STRUCTURE FUNCTIONS – STATUS AND PROSPECTS

Jen-Chieh Peng
University of Illinois at Urbana-Champaign
CIPANP 2003, New York City, May 19 - 24, 2003

① Flavor Structure

flavor dependence of proton distribution functions

② High $\rightarrow$ Low Q^2 Transition

quark-hadron duality and generalized GDH sum rule

③ Transversity

novel distribution and fragmentation functions

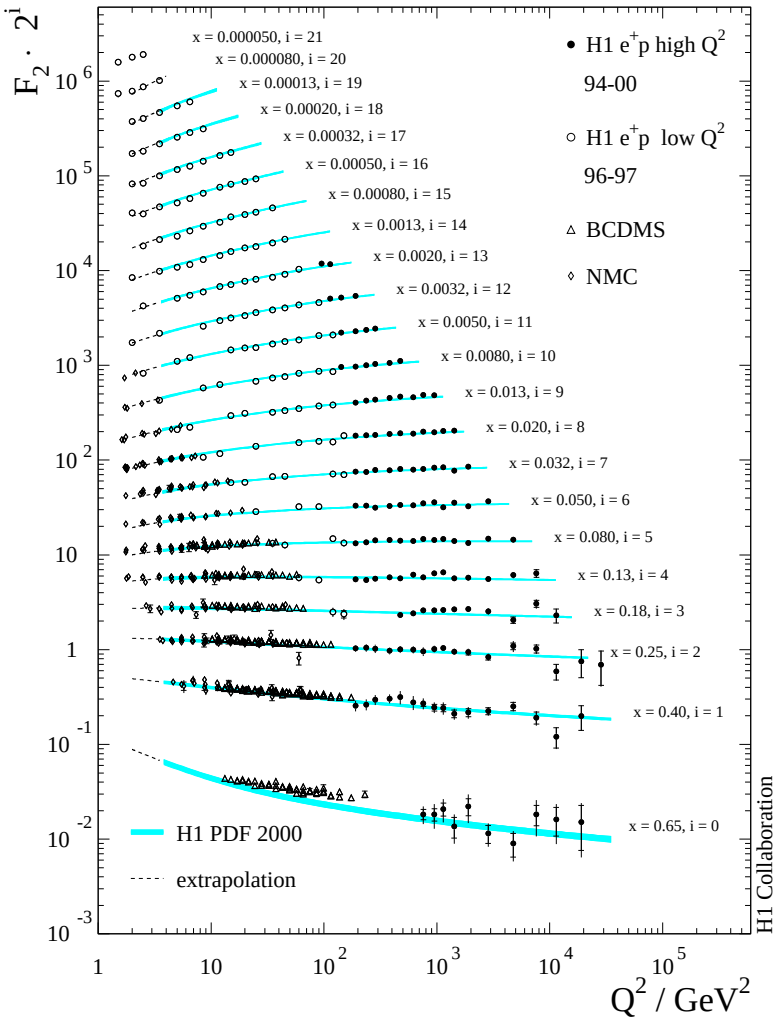
④ Generalized Parton Distributions

mapping out the proton wavefunction

Structure Functions: Why Bother?

Proton Structure Function

$F_2(x, Q^2)$



hep-ex/0304003

Important features:

- Perturbative and non-perturbative QCD
- Essential input for all hard processes

Challenges:

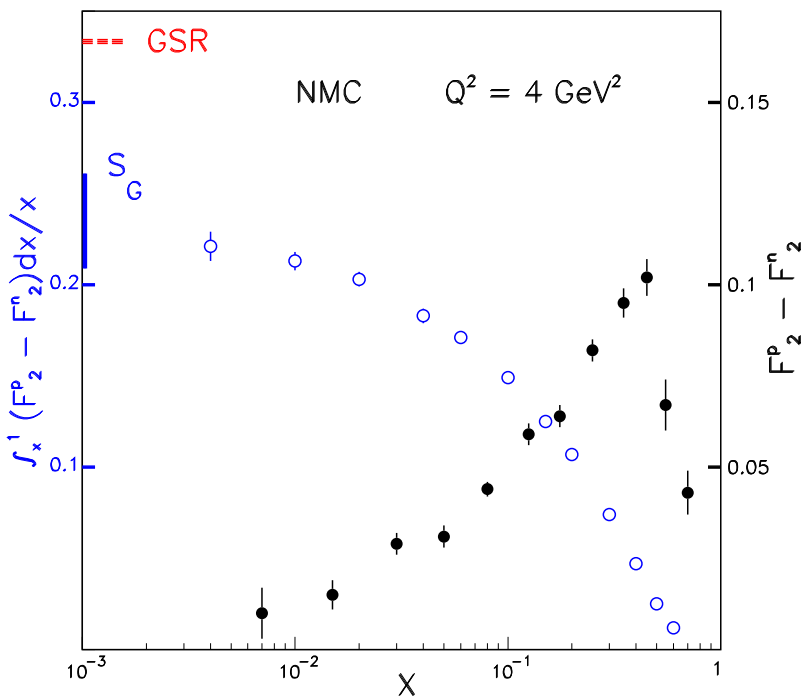
- Spin and flavor structure
- Small and large x behavior
- Transition from high-Q^2 to low-Q^2
- New types of structure functions and fragmentation functions
- Models and lattice calculations for PDFs

Flavor Structure of the Nucleon Sea

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

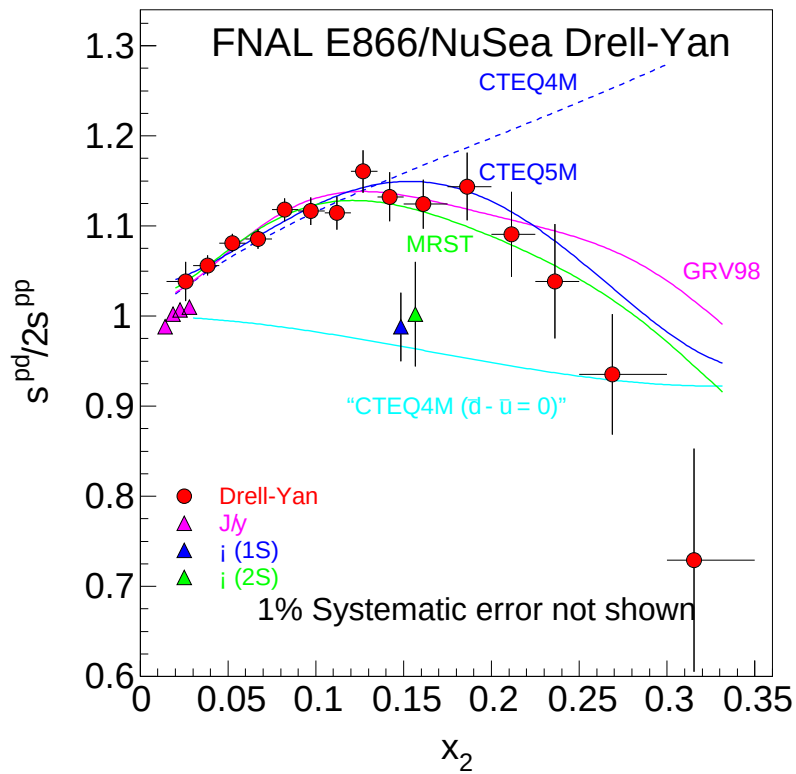
$$S_G = \int_0^1 (F_2^p(x) - F_2^n(x))/x \, dx = \frac{1}{3} \quad \text{(if } \bar{u} = \bar{d}\text{)}$$

Violation of the Gottfried Sum Rule observed by NMC



$$S_G = 0.235 \pm 0.026$$

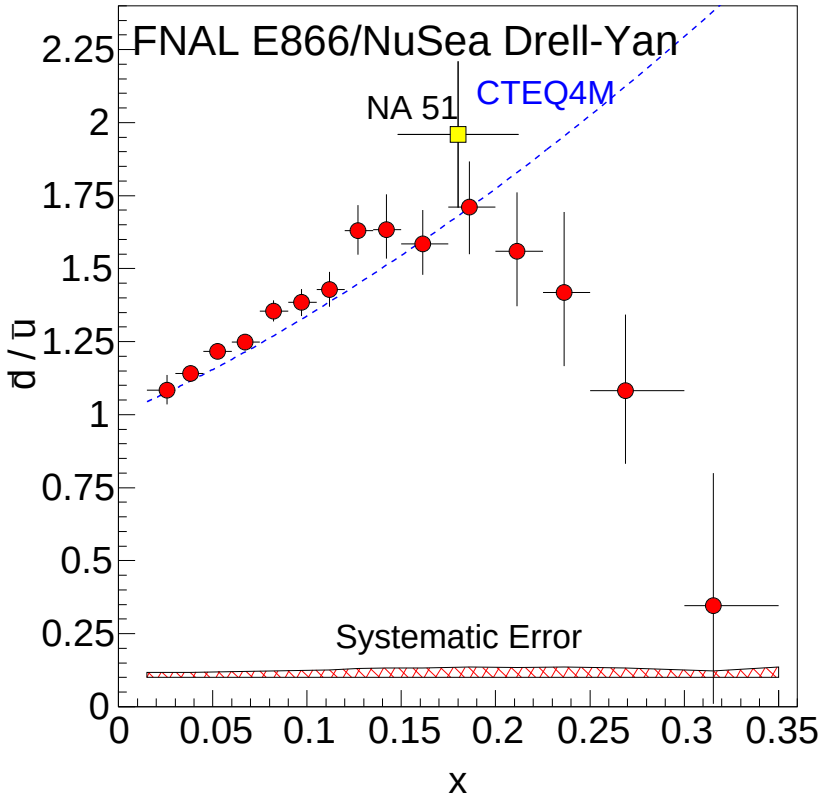
$\bar{d}/\bar{u}$ flavor asymmetry confirmed in Drell-Yan experiments



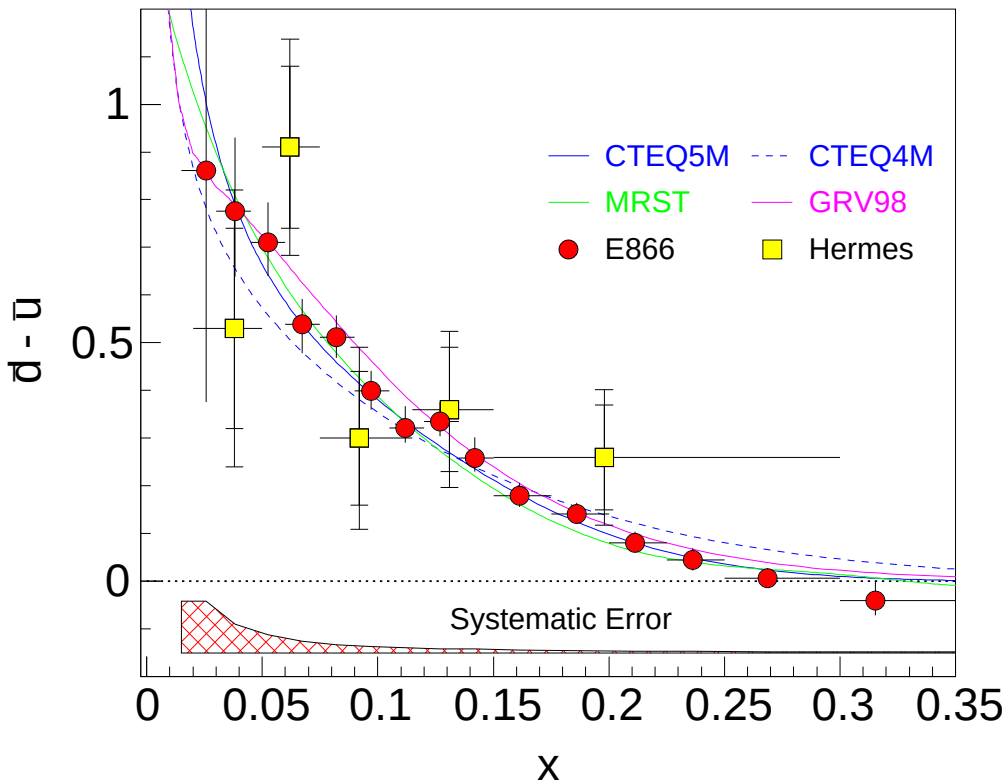
hep-ex/0103030

Flavor Structure of the Nucleon Sea

x-dependence of $\bar{d}/\bar{u}$



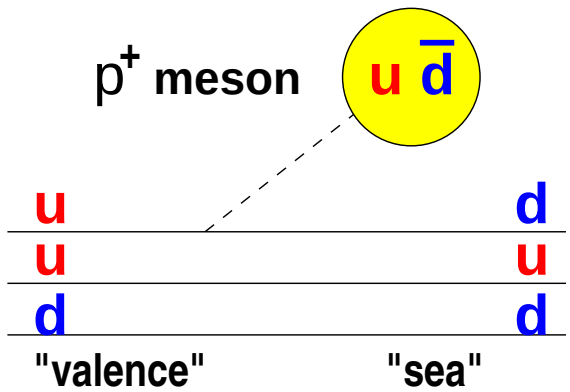
x-dependence of $\bar{d} - \bar{u}$



Several proposals to extend the measurements of $\bar{d}/\bar{u}$ to larger x

Flavor Structure of the Proton Sea

Meson Cloud Models

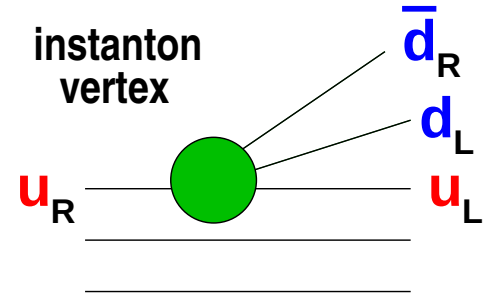


Quark sea from cloud of 0^- mesons: $\bar{d} > \bar{u}$

Chiral-Quark Soliton Model

- quark degrees of freedom in a pion mean-field
- nucleon = chiral soliton
- one parameter: dynamically-generated quark mass
- expand in $1/N_c$: $\bar{d} > \bar{u}$

Instantons



'tHooft instanton vertex $\sim \bar{u}_R u_L \bar{d}_R d_L$

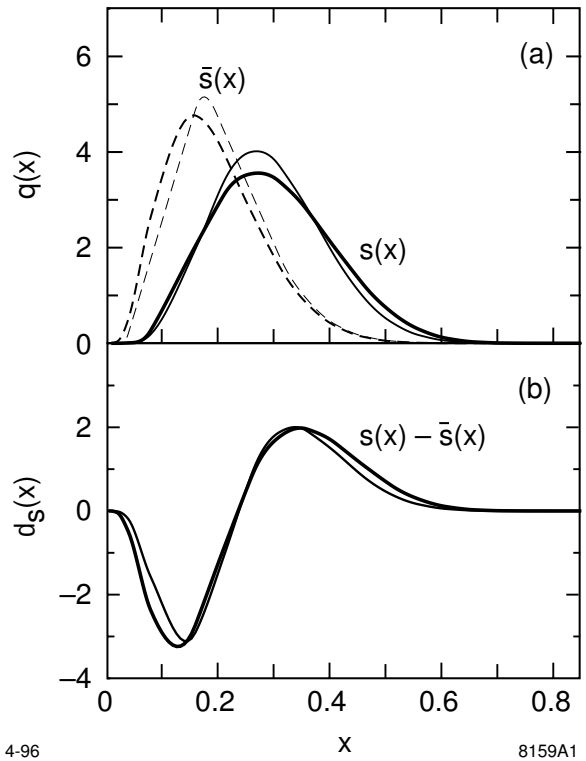
$\Rightarrow$ $\bar{d} > \bar{u}$

These models also have implications on

- asymmetry between $s(x)$ and $\bar{s}(x)$
- flavor structure of the polarized sea

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

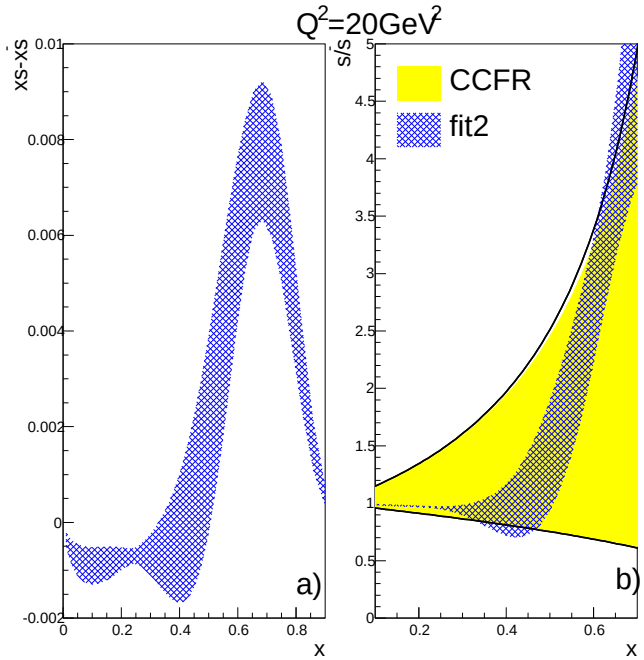
meson cloud model



Brodsky and Ma

Analysis of ν inclusive DIS data

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



Barone et al., hep-ph/9907512

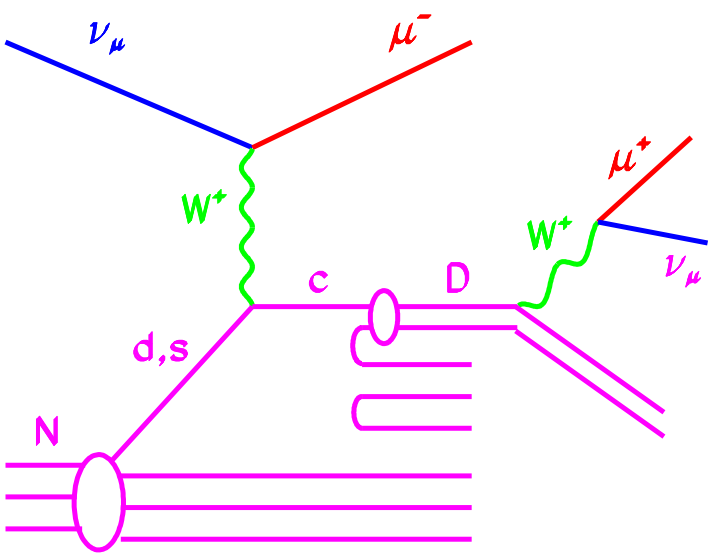
Is $s(x) > \bar{s}(x)$ at large x?

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

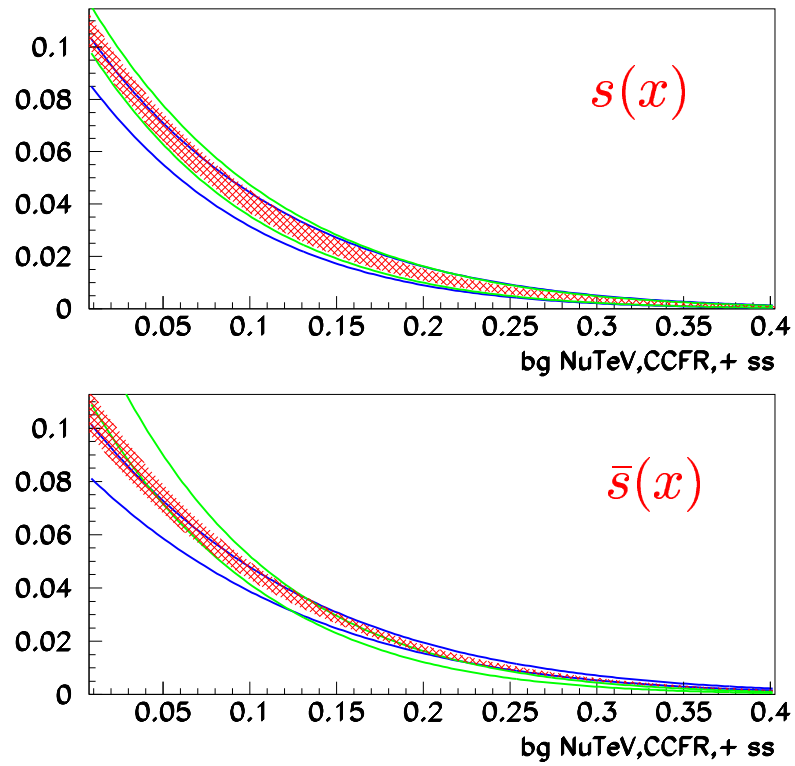
Dimuon Production in ν_μ Fe and $\bar{\nu}_\mu$ Fe DIS from CCFR and NuTeV

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

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



Results from NuTeV/CCFR



Goncharov et al., hep-ex/0102049

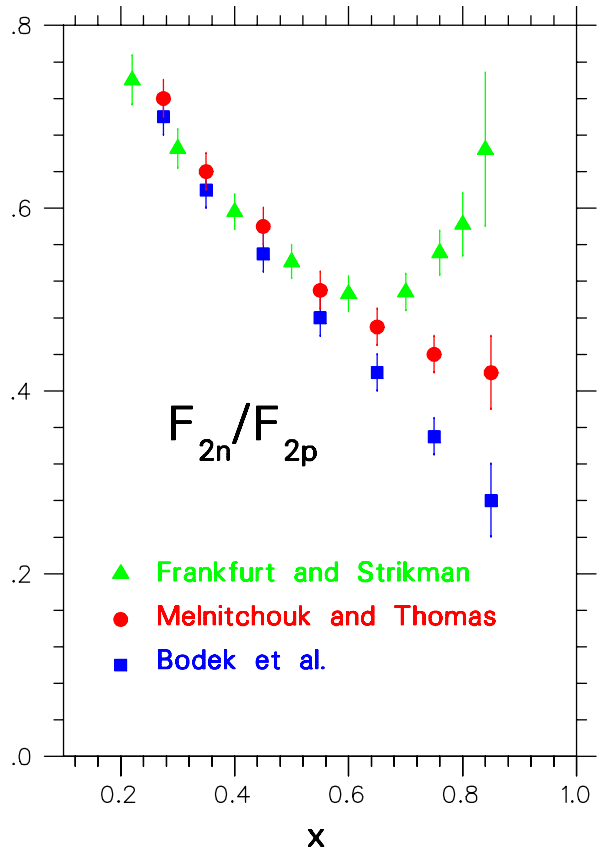
$$s(x) = 0.352\,\frac{\bar{u}(x)+\bar{d}(x)}{2}\,(1-x)^{-0.77} \qquad \bar{s}(x) = 0.405\,\frac{\bar{u}(x)+\bar{d}(x)}{2}\,(1-x)^{-2.04}$$

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

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

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

Model dependence of extracting F_2^n from F_2^d



Need to measure u/d 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)

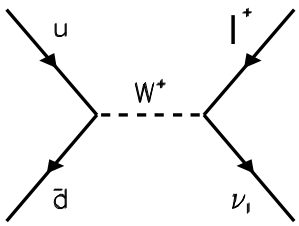
Ignoring terms with $S_Z = 1$ diquarks, then

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

d/u from W production at CDF

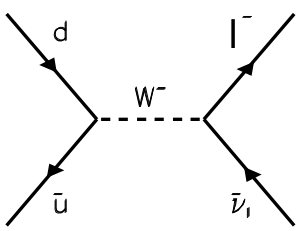
W production in $p - \bar{p}$ collision

$$p + \bar{p} \to W^+ + x$$



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

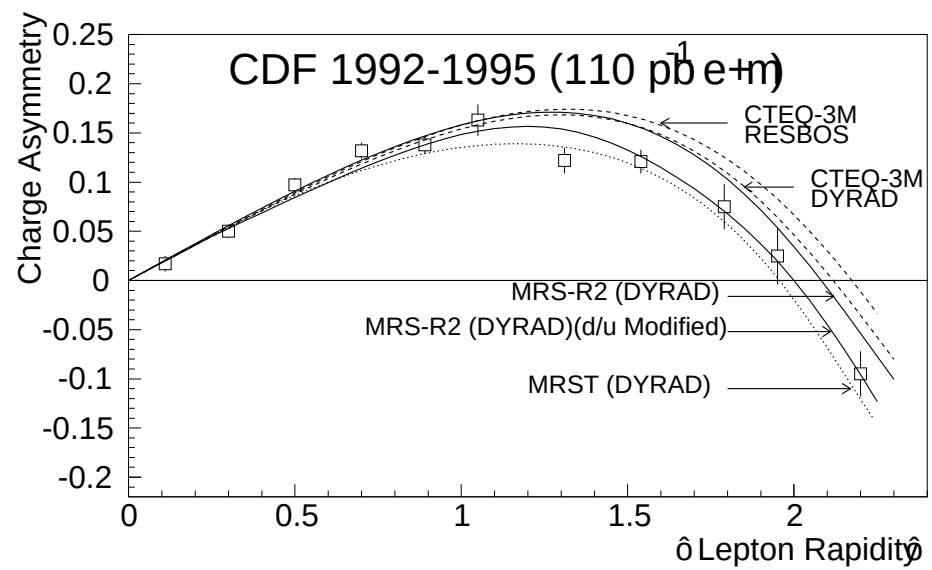
$$p + \bar{p} \to W^- + x$$



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

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

W asymmetry from CDF



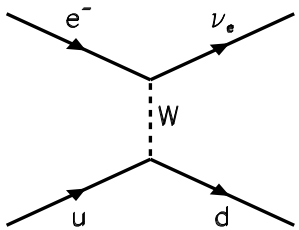
Abe et al., PRL 81 (1998) 5744

"modified" d/u PDF fits the data better

d/u from charged-current DIS at HERA

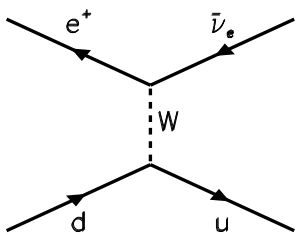
CC DIS at HERA

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

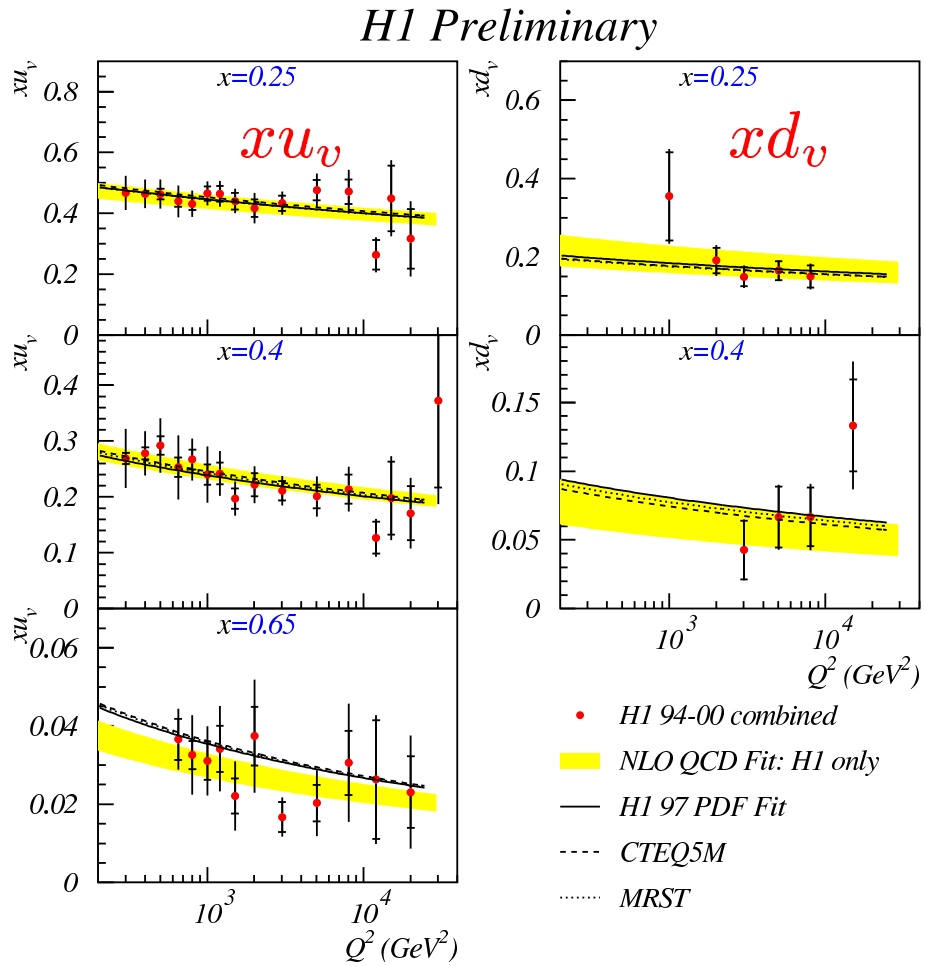


$(e^- + u \to \nu_e + d)$

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



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



hep-ex/0212043

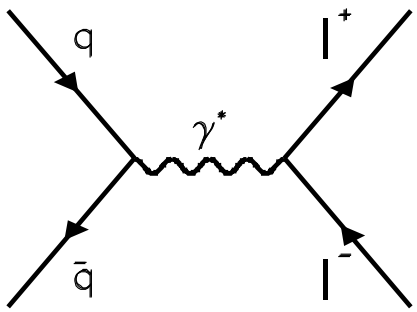
Data indicate that u_v at large x is smaller than PDF parametrizations

More data are forthcoming

$u(x)$ from Drell-Yan

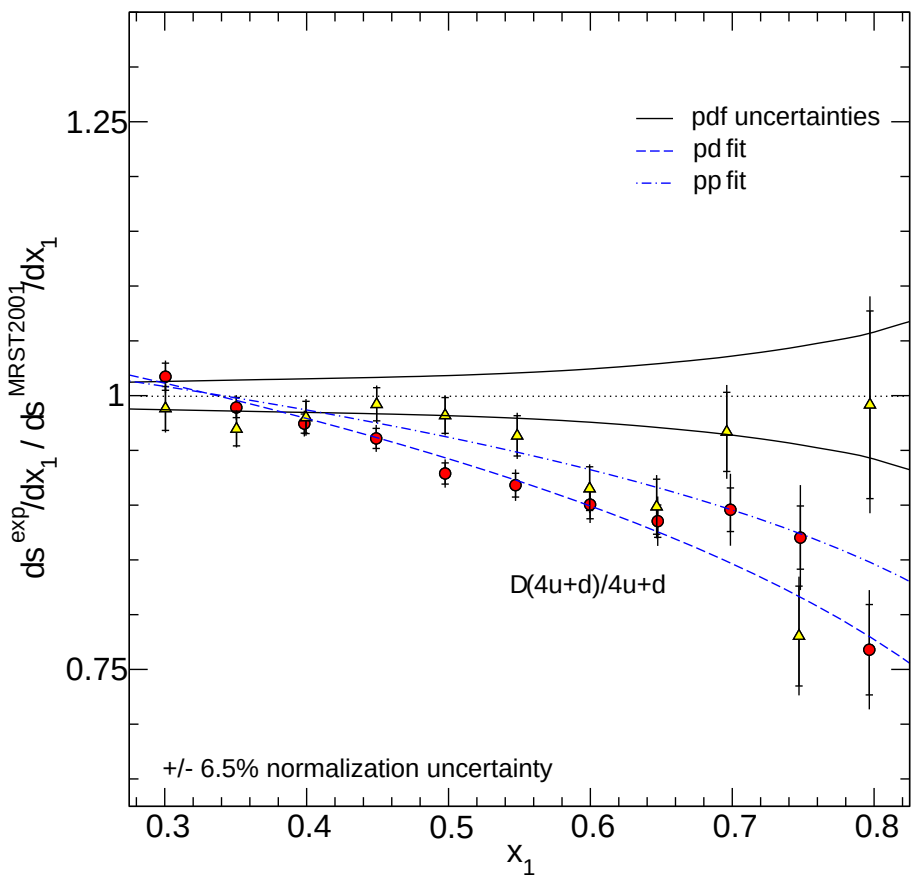
Recent results from Fermilab E866

Proton-induced Drell-Yan is sensitive to $u(x)$



$$\sigma_{DY} \sim u(x_1)\bar{u}(x_2)$$

800 GeV $p+p$ and $p+d$
D-Y cross sections



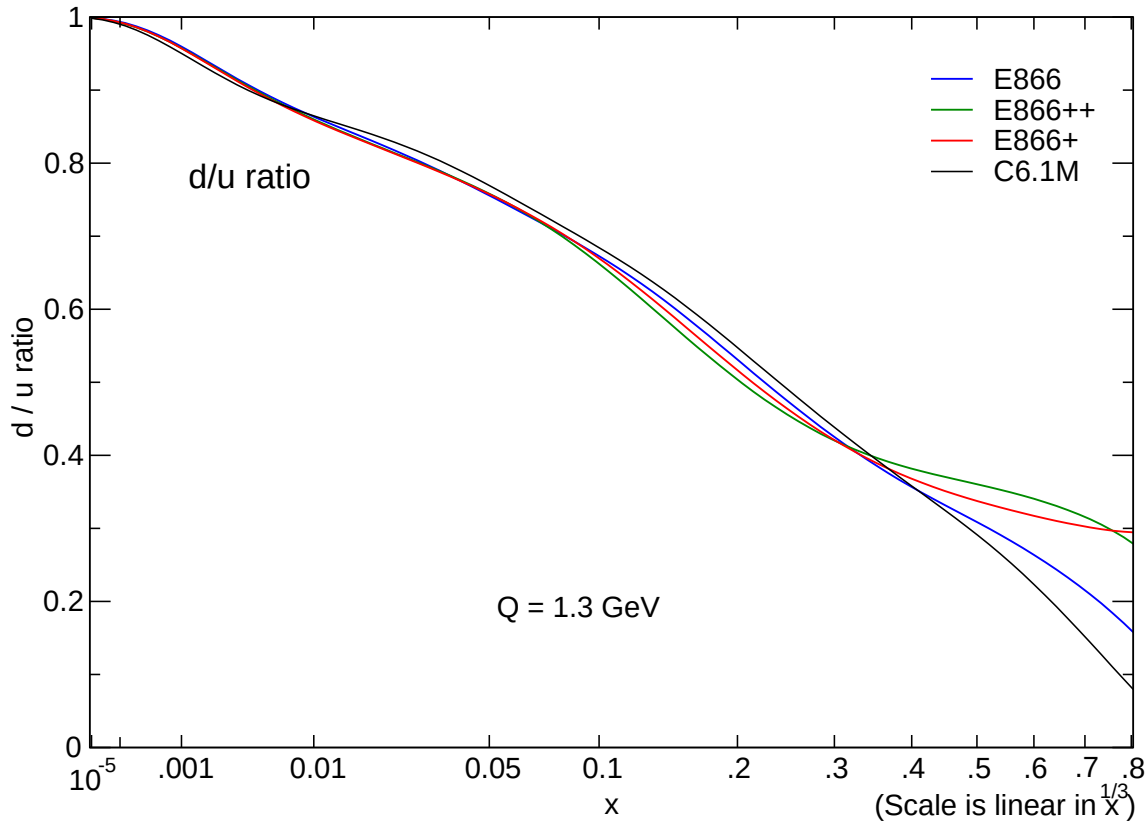
hep-ex/0302019

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

$$\frac{data}{theory} \sim (1-x)^{0.2}$$

Implication on $d(x)/u(x)$ at large x?

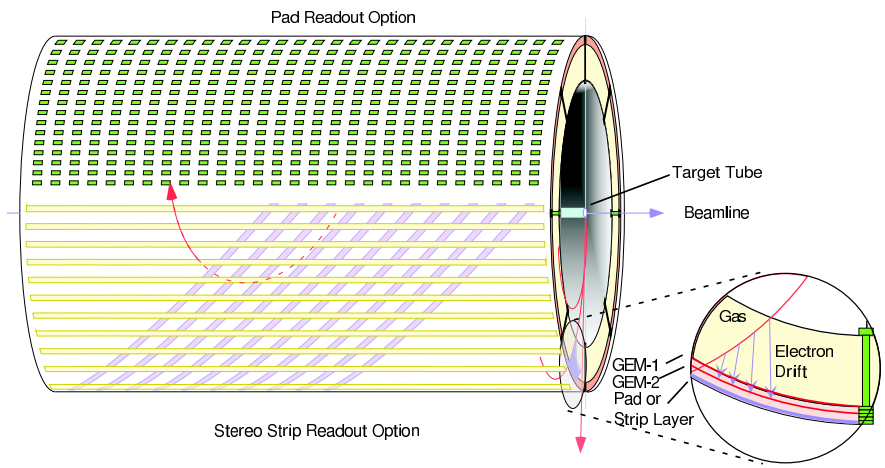
Preliminary result from CTEQ (W.K. Tung, DIS2003)



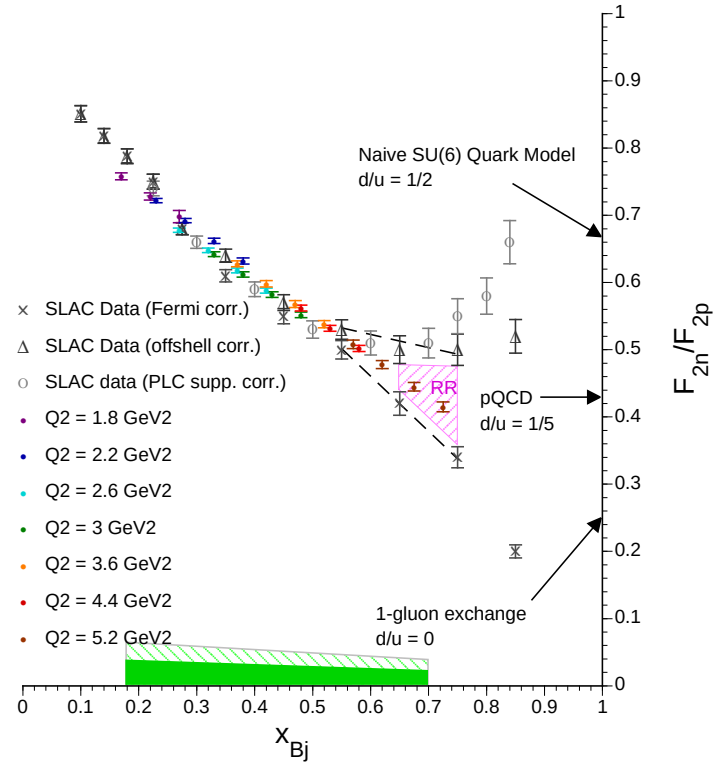
Different curves correspond to different weights assigned to the E866 D-Y data

d/u measurement with neutron tagging

BONUS at Hall-B



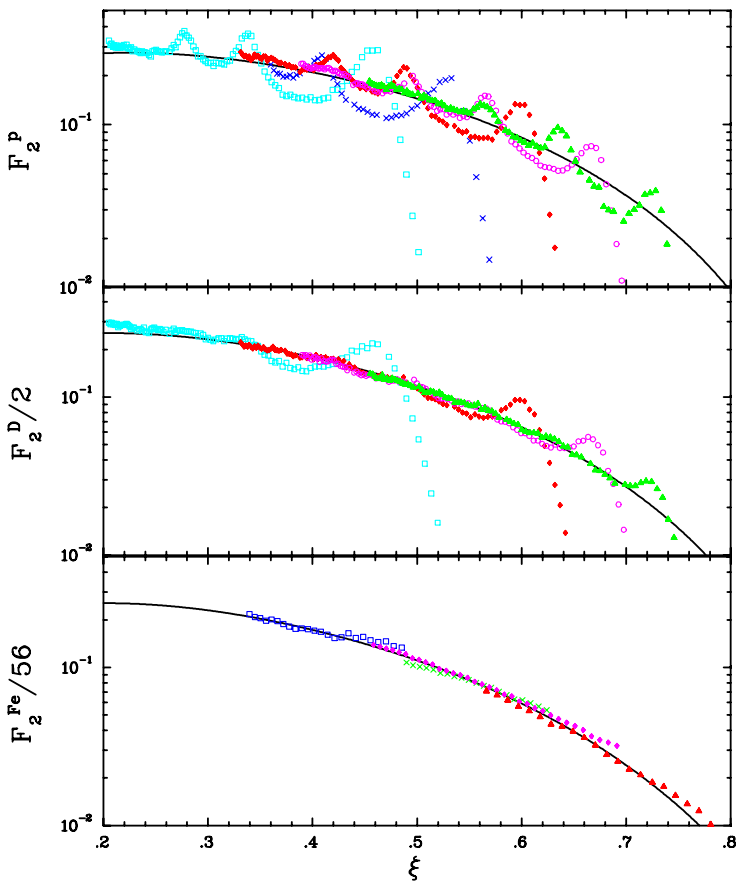
expected F_2^n/F_2^p sensitivities



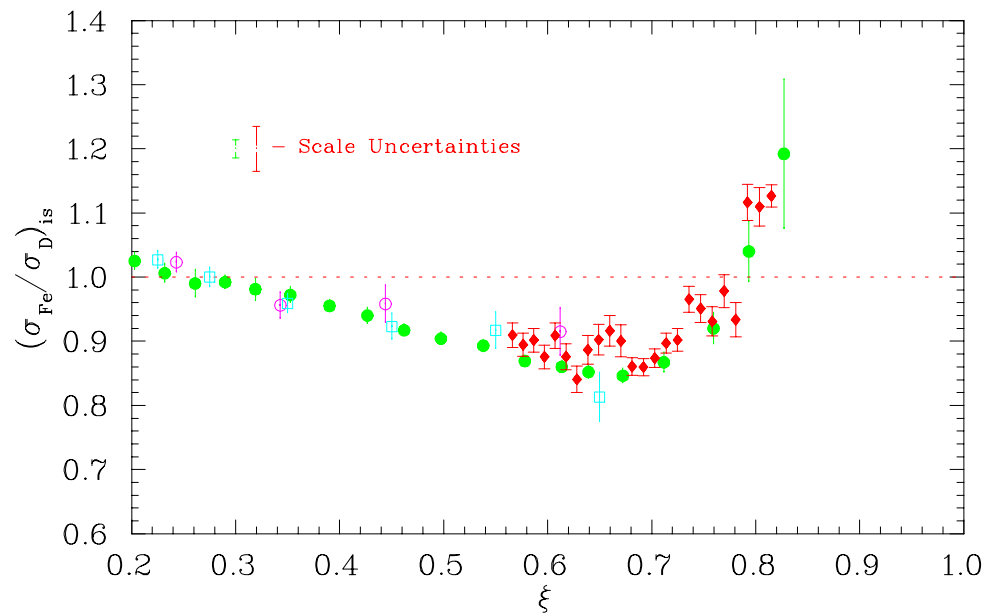
Quark-Hadron Duality

Bloom-Gilman Duality $\longrightarrow$ Averaged F_2 extracted at the resonance regime is consistent with F_2 extracted at the DIS regime

F_2 on H, D, Fe



EMC effect clearly observed



New Data from JLab

Quark-hadron duality could help determining F_2 at large x

Moments of Quark Distributions in Lattice QCD

$$\langle x^n \rangle_q = \int_0^1 x^n (q(x) + (-1)^{n+1} \bar{q}(x))\, dx$$

$$\langle x^n \rangle_{\Delta q} = \int_0^1 x^n (\Delta q(x) + (-1)^{n+1} \Delta \bar{q}(x))\, dx$$

$$\langle x^n \rangle_{\delta q} = \int_0^1 x^n (\delta q(x) + (-1)^{n+1} \delta \bar{q}(x))\, dx$$

Parton Distribution Functions

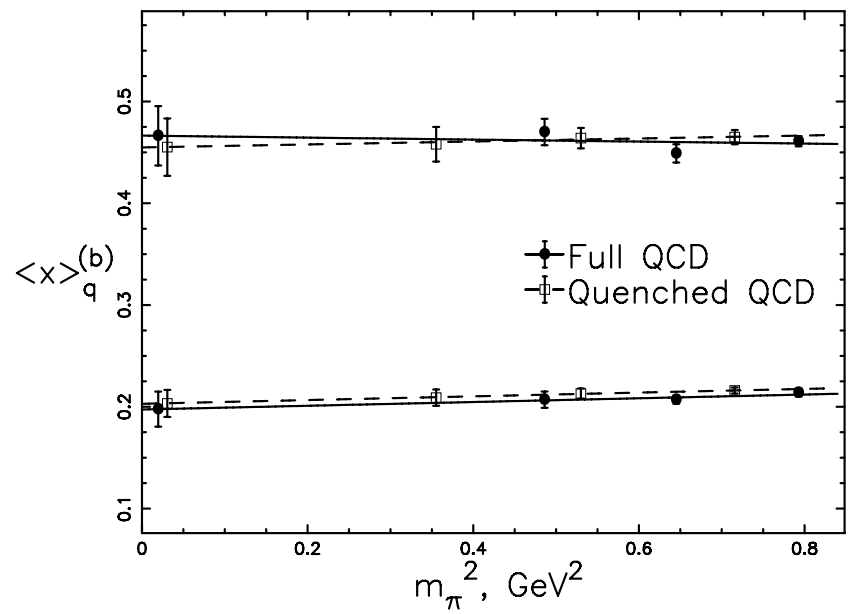
unpolarized: $q(x) = q^{\uparrow}(x) + q^{\downarrow}(x)$

polarized: $\Delta q(x) = q^{\uparrow}(x) - q^{\downarrow}(x)$

polarized: $\delta q(x) = q_{\top}(x) - q_{\perp}(x)$

- **Moments for $n \leq 3$ have been calculated**
- **Comparison of quenched versus full QCD lattice calculations**

First moment of u and d



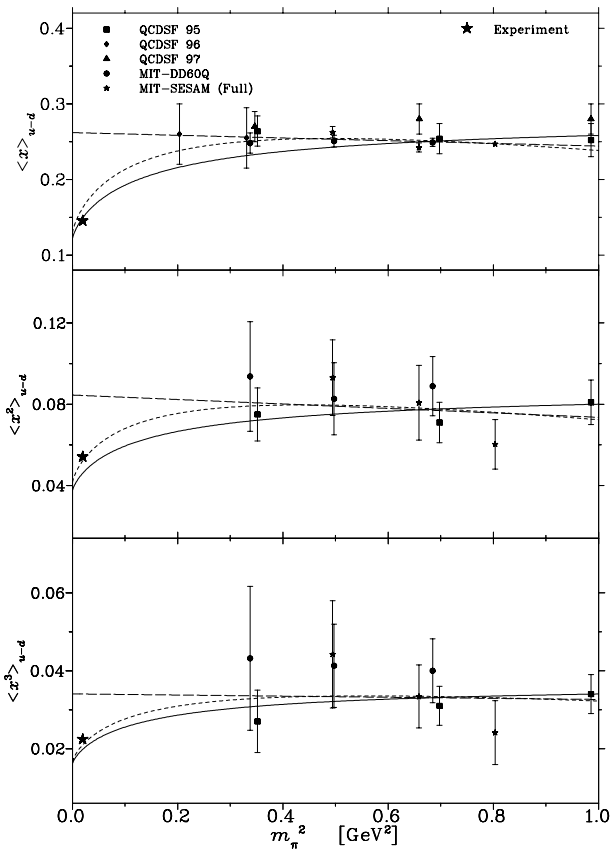
Dolgov et al., hep-lat/0201021

Chiral Extrapolation of Moments of Quark Distributions

$$\langle x^n \rangle = a_n(1 + C_{LNA}\, m_\pi^2\, log\frac{m_\pi^2}{m_\pi^2+\mu^2}) + b_n \frac{m_\pi^2}{m_\pi^2+m_b^2}$$

$$C_{LNA} = -\frac{1+3g_A^2}{(4\pi f_\pi)^2}; \quad b_n = \frac{1}{3^n} - a_n(1-\mu^2 C_{LNA})$$

Moments of $u-d$



Detmold et al., hep-lat/0108002

- **Linear extrapolation to the pion mass gives results inconsistent with the experiment**
- **An extrapolation formula based on the leading nonanalytic behavior imposed by chiral symmetry gives excellent agreement**

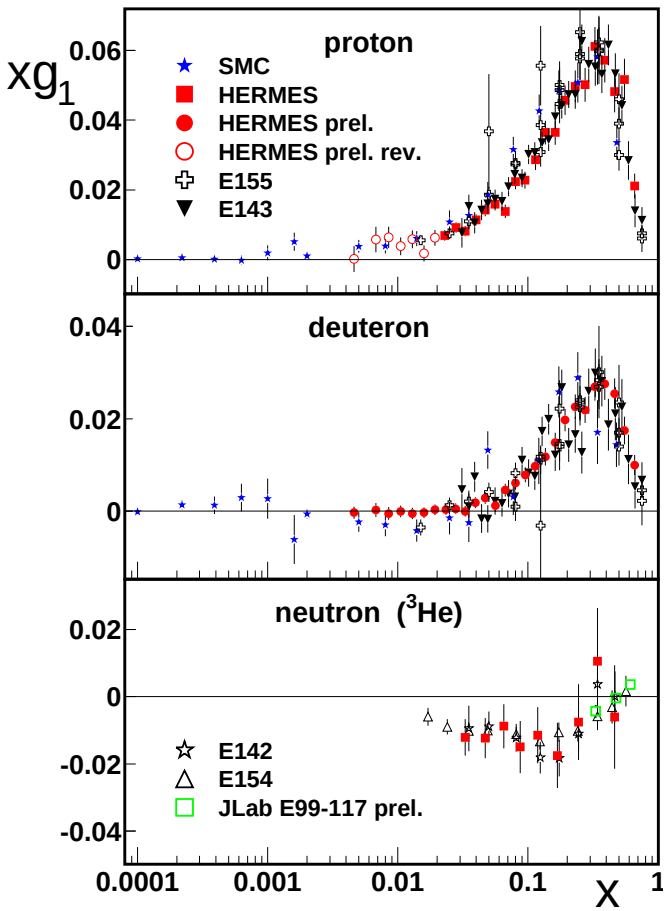
Progress in Spin Structure Function Experiments

- First results on $\Delta\bar{u}(x)$, $\Delta\bar{d}(x)$, and $\Delta s(x)$ from HERMES
- First JLab results on spin-dependent structure functions
  A_1, A_2 , g_1, g_2 and the Generalized GDH integral at low Q^2
- Observation of Azimuthal Single Spin Asymmetry
  Promise for study of new structure functions and fragmentation functions
- Observation of DVCS at HERA and Jlab
  Generalized Parton Distributions
- COMPASS starts data-taking
  160 GeV μ DIS
- Successful commissioning of RHIC-spin
  Measurement of A_N at $\sqrt{s} = 200$ GeV
  First data collected on A_{LL}

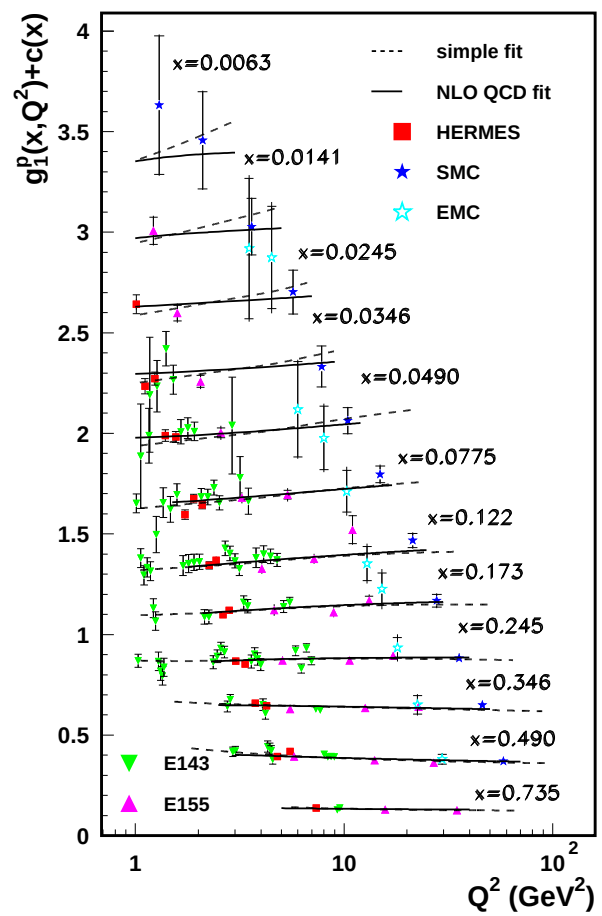
Spin Structure Function: $g_1(x)$

QPM: $g_1(x) = \frac{1}{2}\sum_f e_f^2 \Delta q_f(x)$; $\Delta q(x) = q^+(x) - q^-(x)$

xg_1 for p, d, and ^3He



Scaling violation of g_1^p



Scaling violation of g_1^p is clearly observed!

Moments of g_1^p and g_1^n

Integrals of g_1^p and g_1^n are now well determined

Global PQCD fit to $g_1(x, Q^2)$ gives the following values at $Q^2 = 5$ GeV^2:
PL B493 (2000) 19

- Proton first moment:

$$\Gamma_1^p = \int_0^1 g_1^p(x)\, dx = 0.118 \pm 0.004 \pm 0.007$$

- Neutron first moment:

$$\Gamma_1^n = \int_0^1 g_1^n(x)\, dx = -0.058 \pm 0.005 \pm 0.008$$

- Bjorken Sum Rule ($\Gamma_1^p - \Gamma_1^n = \frac{1}{6}\frac{g_A}{g_V}$)

$$\Gamma_1^p - \Gamma_1^n = 0.176 \pm 0.003 \pm 0.007$$

(in agreement with prediction: 0.182 ± 0.005)

How do Γ_1^p and Γ_1^n vary as a function of Q^2?

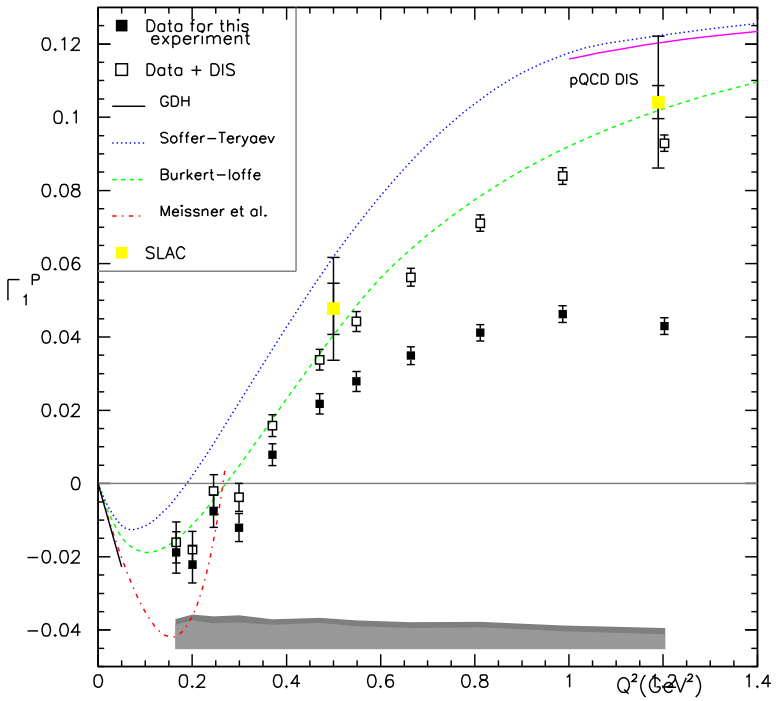
Q^2 Dependence of Γ_1^p and Γ_1^n

GDH sum rule: $\int_{\nu_0}^{\infty}[\sigma_{\frac{1}{2}}(\nu) - \sigma_{\frac{3}{2}}(\nu)]\frac{d\nu}{\nu} = -\frac{2\pi^2\alpha}{M^2}\kappa^2$

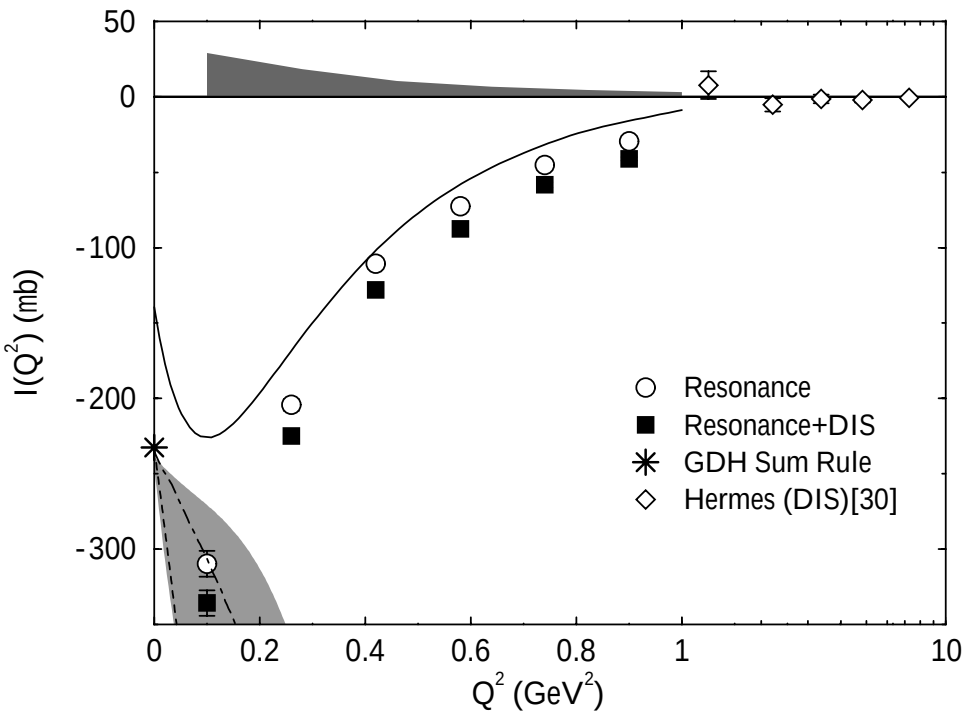
Generalized GDH sum

$$I_{GDH}(Q^2) \equiv \int_{\nu_0}^{\infty}[\sigma_{\frac{1}{2}}(\nu, Q^2) - \sigma_{\frac{3}{2}}(\nu, Q^2)]\frac{d\nu}{\nu} = \frac{16\pi^2\alpha}{Q^2}\Gamma_1(Q^2)$$

JLab Hall-B Prelim Result on Γ_1^p



JLab Hall-A Result on $I_{GDH}^n(Q^2)$

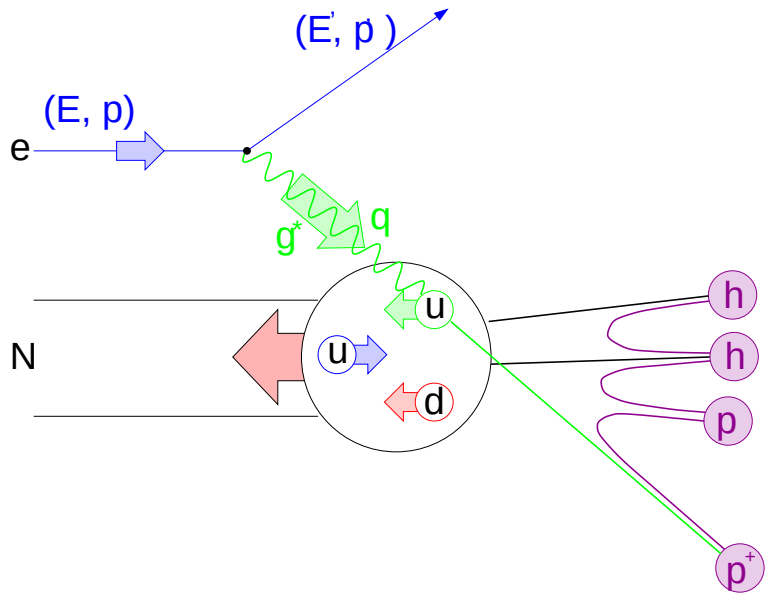


New measurements covering even lower Q^2 are underway

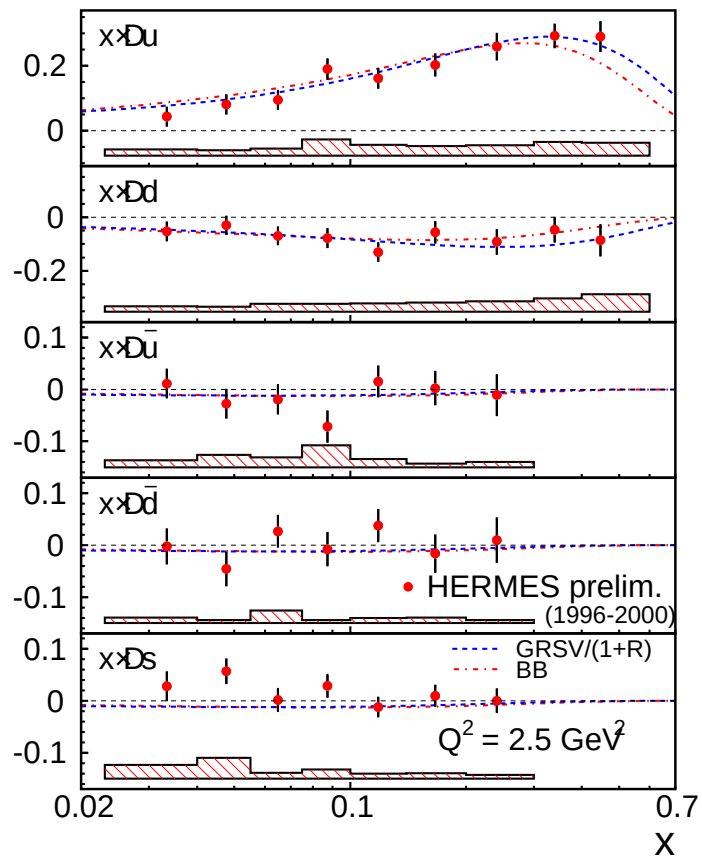
Flavor Structure of the Helicity Distributions

Polarized Semi-Inclusive DIS (SIDIS)

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



Preliminary Hermes semi-Inclusive DIS results

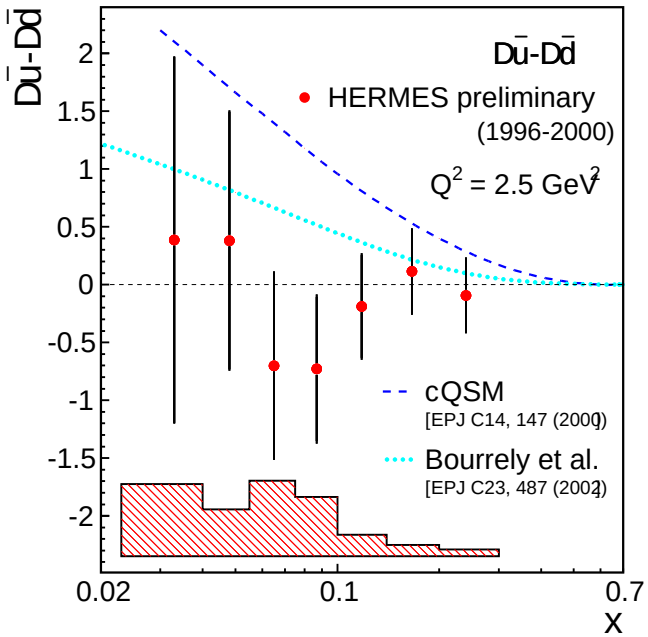


hep-ex/0210049

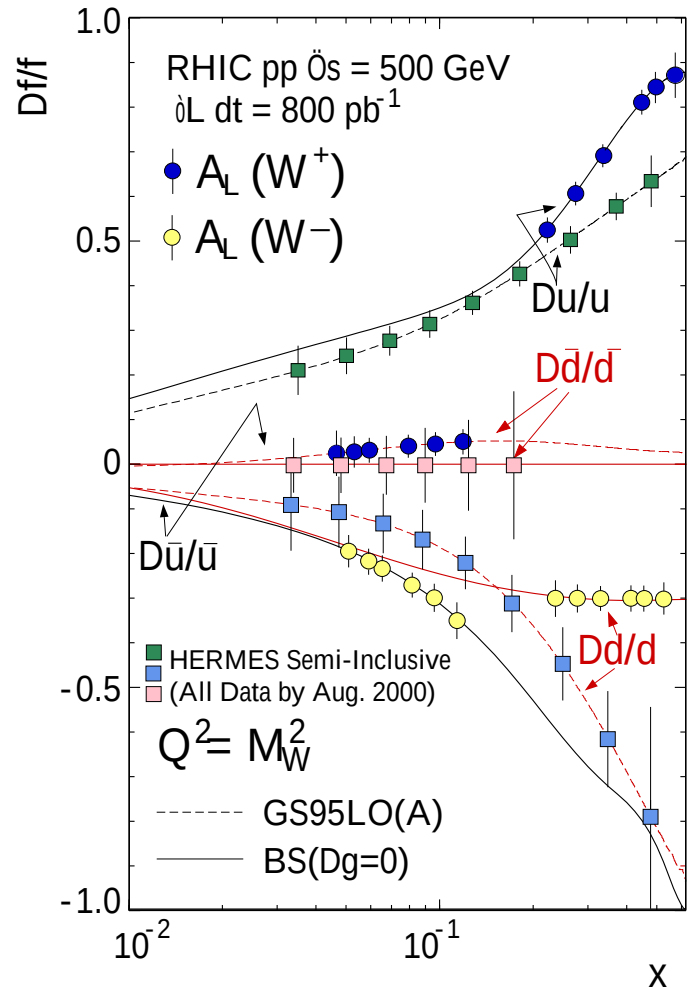
- Quark flavor is tagged by detecting $\pi^{\pm}$ and $K^{\pm}$
- Five-flavor analysis $(\Delta u, \Delta d, \Delta\bar{u}, \Delta\bar{d}, \Delta s(= \Delta\bar{s}))$
- No indication for $\Delta s < 0$

Flavor Structure of the Helicity Distributions

Flavor asymmetry of the polarized sea?



$\vec{p} + p \to W^{\pm} + X$



- No evidence for $\Delta\bar{u} \neq \Delta\bar{d}$
- Measurement of $W^{\pm}$ production at RHIC-spin would provide crucial new information

Transversity

Three twist-2 quark distributions:

- Density distributions: $q(x, Q^2) = q^{\uparrow}(x) + q^{\downarrow}(x)$
- Helicity distributions: $\Delta q(x, Q^2) = q^{\uparrow}(x) - q^{\downarrow}(x)$
- Transversity distributions: $q(x, Q^2) = q_{\top}(x) + q_{\perp}(x)$

Some characteristics of transversity

- $\delta q(x) = \Delta q(x)$ for non-relativistic quarks
- δq and gluons do not mix $\Longrightarrow$ Q^2-evolutions for δq and Δq are different
- Chiral-odd, not accessible in inclusive DIS

It takes two chiral-odd objects to measure transversity

- Drell-Yan (Doubly transversely polarized p-p collision)

  $A_{TT} \sim \sum_i e_i^2 \delta q_i(x) \delta \bar{q}_i(x)$ two chiral-odd $\delta q(x)$
- Semi-inclusive DIS

  $\sigma \sim \sum_q f^{H \to q} \bigotimes \sigma^{eq \to eq} \bigotimes D^{q \to h}$

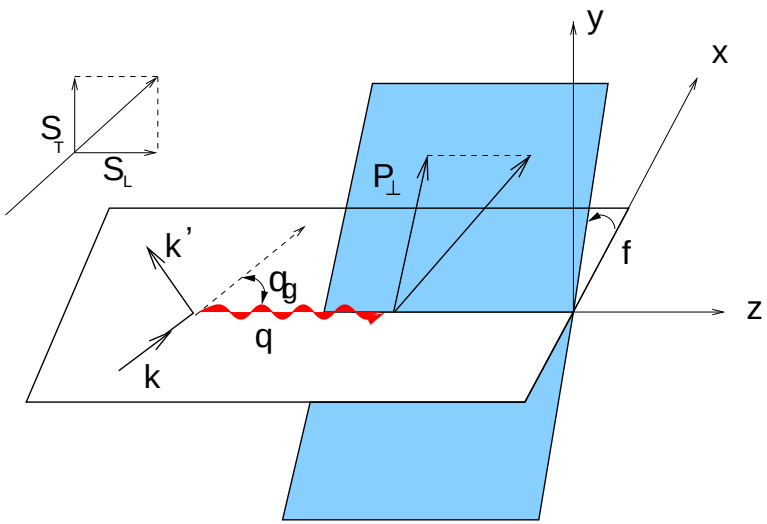
  Chiral-odd distribution function (transversity)

  Chiral-odd fragmentation function (Collins function)

Observation of Single-Spin Azimuthal Asymmetry

$e\vec{p} \to e'\pi x$

longitudinally polarized target



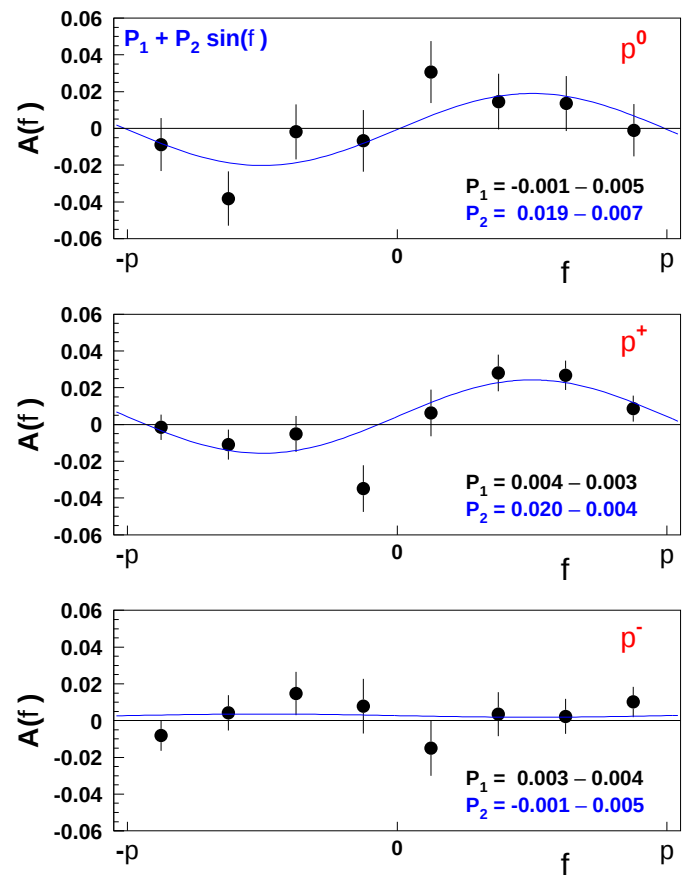
$\langle S_T \rangle \sim 0.15$

non-zero target transverse polarization with respect to virtual photon direction

$$\langle \sin\phi \rangle \propto S_L \sum_q e_q^2 x h_L^q(x) H_1^{\perp,q}(z) \quad \leftarrow \text{twist-3}$$

$$+ S_T \sum_q e_q^2 x h_1^q(x) H_1^{\perp,q}(z) \quad \leftarrow \text{transversity}$$

HERMES



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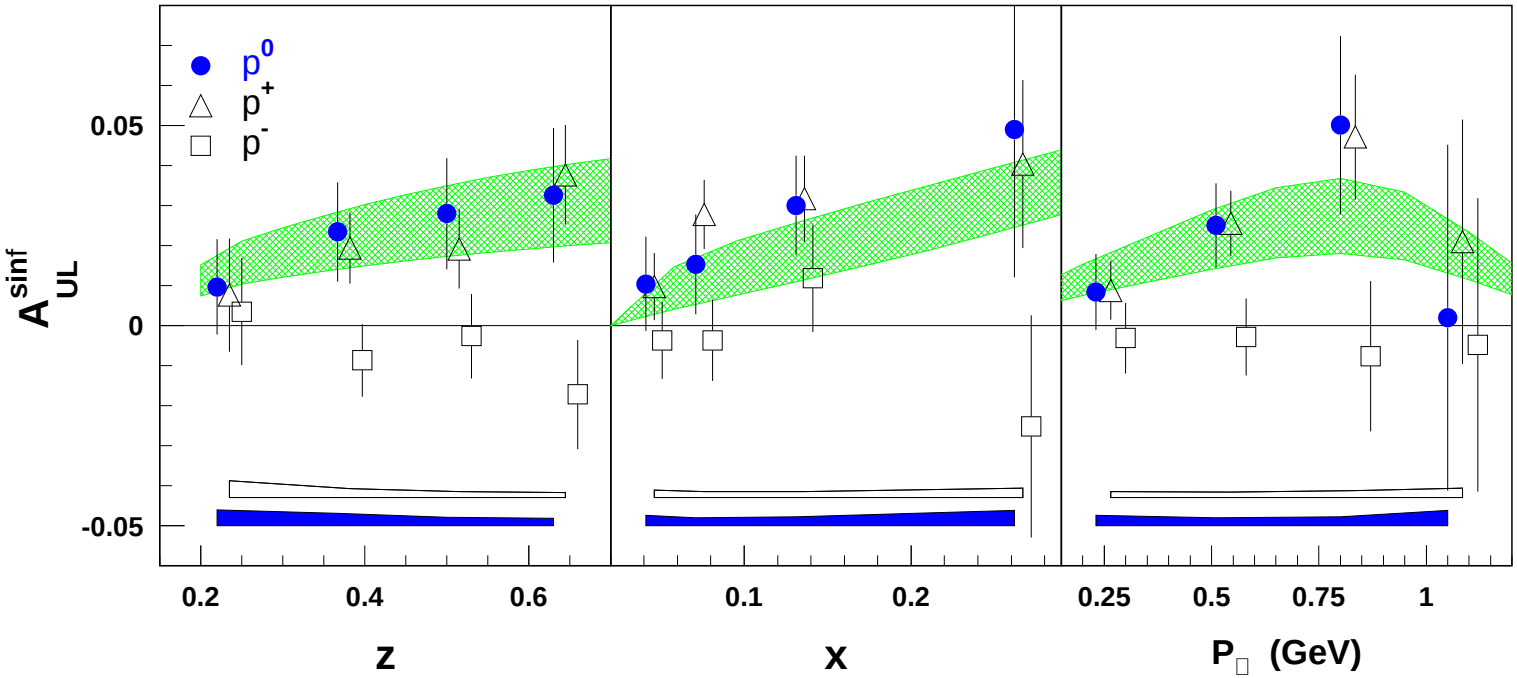
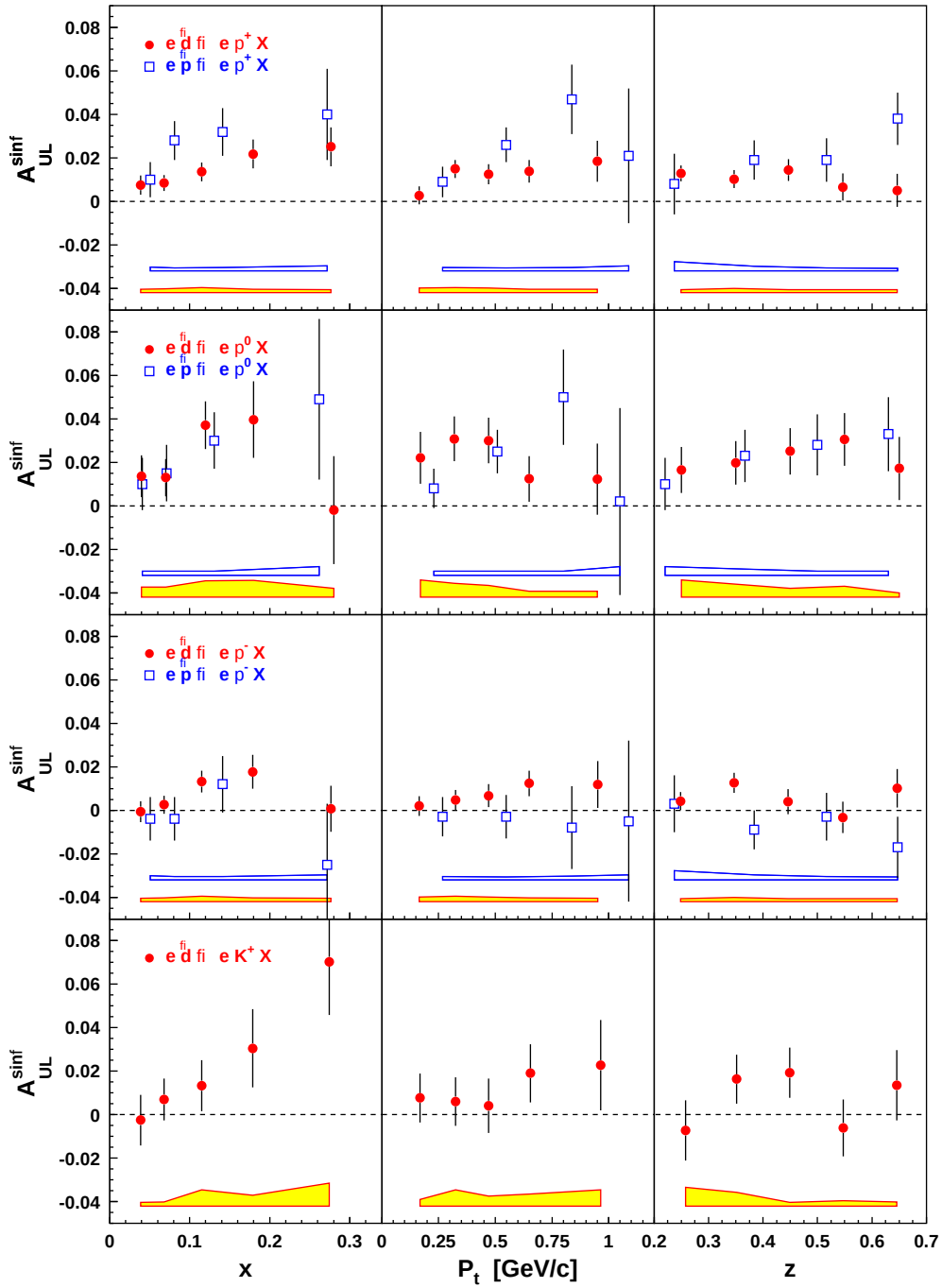
SSA and Transversity



- Transversity is expected to peak around $x = 0.3$ (valence quark effect)
- u-quark-dominance implies large effect for π^+ and π^0, but not for π^-
- Effect should grow with z and with $p_\perp$

Collins fragmentation function appears to be sizable, allowing for the extraction of transversity $\delta q(x)$



HERMES, PL B562 (2003) 182

- New data on longitudinally polarised deuterium target
- π^+, π^-, π^0 and K^+ are detected
- Data well described by models of transversity
- Contribution from another origin (Sivers effect) can not be disentangled, yet..

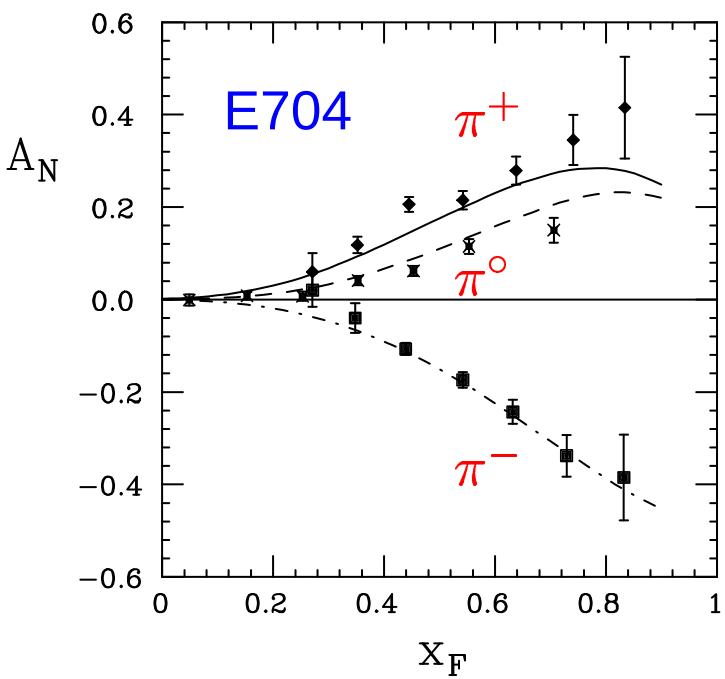
Collins versus Sivers Effect

$\langle \sin\phi \rangle \sim \sum_q e_q^2 h_1^q(x) H_1^{\perp,q}(z)$ ← Transverse distribution function × Collins frag. function

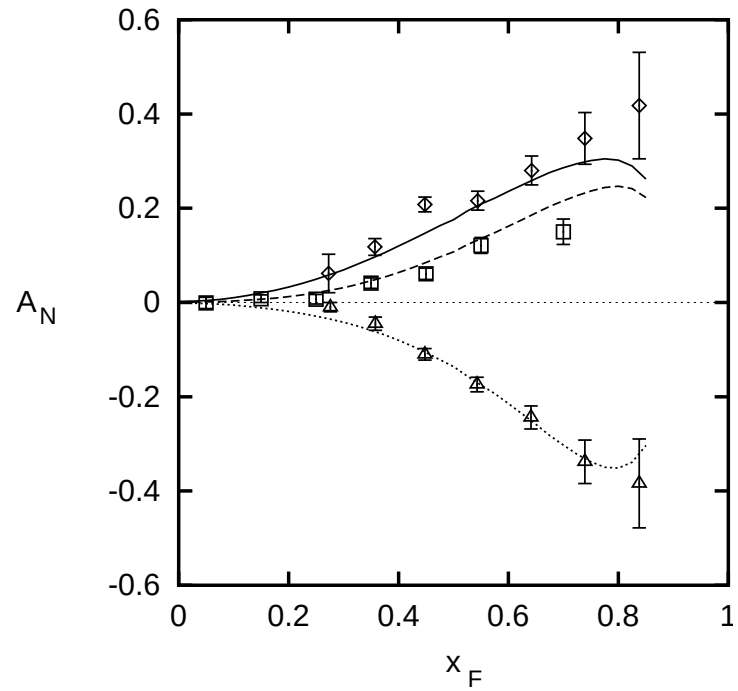
$+ \sum_q e_q^2 f_{1T}^{\perp,q} D_1^q(z)$ ← Sivers distribution function × ordinary frag. function

Single spin asymmetry observed in $p\uparrow p \to \pi x$ (200 GeV $p\uparrow$) could be due to:

Sivers Effect



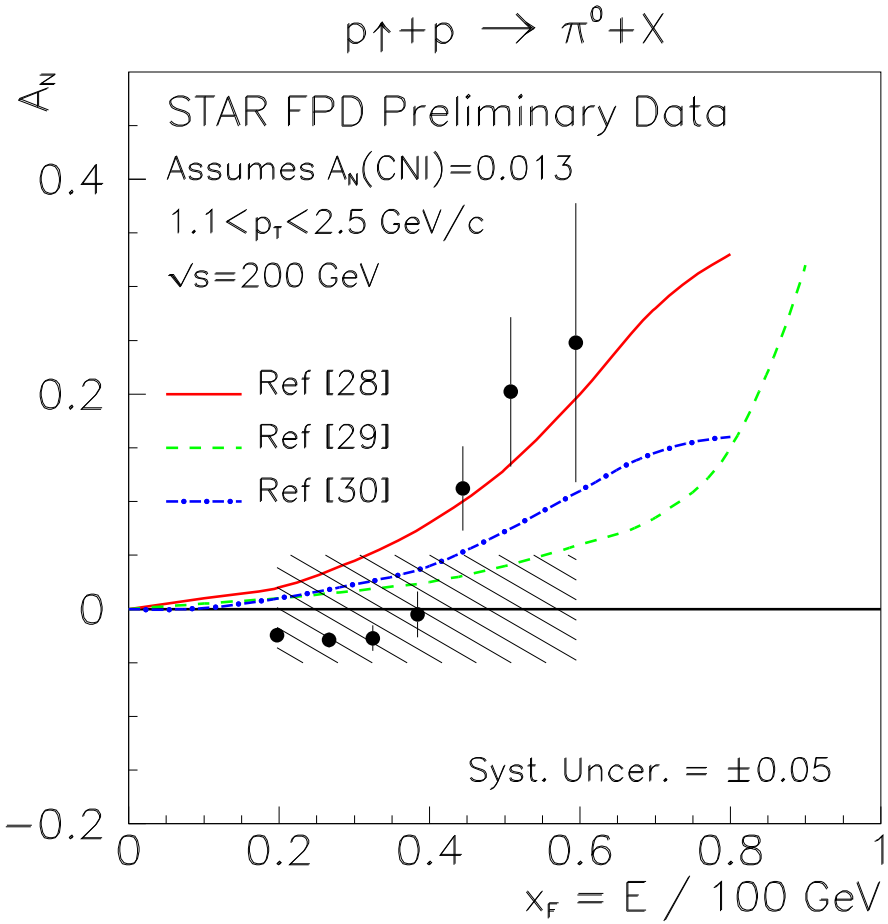
Collins Effect



Collins Function: Correlation between the quark's transverse spin and the transverse momentum of the leading hadron

Sivers Function: Correlation between the quark's transverse spin and transverse momentum within the proton

First A_N Result from STAR



Collins effect

Sivers effect

STAR hep-ex/0212013

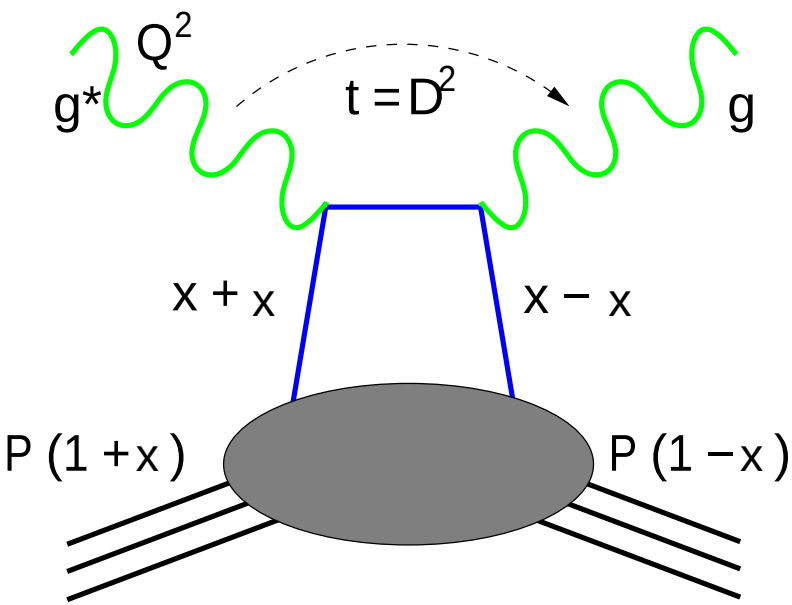
Experiments at HERMES, COMPASS, and RHIC-spin will shed much light on transversity

Generalized Parton Distributions

Study of **hard exclusive processes** leads to a new class of parton distributions.

Cleanest example: Deeply Virtual Compton scattering

DVCS



"handbag diagram"

Four new distributions:

helicity conserving $\rightarrow H(x,\xi,t), E(x,\xi,t)$
helicity-flip $\rightarrow \tilde{H}(x,\xi,t), \tilde{E}(x,\xi,t)$

Bjorken $\mathbf{x}$: average quark momentum fraction

"skewing parameter" ξ

$\rightarrow$ mismatch between quark momenta
$\Rightarrow$ sensitive to partonic ***correlations***

Connection to other Observables

- **DIS structure functions:** forward limit

$$q(x) = H^q(x, \xi = 0, t = 0)$$

$$\Delta q(x) = \tilde{H}^q(x, \xi = 0, t = 0)$$

- **Elastic form factors:** first moments

$$GM(t) = \int_{-1}^{1} dx \sum_q \left[H^q(x, \xi, t) + E^q(x, \xi, t)\right]$$

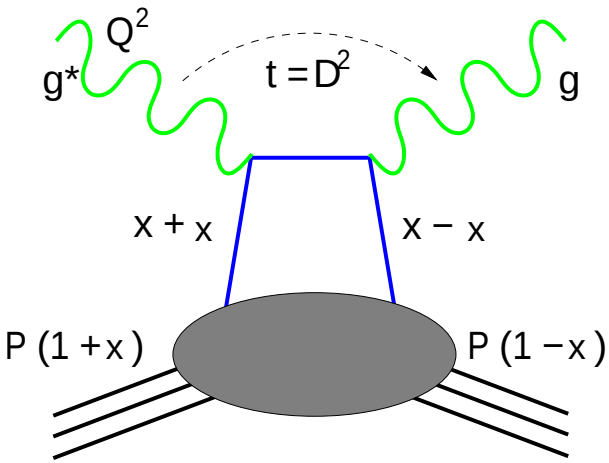
$$GE(t) = \int_{-1}^{1} dx \sum_q \left[H^q(x, \xi, t) + \frac{t}{4M^2} E^q(x, \xi, t)\right]$$

- **Angular momentum** $J^q = \frac{1}{2}\Delta\Sigma + L^q$ **!**

$$J^q = \frac{1}{2} \int_{-1}^{1} x \, dx \, \left[H^q(x, \xi, t = 0) + E^q(x, \xi, t = 0)\right]$$

GPD's offer a complete description of the proton wavefunction

Modelling the GPD's



- **t–dependence** from elastic form factors
- **ξ– (skewedness)** and **x– dependence**
  $\rightarrow$ interpolate between 2 regions:

  - $|x| > \xi$

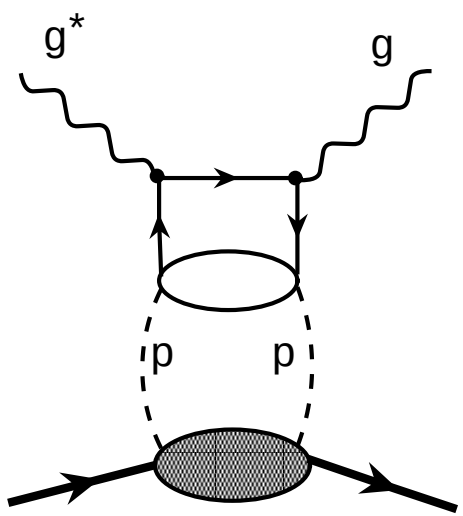
    $\rightarrow x_1, x_2$ both > 0 (quarks)
    or both < 0 (antiquarks)

    $\Rightarrow$ **PDF's** recovered in limit $\boxed{\xi \rightarrow 0}$

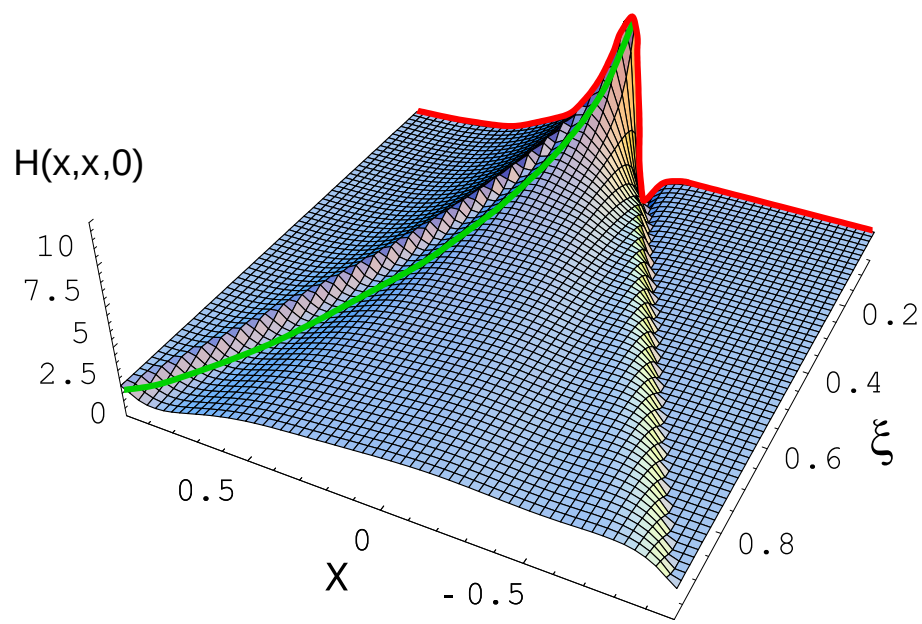
  - $|x| < \xi$

    $\rightarrow$ see correlation between q and $\overline{q}$

    $\Rightarrow$ **"meson-like"** distributions as $\boxed{\xi \rightarrow 1}$



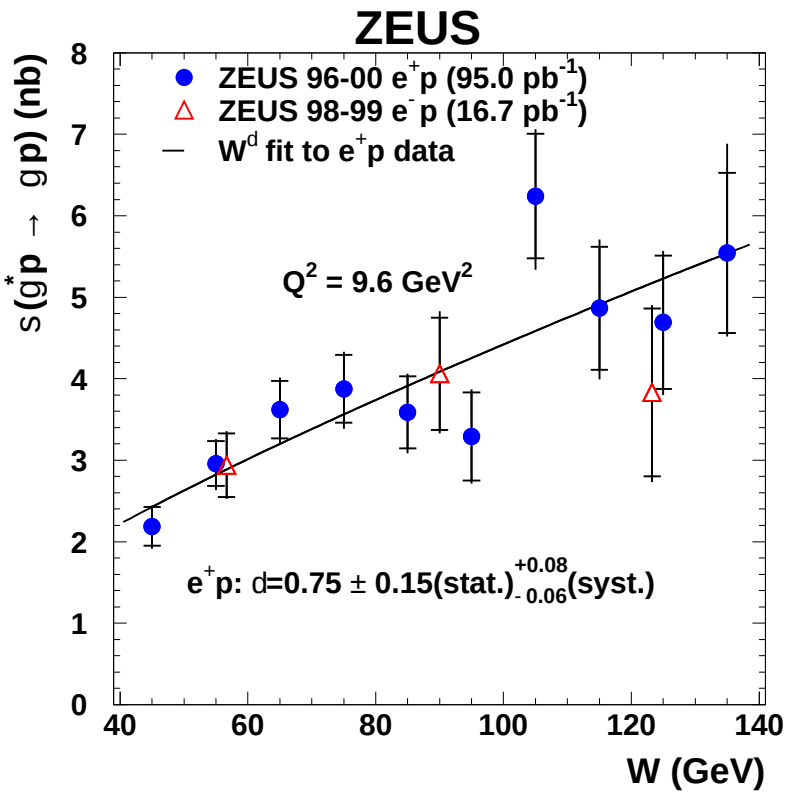
Model of $H^d(x, \xi, t = 0)$ (forward limit) *Vanderhaeghen, Guichon, Guidal, PRD 60 (99) 094017*

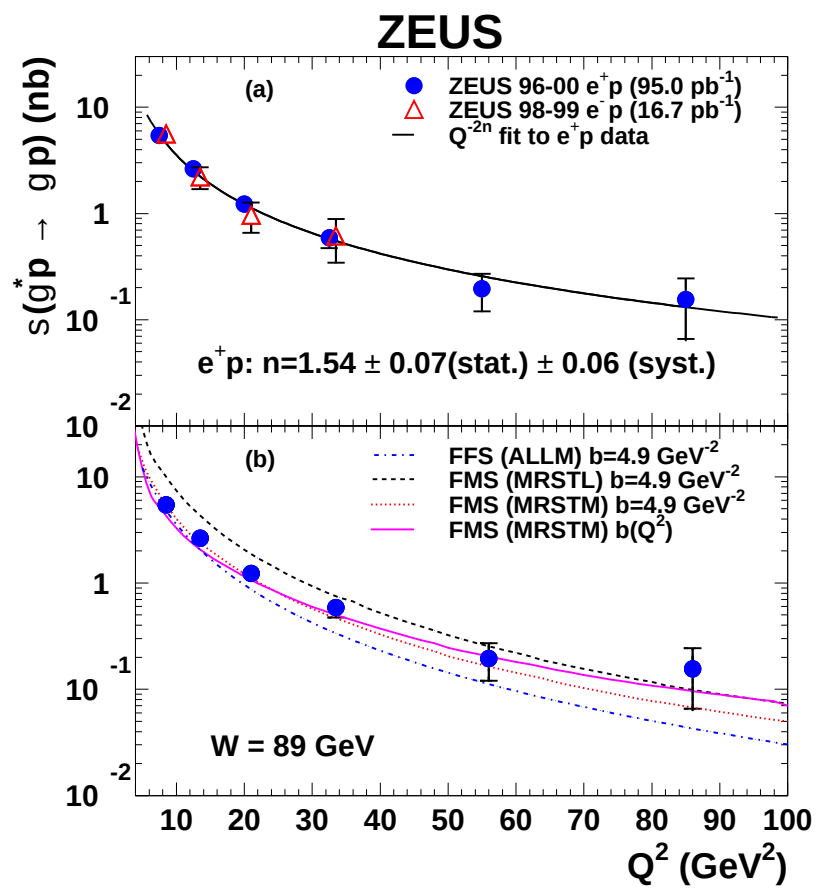


DVCS Cross-Section from H1 and ZEUS

At high energies, DVCS $>$ BH $\rightarrow$ measure cross-section ...

high-energy DVCS explores gluon GPD's ($x \sim 1/W^2$)





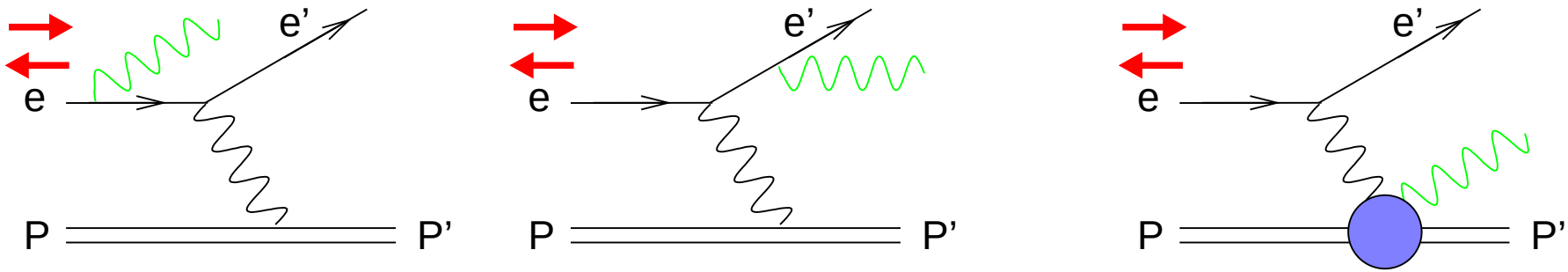
hep-ex/0305028

DVCS xsec agrees well with GPD-based calculations

DVCS: Beam-Spin Azimuthal Asymmetry

At intermediate energies, Bethe-Heitler cross-section $\gg$ DVCS ...

➡ explore ***interference***, using ***polarized beams***



Beam-Spin Asymmetry

$$A_{\mathrm{LU}}(\phi_\gamma) = \frac{\sigma_{\rightarrow} - \sigma_{\leftarrow}}{\sigma_{\rightarrow} + \sigma_{\leftarrow}}$$

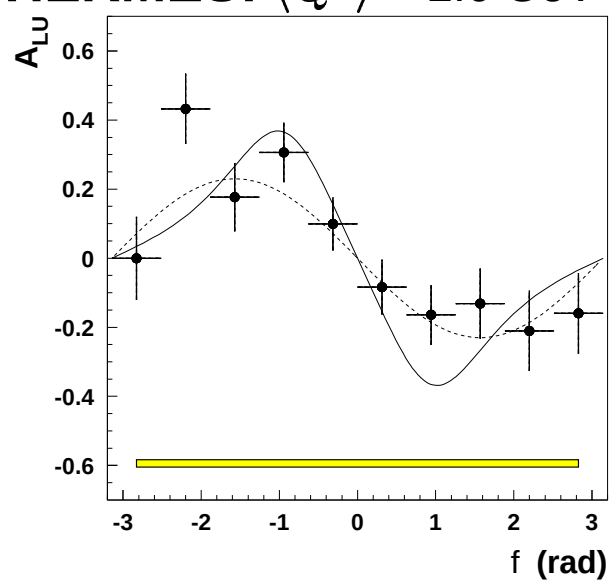
$$\sim \mathbf{Im}\,(\mathbf{BH} \cdot \mathbf{DVCS}^*)\,\sin\phi_\gamma$$

Beam-Charge Asymmetry

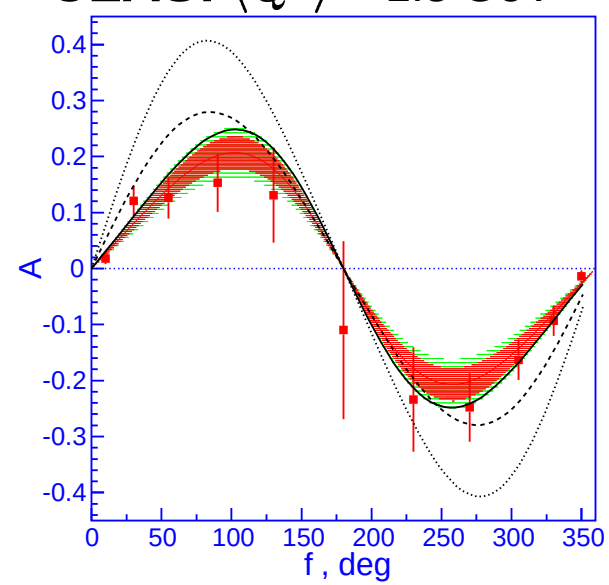
$$\sim \mathbf{Re}\,(\mathbf{BH} \cdot \mathbf{DVCS}^*)\,\cos\phi_\gamma$$

also measured, at HERMES

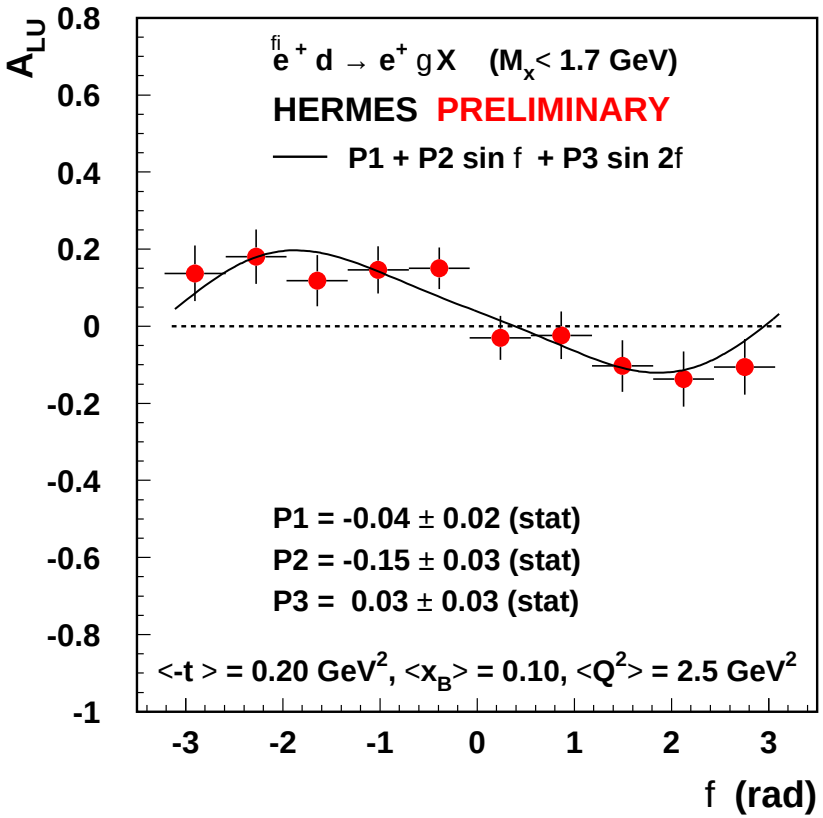
HERMES: $\langle Q^2 \rangle$ = 2.6 GeV^2

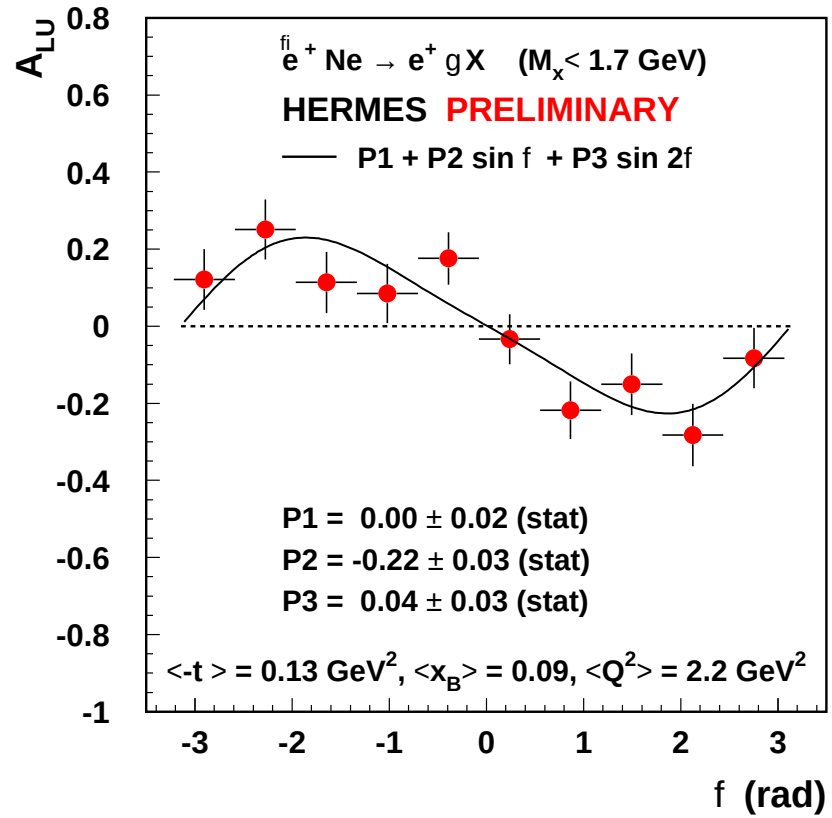


CLAS: $\langle Q^2 \rangle$ = 1.3 GeV^2



DVCS on D and Ne

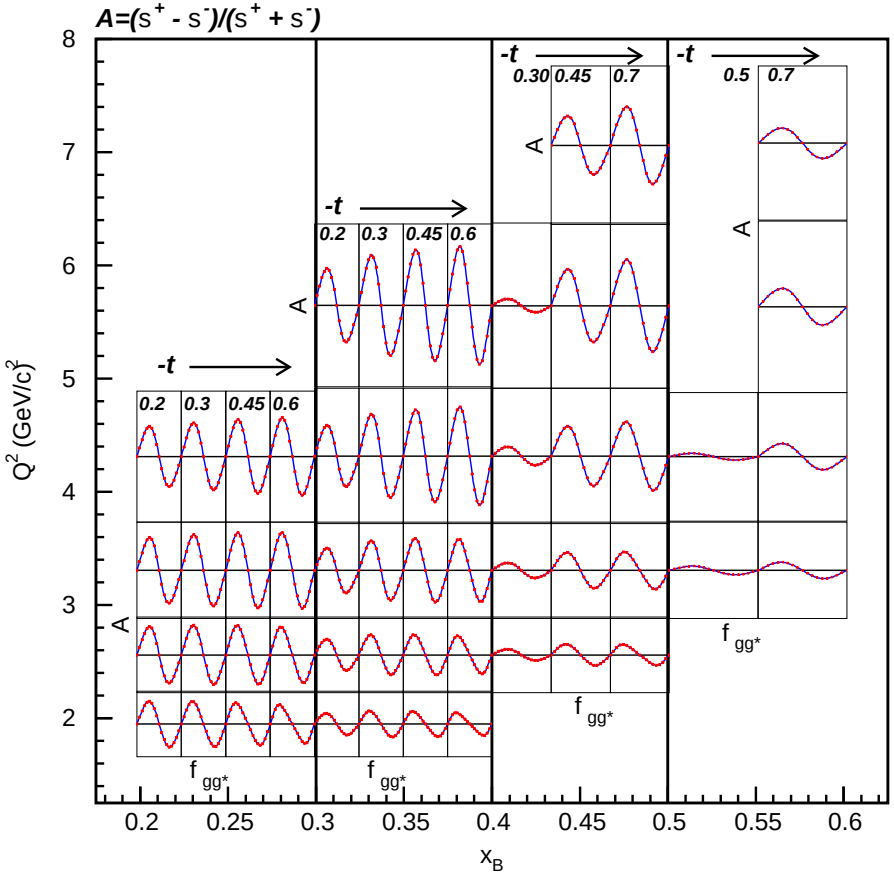




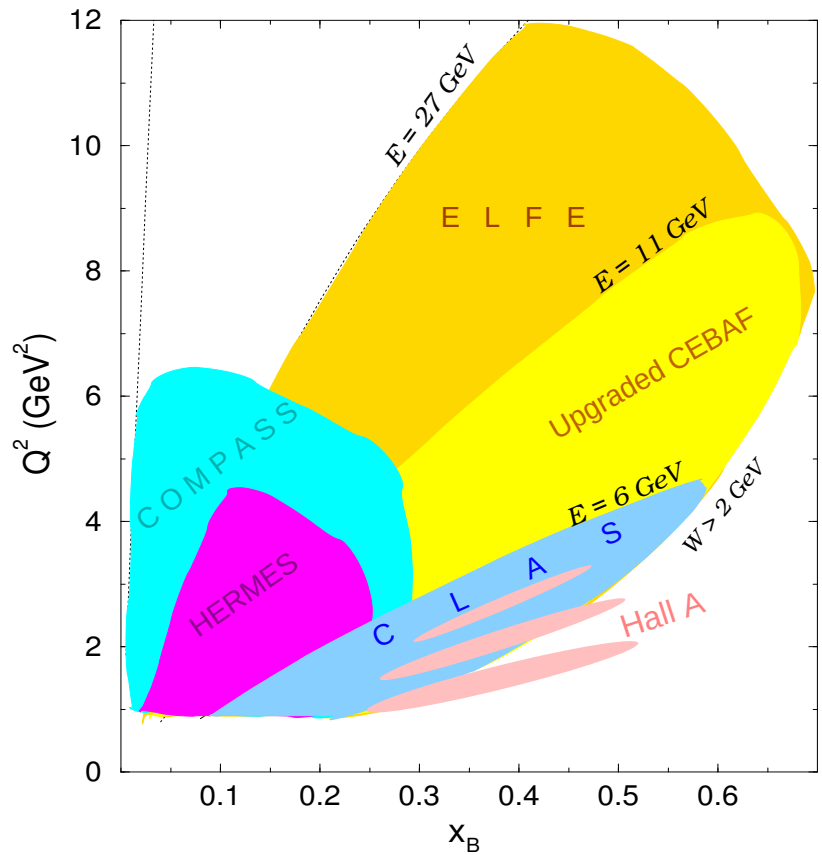
Ellinghaus et al., hep-ex/0212019

Future Prospects for DVCS Experiments

DVCS at JLab 12 GeV Upgrade



Kinematic domain at various facilities



CONCLUSIONS

- Important progress continues to be made in understanding the spin and flavor structure of the nucleon

- Promising new areas of research (transversity, new types of structure functions and fragmentation functions, Generalized parton distributions, etc.) are being identified and vigorously pursued

- New results from many accelerator facilities (HERA, RHIC, JLab, RHIC, CERN, Fermilab, SLAC, etc.) are anticipated in the near future