SIDIS Workshop for PAC30
April 14, 2006

Flavor Decomposition

in Semi-Inclusive DIS

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Outline

- Valence quarks
  - unpolarized d/u ratio
  - polarized $\Delta d/d$ ratio

- Sea quarks
  - flavor asymmetry $\bar{d} - \bar{u}$
  - spin-flavor asymmetry $\Delta\bar{d} - \Delta\bar{u}$
  - polarized strangeness Δs

Semi-inclusive DIS

Semi-inclusive hadron-production offers tremendous opportunity for determining

- $\longrightarrow$ spin-flavor composition of nucleon PDFs *
- $\longrightarrow$ new distributions, not accessible in inclusive DIS

At leading order pQCD, SIDIS cross section factorizes

$$\frac{d\sigma}{dx\ dz\ dQ^2} \sim \sum_q e_q^2\ \underbrace{q(x,Q^2)}_{\text{quark distribution function}}\ \underbrace{D_q^h(z,Q^2)}_{\text{quark} \longrightarrow \text{hadron fragmentation function}}$$

For pion-production off proton target

→ spin-independent cross section

$$\sigma_p^\pi \sim \frac{4}{9}(u\ D_u^\pi + \bar{u}\ D_{\bar{u}}^\pi) + \frac{1}{9}(d\ D_d^\pi + \bar{d}\ D_{\bar{d}}^\pi) + \frac{1}{9}(s\ D_s^\pi + \bar{s}\ D_{\bar{s}}^\pi)$$

→ spin-dependent cross section

$$\Delta\sigma_p^\pi \sim \frac{4}{9}(\Delta u\ \Delta D_u^\pi + \Delta\bar{u}\ \Delta D_{\bar{u}}^\pi) + \frac{1}{9}(\Delta d\ \Delta D_d^\pi + \Delta\bar{d}\ \Delta D_{\bar{d}}^\pi) + \frac{1}{9}(\Delta s\ \Delta D_s^\pi + \Delta\bar{s}\ \Delta D_{\bar{s}}^\pi)$$

Assume spin-independent fragmentation

→ $\Delta D_q^\pi = D_q^\pi$

Isospin symmetry

→ leading fragmentation functions

$$D_u^{\pi^+} = D_{\bar{d}}^{\pi^+} = D_d^{\pi^-} = D_{\bar{u}}^{\pi^-} \equiv D$$

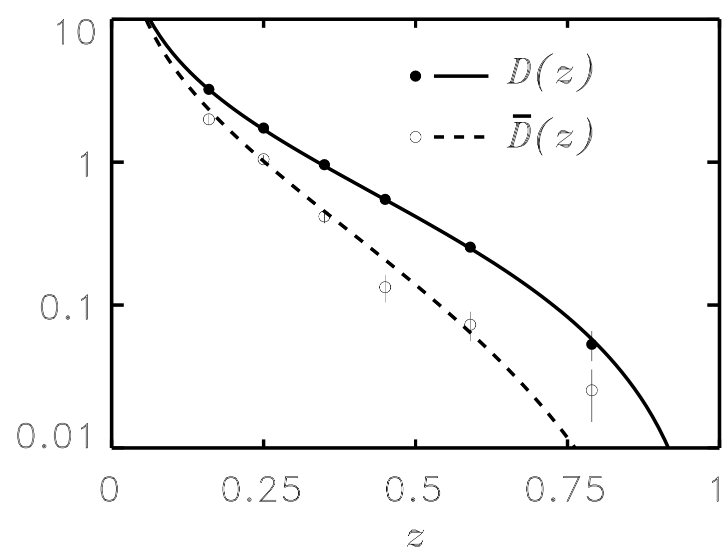
→ non-leading fragmentation functions

$$D_d^{\pi^+} = D_{\bar{u}}^{\pi^+} = D_u^{\pi^-} = D_{\bar{d}}^{\pi^-} = D_s^{\pi^\pm} = D_{\bar{s}}^{\pi^\pm} \equiv \bar{D}$$

Empirically,

→ $(1+z)\bar{D}(z) \approx (1-z)D(z)$

EMC, Aubert et al., PLB110 (1982) 73



Valence quarks

At large x ($x > 0.4$ – 0.5) , $\bar{q}(x) \approx 0$

$$\longrightarrow \quad \sigma_p^{\pi^+} \sim 4\, u(x)\, D(z) \, + \, d(x)\, \bar{D}(z)$$

$$\sigma_p^{\pi^-} \sim 4\, u(x)\, \bar{D}(z) \, + \, d(x)\, D(z)$$

Ratio

$$R^\pi(x,z) = \frac{\sigma_p^{\pi^-}}{\sigma_p^{\pi^+}} = \frac{4\bar{D}(z)/D(z) + d(x)/u(x)}{4 + d(x)/u(x) \cdot \bar{D}(z)/D(z)}$$

$$\rightarrow \frac{1}{4}\frac{d(x)}{u(x)}$$ in $z \rightarrow 1$ limit

Traditional method extracts d/u ratio from inclusive n/p structure function ratio at large x

$\rightarrow$

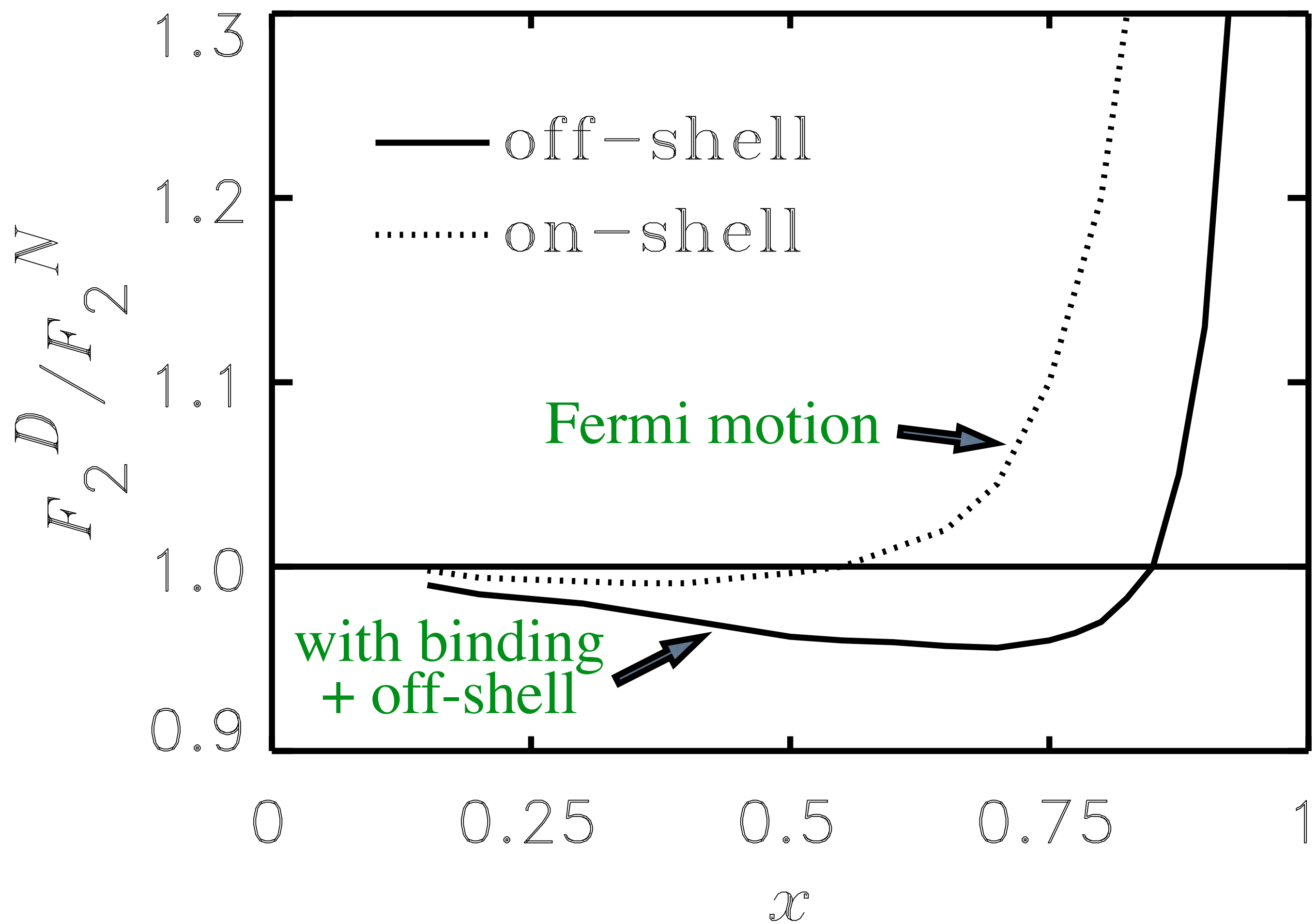
$$F_2^p \sim \frac{4}{9}\, u + \frac{1}{9}\, d$$

$$F_2^n \sim \frac{1}{9}\, u + \frac{4}{9}\, d$$

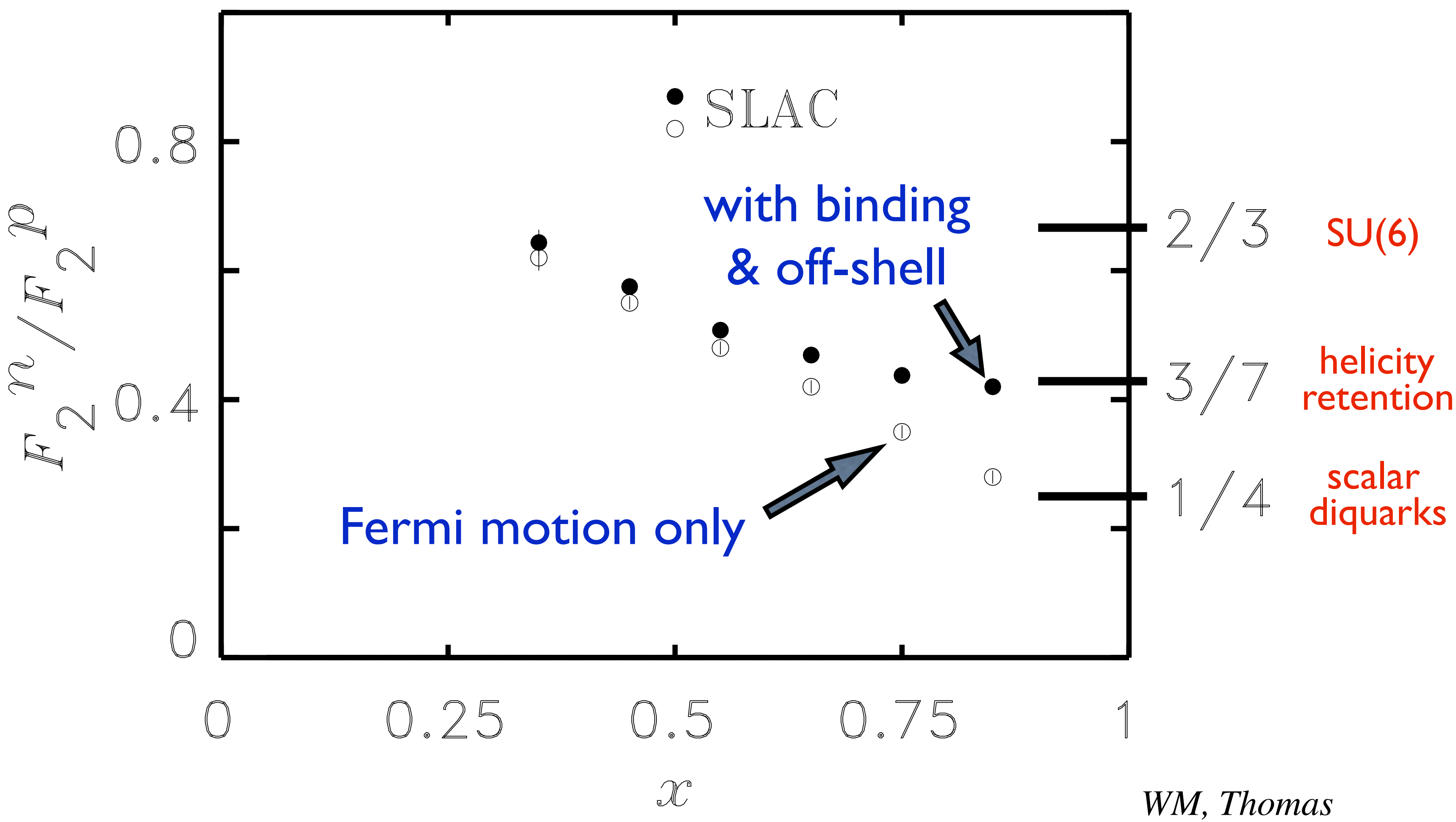
$\rightarrow$

$$\frac{d}{u} \sim \frac{4 - F_2^n / F_2^p}{4F_2^n / F_2^p - 1}$$

$\rightarrow$ suffers from large nuclear corrections at large x



WM, Schreiber, Thomas,
Phys. Rev. D49, 1183 (1994)



WM, Thomas
Phys. Lett. B 377 (1996) 11

→ without EMC effect in d, F_2^n underestimated at large x

Diquarks as Inspiration and as Objects

Frank Wilczek*

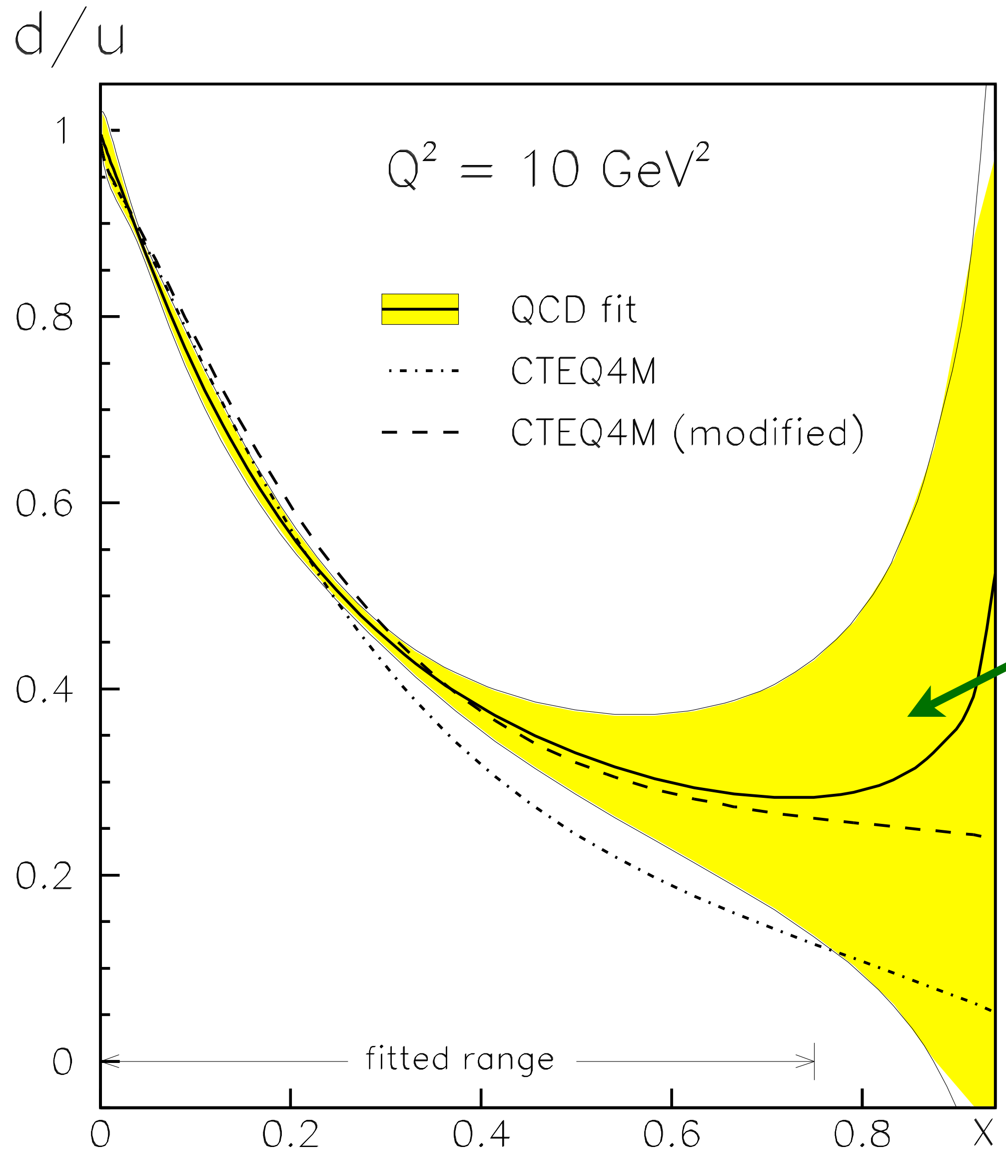
September 17, 2004

hep-ph/0409168

One of the oldest observations in deep inelastic scattering is that the ratio of neutron to proton structure functions approaches $\frac{1}{4}$ in the limit $x \to 1$

$$\lim_{x \to 1} \frac{F_2^n(x)}{F_2^p(x)} \to \frac{1}{4} \tag{1.1}$$

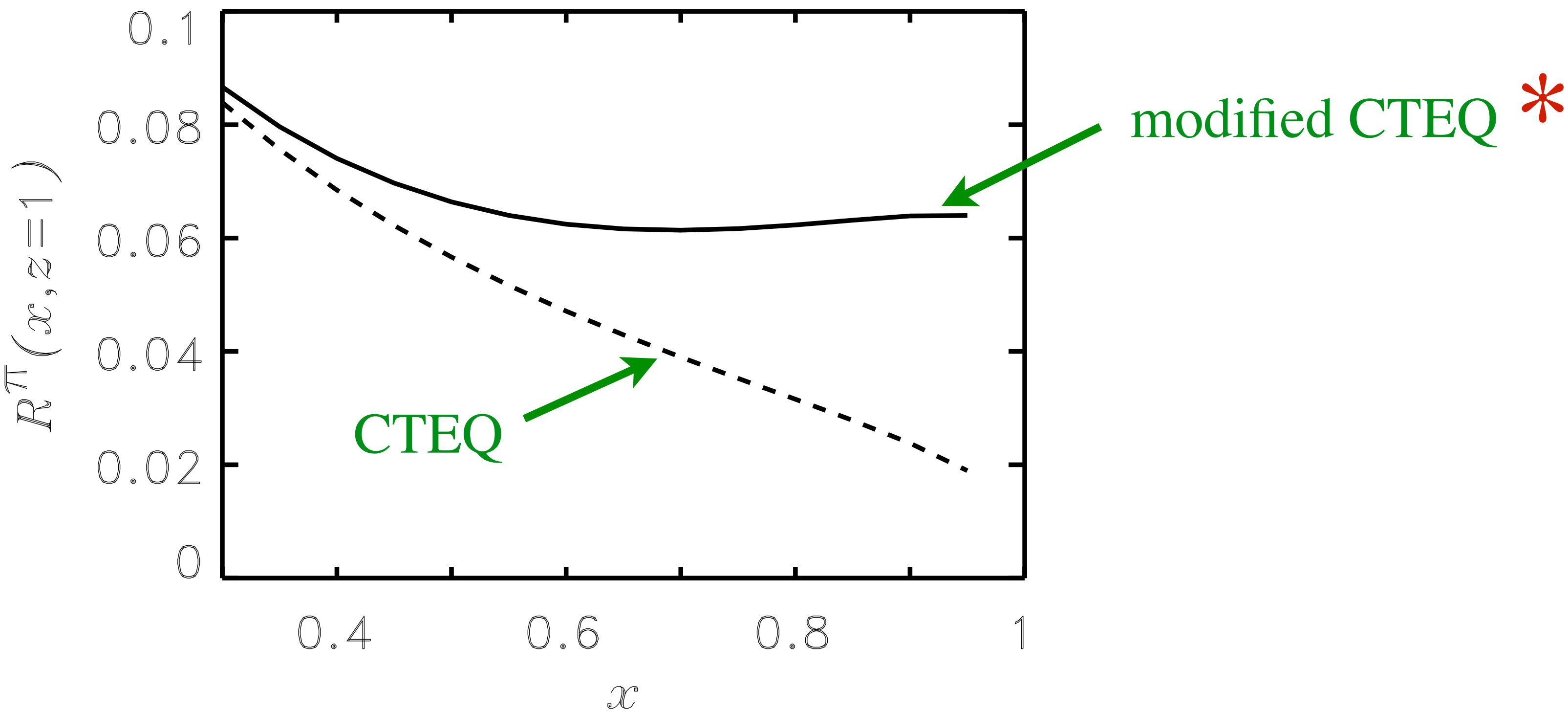
Folklore that experiment gives 1/4 limiting ratio...



uncertainty due to nuclear effects in deuteron

Botje, Eur. Phys. J. C 14 (2000) 285

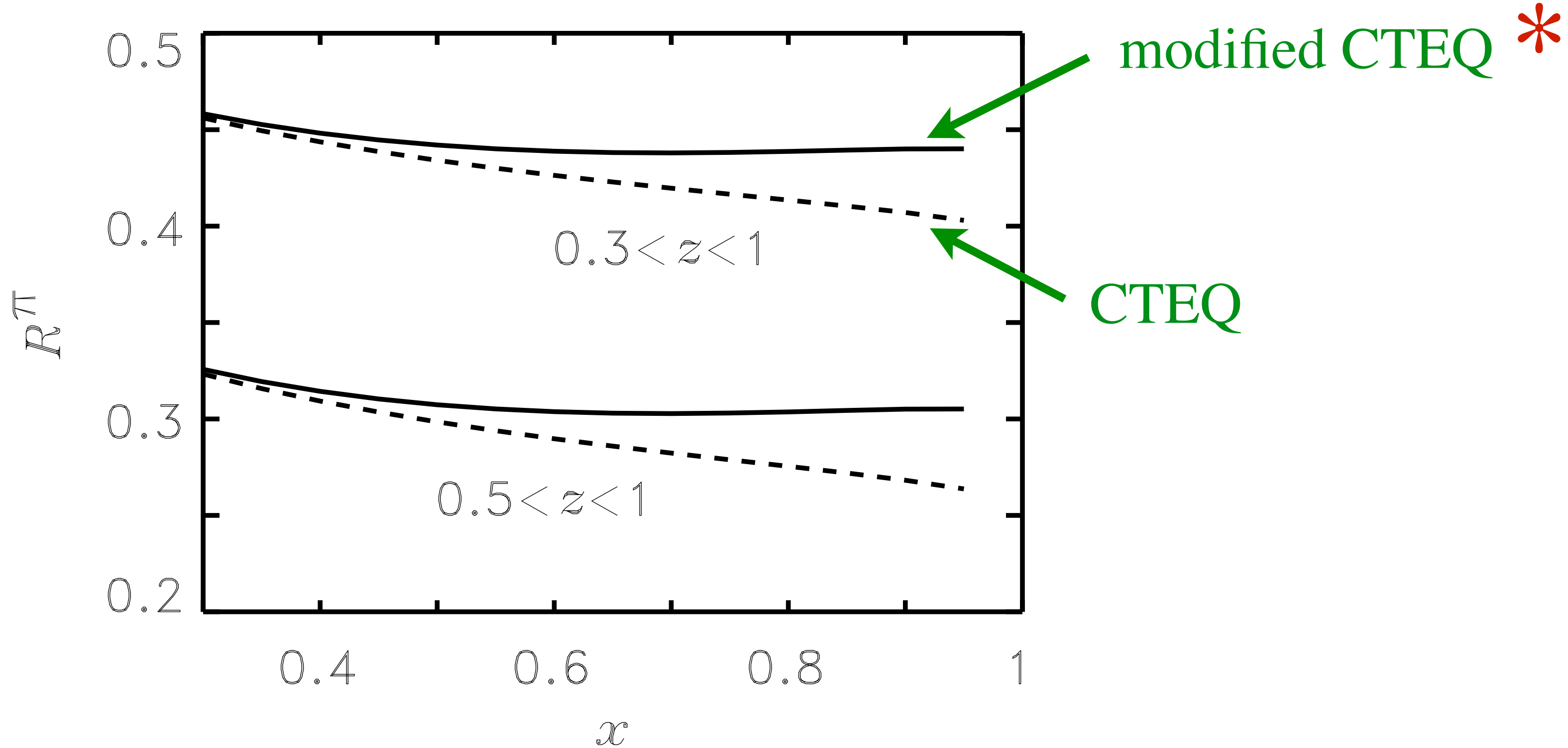
Semi-inclusive ratio at $z = 1$



$$* \quad \frac{d}{u} \rightarrow \frac{d}{u} + \Delta$$

$$\Delta = 0.2\, x^2 e^{-(1-x)^2}$$

Semi-inclusive ratio at $z < 1$



$$* \quad \frac{d}{u} \to \frac{d}{u} + \Delta$$

$$\Delta = 0.2\ x^2 e^{-(1-x)^2}$$

Combine with “neutron” (deuteron) target

$\longrightarrow$ eliminate dependence on fragmentation function

$$\sigma_{\tilde{n}}^{\pi^+} \sim 4\ (\tilde{d}(x) + \epsilon_u(x))\ D(z)\ +\ (\tilde{u}(x) + \epsilon_d(x))\ \bar{D}(z)$$

$$\sigma_{\tilde{n}}^{\pi^-} \sim 4\ (\tilde{d}(x) + \epsilon_u(x))\ \bar{D}(z)\ +\ (\tilde{u}(x) + \epsilon_d(x))\ D(z)$$

smeared quark distribution in nucleon bound in d

$$\tilde{q}(x) = \int \frac{dy}{y}\ f_{N/d}(y)\ q(x/y)$$

$$\epsilon_q(x) = \tilde{q}(x) - q(x)$$

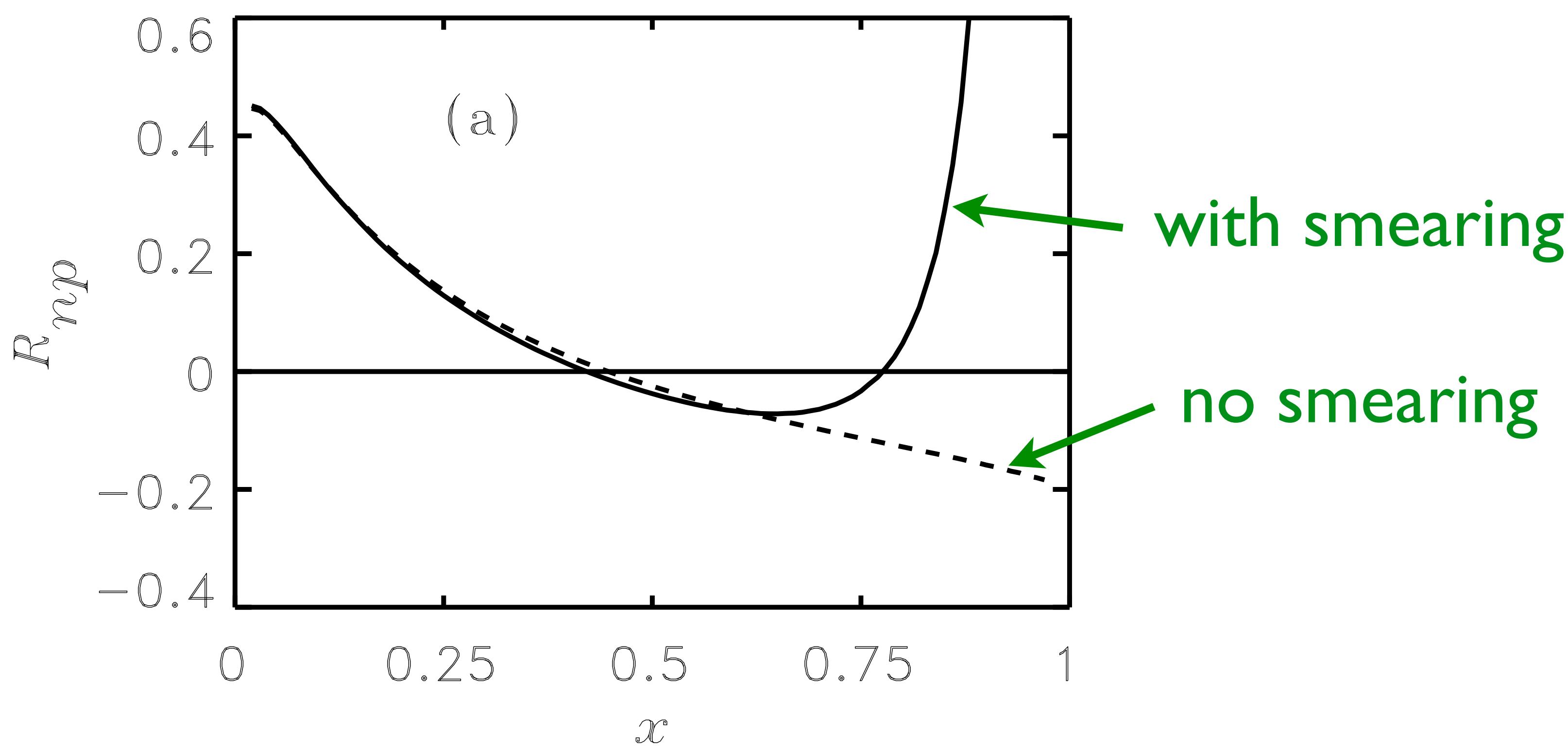
Ratio independent of fragmentation function

$$\rightarrow \quad R_{np} = \frac{\sigma_{\tilde{n}}^{\pi^+} - \sigma_{\tilde{n}}^{\pi^-}}{\sigma_{p}^{\pi^+} - \sigma_{p}^{\pi^-}} = \frac{4\tilde{d}(x) - \tilde{u}(x) + 4\epsilon_u(x) - \epsilon_d(x)}{4u(x) - d(x)}$$

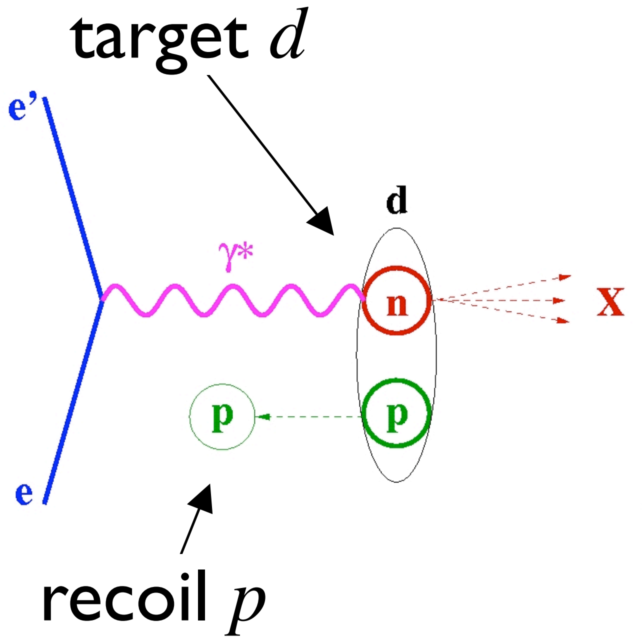
If no nuclear corrections

$$\tilde{q}(x) = q(x)$$

$$\rightarrow \quad R_{np} = \frac{4d(x)/u(x) - 1}{4 - d(x)/d(x)}$$



DIS from "slow" n in deuteron

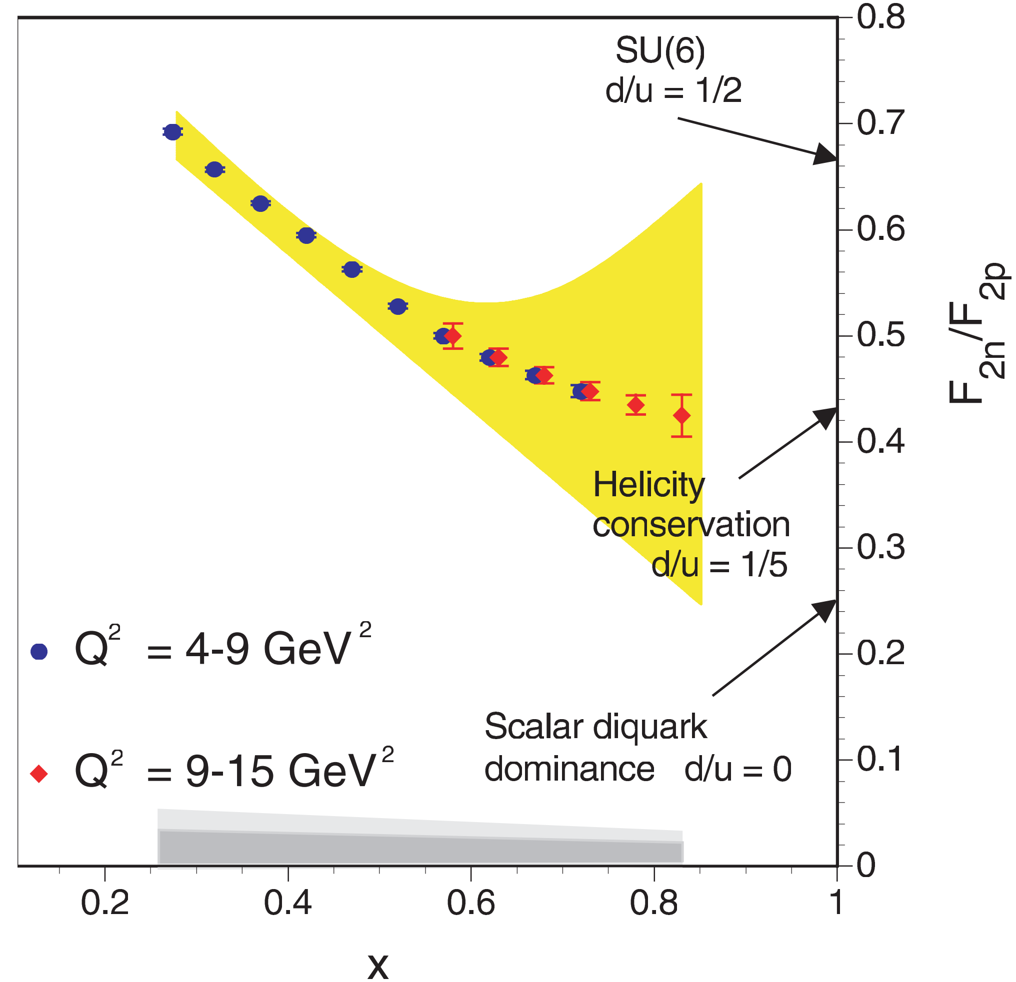


$$e\ d \to e\ p\ X$$

backward slow p

→ neutron nearly on-shell

→ minimize rescattering



JLab Hall B experiment ("BONUS")

Quark polarization at large x

SU(6) symmetry $\rightarrow$

$$\frac{\Delta u}{u} = \frac{2}{3}\,, \quad \frac{\Delta d}{d} = -\frac{1}{3}$$

$$A_1^p = \frac{5}{9}\,, \quad A_1^n = 0$$

scalar diquark dominance $\rightarrow$

$$\frac{\Delta u}{u} \to 1\,, \quad \frac{\Delta d}{d} \to -\frac{1}{3}$$

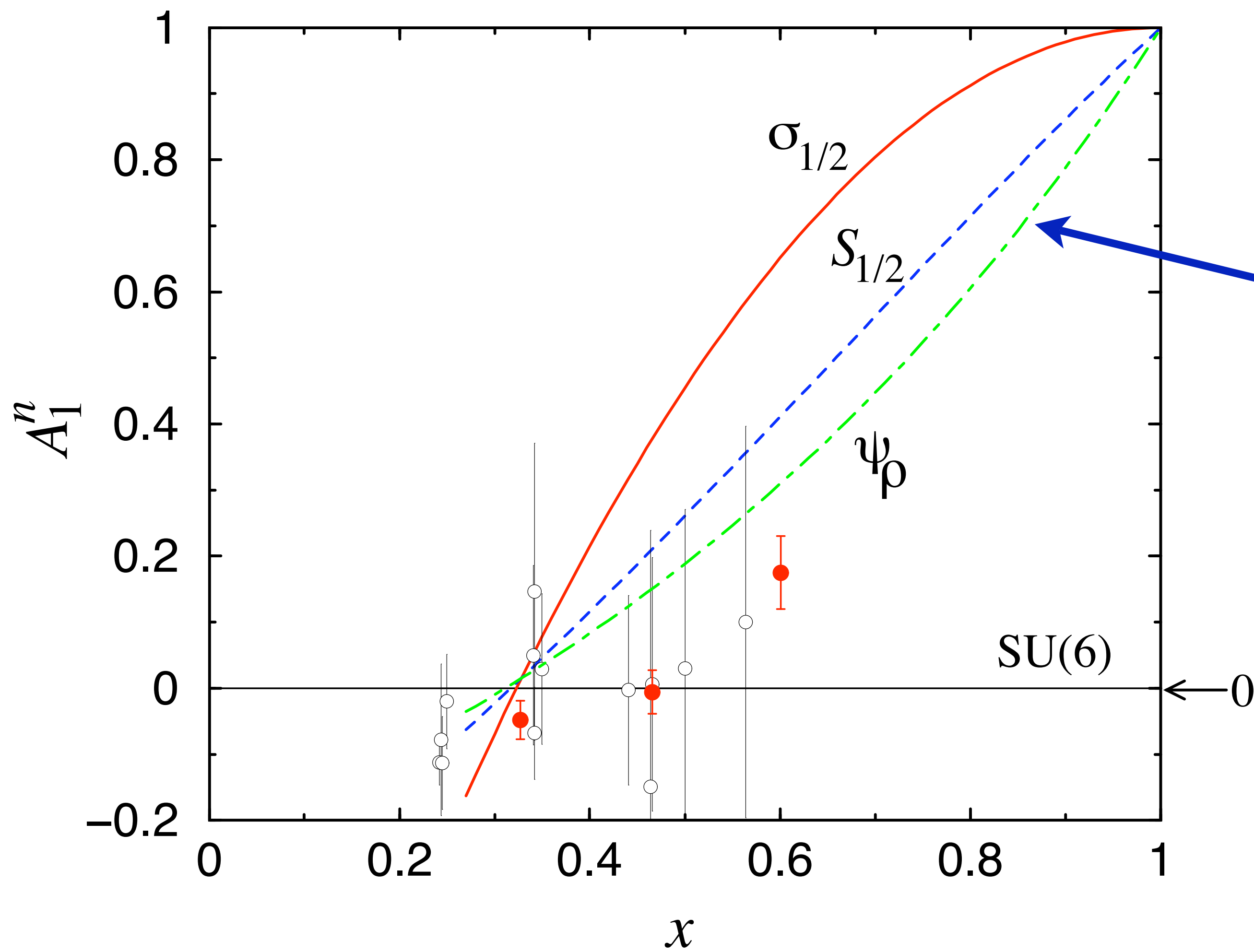
$$A_1^p \to 1\,, \quad A_1^n \to 1$$

pQCD (helicity conservation) $\rightarrow$

$$\frac{\Delta u}{u} \to 1\,, \quad \frac{\Delta d}{d} \to 1$$

$$A_1^p \to 1\,, \quad A_1^n \to 1$$

Inclusive data:

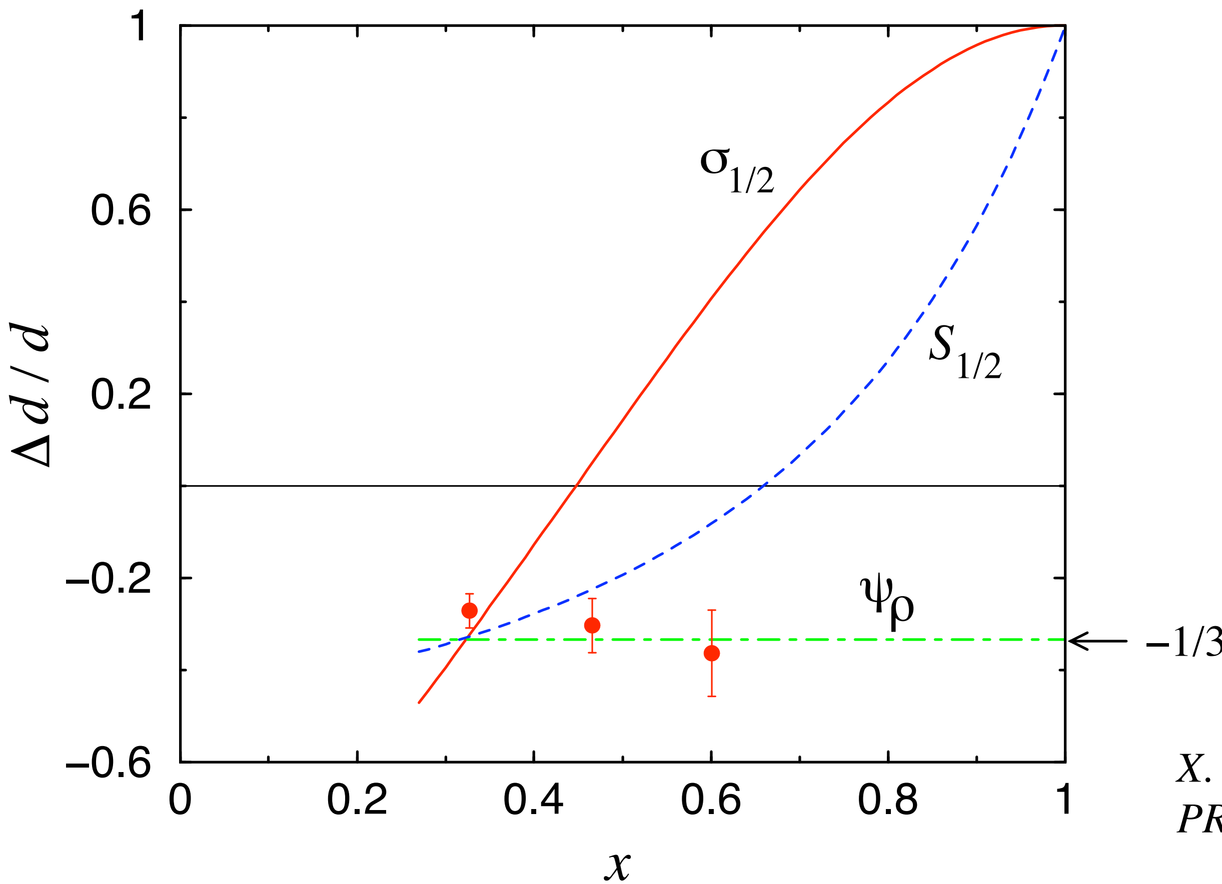


duality-based models

Close, WM, Phys, Rev, C68 (2003) 035210

data*: X. Zheng et al., Phys. Rev. Lett. 92 (2004) 012004*

Indirect extraction: $$\frac{\Delta d}{d} = \frac{4}{15} A_1^n \, (4 + u/d) - \frac{1}{15} A_1^p \, (1 + 4u/d)$$



X. Zheng et al., PRL 92 (2004) 012004

→ no sign yet of pQCD behavior

→ determine directly in SIDIS

Semi-inclusive polarization asymmetry for hadron h

$$A_1^h(x,z) = \frac{\sum_q e_q^2\ \Delta q(x)\ D_q^h(z)}{\sum_{q'} e_{q'}^2\ q'(x)\ D_{q'}^h(z)}$$

$$= \sum_q P_q^h(x,z)\ \frac{\Delta q(x)}{q(x)}$$

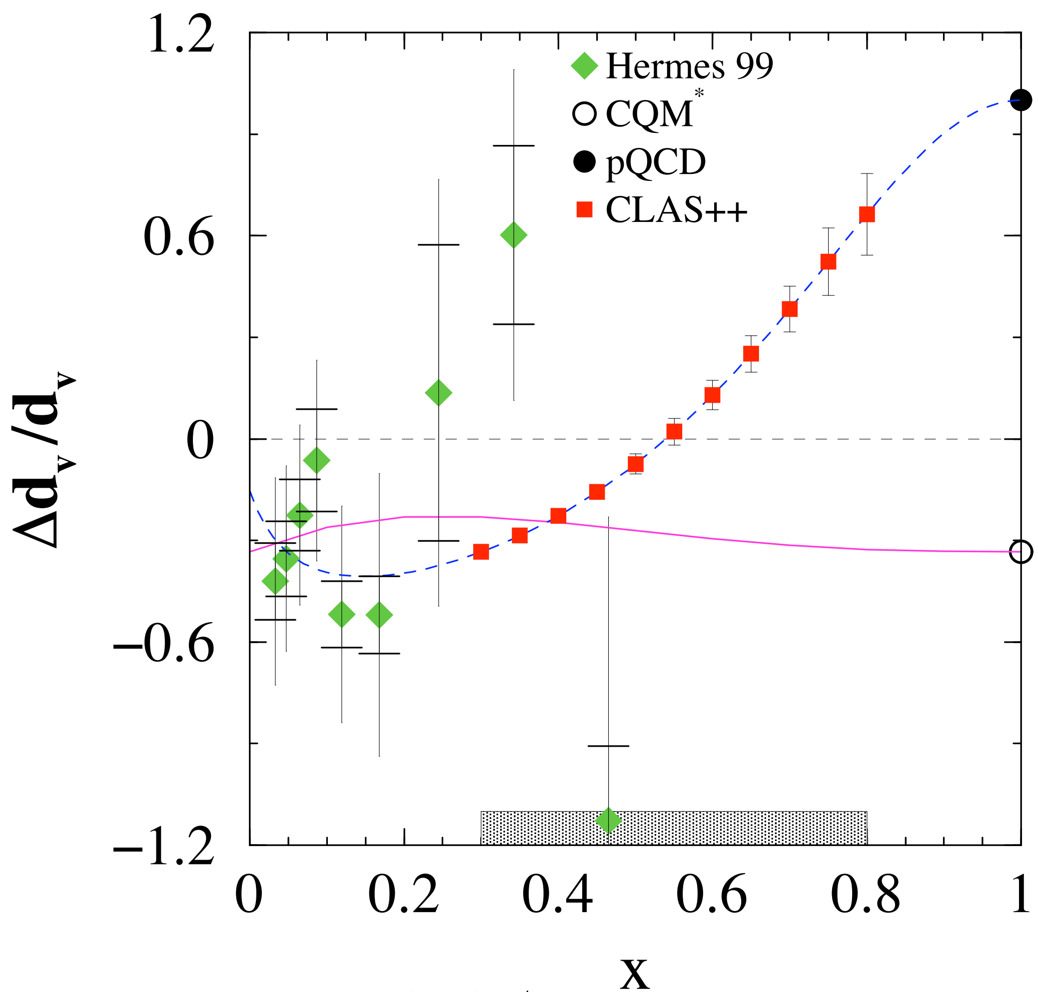
"purity"

$$P_q^h(x,z) = \frac{e_q^2\ q(x)\ D_q^h(z)}{\sum_{q'} e_{q'}^2\ q'(x)\ D_{q'}^h(z)}$$

In practice integrate over z, e.g. $0.2 < z < 0.8$

Existing data (HERMES):

→ $\pi^{\pm}, K^{\pm}$ production on p, d targets



→ note nuclear effects in d for $x > 0.6\text{–}0.7$

More direct method, using $\pi^+ - \pi^-$ difference

$$\frac{\Delta d_v}{d_v} = \frac{\Delta\sigma_p^{\pi^+ - \pi^-} + 4\Delta\sigma_n^{\pi^+ - \pi^-}}{\sigma_p^{\pi^+ - \pi^-} + 4\sigma_n^{\pi^+ - \pi^-}}$$

$$\frac{\Delta u_v}{u_v} = \frac{4\Delta\sigma_p^{\pi^+ - \pi^-} + \Delta\sigma_n^{\pi^+ - \pi^-}}{4\sigma_p^{\pi^+ - \pi^-} + \sigma_n^{\pi^+ - \pi^-}}$$

$\longrightarrow$ sea quarks cancel in $\pi^+ - \pi^-$ difference

Sea quarks

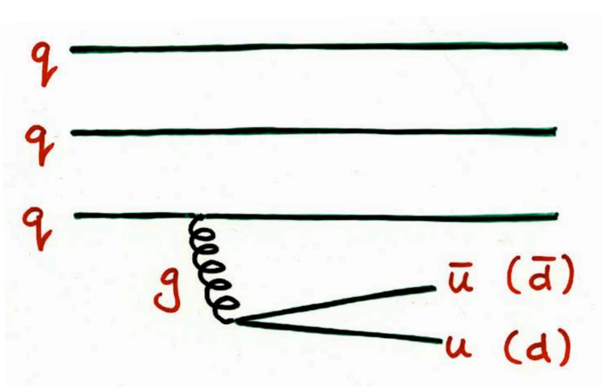
Flavor asymmetry of proton sea

- Because sea quarks & antiquarks are produced *"radiatively"* (by $g \to q\bar{q}$ radiation)

  $\longrightarrow$ expect flavour-symmetric sea
  IF quark masses are the same

  $\longrightarrow$ *e.g.* **since** $m_s \gg m_d \quad \Longrightarrow \quad \bar{d}(x) > \bar{s}(x)$

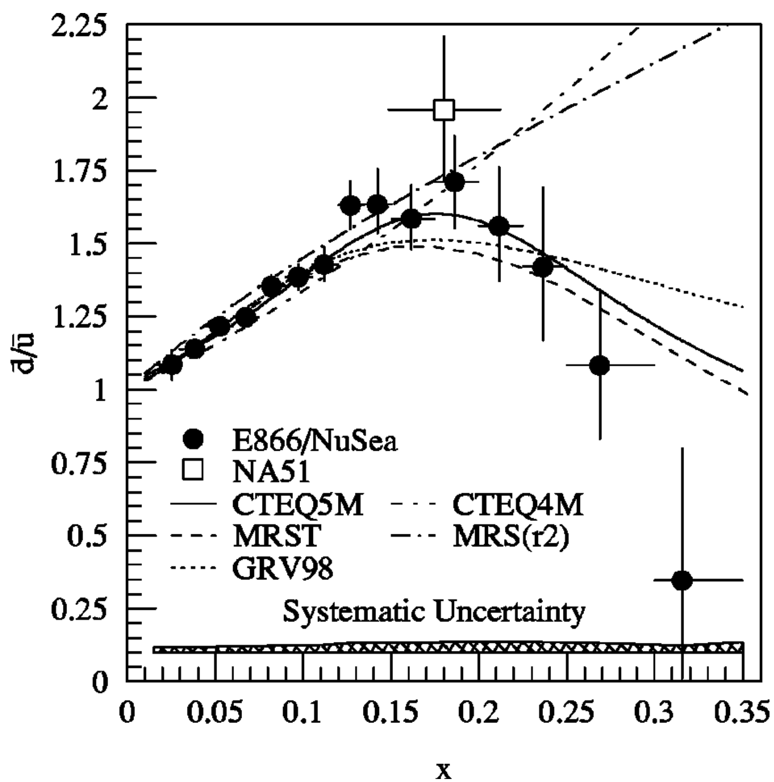
- BUT since $m_u \approx m_d \quad \Longrightarrow \quad$ expect $\bar{d}(x) \approx \bar{u}(x)$

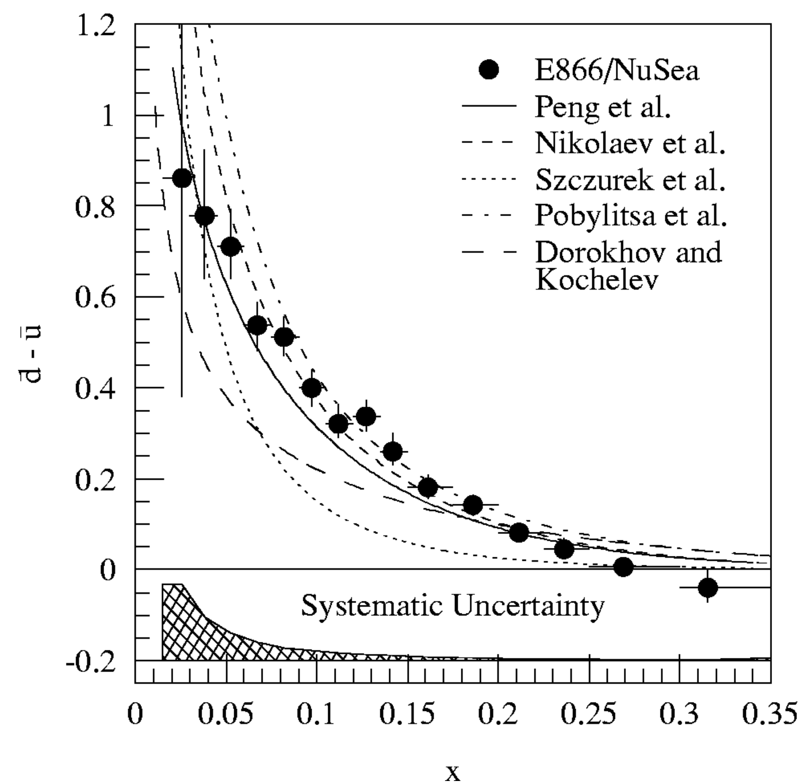


$$\bar{d} = \bar{u}$$

Flavor asymmetry of proton sea

Large $\bar{d} - \bar{u}$ asymmetry in proton observed in DIS (NMC) and Drell-Yan (CERN NA51 and FNAL E866) experiments





$$\int_0^1 dx\ (\bar{d}(x) - \bar{u}(x)) = 0.118 \pm 0.012$$

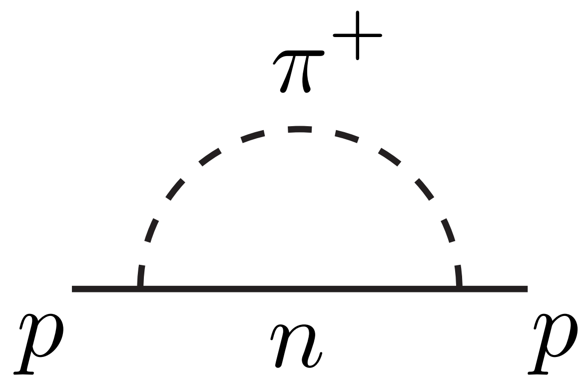
Towell et al., Phys. Rev. D 64 (2001) 052002

Flavor asymmetry of proton sea

- Pion cloud

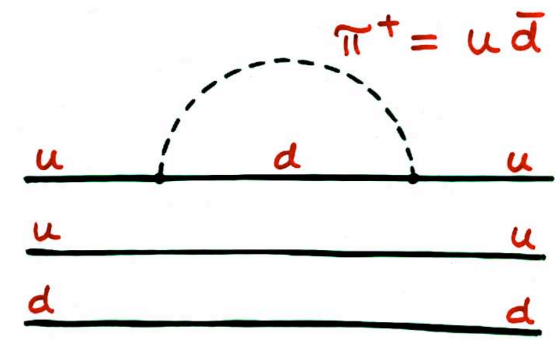
  - some of the time the proton looks like a neutron & π^+

    (Heisenberg Uncertainty Principle)



$$p \rightarrow \pi^+ \; n \rightarrow p$$

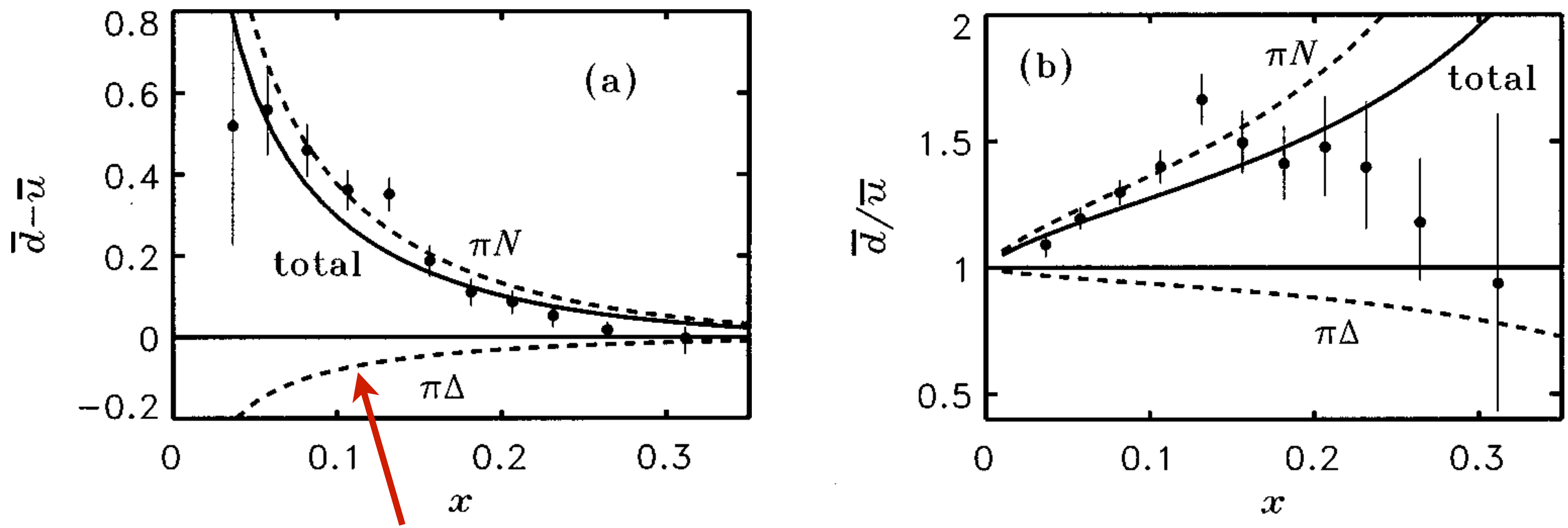
  - at the quark level



$$uud \rightarrow (udd)(\bar{d}u) \rightarrow uud$$

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

Thomas, Phys. Lett. 126B (1983) 97



$$p(uud) \to \pi^{-}(d\bar{u}) + \Delta^{++}(uuu)$$
$$\Rightarrow \bar{u} > \bar{d}$$

WM, Speth, Thomas, PRD59 (1998) 014033

⟹ good description of data at $x < 0.2$

⟹ difficult to understand downturn at large x

Flavor asymmetry of proton sea

- Pauli Exclusion Principle

  ➡ since proton has more valence u than d

  $\longrightarrow$ easier to create $d\bar{d}$ than $u\bar{u}$

  Field, Feynman, Phys. Rev. D15 (1977) 2590

  ➡ explicit calculations of antisymmetrization effects in $g \rightarrow u\bar{u}$ and $g \rightarrow d\bar{d}$

  $\longrightarrow$ perturbative effects small

  $\longrightarrow$ nonperturbative ??

  Ross, Sachrajda, Nucl. Phys. B149 (1979) 497
  Steffens, Thomas, Phys. Rev. 55 (1997) 900

Flavor asymmetry in SIDIS

Semi-inclusive ratio

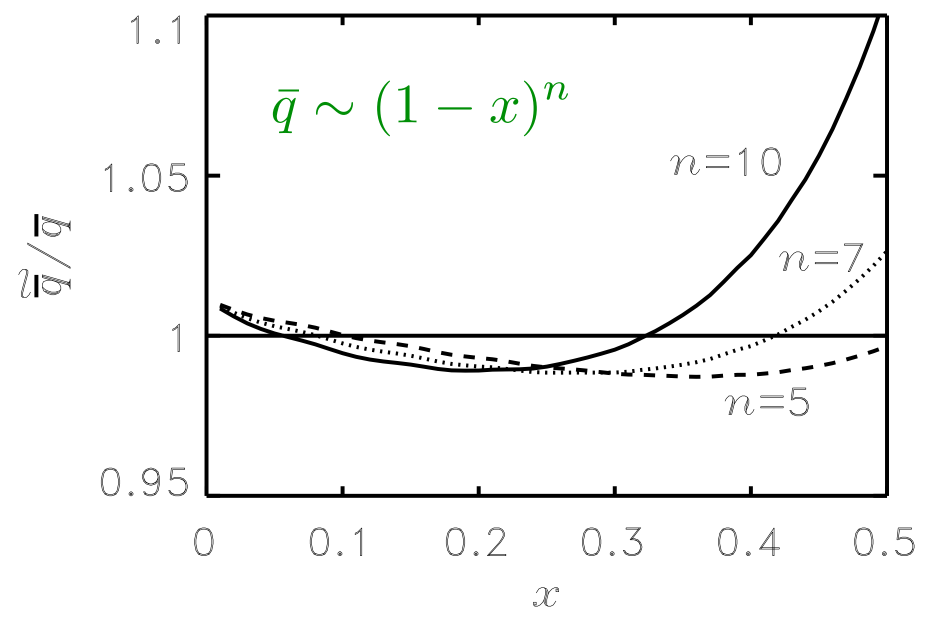
$$R(x,z) = \frac{\sigma_p^{\pi^+ + \pi^-} - \sigma_n^{\pi^+ + \pi^-}}{\sigma_p^{\pi^+ - \pi^-} - \sigma_n^{\pi^+ - \pi^-}}$$

$$= \frac{3}{5}\,\frac{(u-d)-(\bar{d}-\bar{u})}{u_v - d_v}\,\frac{(1+\bar{D}/D)}{(1-\bar{D}/D)}$$

Levelt, Mulders, Schreiber
PLB 263 (1991) 498

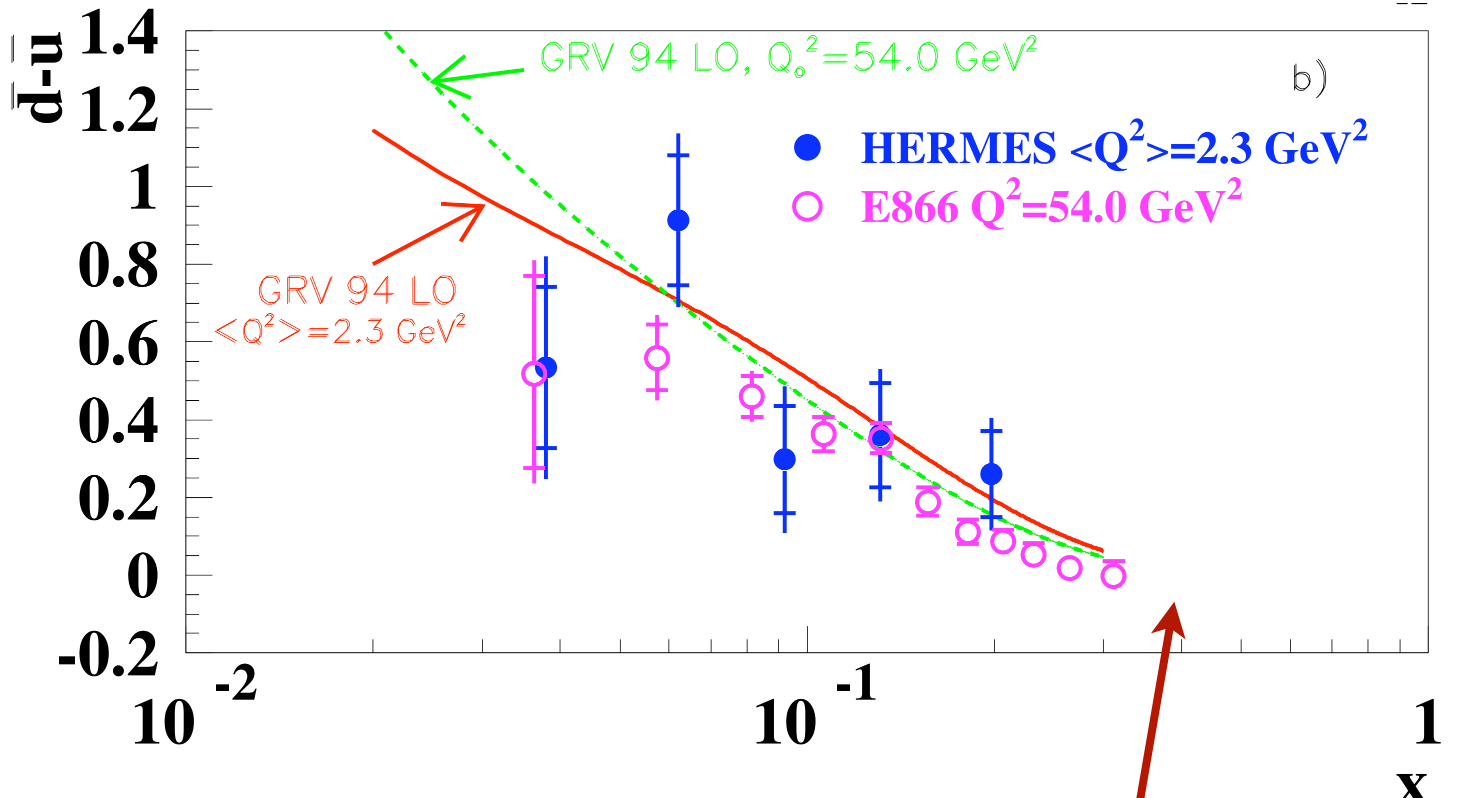
→ sensitive to $\bar{d} - \bar{u}$

→ nuclear smearing in d not significant for $x < 0.4$

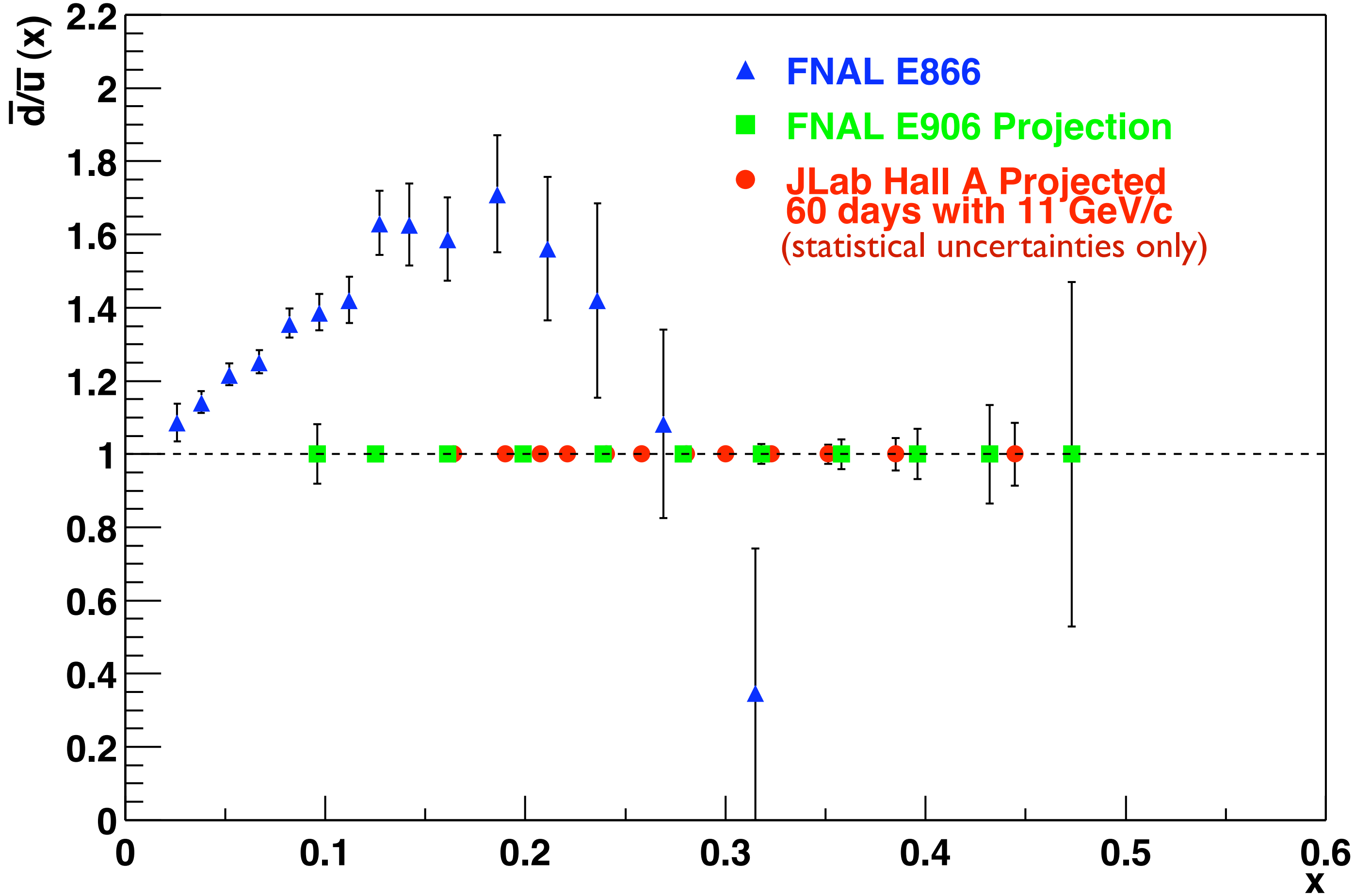


Flavor asymmetry in SIDIS

K. Ackerstaff et al., Phys. Rev. Lett. 81 (1998) 5519



change of sign at large x ??



$\bar{d}/\bar{u}$ (x)
FNAL E866
FNAL E906 Projection
JLab Hall A Projected
60 days with 11 GeV/c
(statistical uncertainties only)
2.2
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0.1
0.2
0.3
0.4
0.5
0.6
x

Flavor asymmetry in SIDIS

Ratio of integrals

$$Q(z) = \frac{\int_0^1 dx\ (\sigma_p^{\pi^+ + \pi^-} - \sigma_n^{\pi^+ + \pi^-})}{\int_0^1 dx\ (\sigma_p^{\pi^+ - \pi^-} - \sigma_n^{\pi^+ - \pi^-})}$$

$$= \frac{9}{5}\ S_G\ \frac{(1 + \bar{D}/D)}{(1 - \bar{D}/D)}$$

Levelt, Mulders, Schreiber
PLB 263 (1991) 498

Gottfried sum

$$S_G = \int_0^1 dx\ \frac{F_2^{p-n}(x)}{x} = \frac{1}{3}\int_0^1 dx\ (u + \bar{u} - d - \bar{d})$$

$\longrightarrow$ independent test of Gottfried sum rule

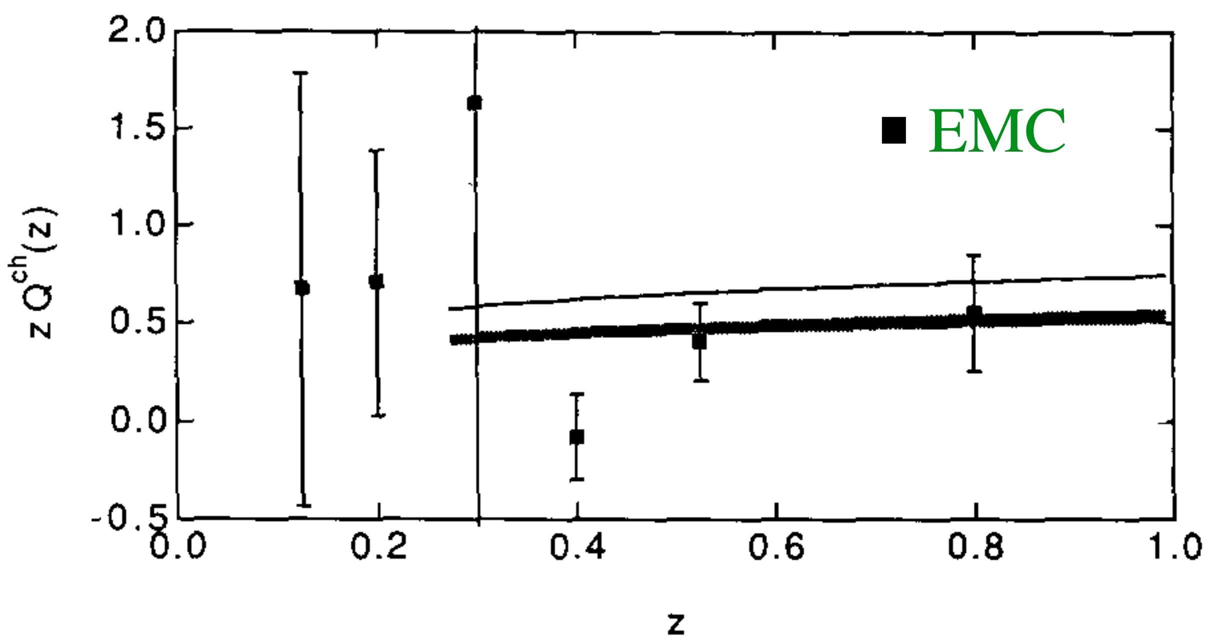
Flavor asymmetry in SIDIS

Ratio of integrals

$$Q(z) = \frac{\int_0^1 dx\ (\sigma_p^{\pi^+ + \pi^-} - \sigma_n^{\pi^+ + \pi^-})}{\int_0^1 dx\ (\sigma_p^{\pi^+ - \pi^-} - \sigma_n^{\pi^+ - \pi^-})}$$

$$= \frac{9}{5}\ S_G\ \frac{(1 + \bar{D}/D)}{(1 - \bar{D}/D)}$$

Levelt, Mulders, Schreiber
PLB 263 (1991) 498



Polarization asymmetry of proton sea

- Neither pQCD nor meson cloud contribute significantly to $\Delta\bar{d} - \Delta\bar{u}$

- ***But*** Pauli Exclusion Principle (antisymmetrization)

$$\Longrightarrow \quad \Delta\bar{u} - \Delta\bar{d} \approx \frac{5}{3}(\bar{d} - \bar{u})$$

Schreiber, Signal, Thomas, Phys. Rev. D44, 2653 (1991)

Steffens, Phys. Rev. C55, 900 (1997)

- Disentangle origin of unpolarized and polarized asymmetries in sea via semi-inclusive DIS

Polarization asymmetry of proton sea

- Extract $\Delta\bar{d} - \Delta\bar{u}$ either via "purity" method or directly via $\pi^+ + \pi^-$ asymmetries on p, n

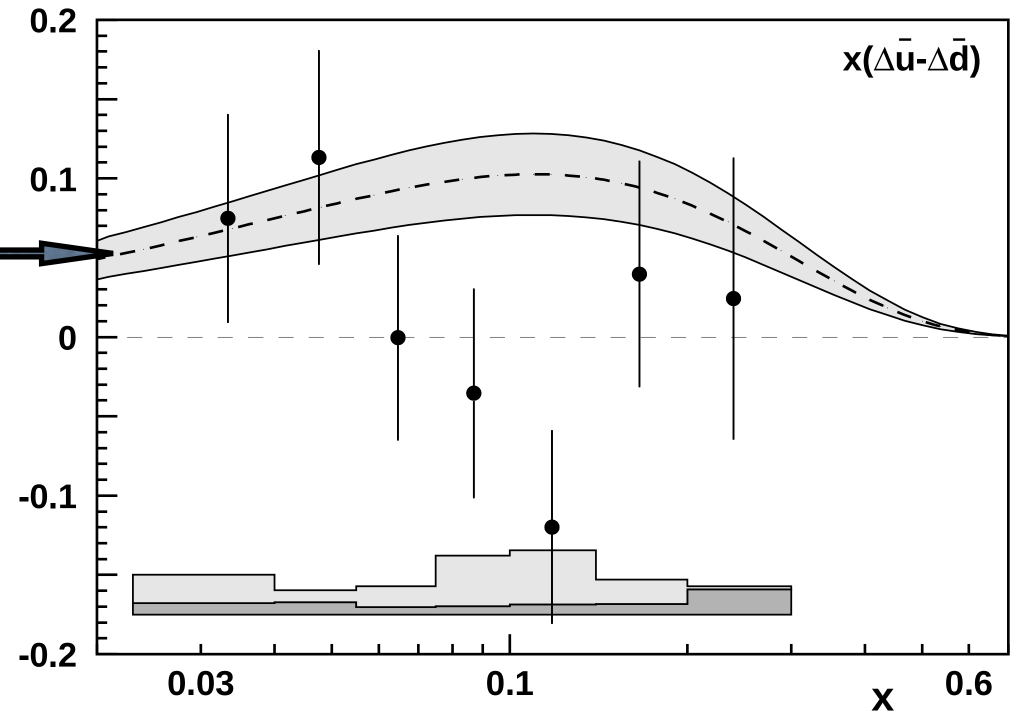
$$\Delta R^{\pi^+ + \pi^-} = \frac{\Delta\sigma_p^{\pi^+ + \pi^-} - \Delta\sigma_n^{\pi^+ + \pi^-}}{\sigma_p^{\pi^+ + \pi^-} - \sigma_n^{\pi^+ + \pi^-}}$$

$$= \frac{(\Delta u + \Delta\bar{u}) - (\Delta d + \Delta\bar{d})}{(u + \bar{u}) - (d + \bar{d})}$$

Polarization asymmetry of proton sea

chiral soliton model

Dressler, Goeke, Polyakov, Weiss, Eur. Phys. J. C14 (2000) 147



Airapetian et al. [HERMES], Phys. Rev. Lett. 92 (2004) 012005

current data cannot distinguish between zero and small nonzero $\Delta\bar{u} - \Delta\bar{d}$

Polarized strangeness

- Extract $\Delta s/s$ from combination of inclusive and semi-inclusive spin-dependent asymmetries & cross sections

$$\frac{\Delta s}{s} = \frac{A_{1p}^{+} A_{1n}^{+} F_1^{n-p} + g_1^p A_{1n}^{+} - g_1^n A_{1p}^{+}}{g_1^{p-n} - (A_{1p}^{+} F_1^p - A_{1n}^{+} F_1^n)}$$

semi-inclusive asymmetry

$$A_{1N}^{+} = \frac{\Delta \sigma_N^{\pi^+ + \pi^-}}{\sigma_N^{\pi^+ + \pi^-}}$$

Christova, Leader
PLB 468 (1999) 299

- Alternatively, obtain $\Delta s/s$ ratio via

$$\frac{\Delta \sigma_p^{\pi^+ + \pi^-}(x,z)}{\sigma_p^{\pi^+ + \pi^-}(x,z) - 2D(z)} = \frac{\Delta s(x)/s(x) - A_1^p(x)}{1 - A_1^p(x) \cdot \Delta s(x)/s(x)}$$

Frankfurt et al.,
PLB 230 (1989) 141

Outlook

- unique opportunity at 12 GeV for determining spin & flavor quark distributions in nucleon via SIDIS
  - $\longrightarrow$ d/u and $\Delta d/d$ ratio at large x
  - $\longrightarrow$ spin and flavor asymmetries $\bar{d}-\bar{u}$ and $\Delta\bar{d}-\Delta\bar{u}$ and polarized strangeness at small x

- first need to establish factorization empirically

- caution in use of p, "n" (d) targets
  - $\longrightarrow$ eliminate $D(z)$ dependence
  - $\longrightarrow$ nuclear corrections at large x (use BONUS for n target?)