (Dorokhov, Kochelev)

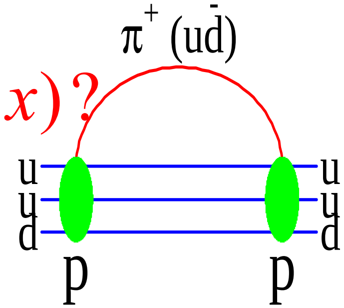
The valence quarks affect the Dirac vacuum and the quark-antiquark sea

Contribution of the meson-cloud to the sea-quark distribution



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





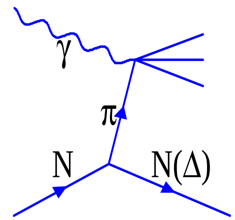
- Meson cloud in the nucleons

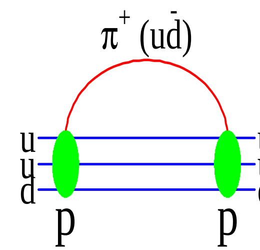
  Sullivan Processed in DIS

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

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

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



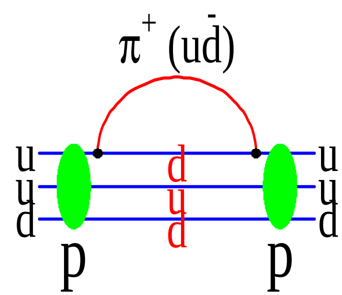


- Chiral quark model

  Goldstone bosons couple to valence quarks

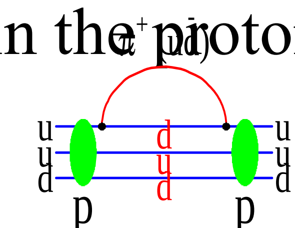
  $\Rightarrow \ u \rightarrow \pi^+ + d$

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



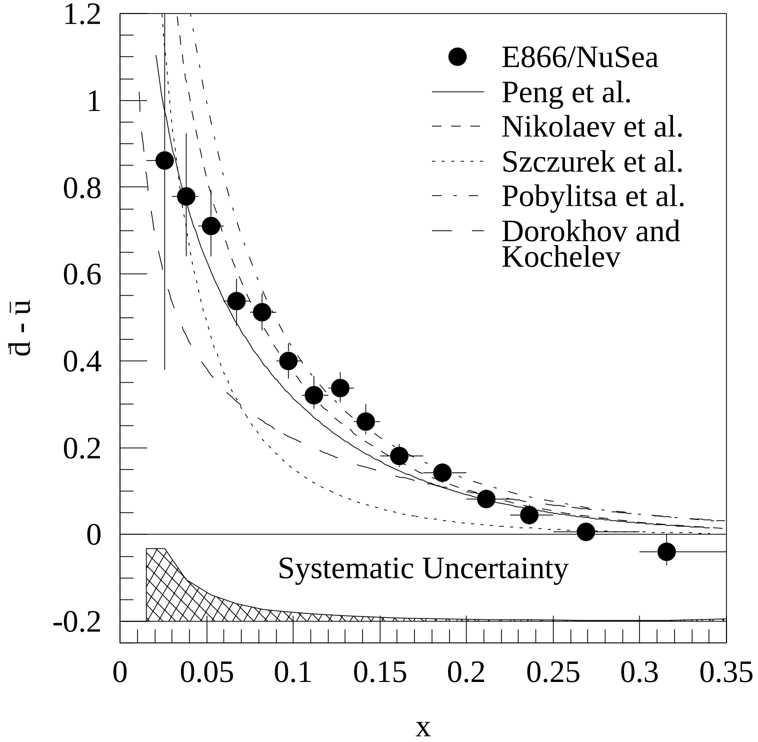
The pion cloud is a source for antiquarks in the proton,

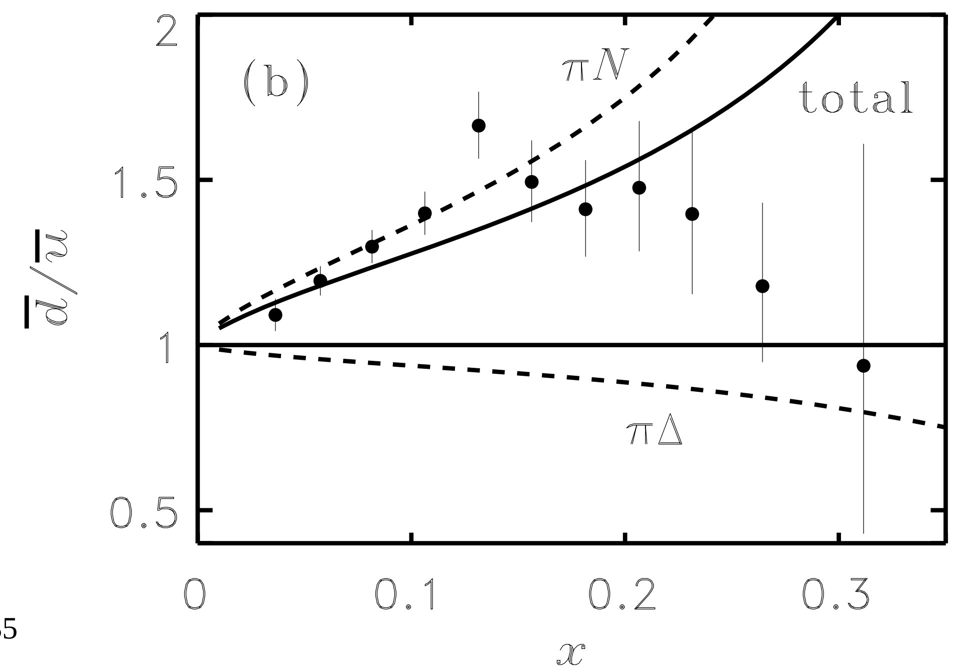
and it leads to $\overline{d} > \overline{u}$



Comparison with models

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



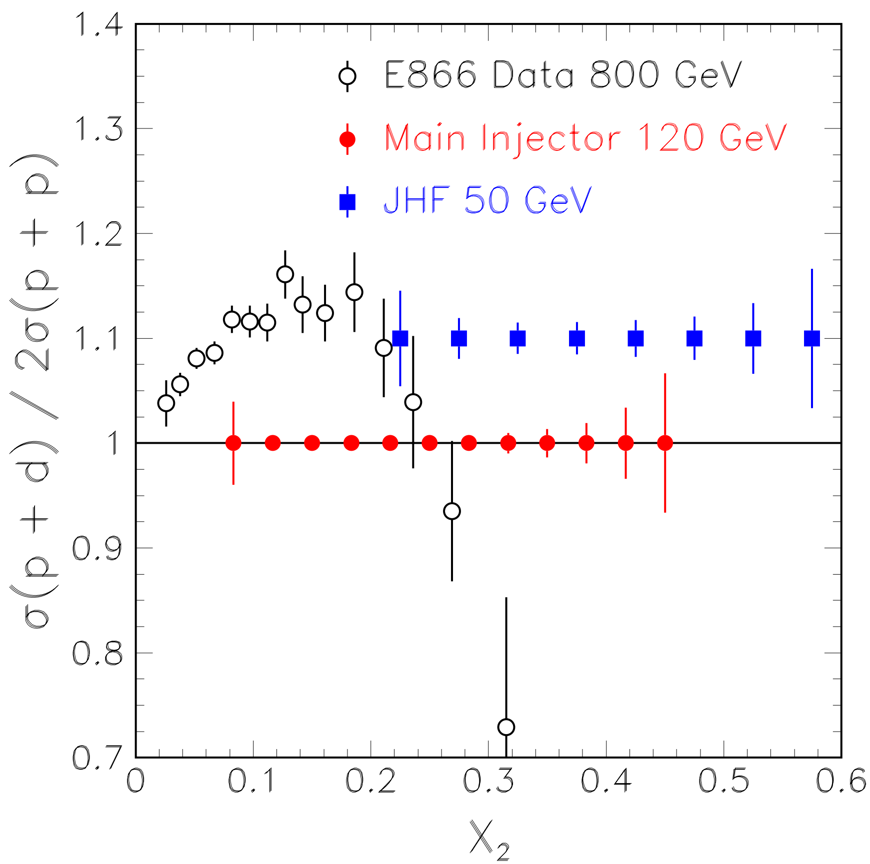


Most models can explain $\bar{d} - \bar{u}$

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

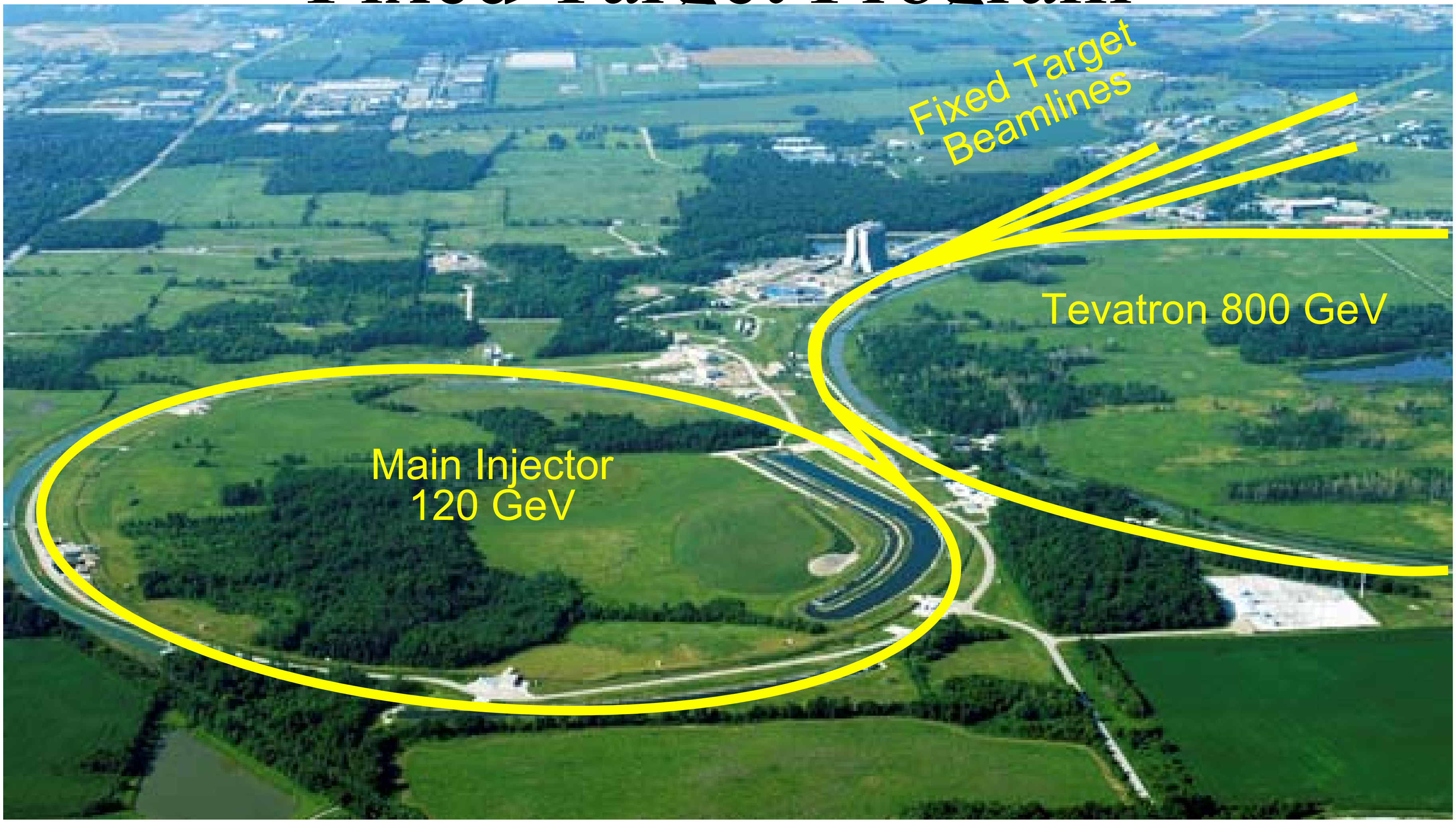
Future experiments to measure $\bar{d}/\bar{u}$ at large x

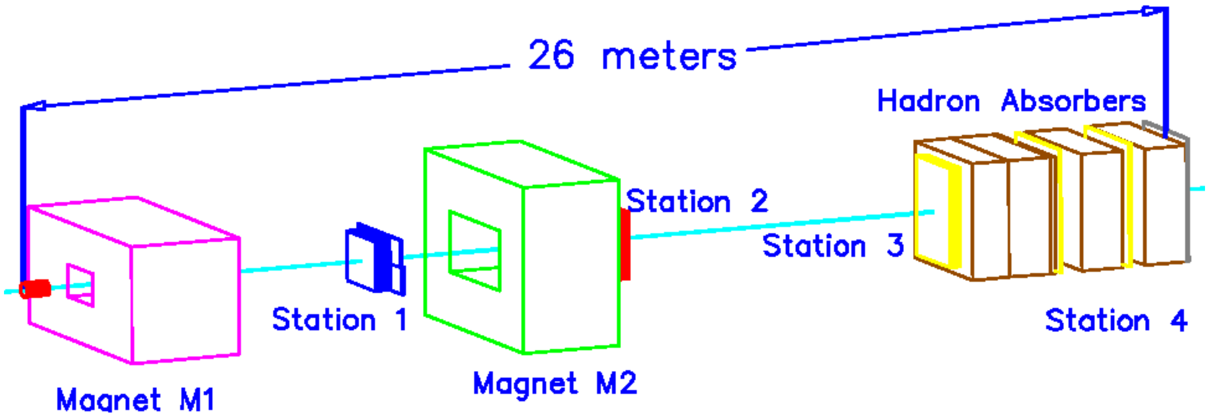
$$\frac{d\sigma_{DY}}{dx_1 dx_2} = \frac{4\pi\alpha^2}{3x_1 x_2}\frac{1}{s}\sum_i e_i^2[q_i(x_1)\bar{q}(x_2) + \bar{q}(x_1)q(x_2)]$$



Large X can be better studied with lower energy beam

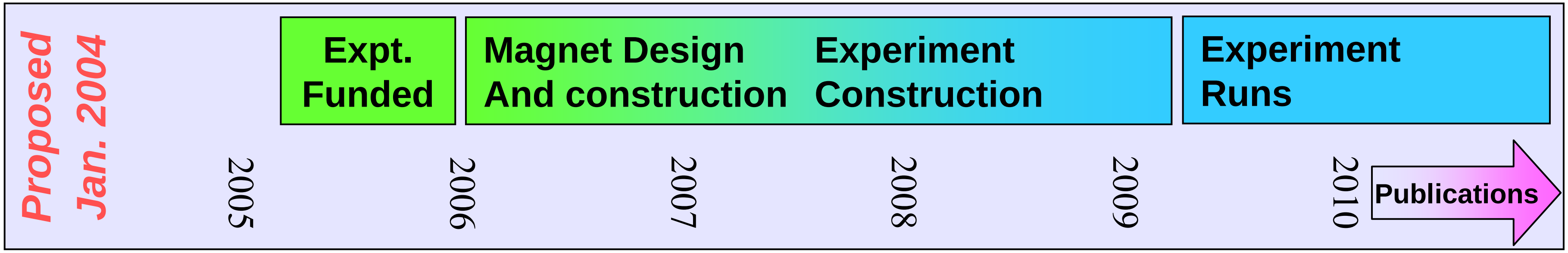
Fermilab Accelerator Complex: Fixed Target Program

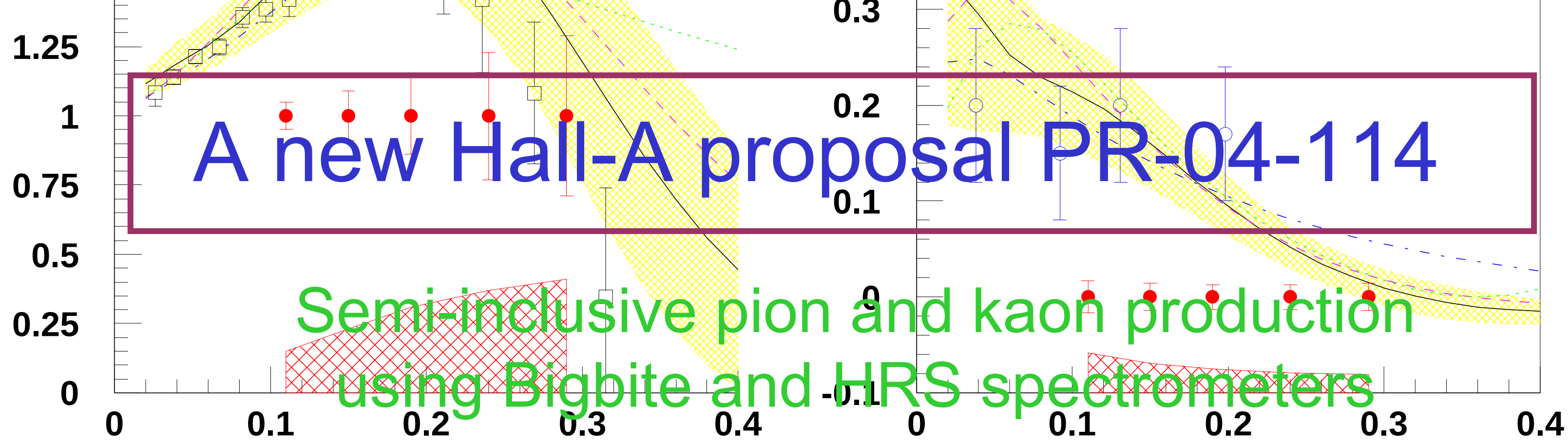




- **Boost difference between 800 and 120 GeV requires shorter experiment.**
  - –Fabrication of new coils for M1 magnet
- **Other items:**
  - –New Station 1 to handle higher rate
  - –Replace some very old scintillators, additional phototubes
- **Approx. Cost $2M**

E906 Schedule

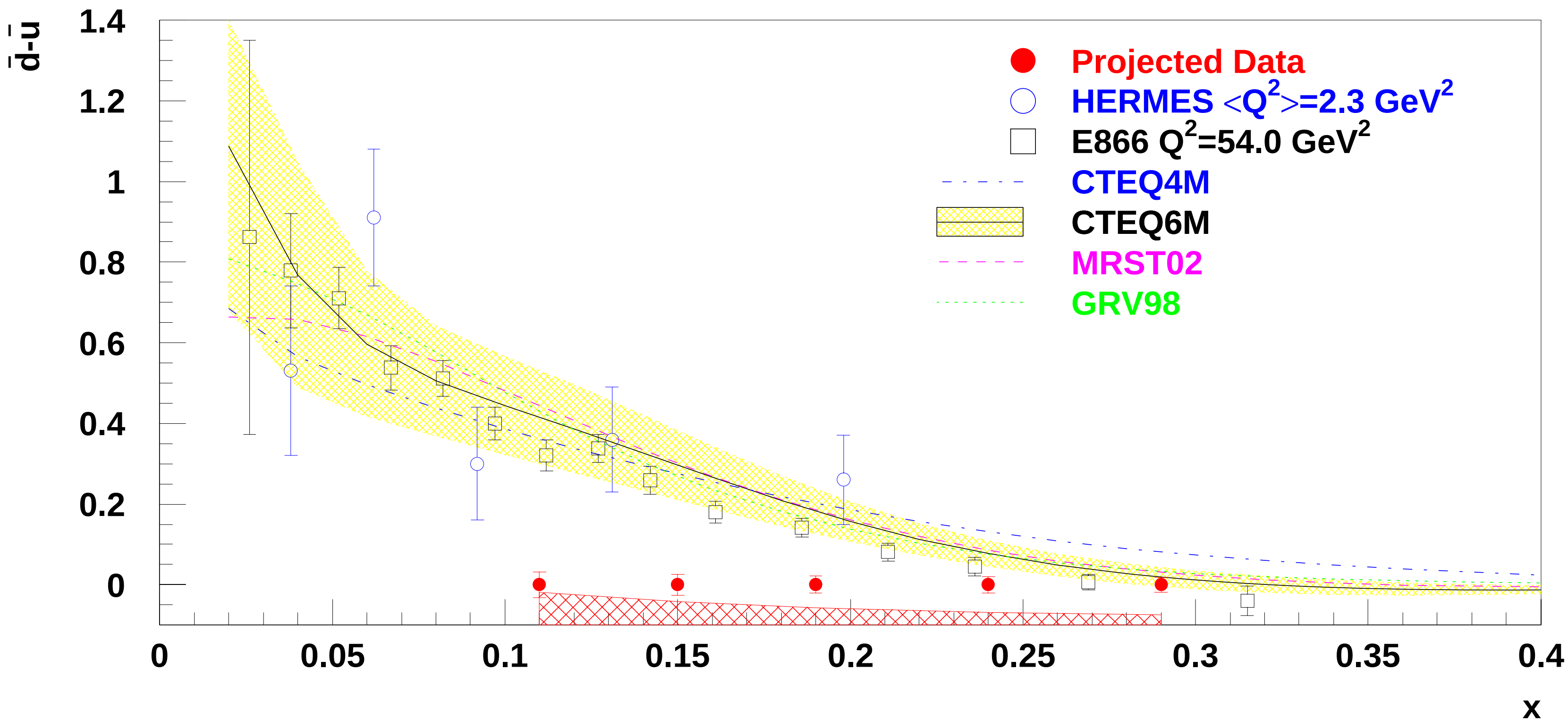




A new Hall-A proposal PR-04-114

Semi-inclusive pion and kaon production using Bigbite and HRS spectrometers

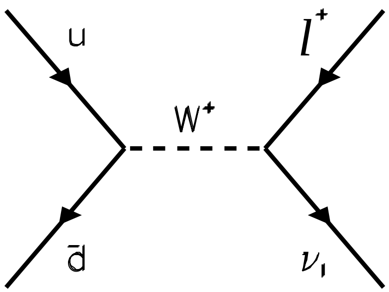
Projected PR-04-114 sensitivity for $\bar{d} - \bar{u}$



$\bar{d}/\bar{u}$ from W production at RHIC

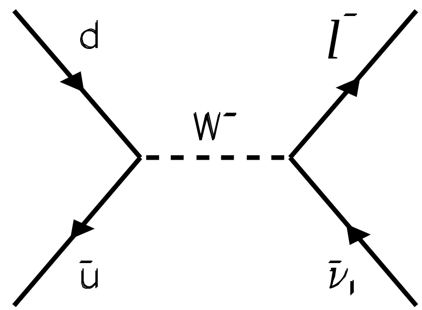
W production in $p-p$ collision

$p+p \to W^+ + x$



$(u+\bar{d} \to W^+)$

$p+p \to W^- + x$



$(d+\bar{u} \to W^-)$

$$\frac{d\sigma}{dx_F}(pp \to W^+X) = \frac{\sqrt{2}\pi}{3} G_F \left(\frac{x_1x_2}{x_1+x_2}\right) \cos^2\theta_c \left[u(x_1)\bar{d}(x_2)+\bar{d}(x_1)u(x_2)\right]$$

$$\frac{d\sigma}{dx_F}(pp \to W^-X) = \frac{\sqrt{2}\pi}{3} G_F \left(\frac{x_1x_2}{x_1+x_2}\right) \cos^2\theta_c \left[\bar{u}(x_1)d(x_2)+d(x_1)\bar{u}(x_2)\right]$$

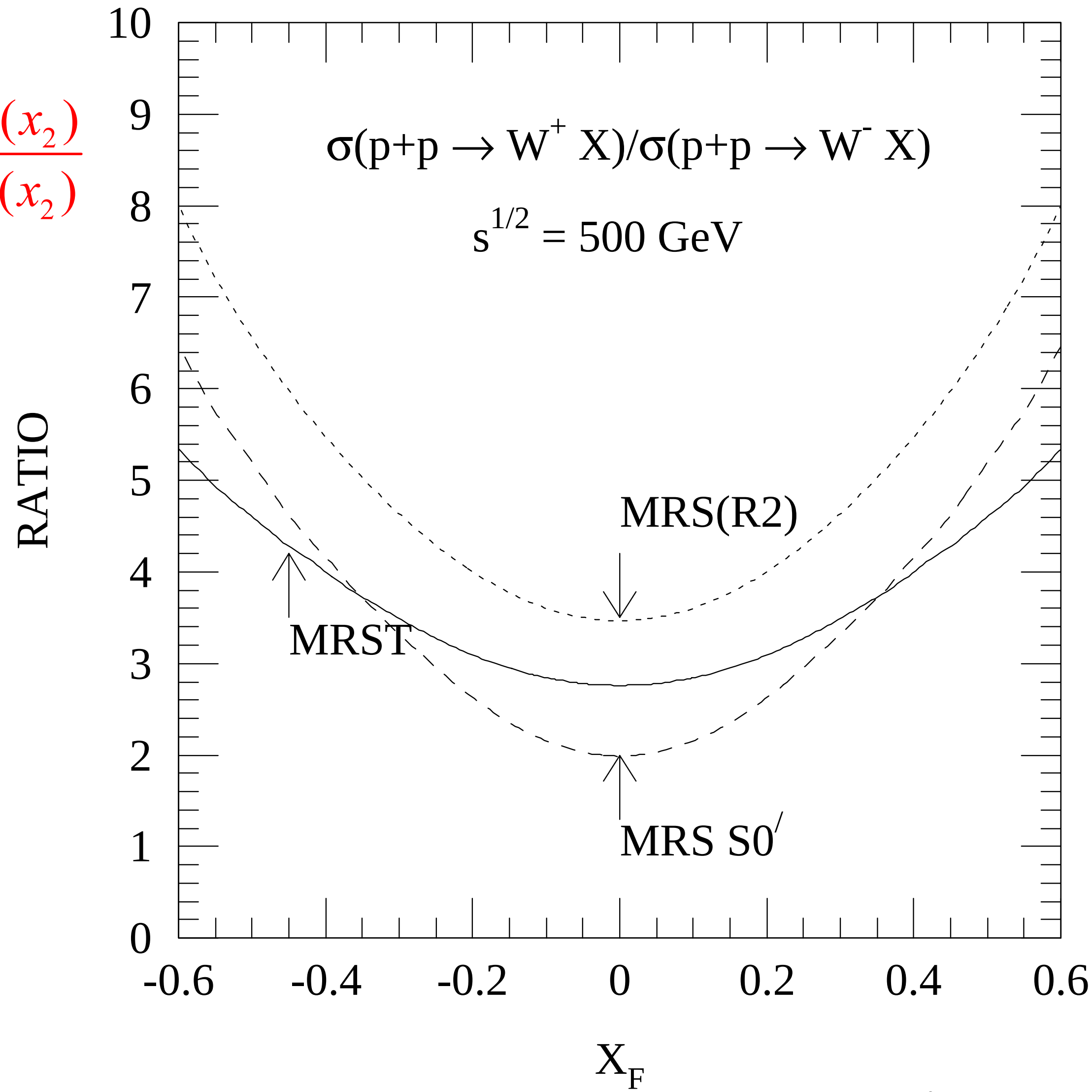
$$R(x_F) \equiv \frac{\frac{d\sigma}{dx_F}(pp \to W^+X)}{\frac{d\sigma}{dx_F}(pp \to W^-X)} \approx \frac{u(x_1)}{d(x_1)} \frac{\bar{d}(x_2)}{\bar{u}(x_2)}$$

Independent of nuclear effect in deuteron!

$\bar{d}/\bar{u}$ from W production at RHIC

$$R(x_F) \equiv \frac{\dfrac{d\sigma}{dx_F}(pp \to W^+ X)}{\dfrac{d\sigma}{dx_F}(pp \to W^- X)} \approx \frac{u(x_1)}{d(x_1)} \frac{\bar{d}(x_2)}{\bar{u}(x_2)}$$

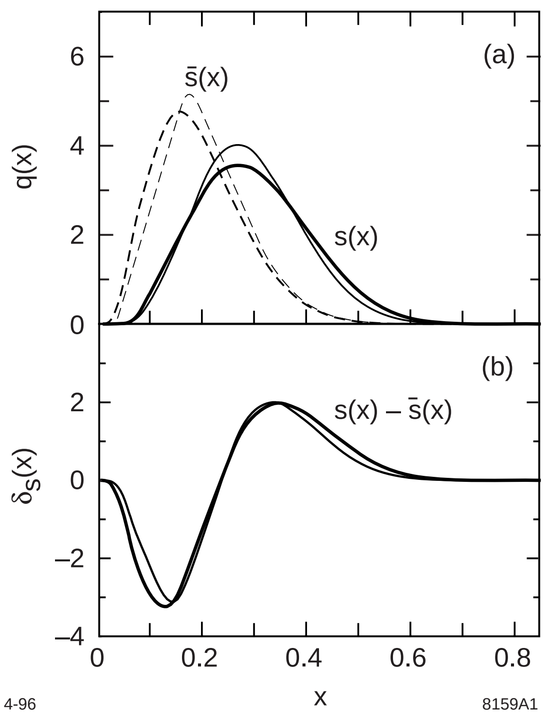
Garvey and Peng,
nucl-ex/0109010



$s(x) = \bar{s}(x)$?

Meson cloud model

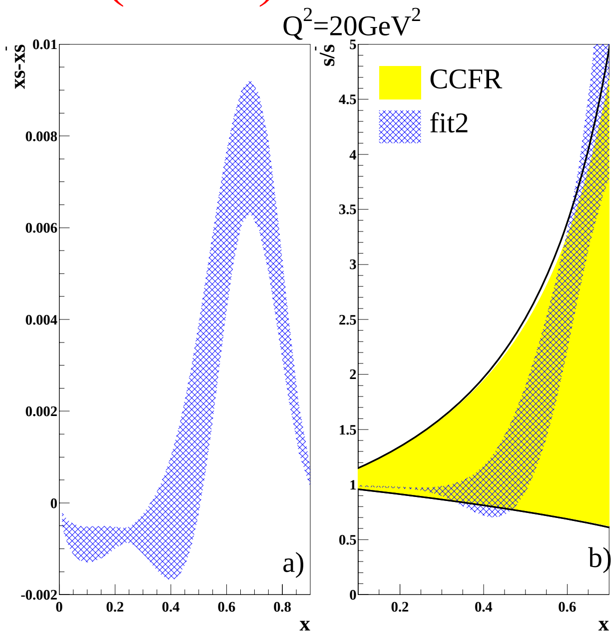
$$p \to K^{+} \Lambda$$
$$(u\bar{s})\,(uds)$$



Brodsky and Ma

Analysis of neutrino DIS data

$x(s-\bar{s})$ $s/\bar{s}$



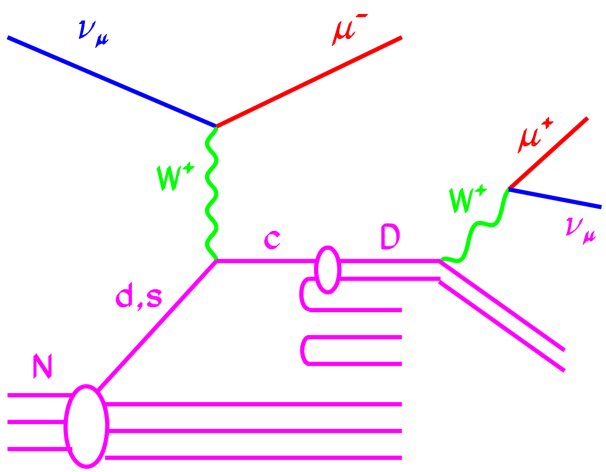
Barone et al.

$$\boxed{s(x) = \bar{s}(x)\ ?}$$

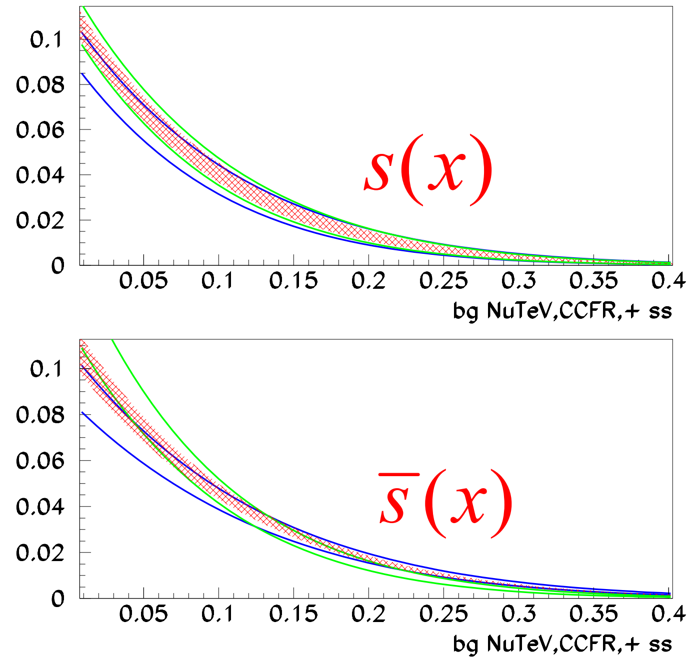
Dimuon production in neutrino DIS from CCFR and NuTeV

$$\nu + s \rightarrow \mu^- + c$$

$$\bar{\nu} + \bar{s} \rightarrow \mu^+ + \bar{c}$$



Results from NuTeV/CCFR

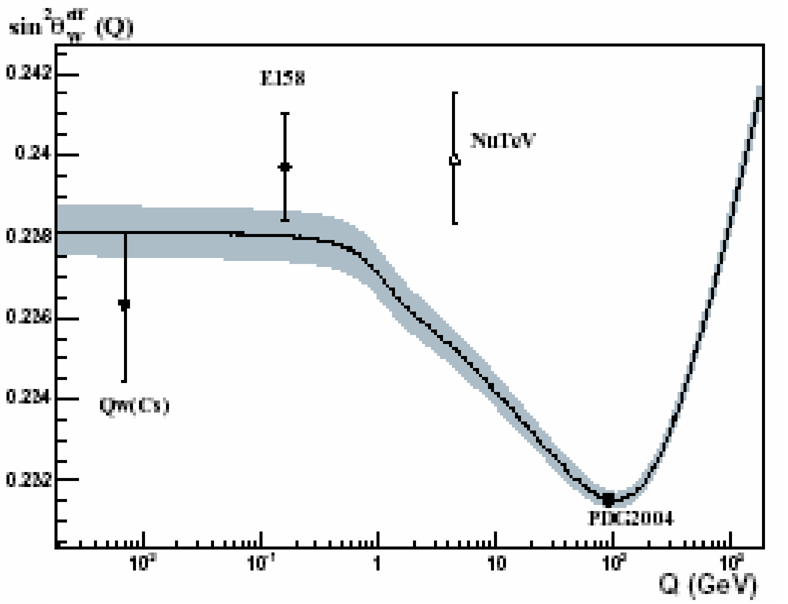


$$s(x) = 0.352\,\frac{\bar{u}(x) + \bar{d}(x)}{2}(1-x)^{-0.77} \qquad \bar{s}(x) = 0.405\,\frac{\bar{u}(x) + \bar{d}(x)}{2}(1-x)^{-2.04}$$

Parity-violating electron scattering is also sensitive to $s/\bar{s}$ asymmetry

$s-\overline{s}$ asymmetry and NuTeV $\sin^2\theta_W$

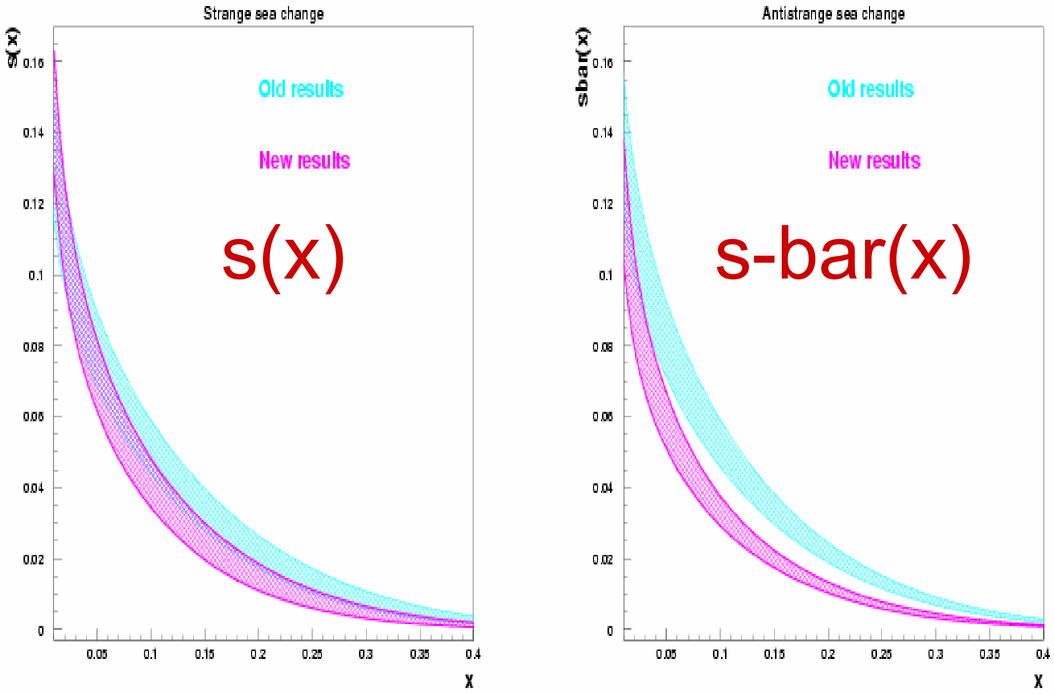
- NuTeV measures $R^- = \frac{\sigma^{\nu}_{NC}-\sigma^{\overline{\nu}}_{NC}}{\sigma^{\nu}_{CC}-\sigma^{\overline{\nu}}_{CC}}$
- From that $\sin^2\theta_W$ is extracted
  - Insensitive to sea quark uncertanties
  - But assumes symmetric strange sea
- QCD requires $\int (s-\overline{s})\, dx = 0$
- No QCD restriction on $S^- \equiv \int x\,(s-\overline{s})dx$
- R^- correction for asymmetric strange sea is proportional to S^-
- $S^- \sim 0.0068$ required for agreement with S.M.



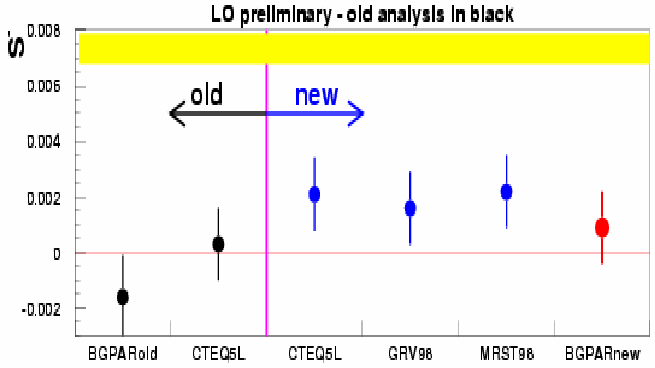
D. Mason, DIS2005 Talk

Recent result from NuTeV

Effect of data fix on strange seas



$$S^- = \int_0^1 x[s(x) - \overline{s}(x)]dx$$



- Yellow region brings NuTeV $\sin^2\theta_W$ to S.M.

D. Mason, DIS 2005 talk

Spin and flavor are closely connected

- Meson Cloud Model

$$u\uparrow \to \pi^0(u\bar{u}) + u\downarrow \qquad u\uparrow \to K^+(u\bar{s}) + s\downarrow$$

- Pauli Blocking Model

A spin-up valence quark would inhibit the probability of generating a spin-down antiquark

- Instanton Model

$$u_L \to u_R d_R \bar{d}_L, \qquad d_L \to d_R u_R \bar{u}_L$$

- Chiral-Quark Soliton Model

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

- Statistical Model

$$\Delta\bar{u}(x) - \Delta\bar{d}(x) \approx \bar{d}(x) - \bar{u}(x)$$

Predictions of $\int_0^1 [\Delta\bar{u}(x) - \Delta\bar{d}(x)]\,dx$

Table 2. Prediction of various theoretical models on the integral $I_\Delta = \int_0^1 [\Delta\bar{u}(x) - \Delta\bar{d}(x)]dx$.

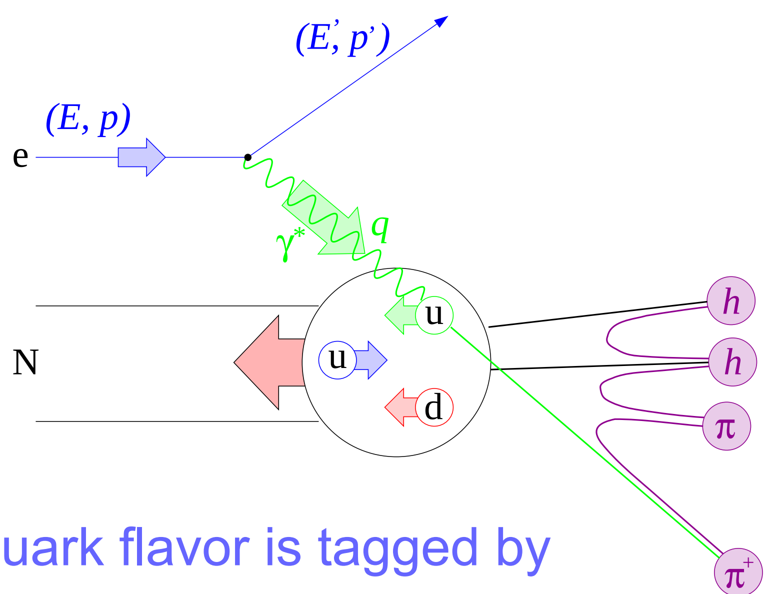
Model	I_Δ prediction	Ref.
Meson cloud (π-meson)	0	[42,43]
Meson cloud (ρ-meson)	$\simeq -0.0007$ to -0.027	[34]
Meson cloud ($\pi - \rho$ interf.)	$= -6\int_0^1 g^p(x)dx$ $\simeq -0.7$	[35]
Meson cloud (ρ and $\pi - \rho$ interf.)	$\simeq -0.004$ to -0.033	[36]
Meson cloud (ρ-meson)	< 0	[37]
Meson cloud ($\pi - \sigma$ interf.)	$\simeq 0.12$	[44]
Pauli-blocking (bag-model)	$\simeq 0.09$	[36]
Pauli-blocking (ansatz)	$\simeq 0.3$	[45]
Pauli-blocking	$= \frac{5}{3}\int_0^1 [\bar{d}(x) - \bar{u}(x)]dx$ $\simeq 0.2$	[46]
Chiral-quark soliton	0.31	[47]
Chiral-quark soliton	$\simeq \int_0^1 2x^{0.12}[\bar{d}(x) - \bar{u}(x)]dx$	[48]
Instanton	$= \frac{5}{3}\int_0^1 [\bar{d}(x) - \bar{u}(x)]dx$ $\simeq 0.2$	[39]
Statistical	$\simeq \int_0^1 [\bar{d}(x) - \bar{u}(x)]dx$ $\simeq 0.12$	[49]
Statistical	$> \int_0^1 [\bar{d}(x) - \bar{u}(x)]dx$ > 0.12	[50]

Peng, Eur. Phys. J. A18 (2003) 395

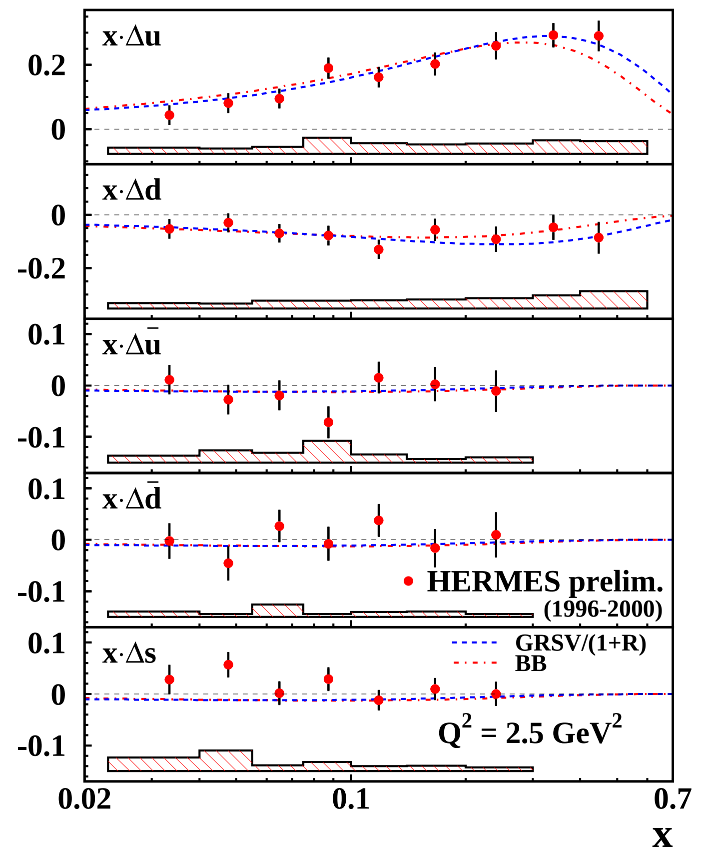
Flavor Structure of the Helicity Distributions

Polarized Semi-Inclusive DIS (SIDIS)

$$\vec{e} + \vec{N} \to e' + h^{\pm} + X$$



HERMES SIDIS data



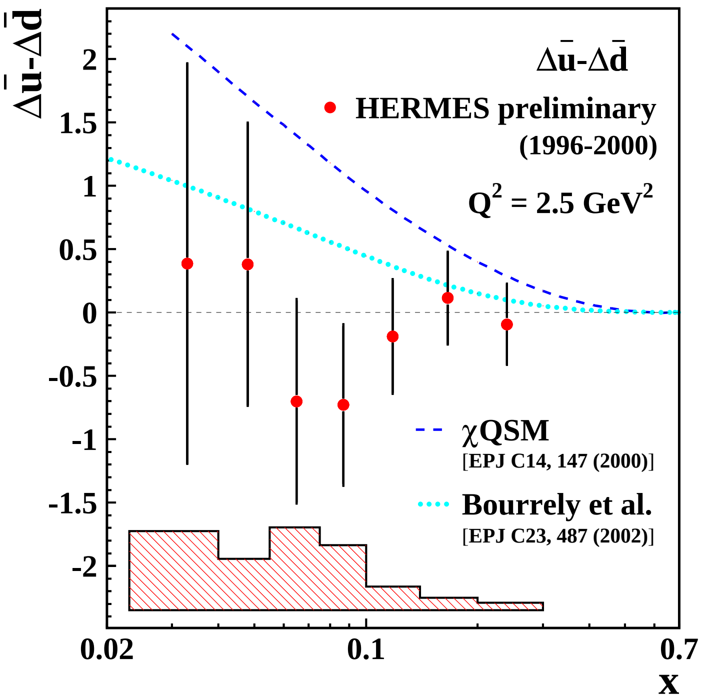
- Quark flavor is tagged by detecting $\pi^{\pm}$ and $K^{\pm}$
- Five-flavor analysis

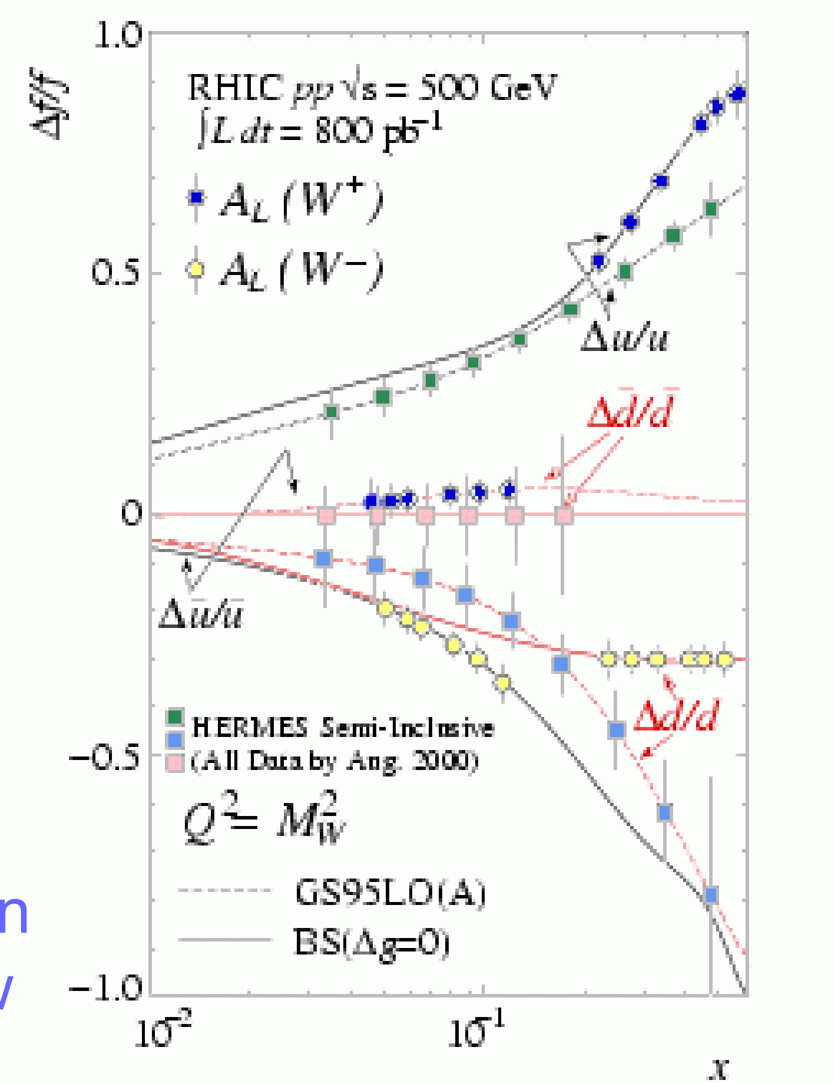
$$(\Delta u,\ \Delta d,\ \Delta\bar{u},\ \Delta\bar{d},\ \Delta s\,(=\Delta\bar{s}))$$

- No indication for $\Delta s < 0$

hep-ex/0210049

Flavor Structure of the Helicity Distributions



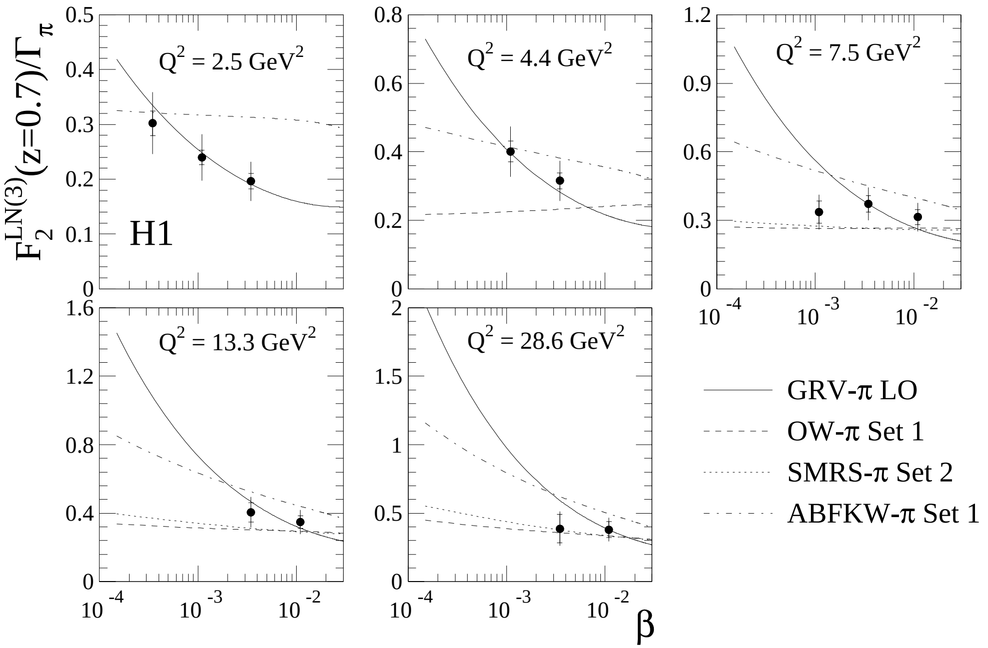


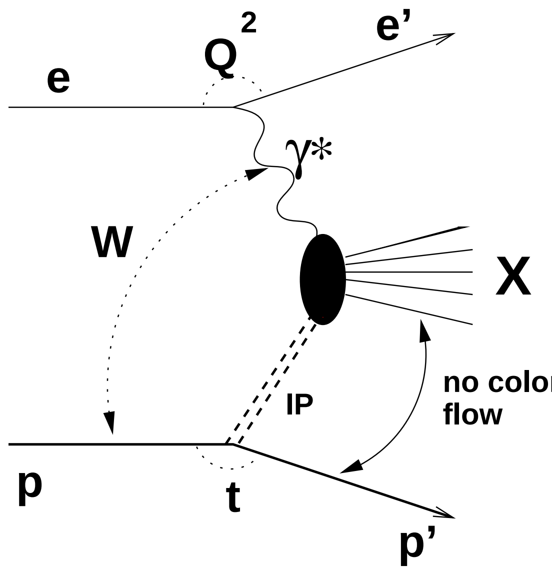
- No evidence for $\Delta\overline{u} \neq \Delta\overline{d}$

- Measurement of $W^{\pm}$ production at RHIC-spin would provide new information

Can one probe the meson cloud directly?

Electron DIS scattering off pomeron or meson was studied at HERA by tagging forward-going proton/neutron

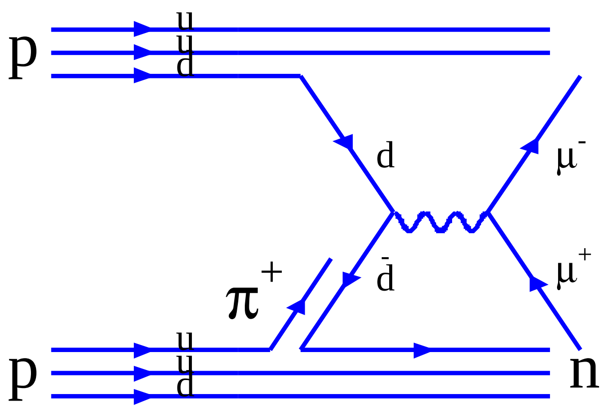




Pion structure functions at $10^{-4} < x < 10^{-2}$ were measured

One could study analogous processes at JLab

Semi-inclusive Drell-Yan production at RHIC?



One can tag on forward-going proton, neutron, Δ, Λ in coincidence with lepton-pair

Assuming factorization, then

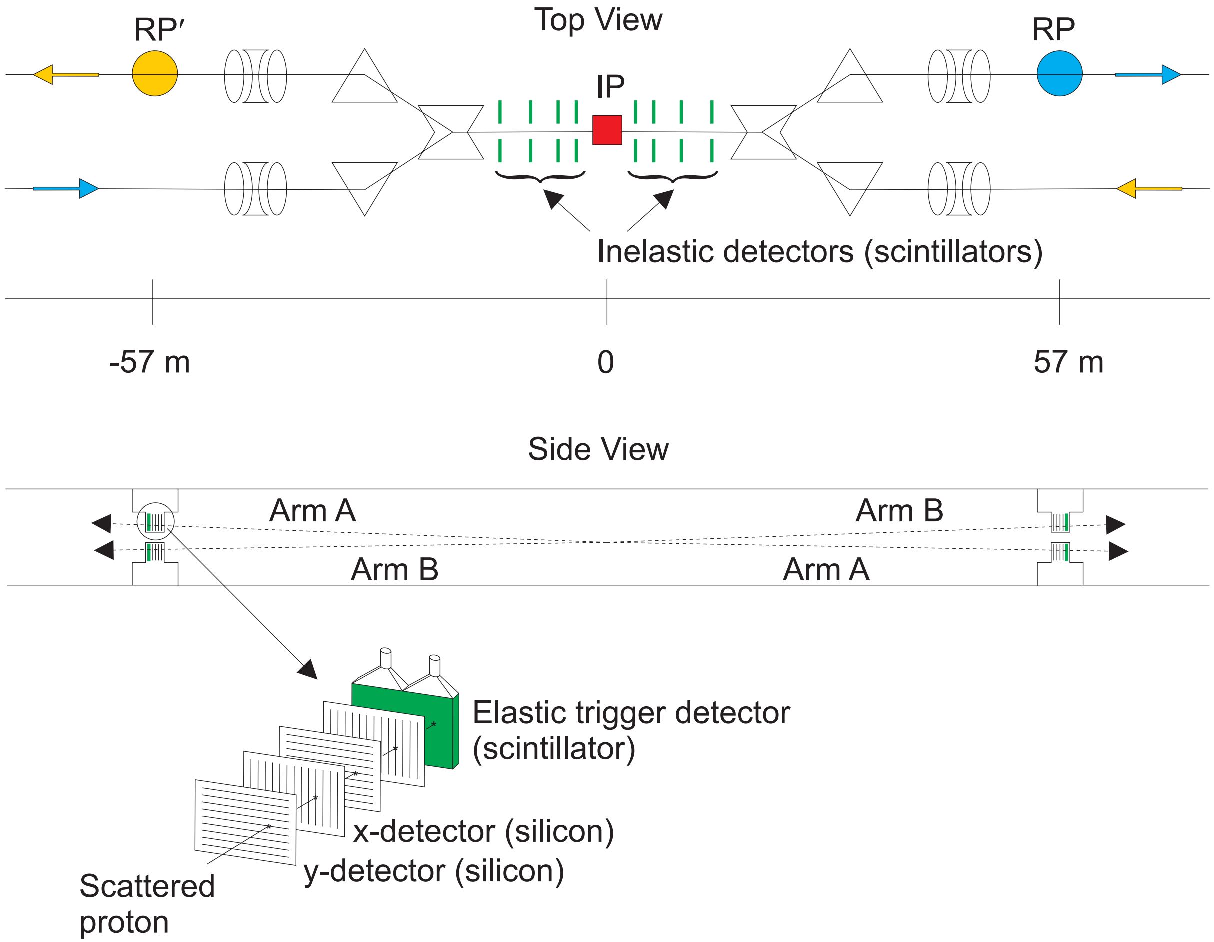
$$d\sigma^{DY}/dy\,dm\,dx_F(p+p\rightarrow n+\mu^+\mu^-+x)$$

$$=d\sigma^{DY}/dm\,dx_F(p+\pi^+\rightarrow \mu^+\mu^-+x)\cdot f_{MB}(y)$$

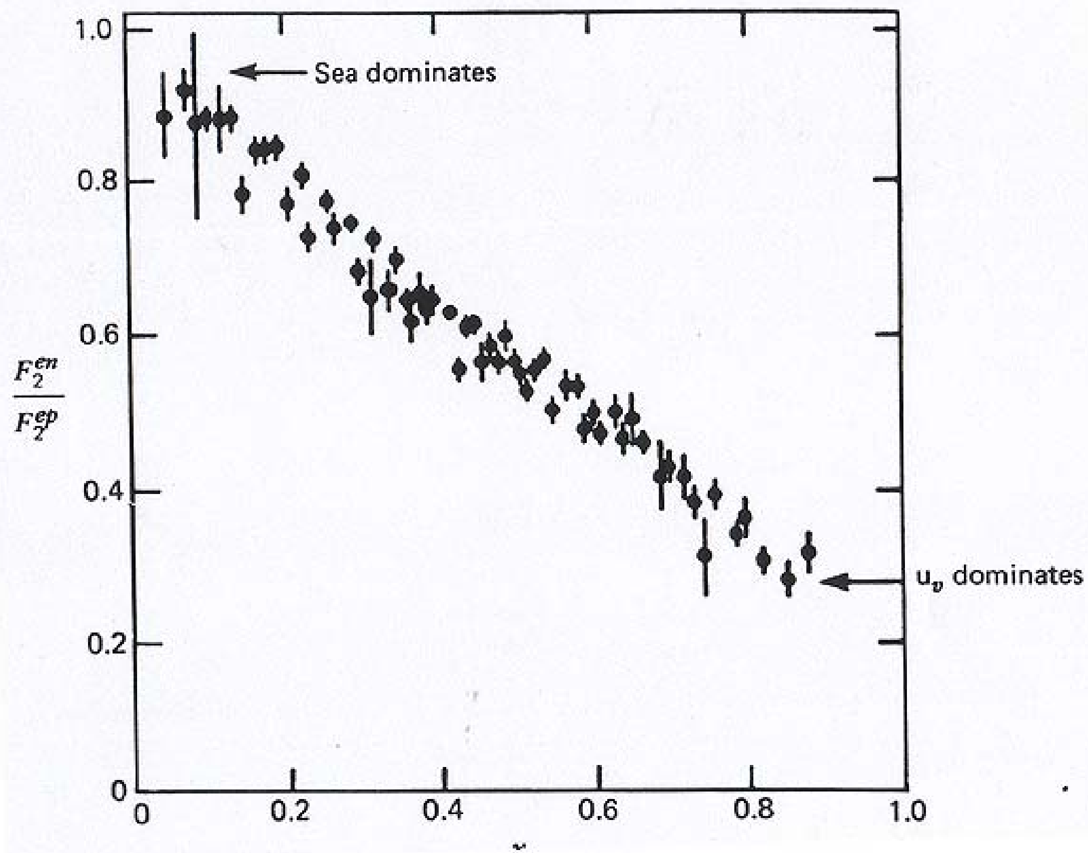
$f_{MB}(y)$ is the probability for $p\rightarrow\pi^+ + n,$ where n carries a fraction y of the proton momentum

Tagged D-Y production could provide information on the antiquark distribution in the mesons and on $f_{MB}(y)$

Tag the forward p using Roman Pots



Is $u(x) = 2d(x)$?

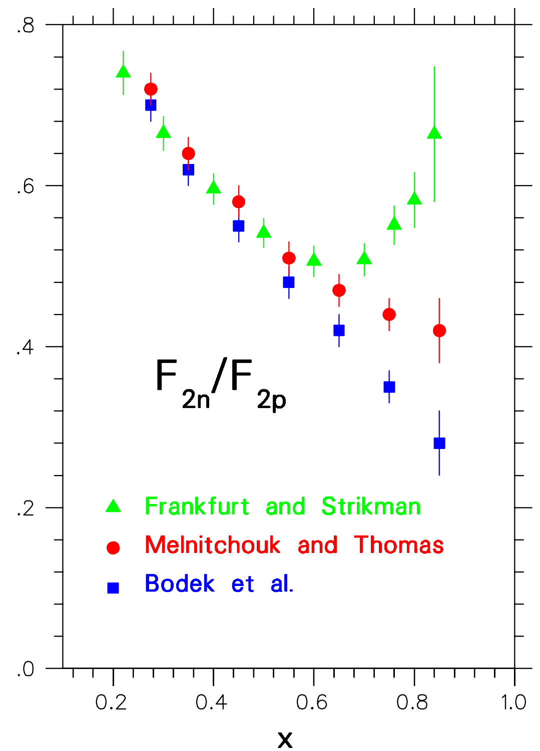


Sea dominates
u_v dominates
$\frac{F_2^{en}}{F_2^{ep}}$
1.0
0.8
0.6
0.4
0.2
0
0
0.2
0.4
0.6
0.8
1.0

$d(x)/u(x)$ at large x

$$\frac{F_2^n}{F_2^p} \approx (1+4\frac{d(x)}{u(x)})/(4+\frac{d(x)}{u(x)})$$ for large x

Model dependence of extracting F_2^n from F_2^d



Need to measure d/u without using deuteron

Model predictions at large *x*

$$| p >\uparrow = \frac{1}{\sqrt{2}} u\uparrow (ud)_{S=0,S_z=0} + \frac{1}{\sqrt{18}} u\uparrow (ud)_{S=1,S_Z=0} - \frac{1}{3} u\downarrow (ud)_{S=1,S_Z=1}$$

$$- \frac{1}{3} d\uparrow (uu)_{S=1,S_Z=0} + \frac{\sqrt{2}}{3} d\downarrow (uu)_{S=1,S_Z=1}$$

1) SU(6) symmetry

$$\frac{d}{u} = \frac{1}{2} \qquad \frac{F_2^n}{F_2^p} = \frac{2}{3}$$

2) Dominance of $S = 0$ diquark configurations (Close, Carlitz)

Ignoring terms with $S = 1$ diquarks, then

$$\frac{d}{u} = 0 \qquad \frac{F_2^n}{F_2^p} = \frac{1}{4}$$

3) Dominance of $S_Z = 0$ diquark configurations (Farrar, Jackson)

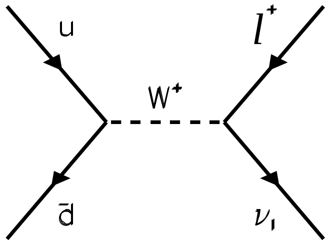
Ignoring terms with $S_Z = 1$ diquarks, then

$$\frac{d}{u} = \frac{1}{5} \qquad \frac{F_2^n}{F_2^p} = \frac{3}{7}$$

$d\,/\,u$ from W production at CDF

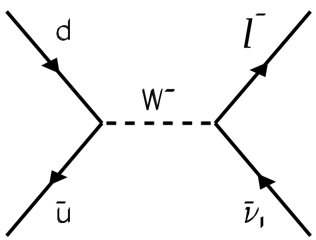
W production in $p-\bar{p}$ collision

$$p+\overline{p}\rightarrow W^{+}+x$$



$$(u+\overline{d}\rightarrow W^{+})$$

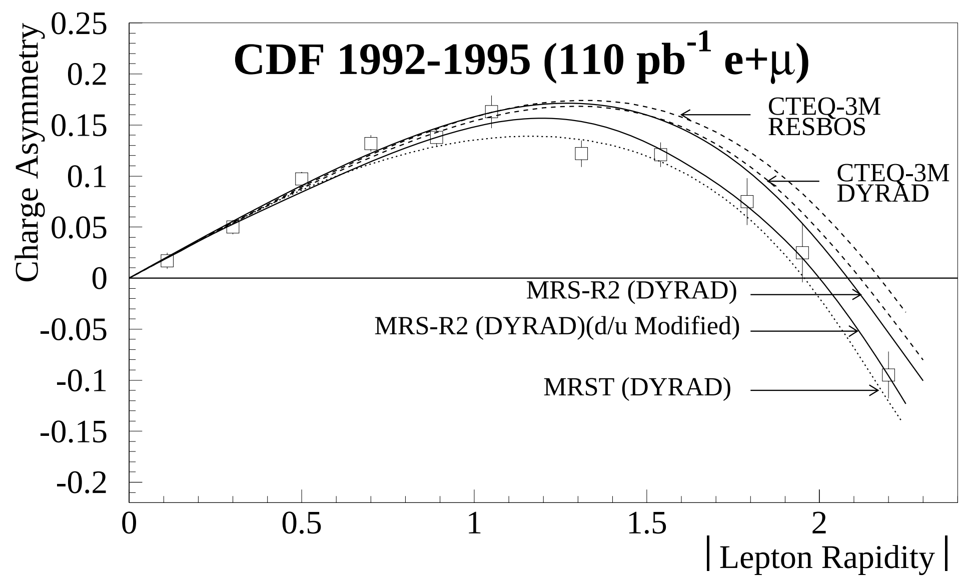
$$p+\overline{p}\rightarrow W^{-}+x$$



$$(d+\overline{u}\rightarrow W^{-})$$

W^+/W^- asymmetry is sensitive to *d/u*

W asymmetry from CDF



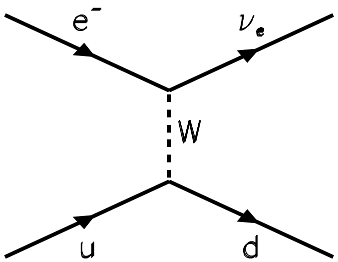
Abe et al., PRL 81 (1998) 5744

“Modified” *d/u* PDF fits the data better

d/u from charged-current DIS at HERA

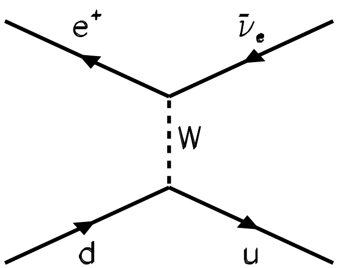
CC DIS at HERA

$$e^- + p \to \nu_e + x$$



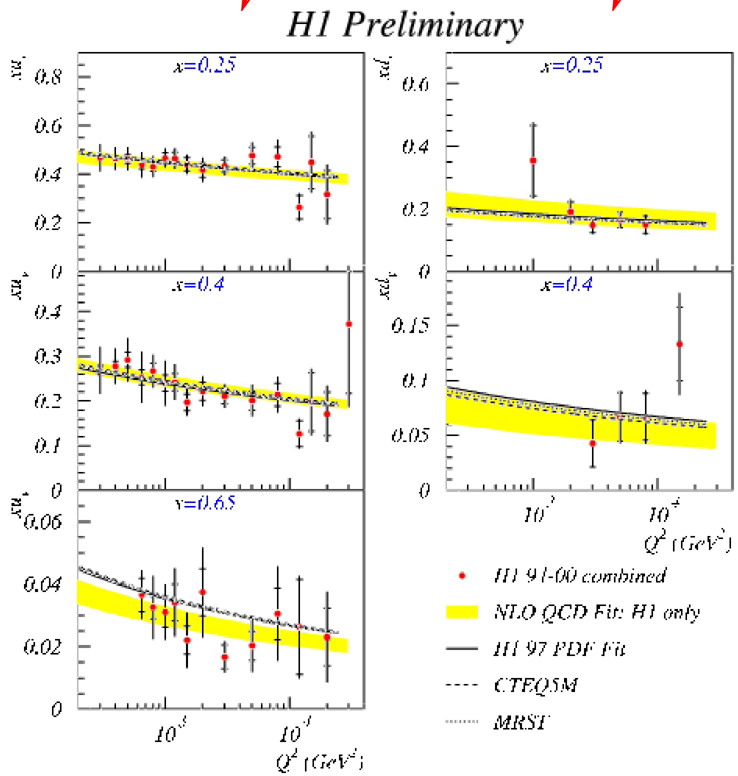
$$(e^- + u \to \nu_e + d)$$

$$e^+ + p \to \bar{\nu}_e + x$$



$$(e^+ + d \to \bar{\nu}_e + u)$$

xu_V xd_V



hep-ex/0212043

Data indicate that u_V at large x is smaller than PDF parametrizations

More data are forthcoming

d/u measurement with neutron tagging

BONUS at Hall-B

Expected F_2^n / F_2^p sensitivities

e + d → e' + p + X

Spectator proton

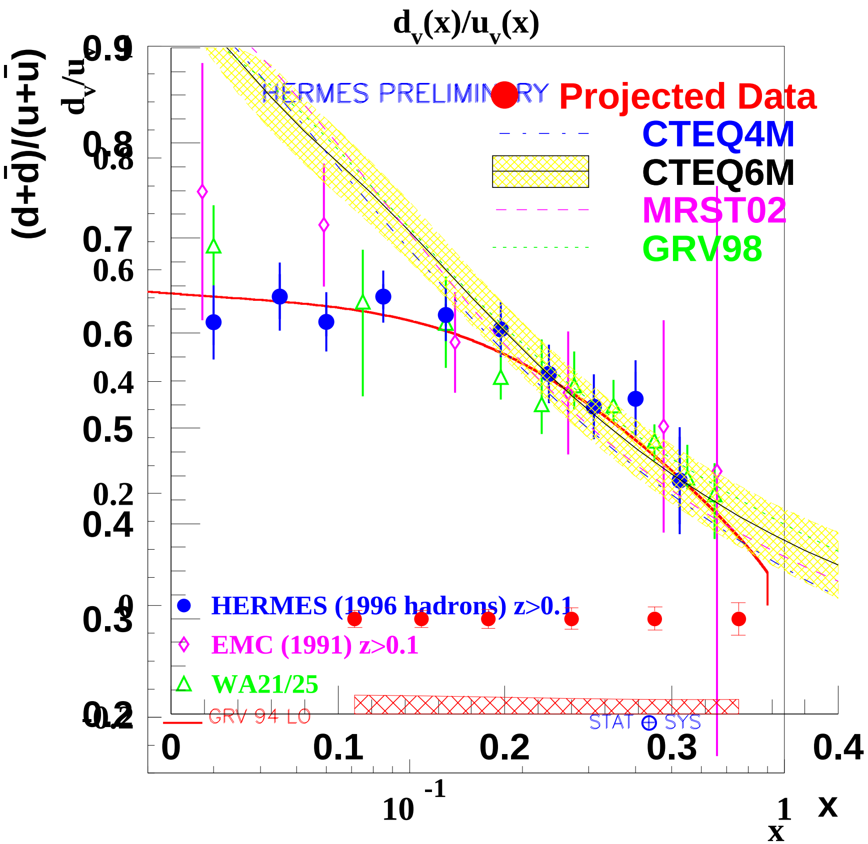
(e + n → e' + X)

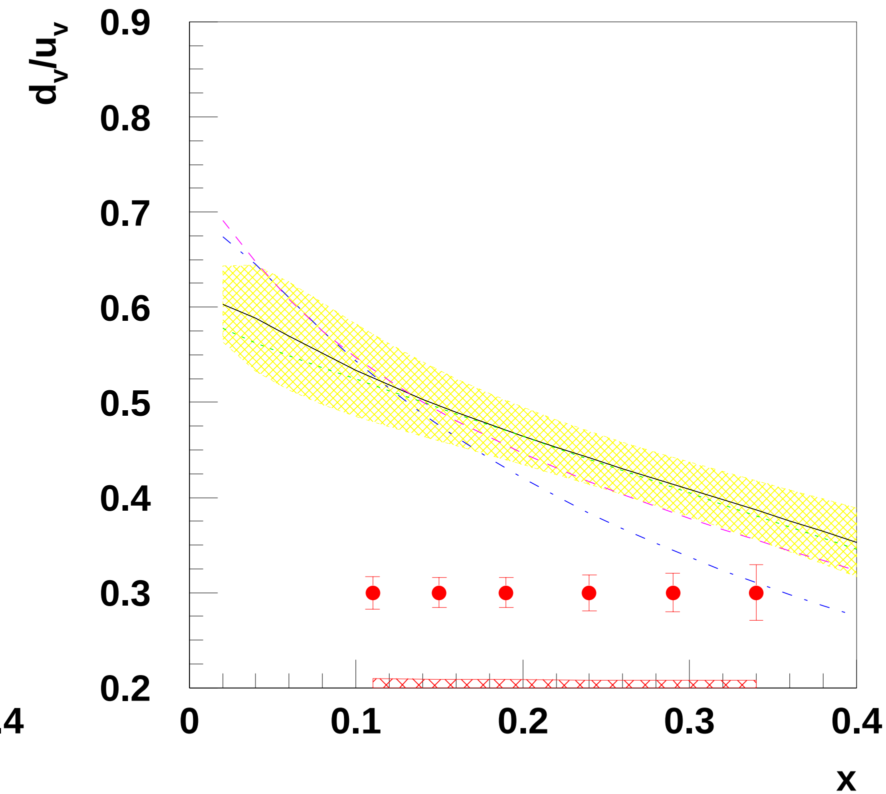
Measurement of $d_v(x)/u_v(x)$ with SIDIS

$$\frac{d_v(x)}{u_v(x)} = \frac{\left(Y_p^{\pi^+}(x,z) - Y_p^{\pi^-}(x,z)\right) + 4\left(Y_n^{\pi^+}(x,z) - Y_n^{\pi^-}(x,z)\right)}{4\left(Y_p^{\pi^+}(x,z) - Y_p^{\pi^-}(x,z)\right) + \left(Y_n^{\pi^+}(x,z) - Y_n^{\pi^-}(x,z)\right)}$$

HERMES Preliminary

Projected P-04-114 sensitivity





Connections between parton distribution functions and fragmentation functions

- Gribov-Lipatov "reciprocity" relation at $z \to 1$

$$D_q(z) = zq(z)$$

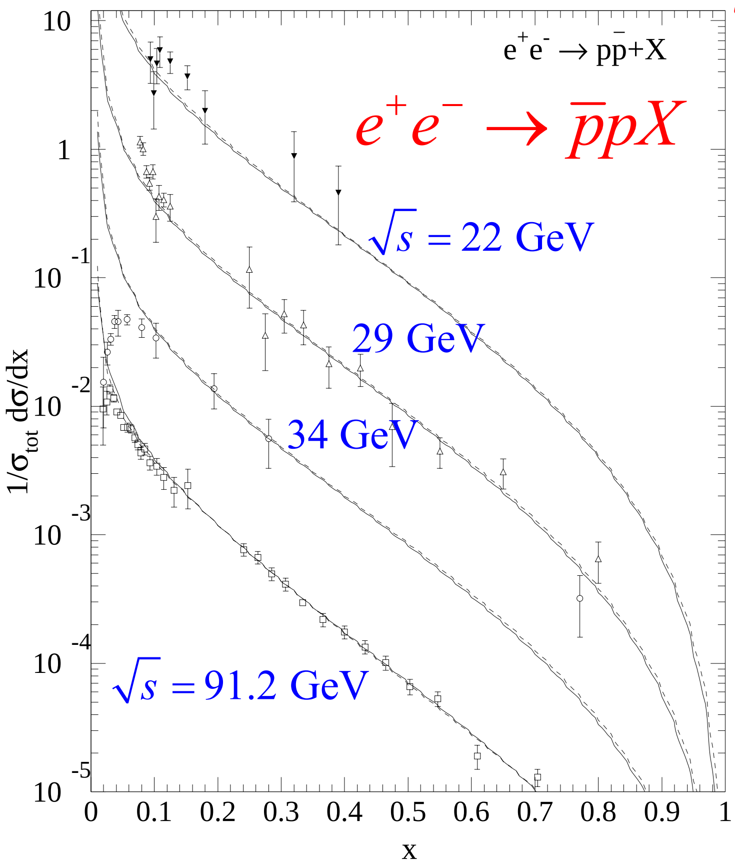
- Implications on the flavor structure of the proton fragmentation functions?

- Flavor structure of the meson fragmentation functions?

Gribov-Lipatov reciprocity relation

$$\Rightarrow \qquad D_i^h(x) = q_i^h(x)$$

$$\Rightarrow \qquad \frac{D_d^p(x)}{D_u^p(x)} = \frac{d(x)}{u(x)} \text{ at large } x$$



Is $\frac{D_d^p(x)}{D_u^p(x)}$ □ constant or

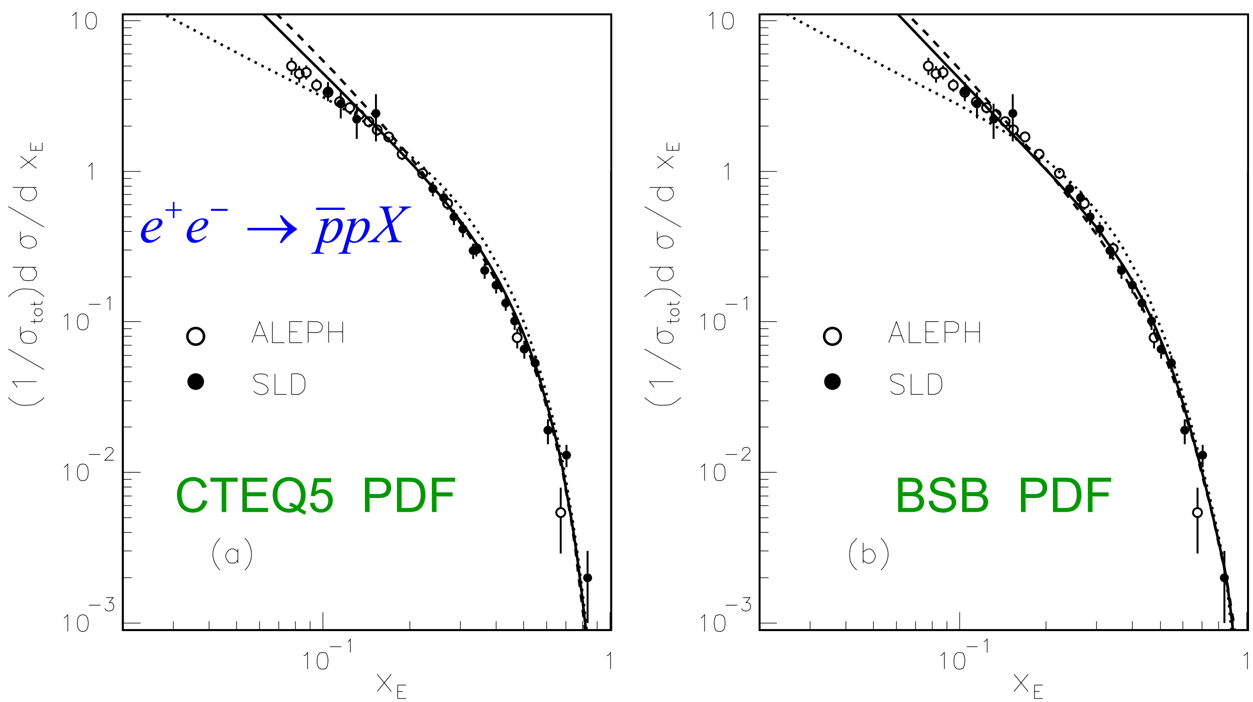
□ $(1-x)$ at large x?

The KKP (Kniehl, Kramer, Potter) proton fragmentation function assumes

$$D_u^p(x) = 2D_d^p(x)$$

Ma, Schmidt, Soffer, Yang assumes the following relations between fragmentation function and parton distributions:

$$D_v(z) = C_v z^\alpha q_v(z); \qquad D_s(z) = C_s z^\alpha q_s(z)$$



Dotted: $C_v = 1,\ C_s = 0,\ \alpha = 0$

Solid: $C_v = 1,\ C_s = 1,\ \alpha = 0.5$

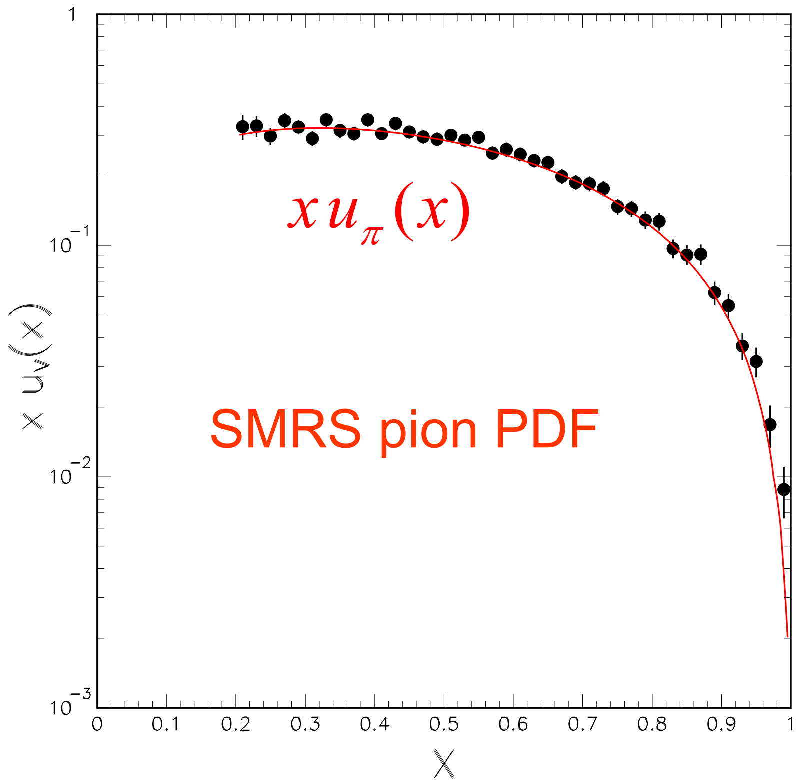
Dashed: $C_v = 1,\ C_s = 3,\ \alpha = 1$

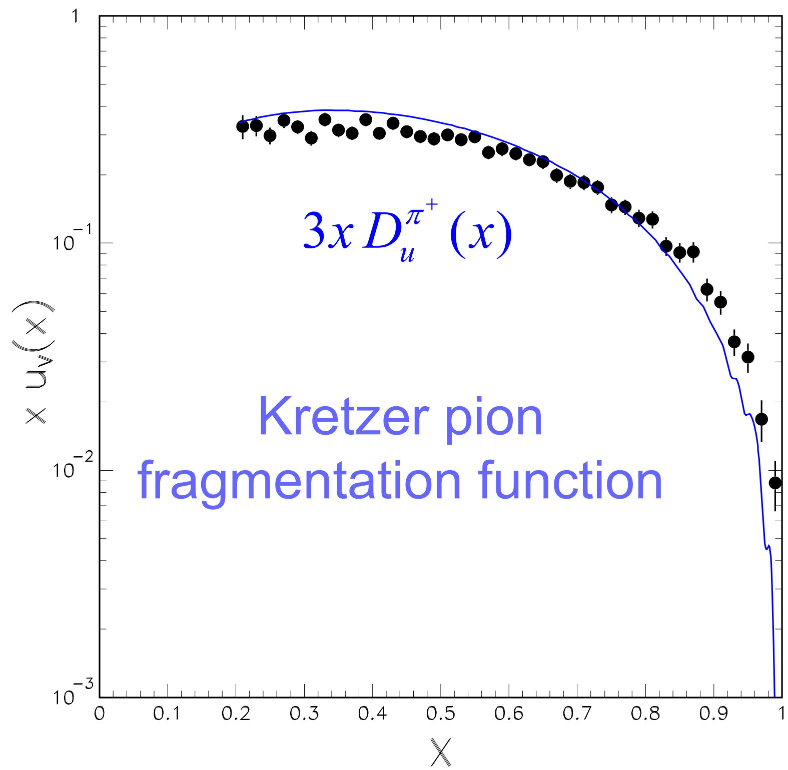
(hep-ph/0208122)

Precise e^+e^- data at large z from Belle could shed light on the connection between PDF and fragmentation functions

Connection between PDF and FF for mesons?

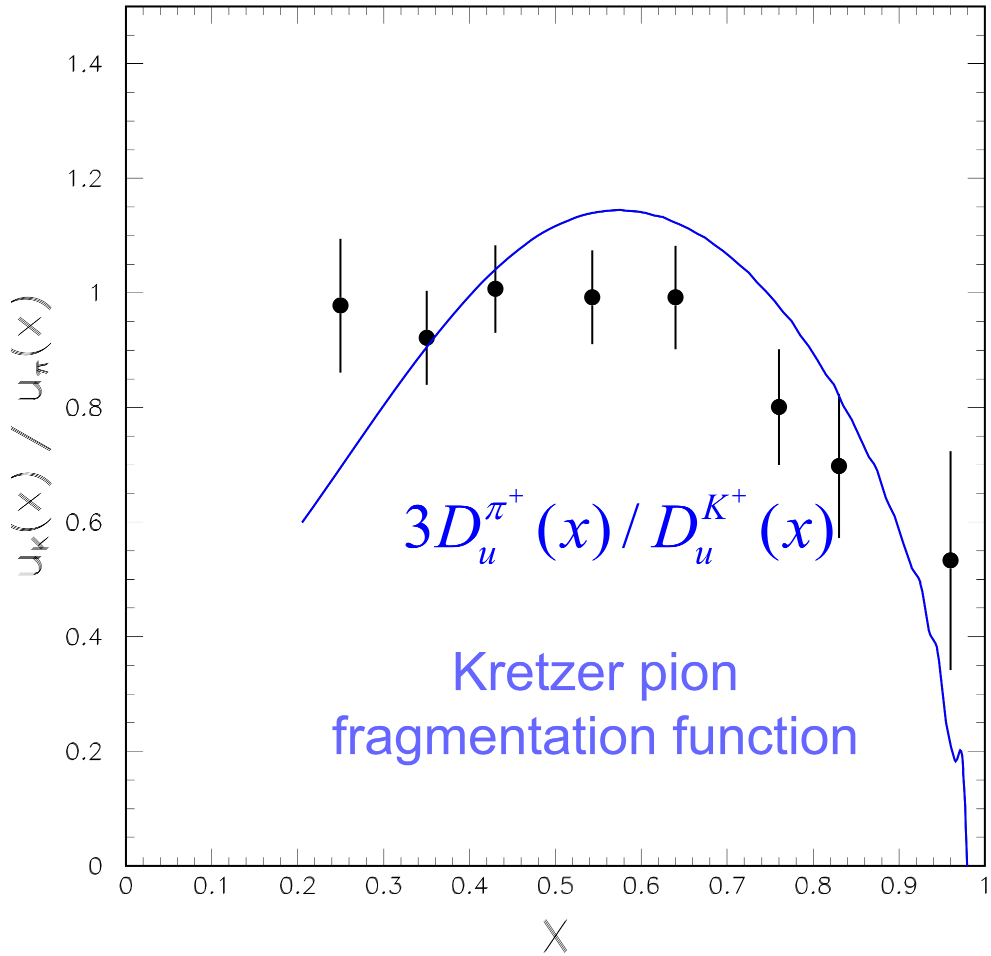
Pion valence quark distribution from E615 Drell-Yan





Connection between PDF and FF for mesons?

$u_K(x)/u_\pi(x)$ from NA3 Drell-Yan experiment

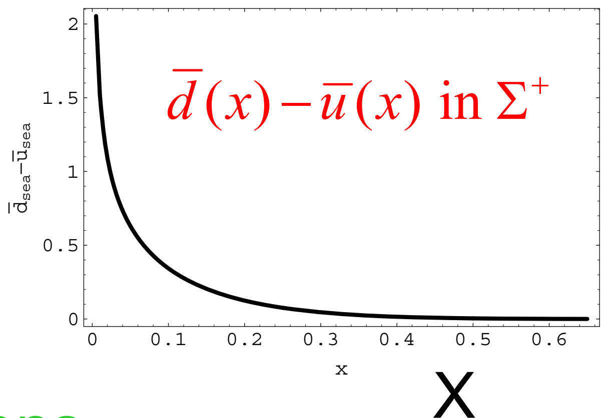


Flavor structure of the fragmentation functions

- $\bar{d}/\bar{u}$ sea-quark flavor asymmetry is observed for the proton
- Can one observe $\bar{d}/\bar{u}$ asymmetry in other hadrons?

1) Hyperons

Pion-cloud model and Pauli-blocking predict $\bar{d} > \bar{u}$ in Σ^+



Σ^+ contains uus valence quarks

(Alberg et al. hep-ph/9809243)

Can be measured with Drell-Yan using Σ^+ beam. Difficult experiment!

2) Pions

Is $\bar{d}_{sea}(x) = \bar{u}_{sea}(x)$ in π^+ ?

Isospin and charge-conjugation symmetries

$\Rightarrow \bar{d}_{sea}(x) = \bar{u}_{sea}(x)$ in π^+

Flavor structure of the fragmentation functions

3) Kaons

Is $\bar{d}_{sea}(x) = \bar{u}_{sea}(x)$ in K^+?

- K^+ contains $u\bar{s}$ valence quarks
- Pauli-blocking implies $u\bar{u}$ sea is blocked, but not the $d\bar{d}$ sea
- Hence, one expects $\bar{d}(x) > \bar{u}(x)$ for K^+

Difficult to measure sea-quark distributions in K^+!

Can the $\bar{u}/\bar{d}$ flavor asymmetry be observed in the kaon fragmentation functions?

$$\text{Is } D_{\bar{d}}^{K^+}(z) > D_{\bar{u}}^{K^+}(z)?$$

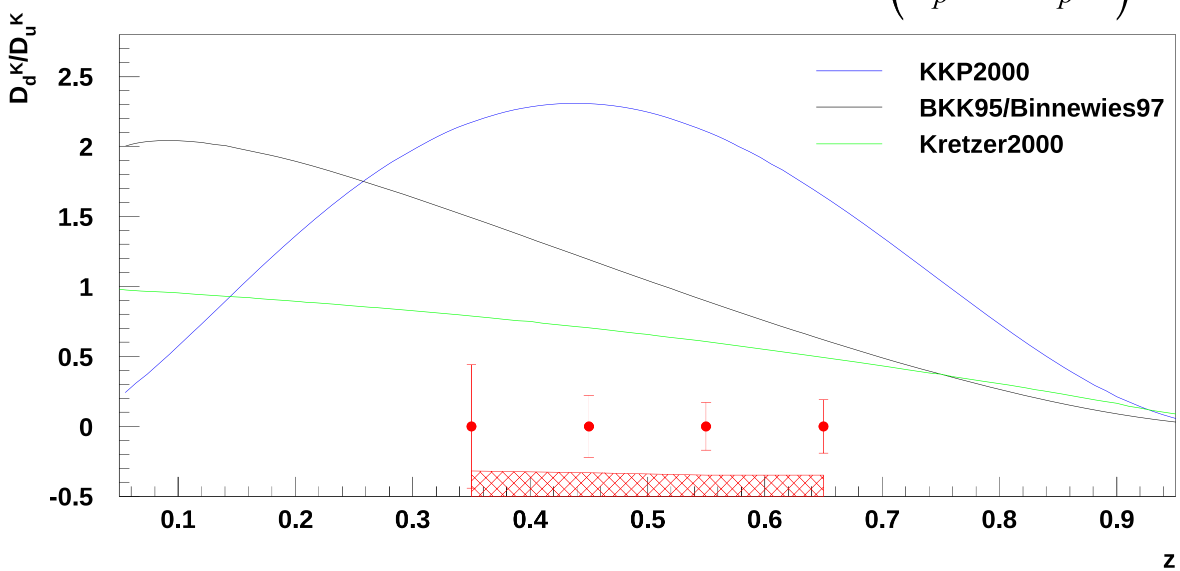
What is known about kaon fragmentation functions?

KKP global fit: $\int_{0.05}^{1} dz\, z\, D_{u,s}^{K^\pm}(z,Q_0^2) = 0.19, \qquad \int_{0.05}^{1} dz\, z\, D_{d}^{K^\pm}(z,Q_0^2) = 0.25$

This implies: $\int_{0.05}^{1} dz\, z\, D_{\bar{u}}^{K^+}(z,Q_0^2) < 0.065, \qquad \int_{0.05}^{1} dz\, z\, D_{\bar{d}}^{K^+}(z,Q_0^2) = 0.25$

$D_{\bar{d}}^{K^+}(z) >> D_{\bar{u}}^{K^+}(z)?$

$$\frac{D_d^{K^\pm}}{D_u^{K^\pm}} \approx 4\,\frac{\left(Y_n^{K^+}+Y_n^{K^-}\right) - r\cdot\left(Y_p^{K^+}+Y_p^{K^-}\right)}{\left(Y_p^{K^+}+Y_p^{K^-}\right) - r\cdot\left(Y_n^{K^+}+Y_n^{K^-}\right)}$$



Lingyan Zhu
(PR-04-114)

Connections between the parton distribution and fragmentation functions?

Summary

- The flavor asymmetry of light sea quarks is well established. Future measurements of the sea quarks at medium and high x are anticipated.
- Flavor and spin structures of the nucleon are closely connected.
- Connection between the parton distribution function and the parton fragmentation functions need to be better understood.
- The flavor structure of nucleon and meson parton distributions and fragmentation functions continues to be an interesting area for further investigations.

A NEW NEUTRON EDM EXPERIMENT

Jen-Chieh Peng

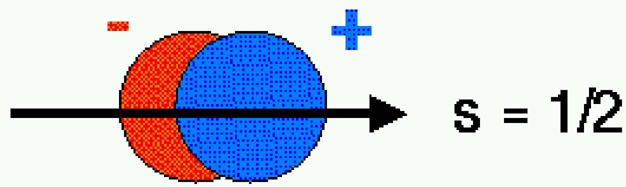
University of Illinois

- Physics motivations for neutron EDM measurements
- Status of neutron EDM measurements
- Proposal for a new neutron EDM experiment
  - Proposed approach
  - Technical challenges

Neutron

- A permanent EDM $\vec{d}$

$\vec{d} \cdot \vec{E}$



- The current value is roughly < 10^{-25} e•cm

$$\vec{d}_n = \int \vec{x}\rho(x)\, d^3x = d_n \hat{s}$$

- We hope to obtain roughly < 10^{-28} e•cm with UCN in superfluid He

Non-zero d_n violates both P and T

Under a parity operation:

$$\hat{s} \rightarrow \hat{s}, \quad \vec{E} \rightarrow -\vec{E}$$

$$\vec{d}_n \cdot \vec{E} \rightarrow -\vec{d}_n \cdot \vec{E}$$

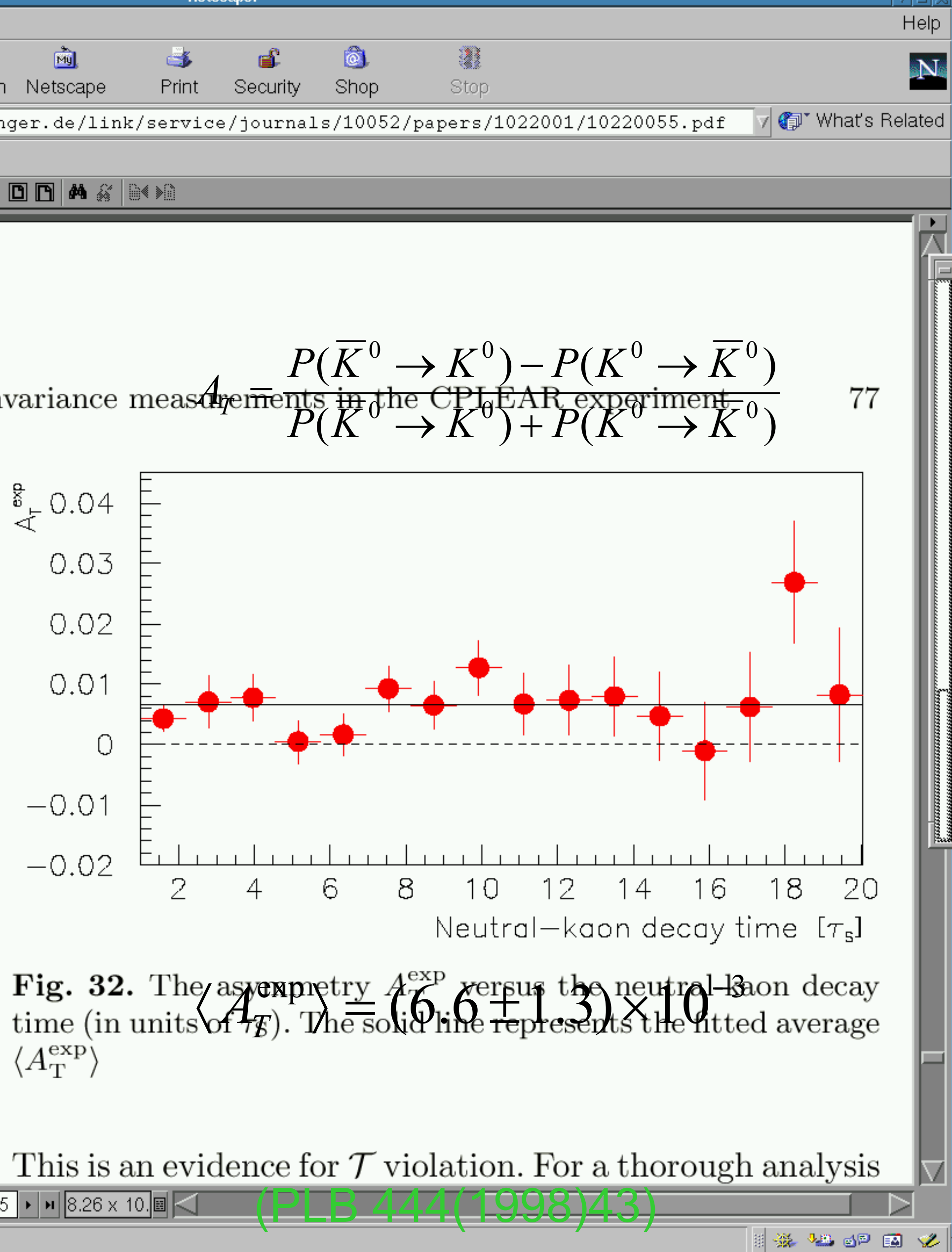
Under a time-reversal operation:

$$\hat{s} \rightarrow -\hat{s}, \quad \vec{E} \rightarrow \vec{E}$$

$$\vec{d}_n \cdot \vec{E} \rightarrow -\vec{d}_n \cdot \vec{E}$$

tion Experiments

n System



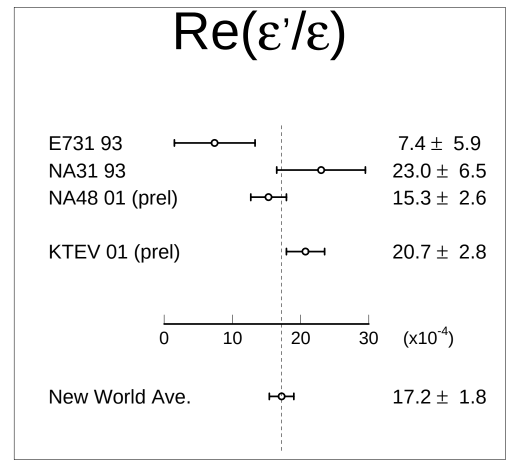
$$A_T = \frac{P(\bar{K}^0 \to K^0) - P(K^0 \to \bar{K}^0)}{P(\bar{K}^0 \to K^0) + P(K^0 \to \bar{K}^0)}$$

$$\langle A_T^{exp} \rangle = (6.6 \pm 1.3) \times 10^{-3}$$

(PLB 444(1998)43)

Observation of Direct CP-violation

$$R = \frac{\Gamma(K_L \to \pi^+\pi^-)/\Gamma(K_S \to \pi^+\pi^-)}{\Gamma(K_L \to \pi^0\pi^0)/\Gamma(K_S \to \pi^0\pi^0)}$$



$$\mathrm{Re}(\varepsilon'/\varepsilon) = (17.2 \pm 1.8) \times 10^{-4}$$

ε´ is not zero

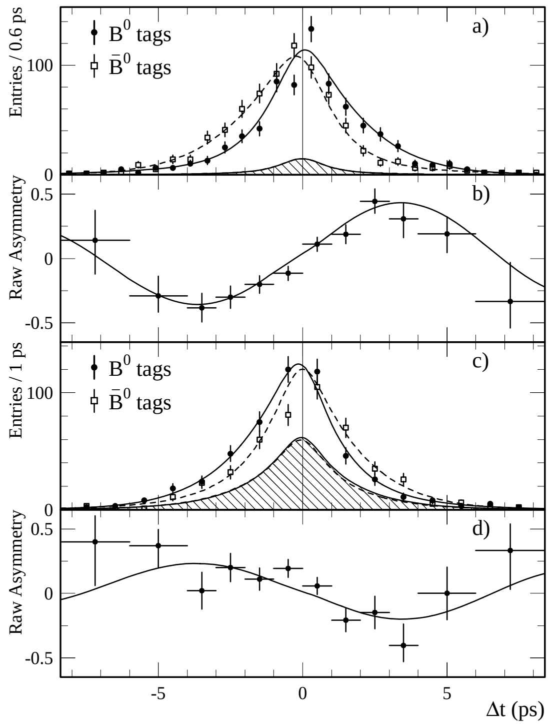
(hep-ex/0110020)

Recent CP-Violation Experiments

Neutral B-Meson System

Observation of CP-violation at CDF BaBar and Belle

$$A_{CP}(\Delta t) = \frac{f_+(\Delta t) - f_-(\Delta t)}{f_+(\Delta t) + f_-(\Delta t)} = -\eta_f \sin 2\beta \sin(\Delta m_d \Delta t)$$



BaBar: $\sin 2\beta = 0.741 \pm 0.067 \pm 0.034$

(hep-ex/0207042)

Belle: $\sin 2\beta = 0.719 \pm 0.074 \pm 0.035$

(hep-ex/0207098)

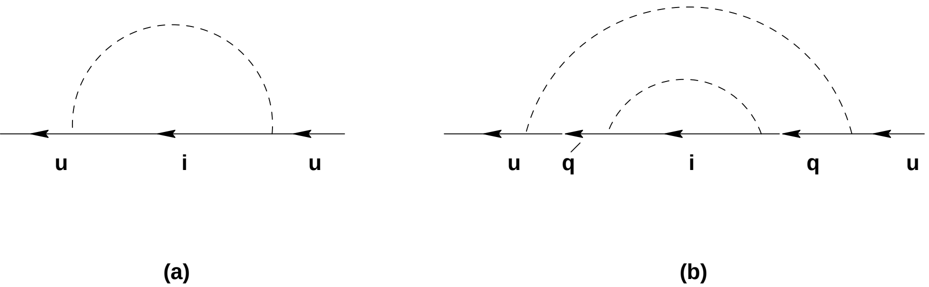
Neutron EDM → direct CP-violation in light-quark baryon system

Neutron EDM in Standard Model

1) Electroweak Process

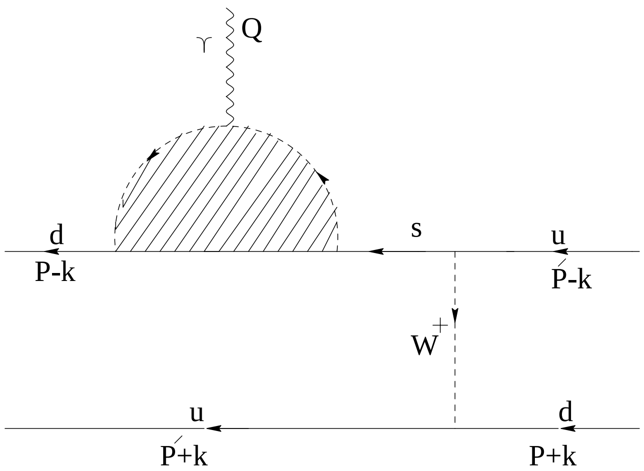
a) Contributions from single quark's EDM:

$$d_n \approx \frac{1}{3} d_u - \frac{4}{3} d_d$$



One and two-loop contributions are zero.
Three-loop contribution is ~10^{-34} *e•cm*

b) Contributions from diquark interactions:



$$d_n = \frac{38}{9\pi^3}(G_F m_N^2)^2 \frac{m_t^2}{m_s^2}\frac{m_N^2}{m_W^2}\frac{\Lambda}{m_N^4}\frac{e}{m_N}(\mathrm{Im}\,V)$$

$$\mathrm{Im}\,V = c_1 s_1^2 c_2 s_2 c_3 s_3 \sin(\delta)$$

$d_n \sim 10^{-32}$ *e•cm*

(hep-ph/0008248)

Neutron EDM in Standard Model

2) Strong Interaction

Θ term in the QCD Lagrangian :

$$L_\theta = \frac{\theta\, g_s^2}{32\pi^2} G_{\mu\nu} \widetilde{G}^{\mu\nu}$$

Θ term's contribution to the neutron EDM :

$$d_n = \frac{e}{m_p} \frac{g_{\pi NN} \overline{g}_{\pi NN}}{4\pi^2} \ln \frac{m_\rho}{m_\pi}$$

$$\overline{g}_{\pi NN} = -\theta \frac{m_u m_d}{m_u + m_d} \frac{\sqrt{2}}{f_\pi} \frac{M_\Xi - M_\Sigma}{m_s}$$

$d_n < 10^{-25}$ e•cm → $|\,\theta\,| < 3 \times 10^{-10}$

Spontaneously broken Pecci-Quinn symmetry?

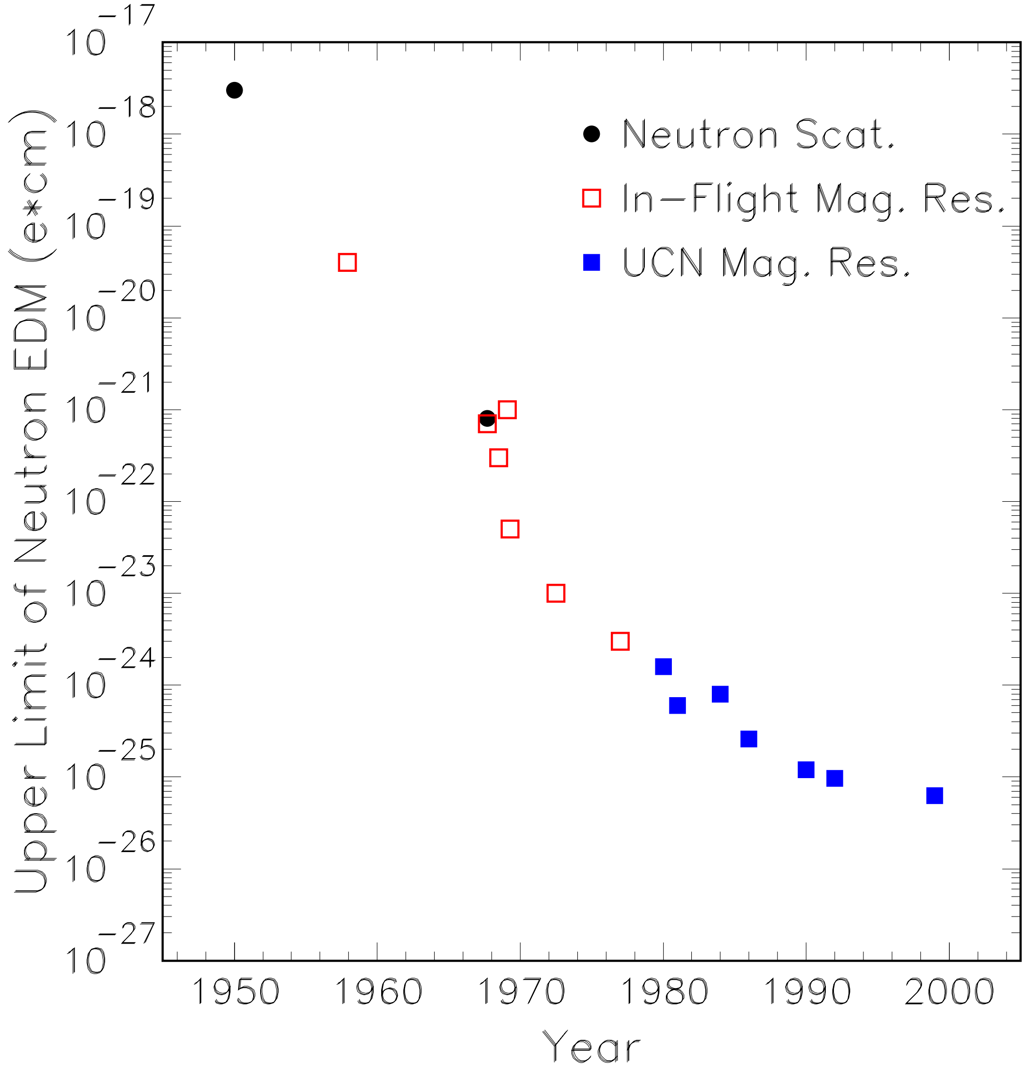
No evidence of a pseudoscalar axion!

Physics Motivation for Neutron EDM Measurement

- Time Reversal Violation
- CP Violation (in the light-quark baryon sector)
- Physics Beyond the Standard Model
  - Standard Model predicts $d_n \sim 10^{-31}$ e•cm
  - Super Symmetric Models predict $d_n \leqslant 10^{-25}$ e•cm
- Baryon Asymmetry of universe
  - Require CP violation beyond the SM

	SM Prediction	Experiment
e	10^{-40} e•cm	10^{-27} e•cm
μ	10^{-38} e•cm	10^{-19} e•cm
n	10^{-31} e•cm	10^{-25} e•cm

History of Neutron EDM Measurements



Current neutron EDM upper limit: < 6.3 x 10^{-26} e•cm (90% C.L.)

List of Neutron EDM Experiments

Ex. Type	<v>(m/cm)	E (kV/cm)	B (Gauss)	Coh. Time (s)	EDM (e.cm)	year
Scattering	2200	10^{25}	--	10^{-20}	$< 3 \times 10^{-18}$	1950
Beam Mag. Res.	2050	71.6	150	0.00077	$< 4 \times 10^{-20}$	1957
Beam Mag. Res.	60	140	9	0.014	$< 7 \times 10^{-22}$	1967
Bragg Reflection	2200	10^{9}	--	10^{-7}	$< 8 \times 10^{-22}$	1967
Beam Mag. Res.	130	140	9	0.00625	$< 3 \times 10^{-22}$	1968
Beam Mag. Res.	2200	50	1.5	0.0009	$< 1 \times 10^{-21}$	1969
Beam Mag. Res.	115	120	17	0.015	$< 5 \times 10^{-23}$	1969
Beam Mag. Res.	154	120	14	0.012	$< 1 \times 10^{-23}$	1973
Beam Mag. Res.	154	100	17	0.0125	$< 3 \times 10^{-24}$	1977
UCN Mag. Res.	<6.9	25	0.028	5	$< 1.6 \times 10^{-24}$	1980
UCN Mag. Res.	<6.9	20	0.025	5	$< 6 \times 10^{-25}$	1981
UCN Mag. Res.	<6.9	10	0.01	60-80	$< 8 \times 10^{-25}$	1984
UCN Mag. Res.	<6.9	12-15	0.025	50-55	$< 2.6 \times 10^{-25}$	1986
UCN Mag. Res.	<6.9	16	0.01	70	$< 12 \times 10^{-26}$	1990
UCN Mag. Res.	<6.9	12-15	0.018	70-100	$< 9.7 \times 10^{-26}$	1992
UCN Mag. Res.	<6.9	4.5	0.01	120-150	$< 6.3 \times 10^{-26}$	1999

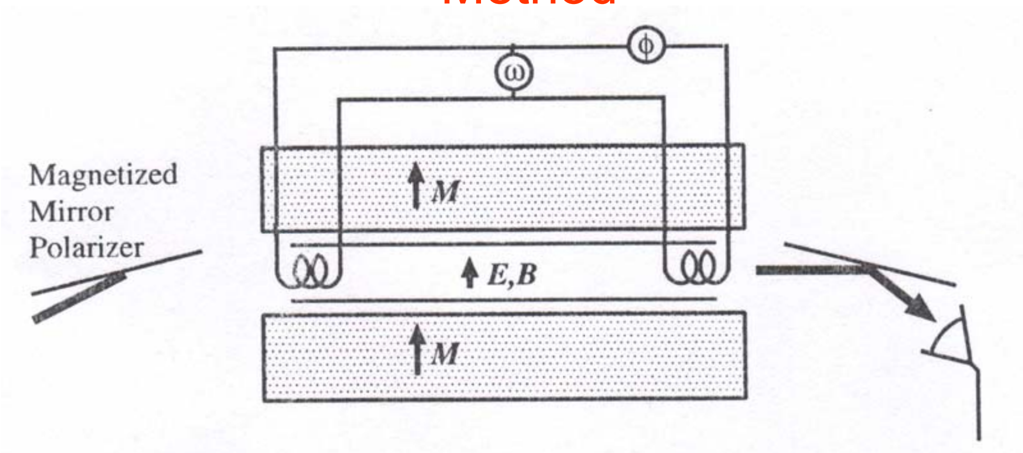
$$H = -\vec{\mu} \cdot \vec{B} \pm \vec{d} \cdot \vec{E}$$

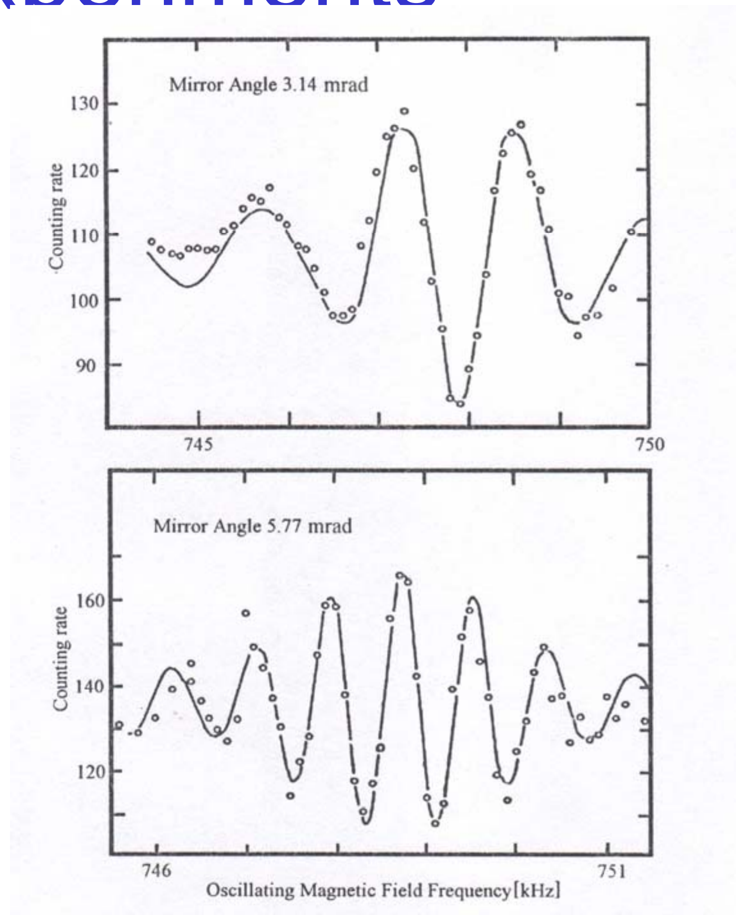
B = 1mG => 3 Hz neutron precession freq.

d = 10^{-26} e•cm, E = 10 KV/cm => 10^{-7} Hz shift in precession freq.

Neutron Beam EDM Experiments

Ramsey's Separated Oscillatory Field Method





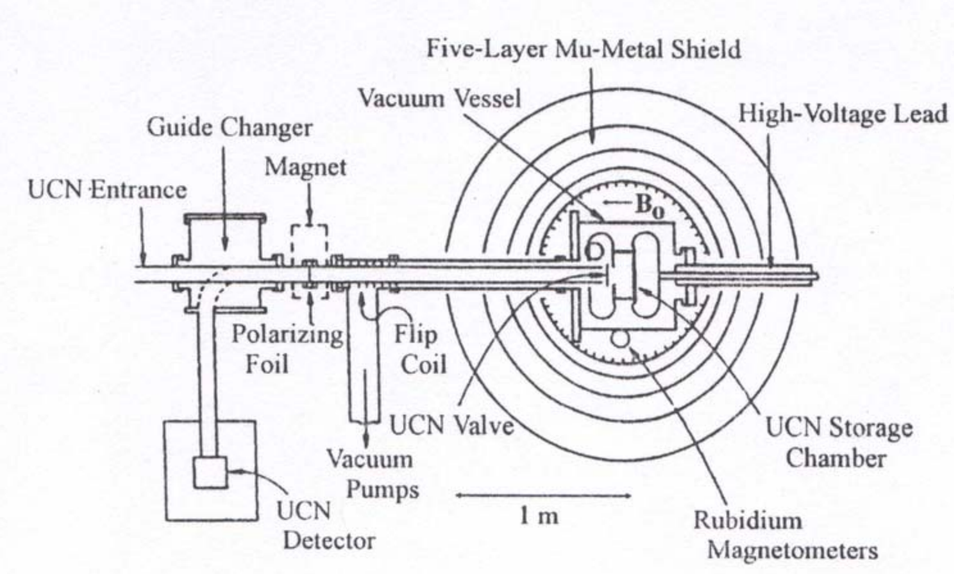
Limitations:

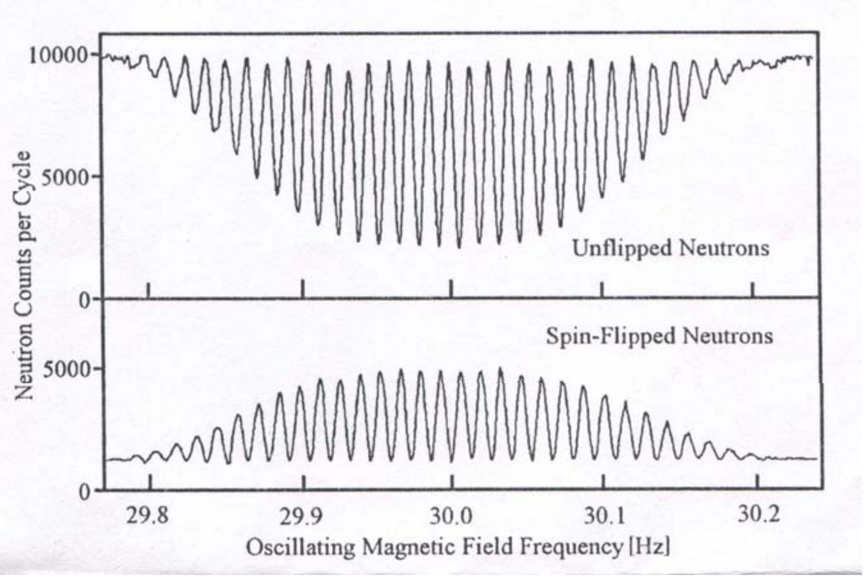
- Short duration between the two RF pulses
- Systematic error due to motional magnetic field (v x E)

Both can be improved using lower-energy neutrons

Neutron EDM Experiment with Ultra Cold Neutrons

Most Recent ILL Measurement

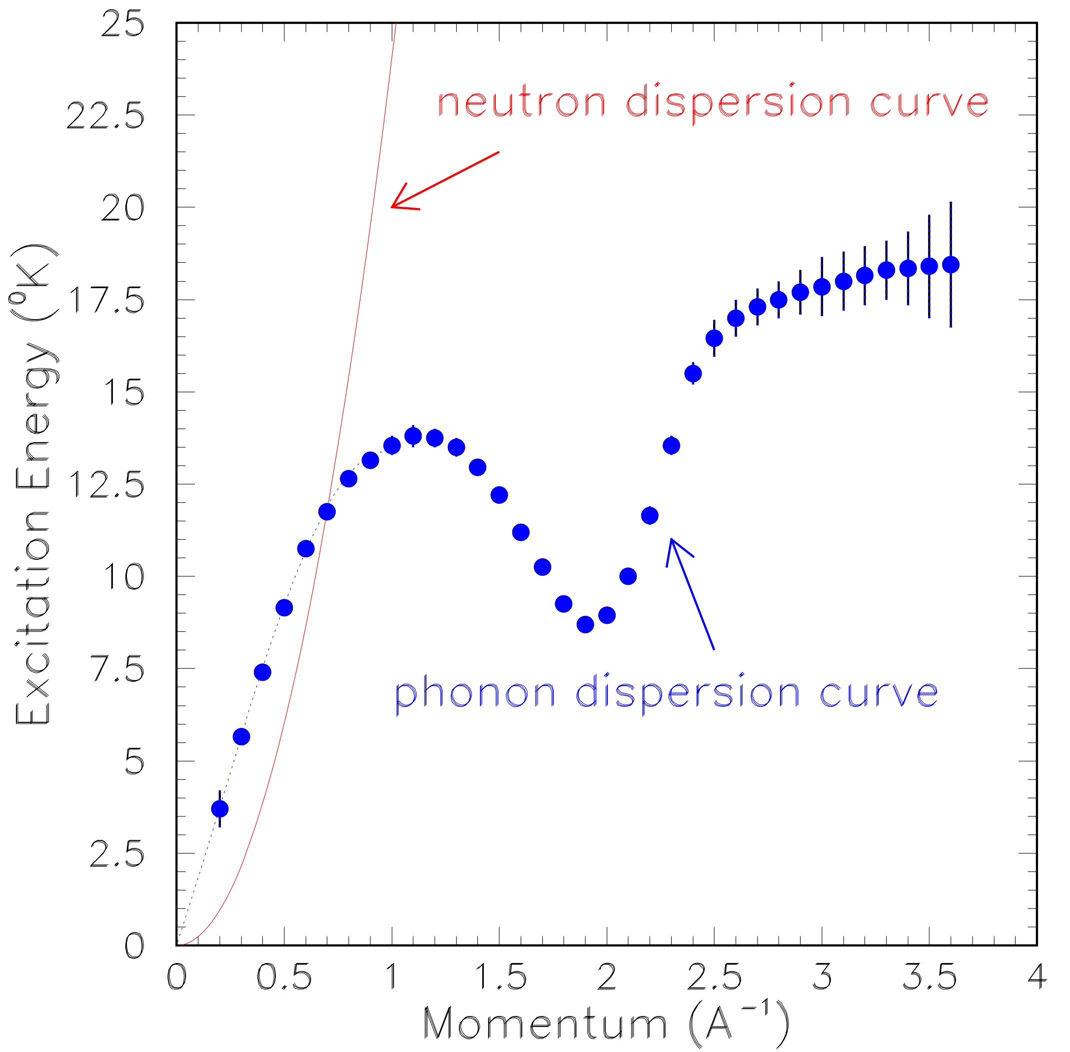




- Use ^{199}Hg co-magnetometer to sample the variation of B-field in the UCN storage cell
- Limited by low UCN flux of ~ 5 UCN/cm^3
- Figure–of-merit ~ $E(N\,T)^{1/2}$

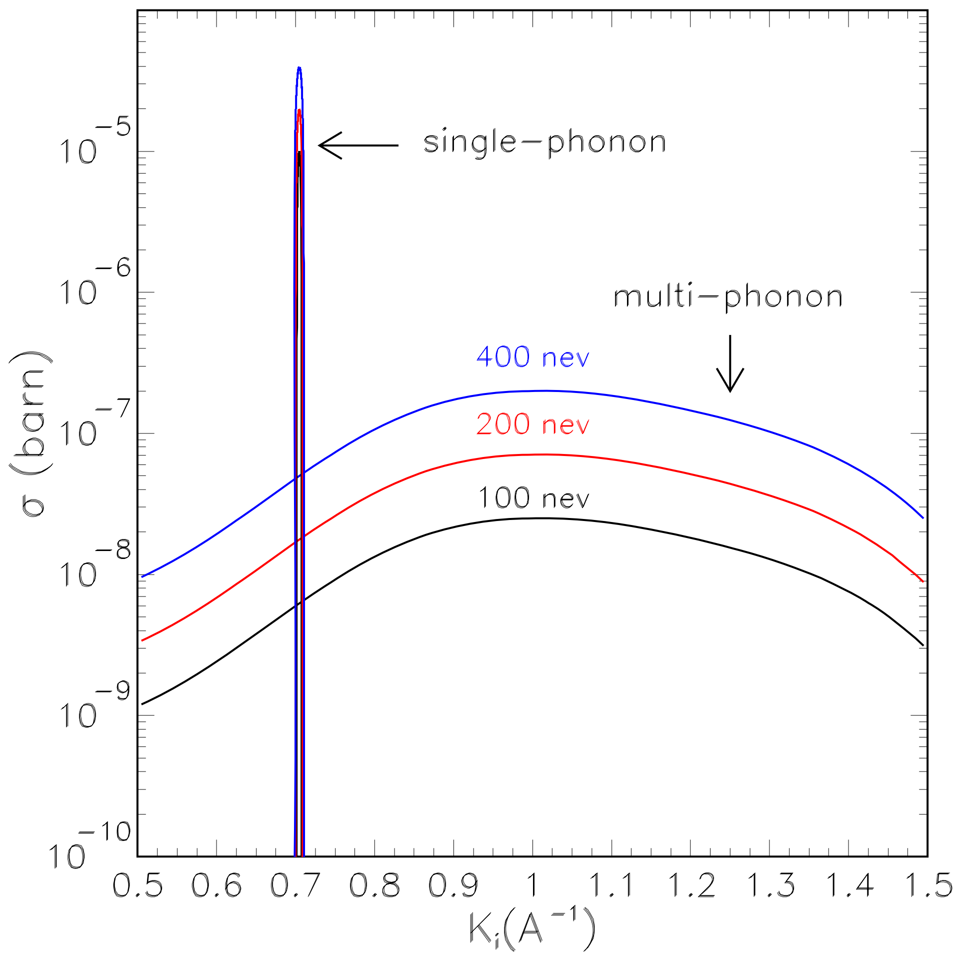
A new approach aims at $N \rightarrow 100\,N$, $T \rightarrow 5\,T$, $E \rightarrow 5\,E$

UCN Production in Superfluid ^{4}He



Incident cold neutron with momentum of 0.7 A^{-1} (1 mev) can excite a phonon in ^{4}He and become an UCN

UCN Production Cross Sections for Single and Multi-Phonon Processes

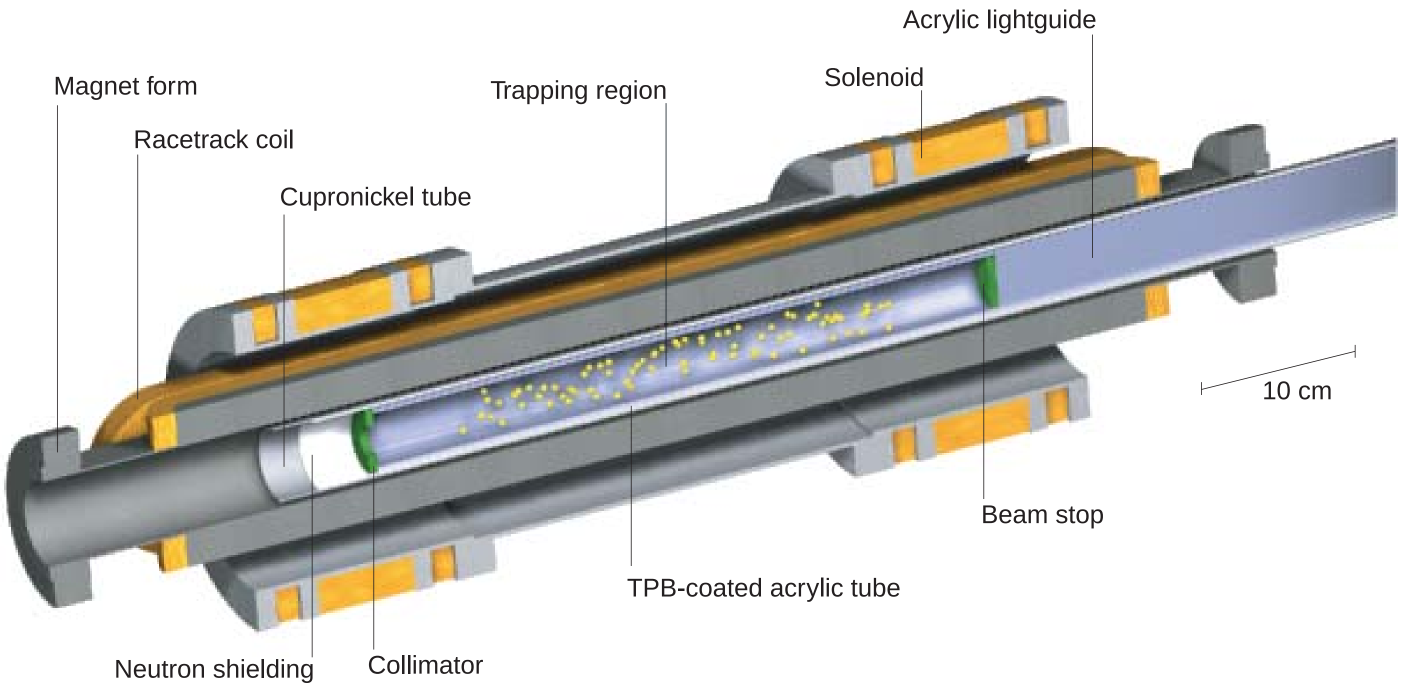


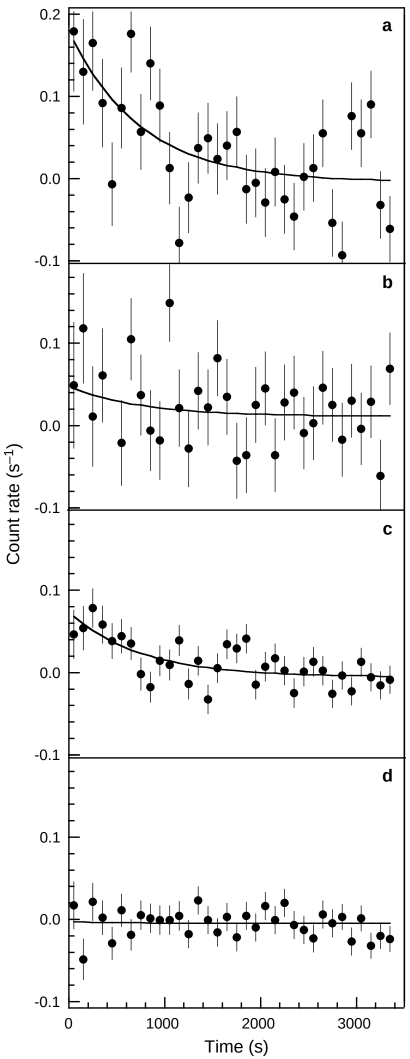
Multi-phonon process can contribute an additional ~ 40% of the UCN yields

UCN Production in Superfluid ^{4}He

Magnetic Trapping of UCN

(Nature 403 (2000) 62)





560 ± 160 UCNs trapped per cycle (observed)

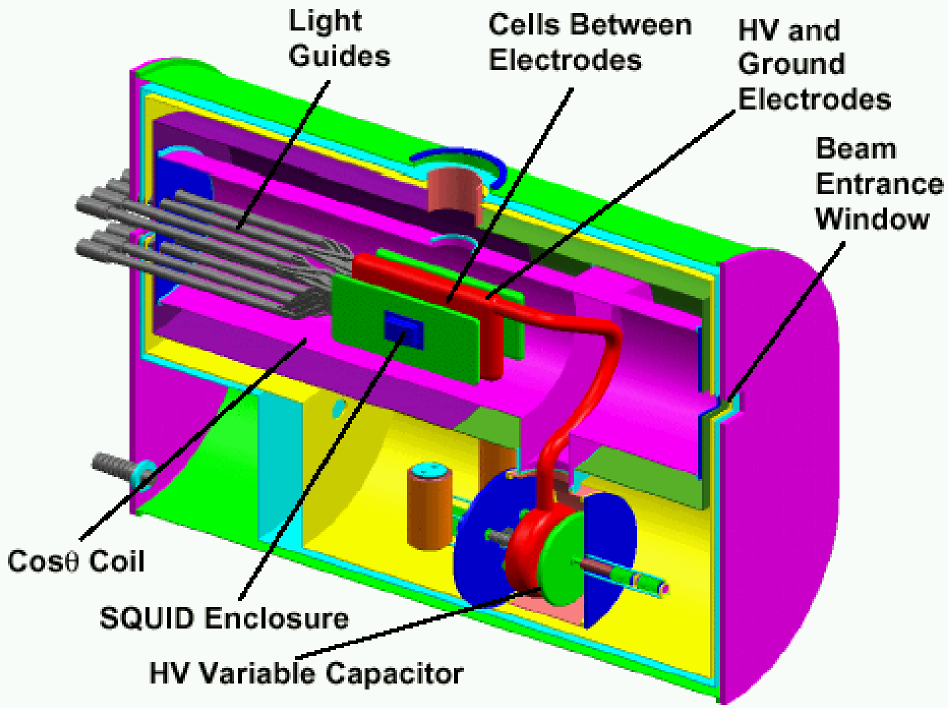
480 ± 100 UCNs trapped per cycle (predicted)

UCN Losses in Superfluid ^{4}He Bottle

- Neutron beta decay
- Wall absorption
- Upscattering in superfluid ^{4}He
  - Single-phonon upscaatering rate ~ $e^{-1/KT}$
  - Multi-phonon upscattering rate ~ T^7
- n – ^{3}He absorption
  - Require purified ^{4}He with ^{3}He/^{4}He < 10^{-11}

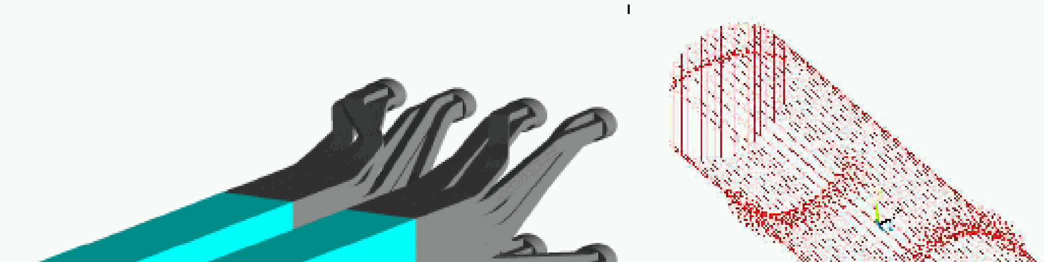
$$n + {}^3He \rightarrow p + t + 764\,KeV$$

Total spin	σ_{abs} at v = 5m/sec
J = 0	~ 4.8 x 10^6 barns
J = 1	~ 0



(Based on the idea originated by R. Golub and S. Lamoreaux in 1994)

Fig. V.E.1 Design features of the central part of the apparatus including the two neutron / ^{3}He cells and the surrounding static electric field electrodes and the magnetic field Cos Θ coil.

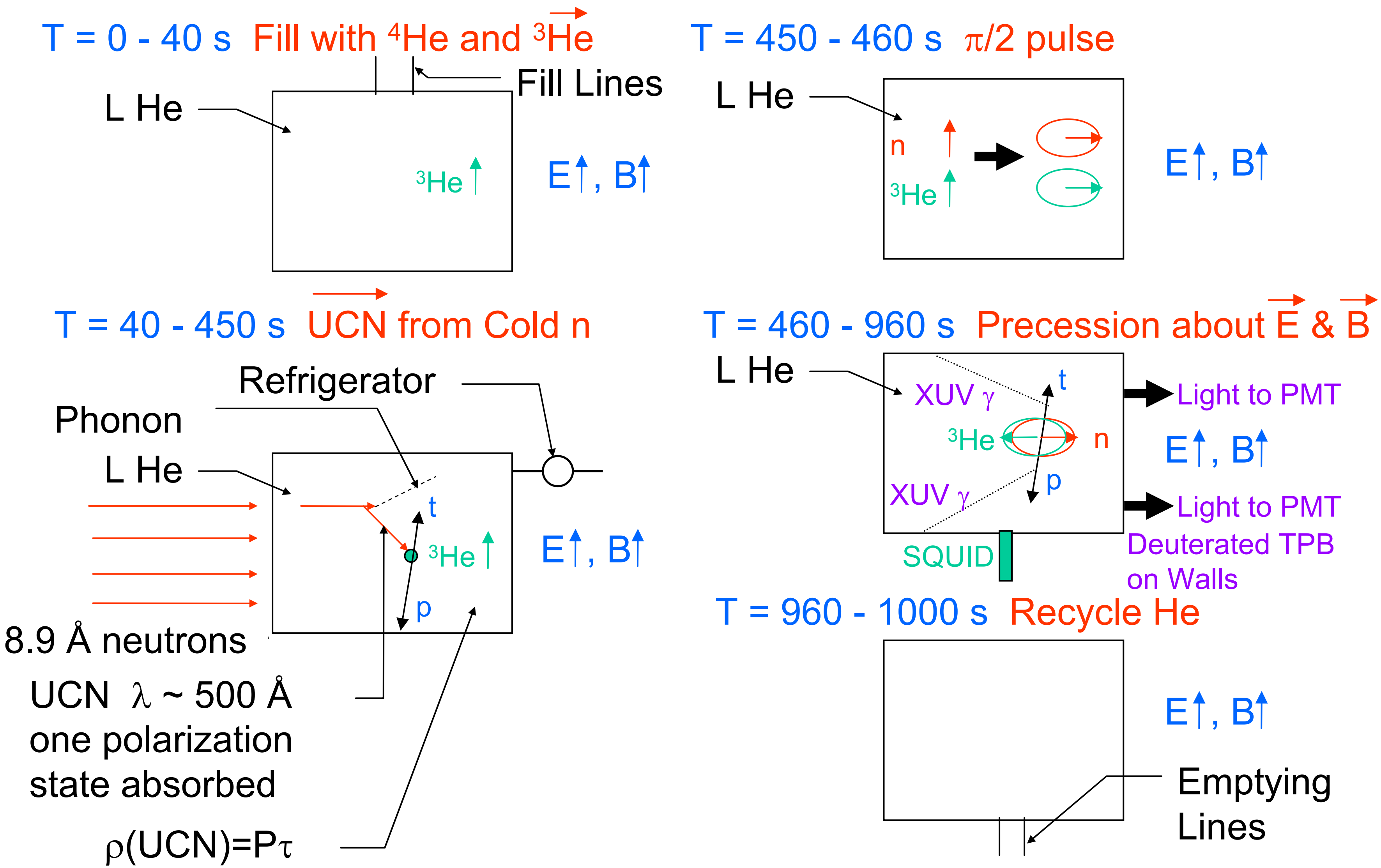


Neutron EDM Measurement Cycle

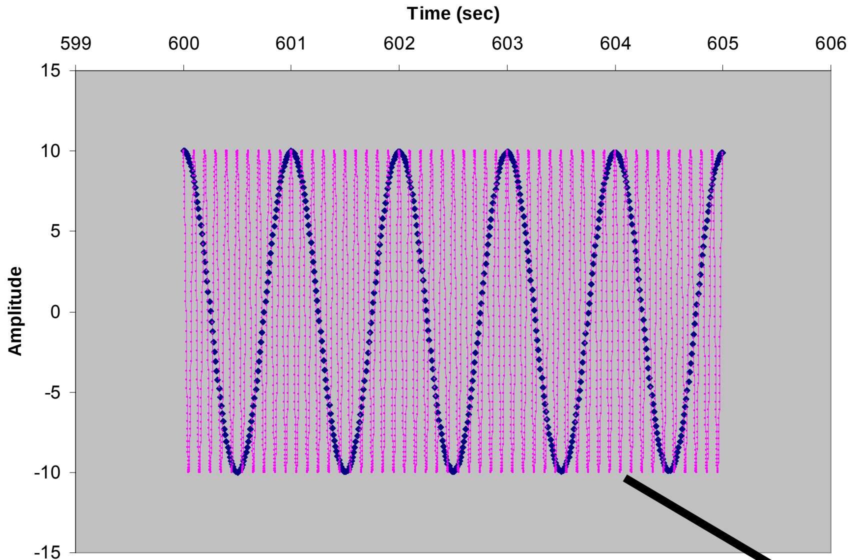
- Fill cells with superfluid ^{4}He containing polarized ^{3}He
- Produce polarized UCNs with polarized cold neutron beam
- Flip n and ^{3}He spin by 90^o using a $\pi/2$ RF coil
- Precess UCN and ^{3}He in a uniform B field (~1mG) and a strong E field (~50KV/cm). ($\nu(^3$He) ~ 3.3 Hz, ν(n) ~ 3 Hz)
- Detect scintillation light from the reaction n + ^{3}He → p + t (and from other sources, including neutron beta decays)
- Empty the cells and change E field direction and repeat the measurement

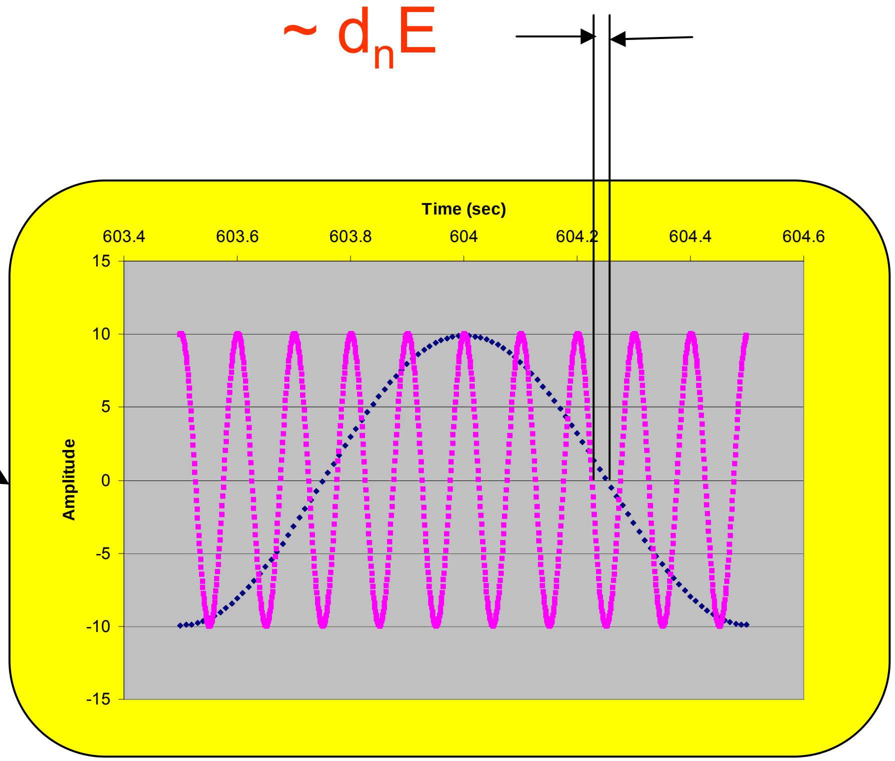
$$\phi(t) = Ne^{-\Gamma_{tot}t}\{\frac{1}{\tau_\beta} + \frac{1}{\tau_3}[1 - P_3 P_n \cos(\omega_r t + \phi)]\}$$

EXPERIMENT CYCLE



THE SIGNAL





^{3}He(n,p)t Scintillation Light

$\nu \sim (\gamma_3 - \gamma_n)$

SQUID $\nu \sim \gamma_3$

Dressed Spin in Neutron EDM

- Neutrons and ^3He naturally precess at different frequencies (different g factors)
- Applying an RF field perpendicular to the constant B field, the effective g factors of neutrons and ^3He will be modified (dressed spin effect)
- At a critical dressing field, the effective g factors of neutron and 3He can be made identical !

Critical dressing of neutrons and ^{3}He

Reduce the danger of B_0 instability between measurements

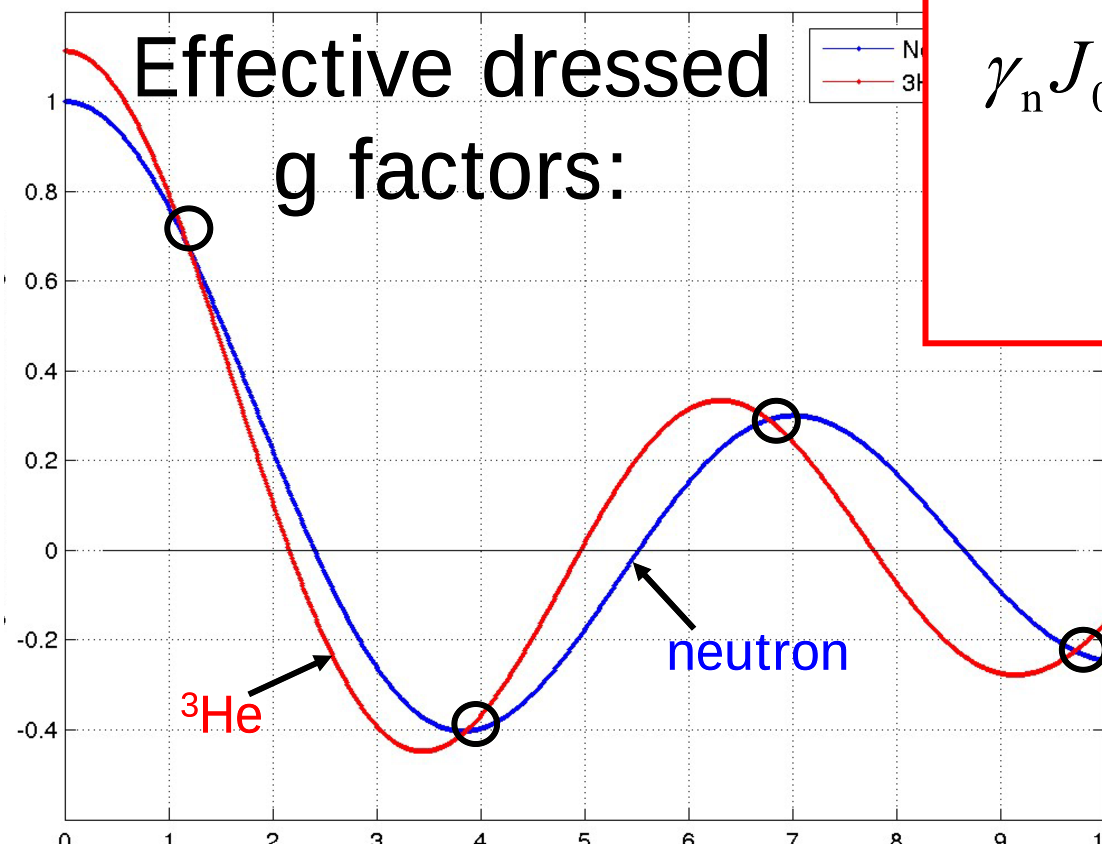
Crossing points equalize neutron and ^{3}He g factors:

$$g_{\text{neutron}} = g_{3\text{He}}$$

$$\gamma_{\text{n}} J_0\left(\frac{\gamma_{\text{n}} B_1}{\omega}\right) = g_3 J_0\left(\frac{\gamma_3 B_1}{\omega}\right)$$

$$J_0(x_c) = \alpha J_0(\alpha x_c)$$

Effective dressed g factors:

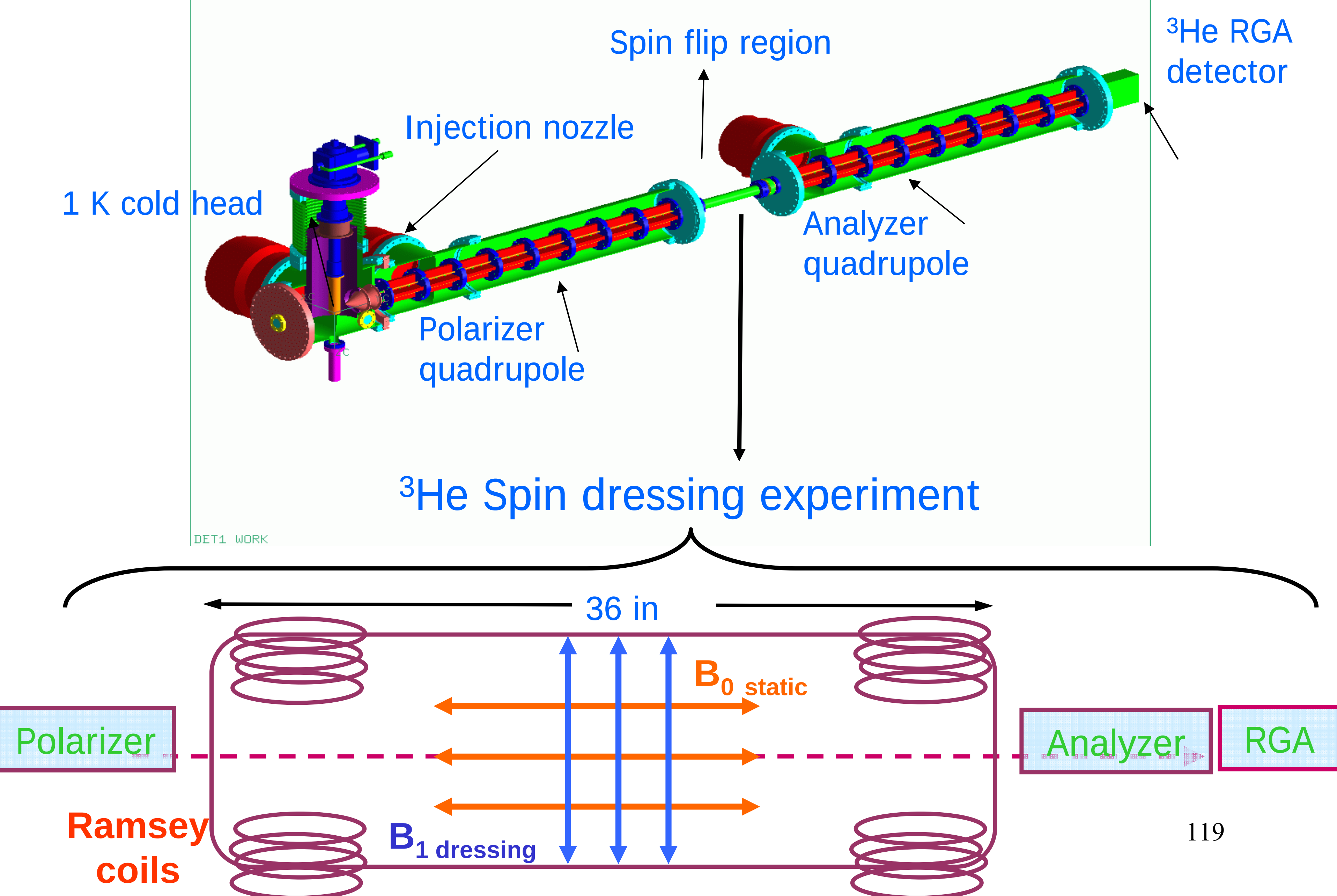


$$x = \gamma_{\text{n}} B_1 / \omega$$

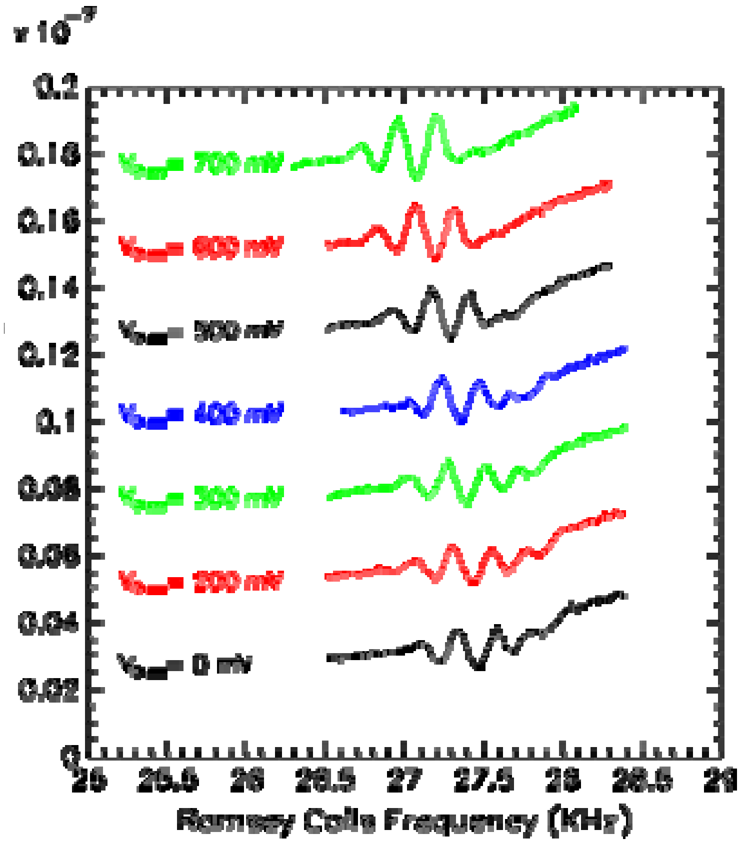
x_c	B_1
1.19	0.408
3.86	1.324
6.77	3.333
9.72	4.348

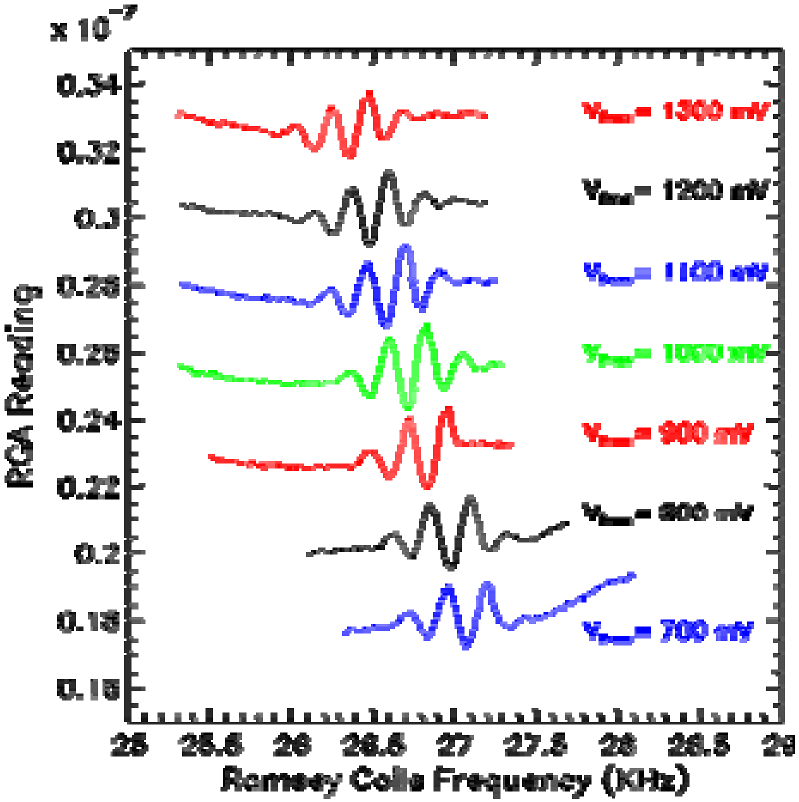
$\alpha = 1.1127$

Los Alamos Polarized ^{3}He Source



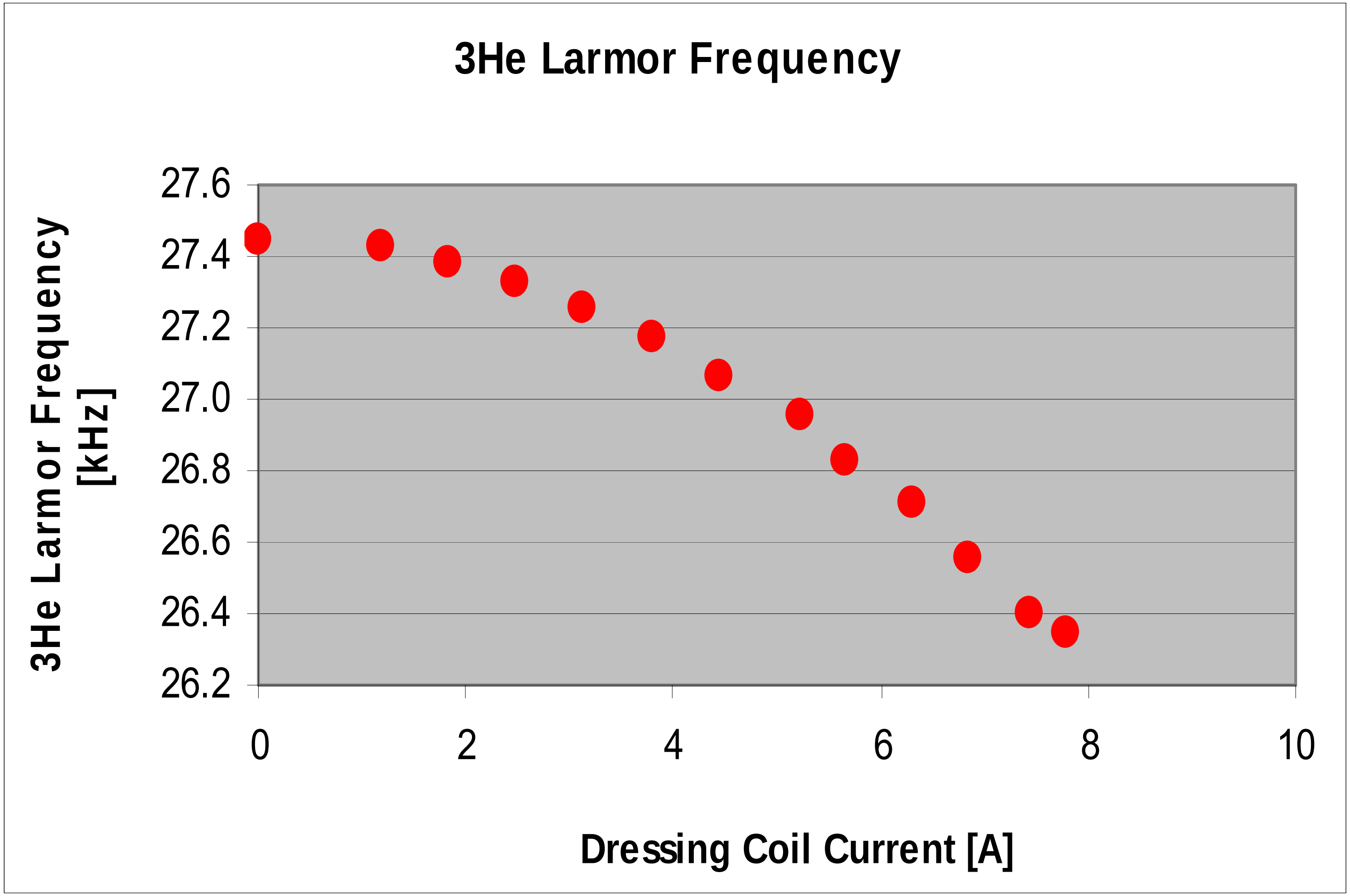
First observation of ^{3}He dressed-Spin Effect



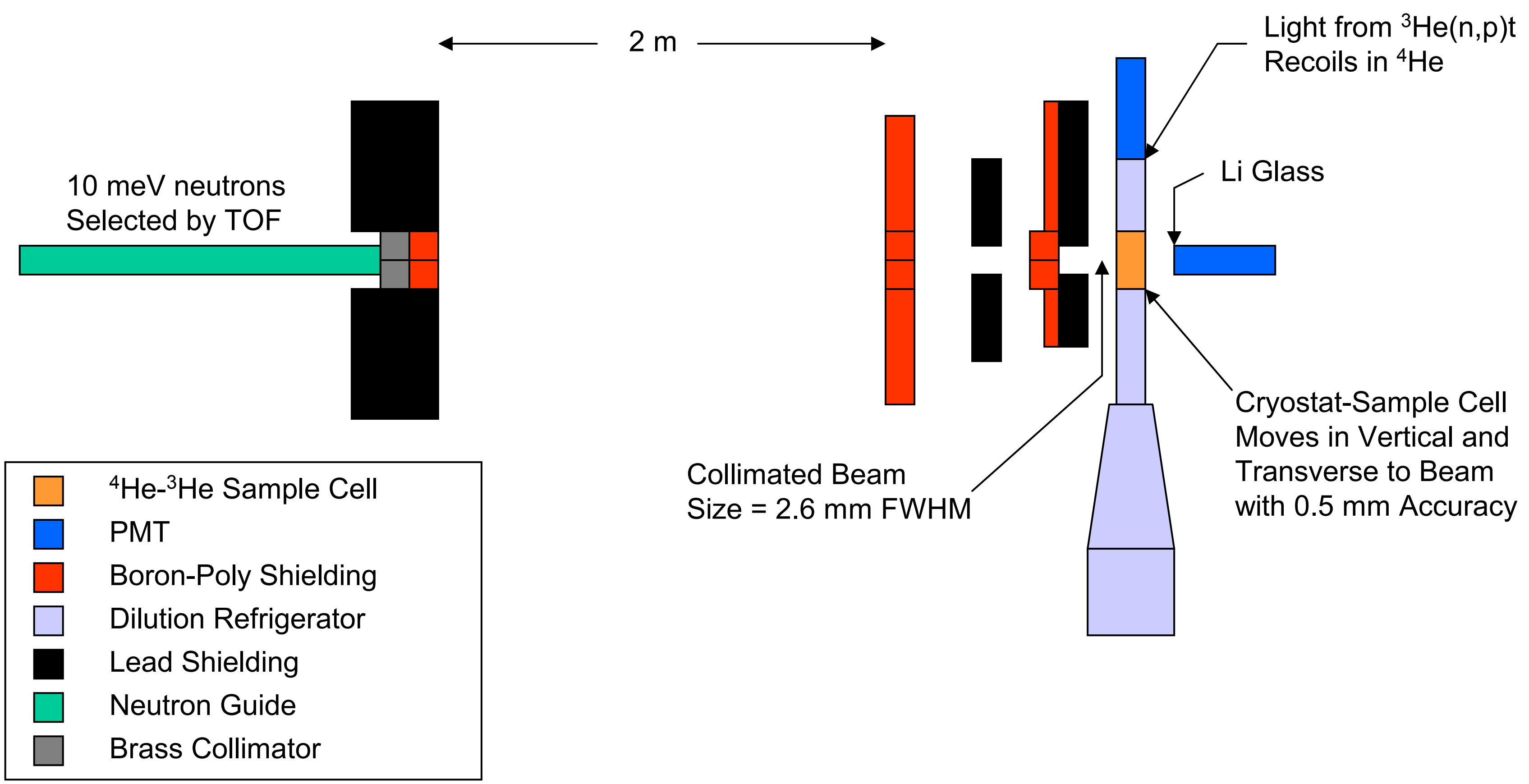


Dressing field 43.5 kHz

Dependence of ^{3}He precession on dressing field

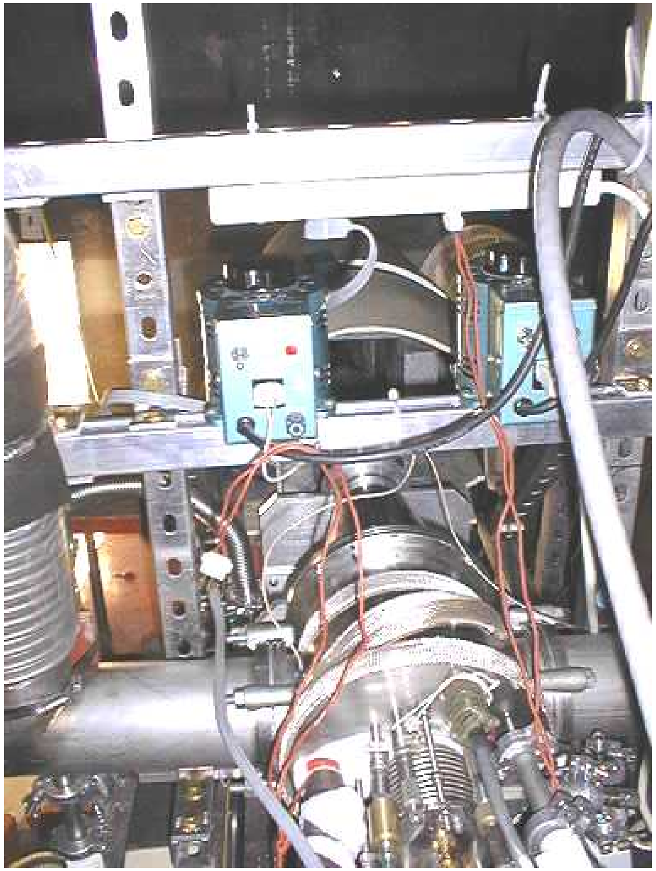


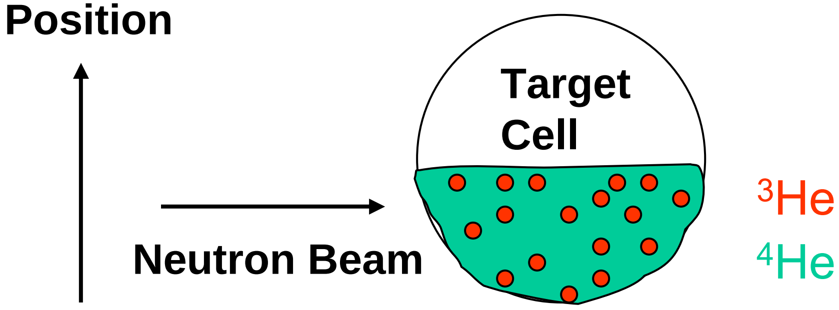
EXPERIMENTAL LAYOUT
LANSCE FP 11a

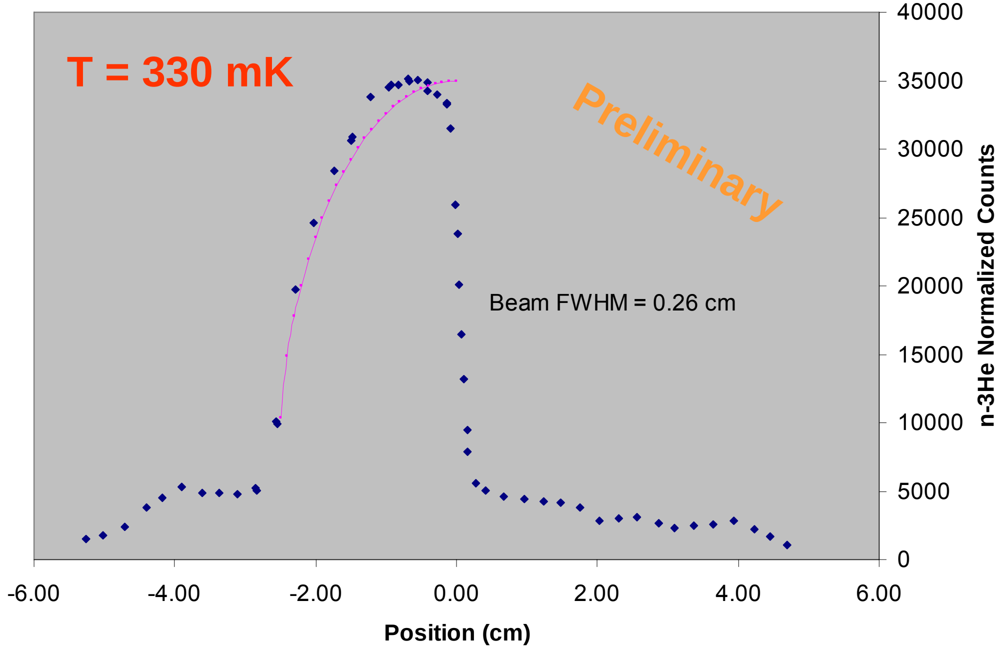


^{3}He Distributions in Superfluid ^{4}He

Dilution Refrigerator at LANSCE Flight Path 11a

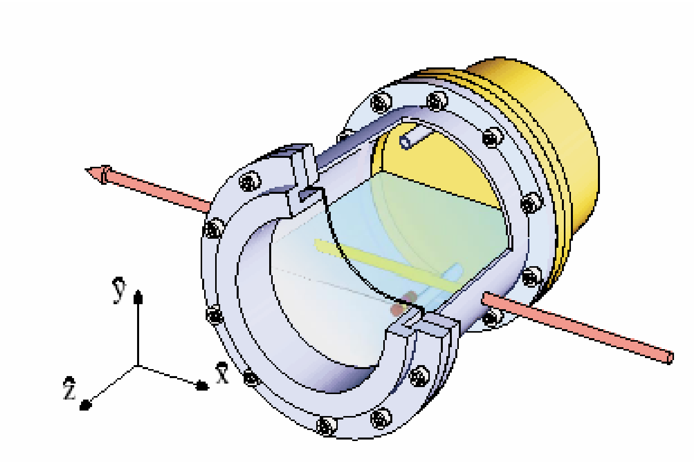


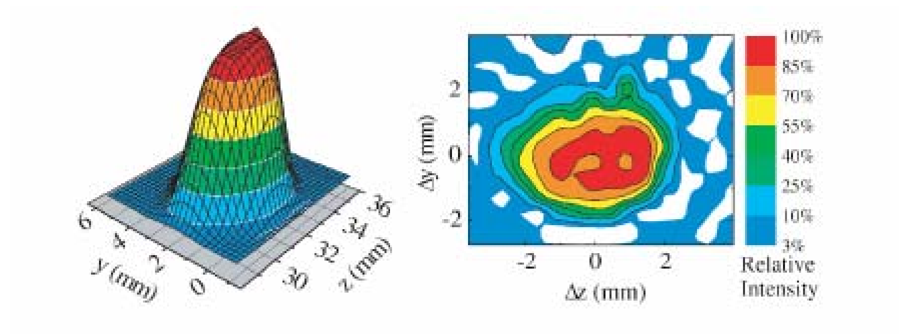


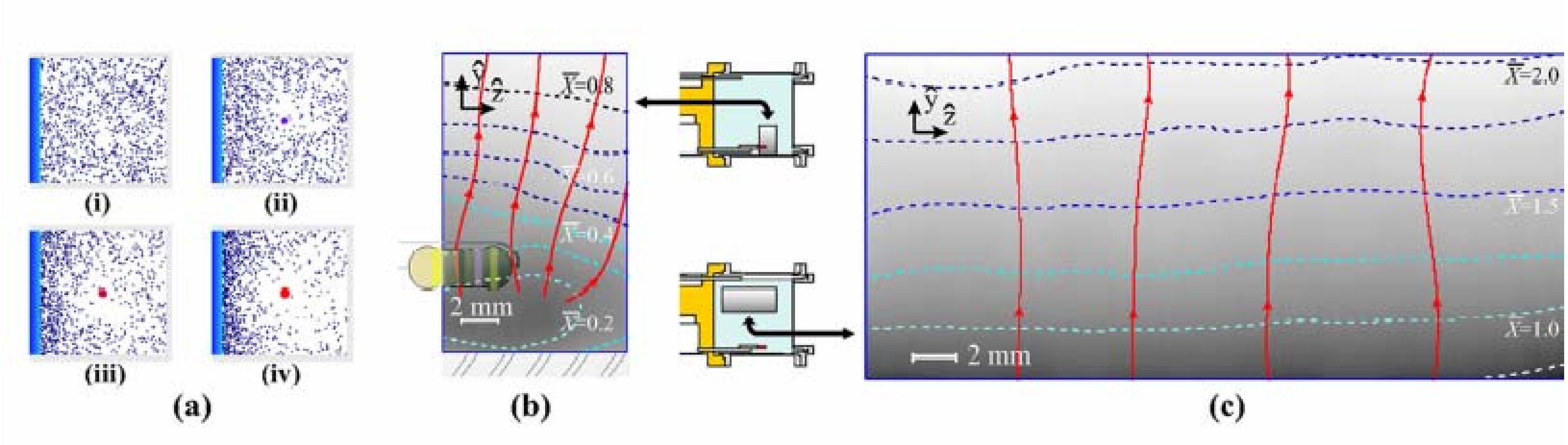


Physica B329-333, 236 (2003)

Neutron Tomography of Impurity-Seeded Superfluid Helium

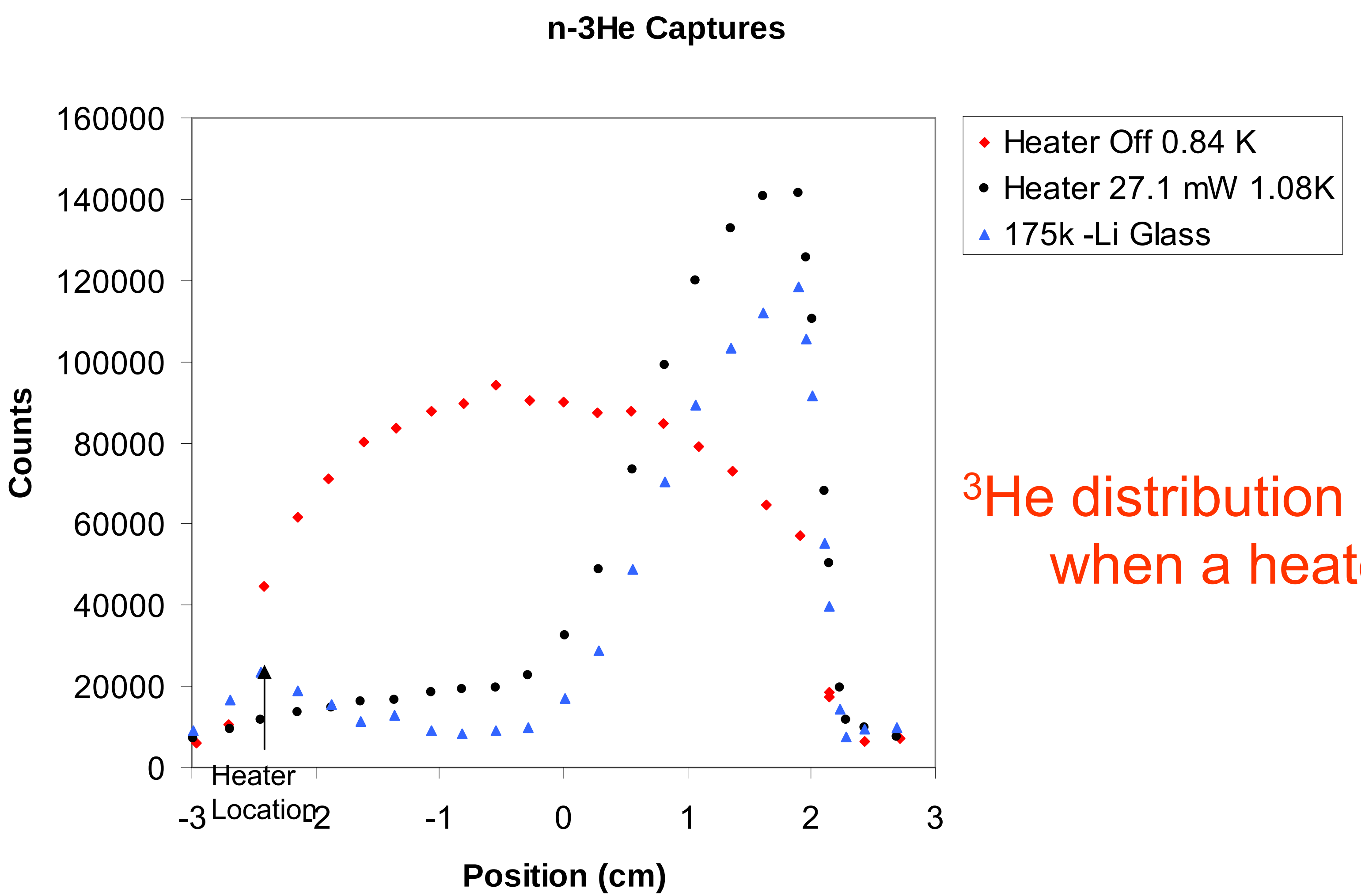






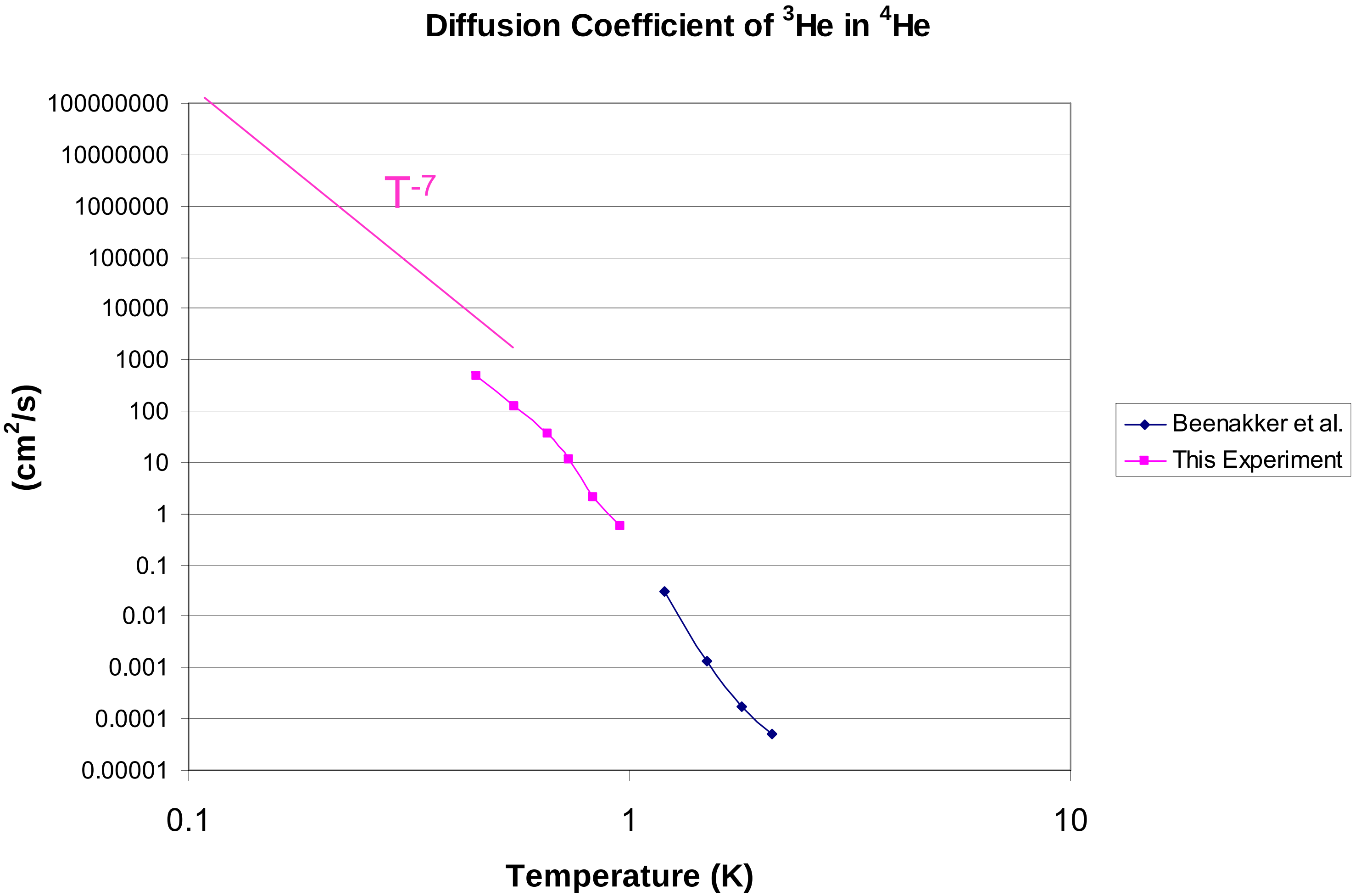
Phys. Rev. Lett. 93, 105302 (2004)

HEAT EFFECTS



^{3}He distribution is modified when a heater is on

Temperature Dependence of ^{3}He Diffusion Coefficient in ^{4}He



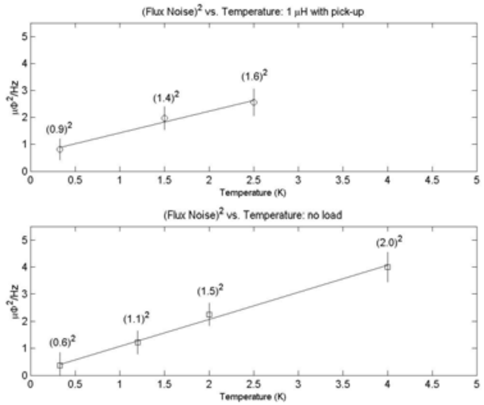
Europhysics Letters 58, 781 (2002).

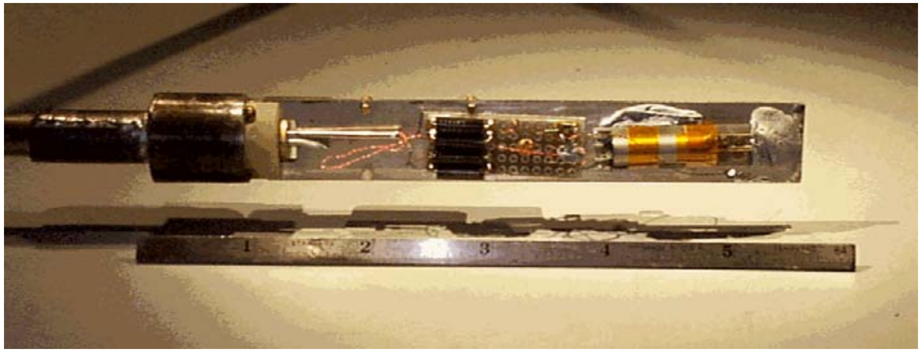
SQUIDs

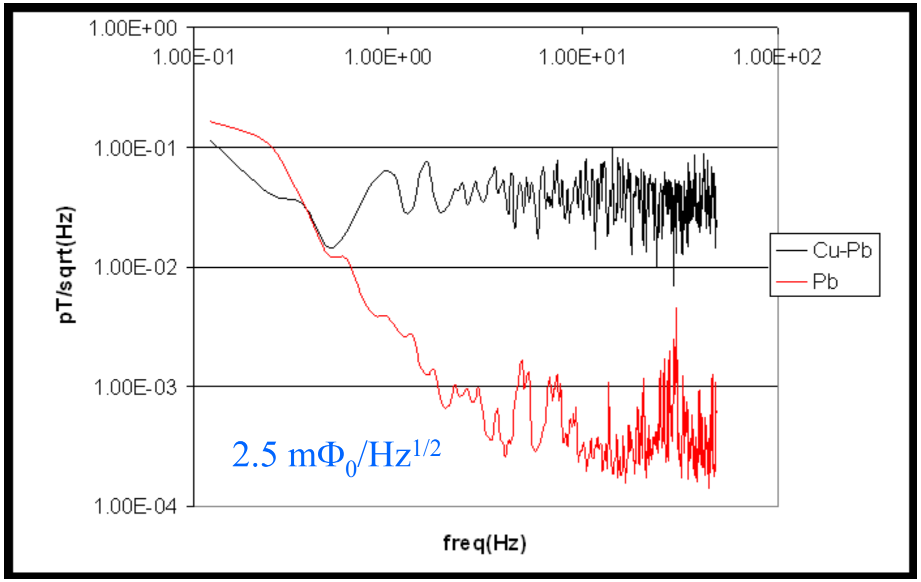
M. Espy, A. Matlachov ~100 cm^2 superconducting pickup coil

Flux = 2 x 10^{-16} Tm^2 = 0.1 Φ_0

Noise = 4 mΦ_0/Hz$^{1/2}$ at 10 Hz ~ $T^{1/2}$



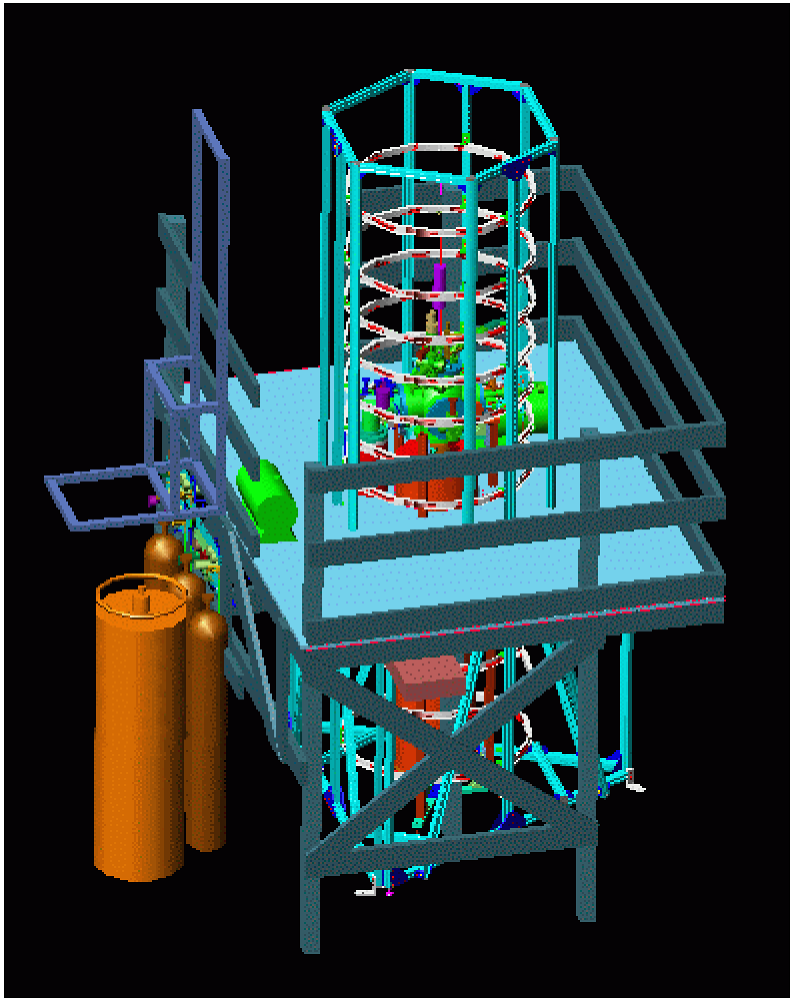




Some Critical Tests to be Performed

- Neutron storage time in superfluid ^{3}He
  - A test run is scheduled at NIST Nov. – Dec. 2003
- High voltage stability above 30 kV/cm
  - Being tested at Los Alamos
- Suppression of beta and gamma background with PID
  - To be tested during the NIST run
- ^{3}He spin relaxation time in the cell
  - Being tested at Duke and at UIUC

UIUC Test Apparatus for Polarized ^{3}He Relaxation at 600 mK



Summary

- Neutron EDM measurement addresses fundamental questions in physics and cosmology .
- A new collaboration is formed to explore the feasibility of a new approach using UCN production in superfluid helium and polarized ^{3}He as co-magnetometer and analyser.
- The goal of the proposed measurement is to improve the current neutron EDM sensitivity by two orders of magnitude.
- Several tests have been carried out. Additional feasibility studies are being performed at several institutes. A full proposal will be submitted in 2004.