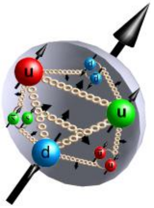

The Structure of Nucleon

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Aug. 29, 2025, 郑州

2025强子物理与有效场论前沿讲习班

粒子发现简史（1）

核子：质子与中子

- 1897年Thomson发现电子，测量了质量电荷比。
- 1909年，Millikan的油滴实验测量了电子的电荷。
- 1911年，Rutherford根据α散射实验假设原子是由很密集的原子核及其外面的电子云所组成的，可以解释α粒子在大角度的散射现象。
- 1919年Rutherford发现质子。
- 1932年Chadwick发现中子。
- 1896年发现原子核的β衰变，1931年，Pauli为了解释这一疑难，提出β衰变时，除了发射一个电子外，还发射某种未知的轻的中性粒子。
- 1933年，费米命名这种粒子为中微子。1956年，Cohen和Reines发现反中微子。

James Chadwick and the Neutron

During 1925-1935

Picked up where Rutherford left off with more scattering experiments… (higher energy though!)

- Performed a series of scattering experiments with α-particles (recall a particles are He nucleus),

$$^{4}_{2}He + {}^{9}Be \longrightarrow {}^{12}C + {}^{1}_{0}n$$

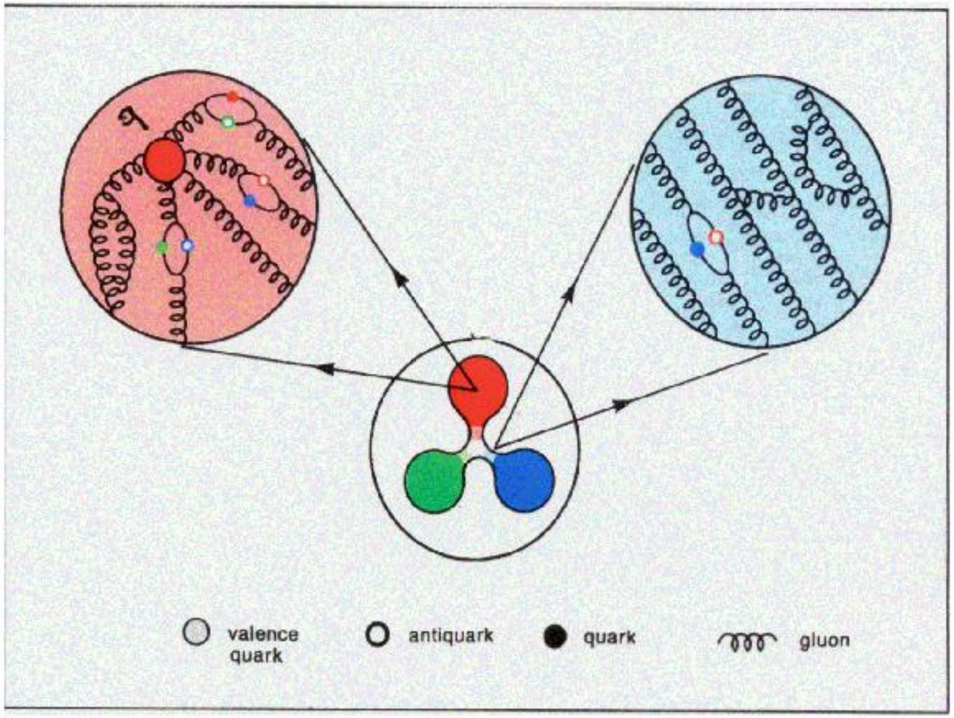
- Chadwick postulated that the emergent radiation was from a new, neutral particle, the neutron.

- Applying energy and momentum conservation he found that the mass of this new object was ~1.15 times that of the proton mass.

1891-1974

⇨ Awarded the Nobel Prize in 1935

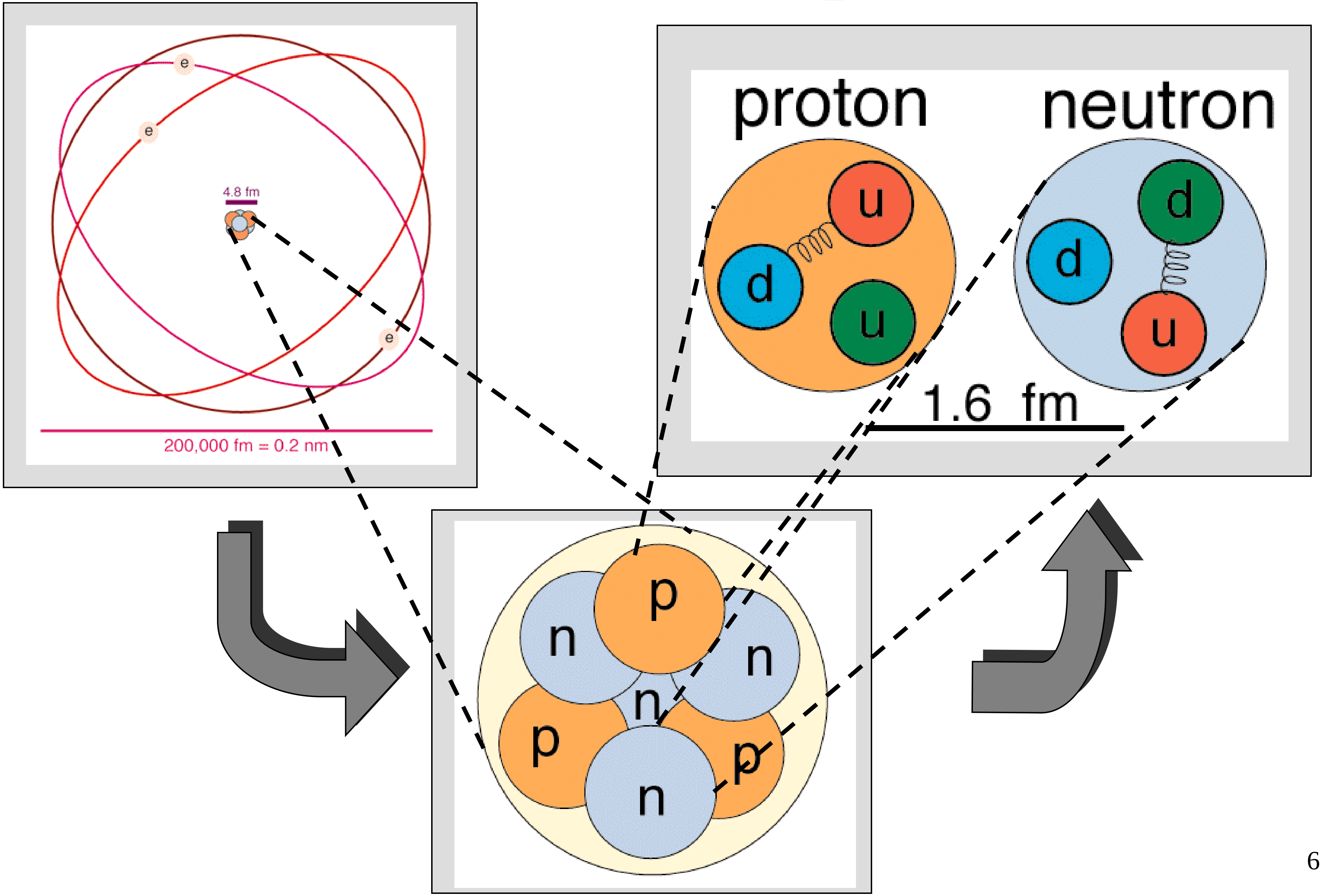
Nucleons: Building Block of Matter



- Nucleon anomalous magnetic moment ***(Stern, Nobel Prize 1943)***
- Electromagnetic form factor from electron scattering ***(Hofstadter, Nobel Prize 1961)***
- Deep-in-elastic scattering, quark underlying structure of the nucleon ***(Freedman, Kendell, Feldman, Nobel Prize 1990)***

Understanding the underlying nucleon structure from quantum chromodynamics is essential

Back to matter & quarks…



Our view of the nucleon
in progress with history

• Point-Like	1919
• Finite Size with Radius	1930s-1950s
• Quark Model	1960s
• QCD and Gluons	1970s
• Puzzles and Anomalies	1980s-present

- Quark Sea of the Nucleon
- Baryon-Meson Fluctuations
- Statistical Features
- ……

History

- 1940s, 1950s: Proliferation of hadrons (i.e. strongly interacting particles)

  $$p,\ n,\ \pi,\ K,\ \Lambda,\ \Sigma,\ \Xi,\ \ldots$$

  in natural groupings of singlets, octets, …

- Gell-Mann & Zweig (1964) :Hadrons are made of quarks

  $$3\times3\times3 = 1+8+8+10$$

  $$3\times\bar{3} = 1+8$$

  for a quark flavour triplet (u,d,s)

Quarks ?

- First things first: Where did the name "quarks" come from?

Murray Gell-Mann had just been reading *Finnegan's Wake* by James Joyce which contains the phrase "*three quarks for Muster Mark*". He decided it would be funny to name his particles after this phrase.

Murray Gell-Mann had a strange sense of humor!

In 1964, Murray Gell-mann & George Zweig (independently) came up with the idea that one could account for the entire "Zoo of Particles", if there existed objects called quarks.

Murray Gell-Mann

George Zweig

The quarks come in 3 types ("flavors"): **up(u), down(d), and strange(s)** and they are fractionally charged with respect to the electron's charge

Flavor	Q/e
u	+2/3
d	-1/3
s	-1/3

Three Families of Quarks

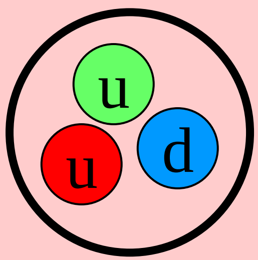
Woohhh, fractionally charged particles?

	Generations (Increasing mass →)		
	I	**II**	**III**
Charge = **-1/3**	**d** **(down)**	**s** **(strange)**	**b** **(bottom)**
Charge = **+2/3**	**u** **(up)**	**c** **(charm)**	**t** **(top)**

Also, each quark has a corresponding antiquark.
The **antiquarks** have **opposite charge** to the quarks

Let's make baryons!

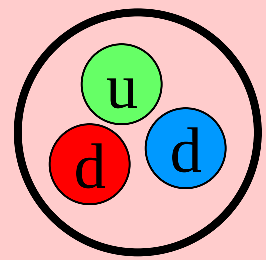
Quark	up	down	strange
Charge Q	+2/3	-1/3	-1/3
Mass	~5 [MeV/c^2]	~10 [MeV/c^2]	~200 [MeV/c^2]
	u u u	d d d	s s s



Proton

Q = +1

M=938 MeV/c^2



Neutron

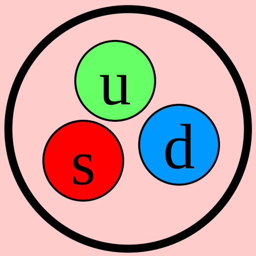
Q = 0

M=940 MeV/c^2

Note: The neutron differs from a proton only by "**d**" ←→ "**u**" quark replacement!

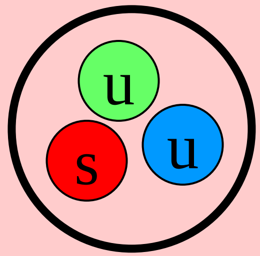
Let's make some more baryons !

Quark	up	down	strange
Charge, Q	+2/3	-1/3	-1/3
Mass	~5 [MeV/c^2]	~10 [MeV/c^2]	~200 [MeV/c^2]
	u u u	d d d	s s s



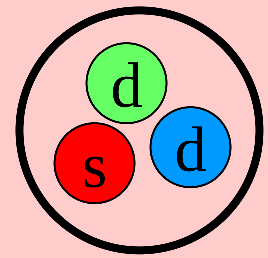
Lambda (Λ)

Q = 0
M=1116 MeV/c^2
Lifetime~2.6×10^{-10}[s]



Sigma (Σ^+)

Q = +1
M=1189 MeV/c^2
Lifetime~0.8×10^{-10}[s]



Sigma (Σ^-)

Q = -1
M=1197 MeV/c^2
Lifetime~1.5×10^{-10}[s]

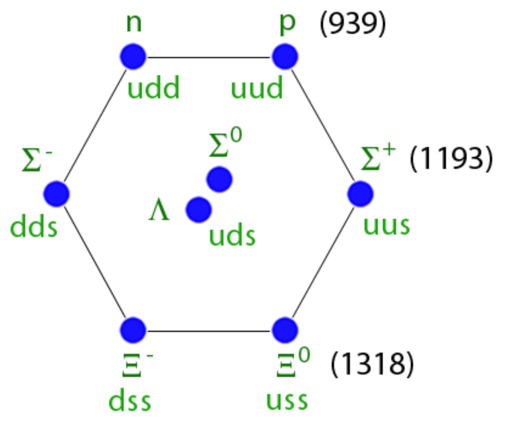
These particles have been observed, they really exist, but decay fairly rapidly.

Is Σ^- the antiparticle of Σ^+ ??

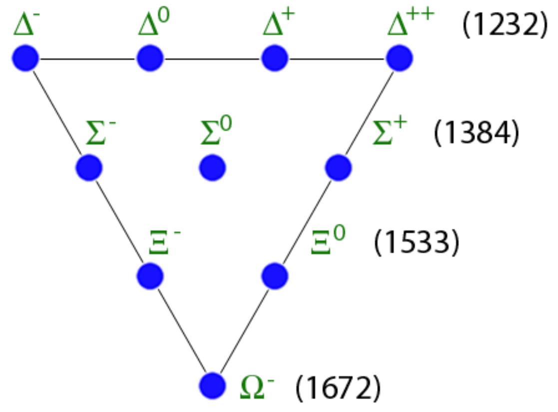
Classification of Baryons

- All baryons observed and confirmed so far
  - classified as singlets, octets and decuplets of SU(3) flavor group
    -> constructed of 3 quarks only
  - The prediction of Ω is a great success of the quark model

baryon octet with $J^P = \frac{1}{2}^+$



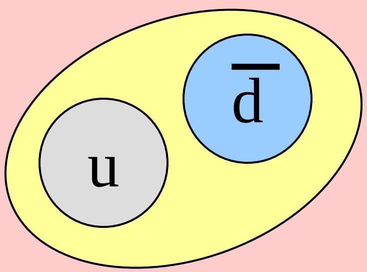
baryon decuplet with $J^P = (3/2)^+$



Mesons

- **Mesons** are also in the **hadron family**.

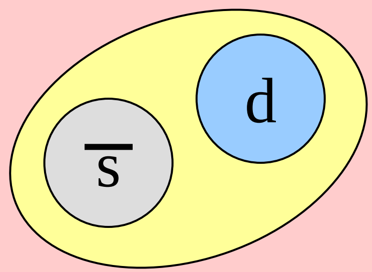
- They are formed when a **quark** and an **anti-quark** “bind” together. (We’ll talk more later about what we mean by “bind”).



What’s the charge of this particle?

Q=+1, and it’s called a π^+

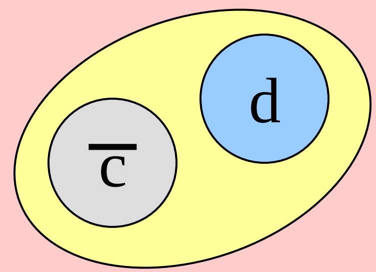
M~140 [MeV/c^2]
Lifetime~2.6x10^{-8} [s]



What’s the charge of this particle?

Q= 0, this strange meson is called a K^0

M~500 [MeV/c^2]
Lifetime~0.8x10^{-10} [s]



What’s the charge of this particle?

Q= -1, and this charm meson is called a D^-

M~1870 [MeV/c^2]
Lifetime~1x10^{-12} [s]

How sure was Gell-Mann of quarks ?

When the quark model was proposed, it was just considered to be a convenient description of all these particles..

A mathematical convenience to account for all these new particles…

After all, fractionally charged particles… come on !

An excerpt from Gell-Mann's 1964 paper:

"A search for stable quarks of charge –1/3 or +2/3 and/or stable di-quarks of charge –2/3 or +1/3 or +4/3 at the highest energy accelerators would help to reassure us of the **non-existence of real quarks**".

Well….

Introduction: History of Deep Inelastic Scattering

1911 — **Rutherford**

Elastic scattering of α – particles on atoms

→ Discovery of atomic nucleus

→ Size of nucleus 10^{-5} size of atom

1968 — **SLAC-MIT**

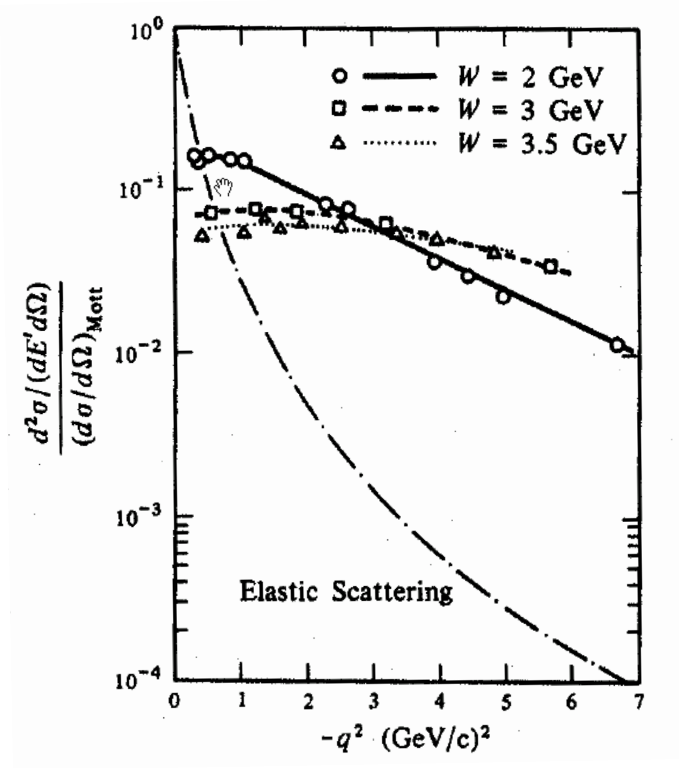
Deep inelastic scattering of e^- of p, d

Observation of ~flat Q^2 dependence of $R = \sigma_{inel}/\sigma_{Mott}$

R can be interpreted as form factor (describing form of scatterer)

R~const → pointlike scatterers inside proton

→ Partons later identified with quarks



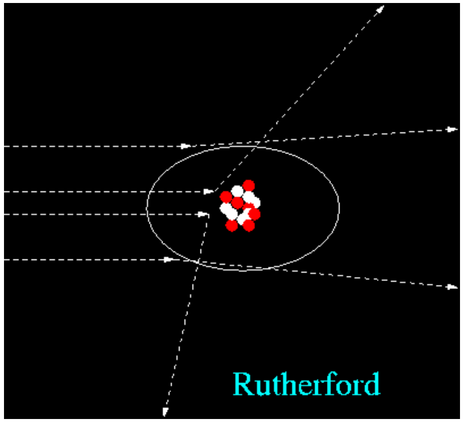
The crucial experiment

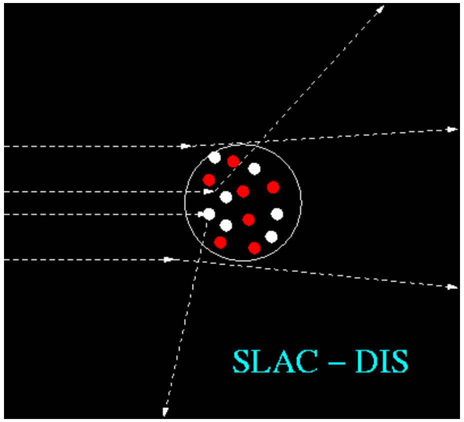
Deep inelastic scattering- the ‘Rutherford experiment’ of particle physics

First view of quarks

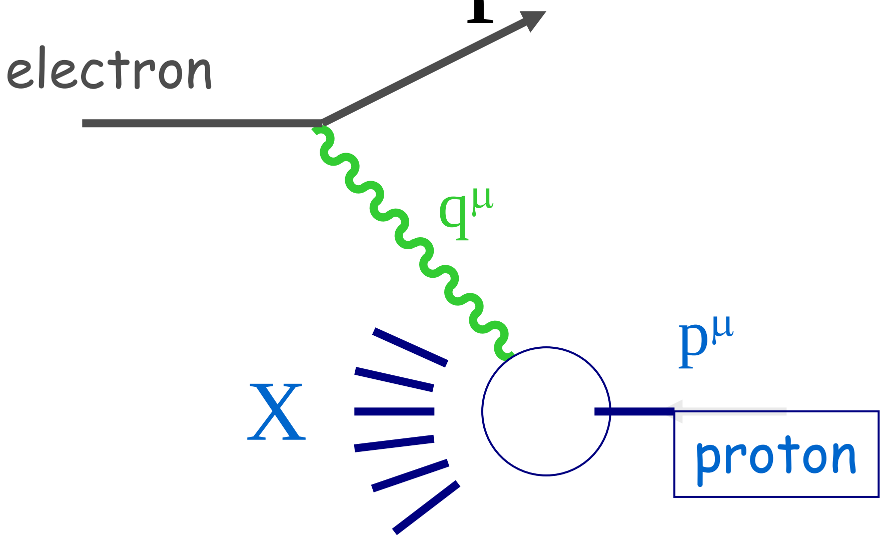
Friedman, Kendall, Taylor (1969)

Bjorken, Feynman





Deep Inelastic Scattering



- Variables

$$Q^2 = -q^2$$

$$x = Q^2 / 2p \cdot q \quad \text{Bjorken } x$$

(also $y = Q^2/xE^2$)

- Resolution

$$\lambda = \frac{h}{Q} = \frac{2 \times 10^{-16} \text{m GeV}}{Q}$$

at HERA, $Q^2 < 10^5$ GeV^2

$\Rightarrow \lambda > 10^{-18}$ m $= r_p/1000$

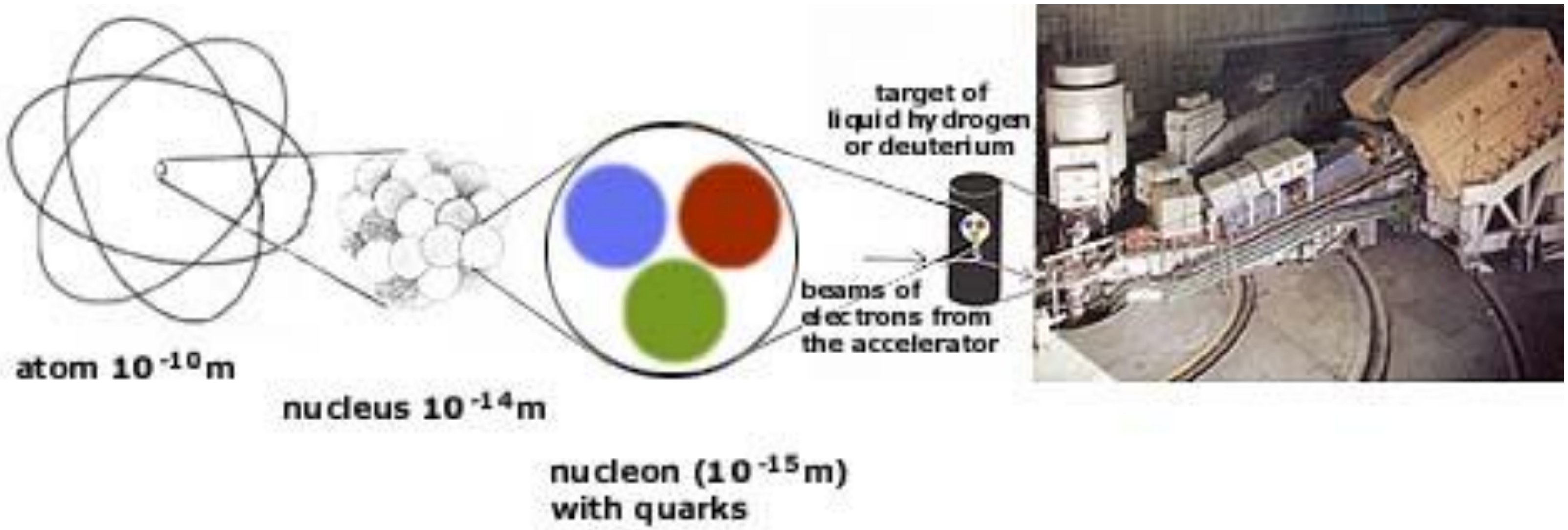
- Inelasticity

$$x = \frac{Q^2}{Q^2 + M_X^2 - M_p^2}$$

$\Rightarrow 0 < x \leq 1$

Are protons/neutrons fundamental ?

In 1969, a Stanford-MIT Collaboration was performing scattering experiments $e^- + p \rightarrow e^- + X$ (X = anything)



What they found was remarkable; the results were as surprising as what Rutherford had found more than a half-century earlier!

The number of high angle scatters was far in excess of what one would expect based on assuming a uniformly distributed charge distribution inside the proton.

It's as if the proton itself contained ***smaller constituents***

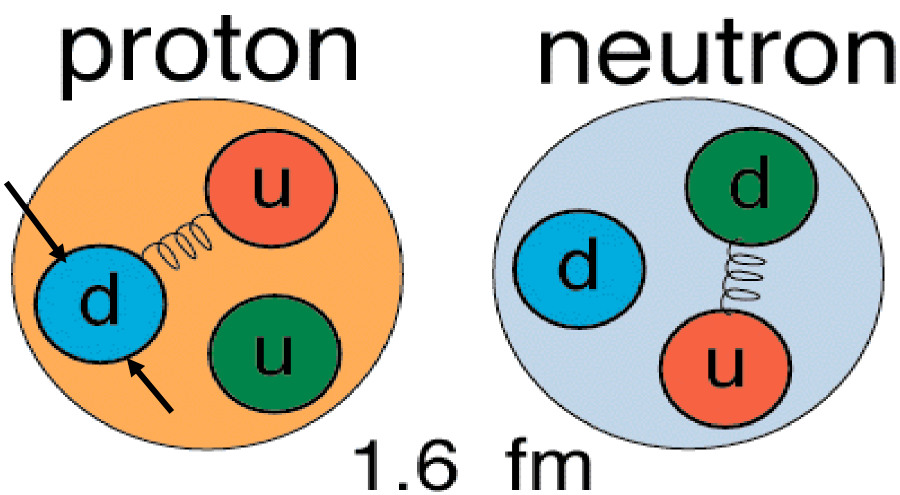
Quarks

Since 1969, many other experiments have been conducted to determine the underlying structure of protons/neutrons.

All the experiments come to the same conclusion.
➔ Protons and neutrons are composed of smaller constituents.

These quarks are the <u>same ones</u> <u>predicted by Gell-Mann & Zweig in 1964</u>.

1×10^{-18} m (at most)

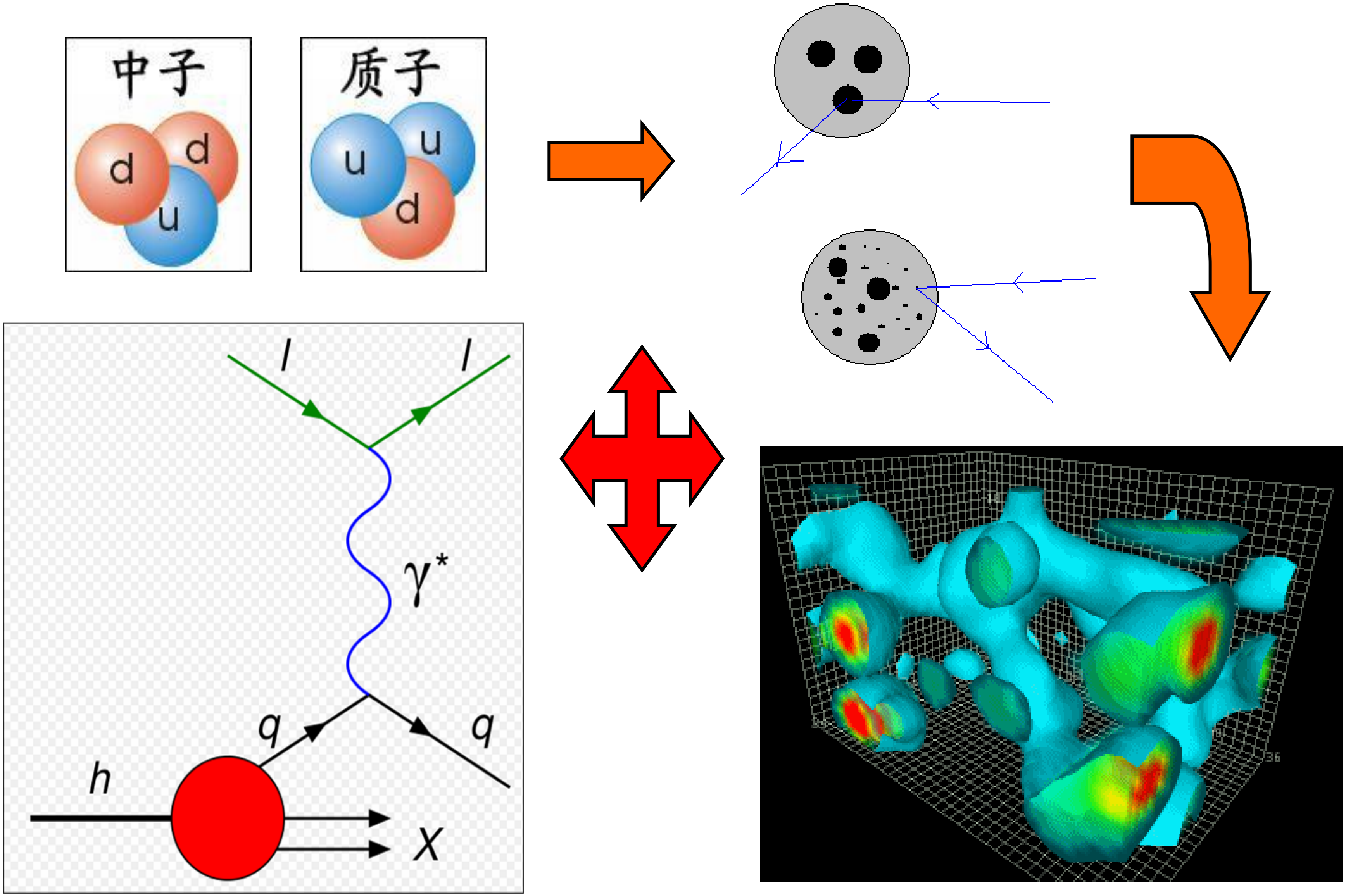


(1.6×10^{-15} m)

- Protons
  - 2 "**up**" quarks
  - 1 "**down**" quark
- Neutrons
  - 1 "**up**" quark
  - 2 "**down**" quarks

Are there any other quarks other than UP and DOWN ?

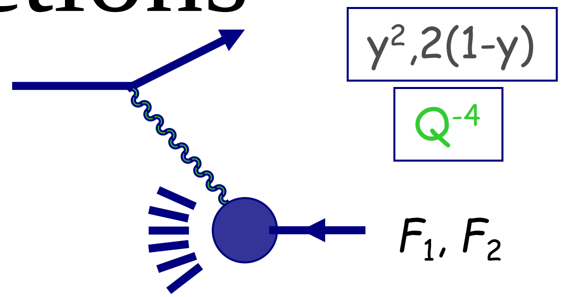
部分子模型与深度非弹性散射



Structure Functions

- in general, we can write

$$\frac{d^2\sigma}{dx\,dQ^2} = \frac{2\pi\alpha^2}{Q^4}\left[y^2 F_1 + 2(1-y)F_2\right]$$

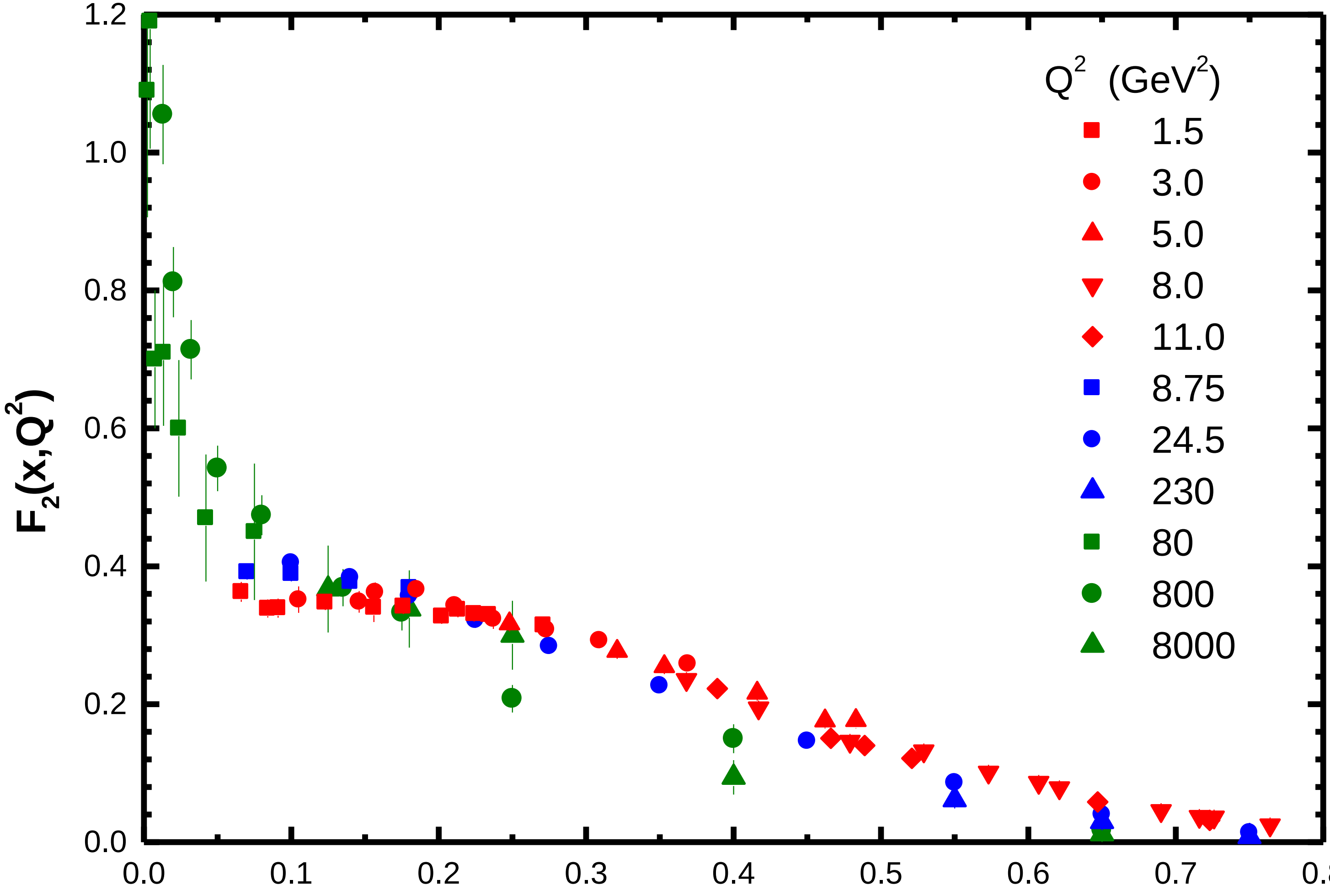


where the $F_i(x,Q^2)$ are called structure functions

- experimentally, for $Q^2 > 1$ GeV^2
  - $F_i(x,Q^2) \rightarrow F_i(x)$ "scaling"
  - $2xF_1(x) \approx F_2(x)$
- toy model: muon target with 4-momentum ξp^μ

$$\frac{d^2\sigma}{dQ^2} = \frac{2\pi\alpha^2}{Q^4}\left[1+(1-y)^2\right] \Rightarrow F_1(x) = F_2(x) = \delta(x-\xi)$$

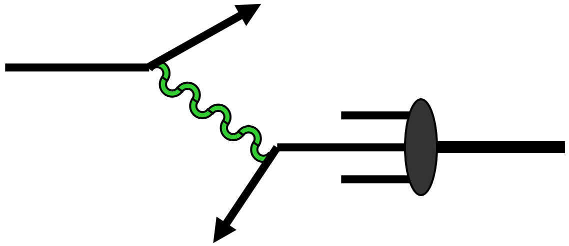
30 years of Deep Inelastic Scattering



The parton model (Feynman 1969)

- photon scatters incoherently off massless, pointlike, spin-1/2 quarks
- probability that a quark carries fraction ξ of parent proton's momentum is $q(\xi)$, $(0 < \xi < 1)$

infinite momentum frame



$$F_2(x) = \sum_{q,\bar{q}} \int_0^1 d\xi \; e_q^2 \, \xi \, q(\xi) \, \delta(x-\xi) = \sum_{q,\bar{q}} e_q^2 \, x \, q(x)$$

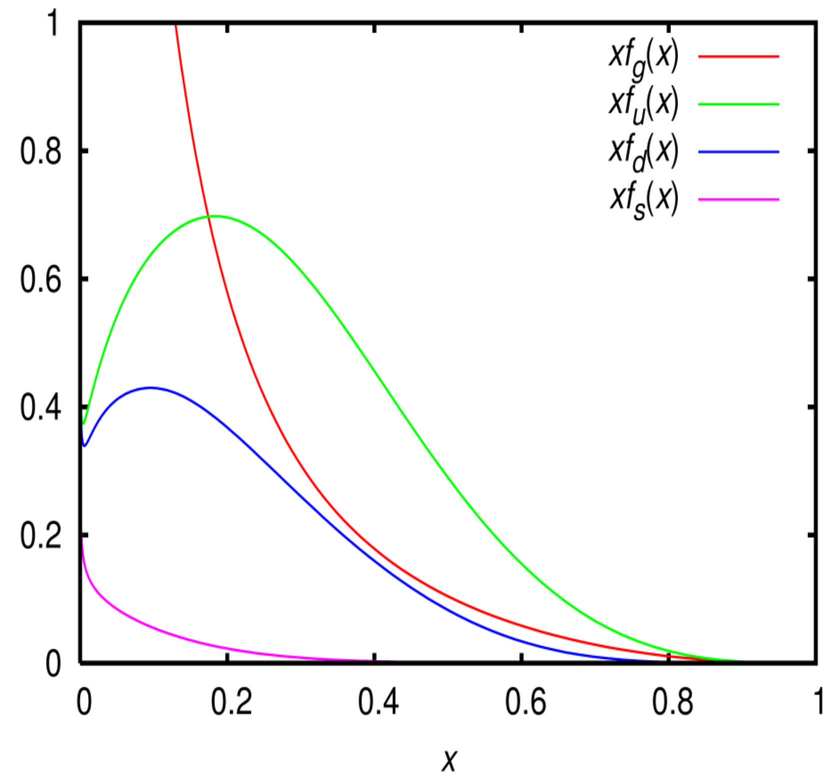
$$= \frac{4}{9} \, x u(x) + \frac{1}{9} \, x d(x) + \frac{1}{9} \, x s(x) + \ldots$$

- the functions u(x), d(x), s(x), … are called parton distribution functions (pdfs) - they encode information about the proton's deep structure

部分子分布函数 (PDFs)

- 部分子分布函数 f(x) 指的是在强子中找到某部分子（夸克或者胶子）带有的动量占强子的动量的比例为 x 的几率
- 由于在束缚态中的复杂的非微扰效应，我们还很难从 QCD 的第一性原理出发得到 f(x)!

lattice QCD



结构函数： $F_2(x) = 2xF_1(x) = x\sum_f e_f^2 f(x)$

Extracting pdfs from experiment

- different beams (e,μ,ν,…) & targets (H,D,Fe,…) measure different combinations of quark pdfs
- thus the individual q(x) can be extracted from a set of structure function measurements
- the measured range is

  $10^{-5} < x < 1$
- gluon not measured directly, but carries about 1/2 the proton's momentum

$$F_2^{ep} = \frac{4}{9}(u+\bar{u}) + \frac{1}{9}(d+\bar{d}) + \frac{1}{9}(s+\bar{s}) + \ldots$$

$$F_2^{en} = \frac{1}{9}(u+\bar{u}) + \frac{4}{9}(d+\bar{d}) + \frac{1}{9}(s+\bar{s}) + \ldots$$

$$F_2^{\nu p} = 2\left[d + s + \bar{u} + \ldots\right]$$

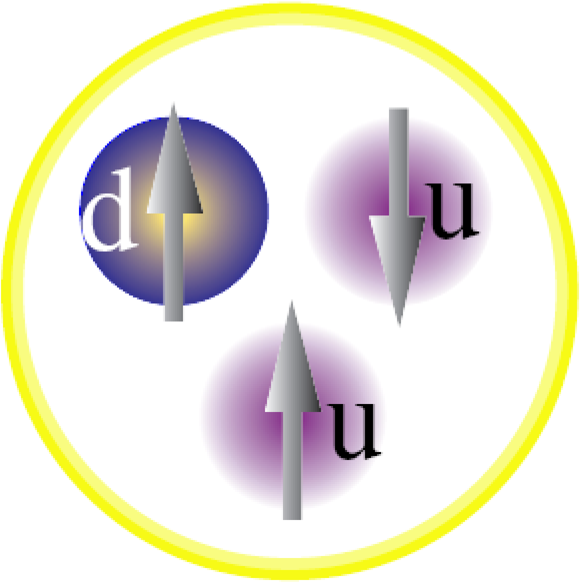
$$F_2^{\nu n} = 2\left[u + \bar{d} + \bar{s} + \ldots\right]$$

$$s = \bar{s} = \frac{5}{6} F_2^{\nu N} - 3F_2^{eN}$$

$$\sum_q \int_0^1 dx\, x\left(q(x) + \bar{q}(x)\right) = 0.55$$

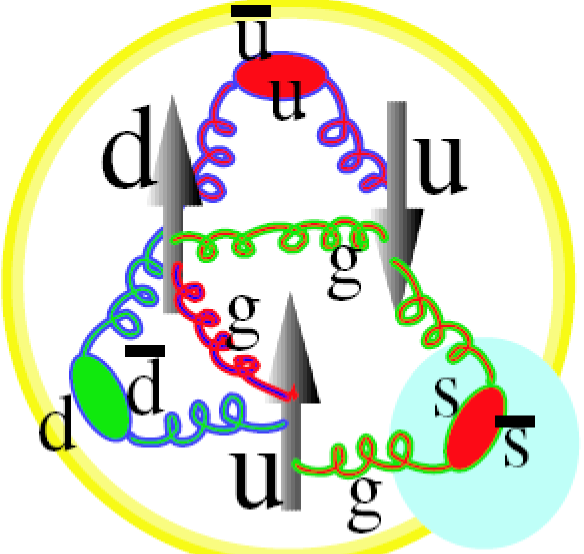
The structure of the nucleon

Constituent Quarks



($Q^2 = 0$ GeV^2)
baryon octet
masses,magn. momenta

Parton Distributions



($Q^2 > 1$ GeV^2)
structure functions
momentum, spin

Surprises & Unknown

about the Quark Structure of Nucleon: Sea

- **Spin Structure:**

$$\Sigma = \Delta u + \Delta d + \Delta s \approx 0.3$$

spin "crisis" or "puzzle": where is the proton's missing spin?

- **Strange Content**

$$\Delta s \neq 0 \quad s(x) \neq \bar{s}(x)$$

Brodsky & Ma, PLB381(96)317

- **Flavor Asymmetry**

$$\bar{u} \neq \bar{d}$$

- **Isospin Symmetry Breaking**

$$\bar{u}_p \neq \bar{d}_n \quad \bar{d}_p \neq \bar{u}_n$$

Ma, PLB 274 (92) 111
Boros, Londergan, Thomas, PRL81(98)4075

The flavor asymmetry of nucleon sea

- Gottfried sum rule (GSR)

$$I_G = \int_0^1 [F_2^p(x) - F_2^n(x)] \frac{dx}{x}$$

$$I_G = \frac{1}{3}\int_0^1 dx[u_v(x) - d_v(x)] + \frac{2}{3}\int_0^1 dx[\bar{u}(x) - \bar{d}(x)] = \frac{1}{3}$$

- NMC results in 1994 (first in 1991)

$$I_G = 0.235 \pm 0.026 < \frac{1}{3}$$

Imply

$$\bar{u} < \bar{d}$$

部分子分布函数

- 价夸克数目守恒与总动量守恒

$$u_V = \int_0^1 [u(x) - \bar{u}(x)]\, dx = 2,$$

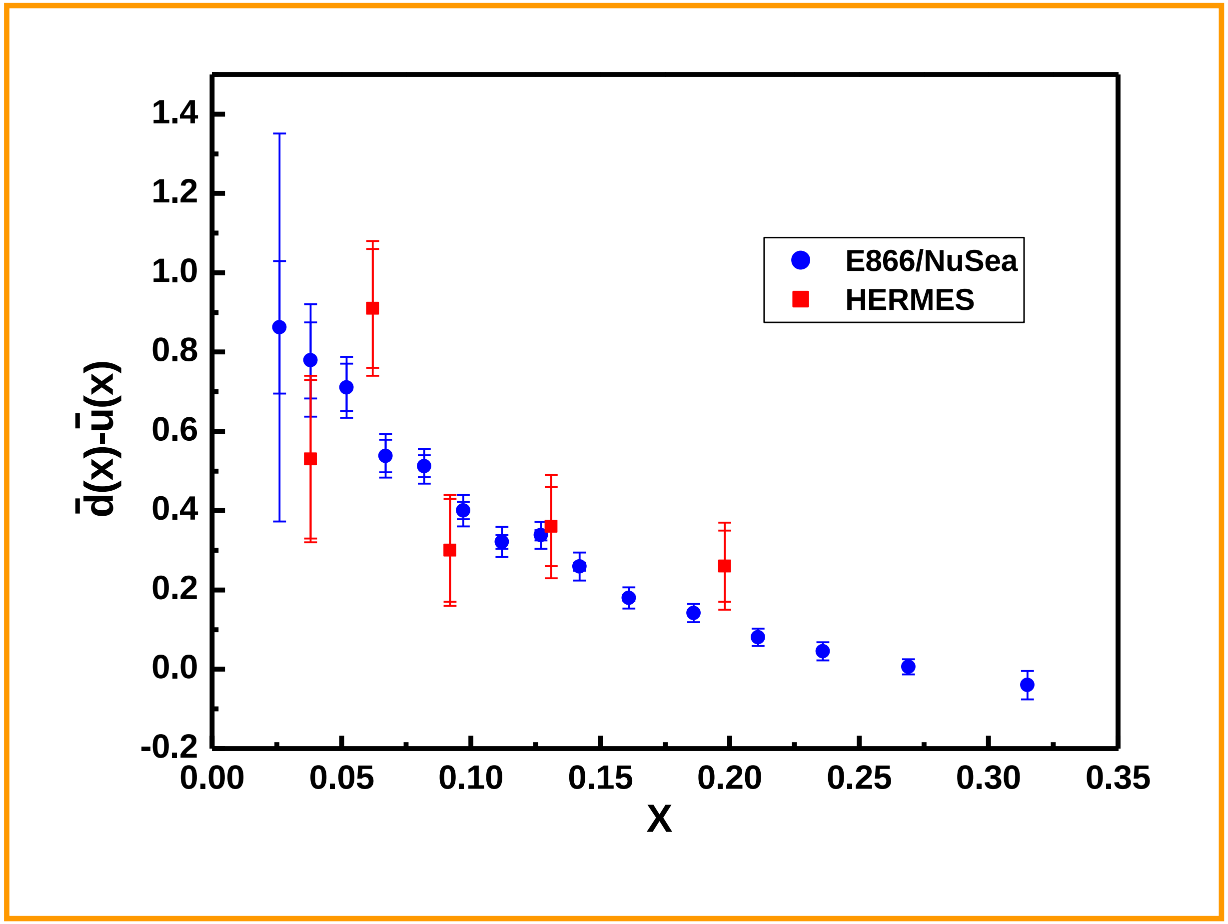
$$d_V = \int_0^1 [d(x) - \bar{d}(x)]\, dx = 1,$$

$$\int_0^1 [u(x) + \bar{u}(x) + d(x) + \bar{d}(x) + g(x)] x\, dx = 1.$$

- Gottfried sum：
  SG=0.235

$$S_G = \int_0^1 \frac{F_2^p(x) - F_2^n(x)}{x}\, dx = \frac{1}{3} + \frac{2}{3}\int_0^1 [\bar{u}(x) - \bar{d}(x)]\, dx$$

Light flavor sea quarks in proton



Explanations for this asymmetry

- **Chiral quark model**
- **Meson cloud model**

(directly including mesons)

- **Lattice gauge approach**
- **Instanton induced interaction**
- **Statistical model**
- **Chiral quark soliton model**

(not directly including mesons)

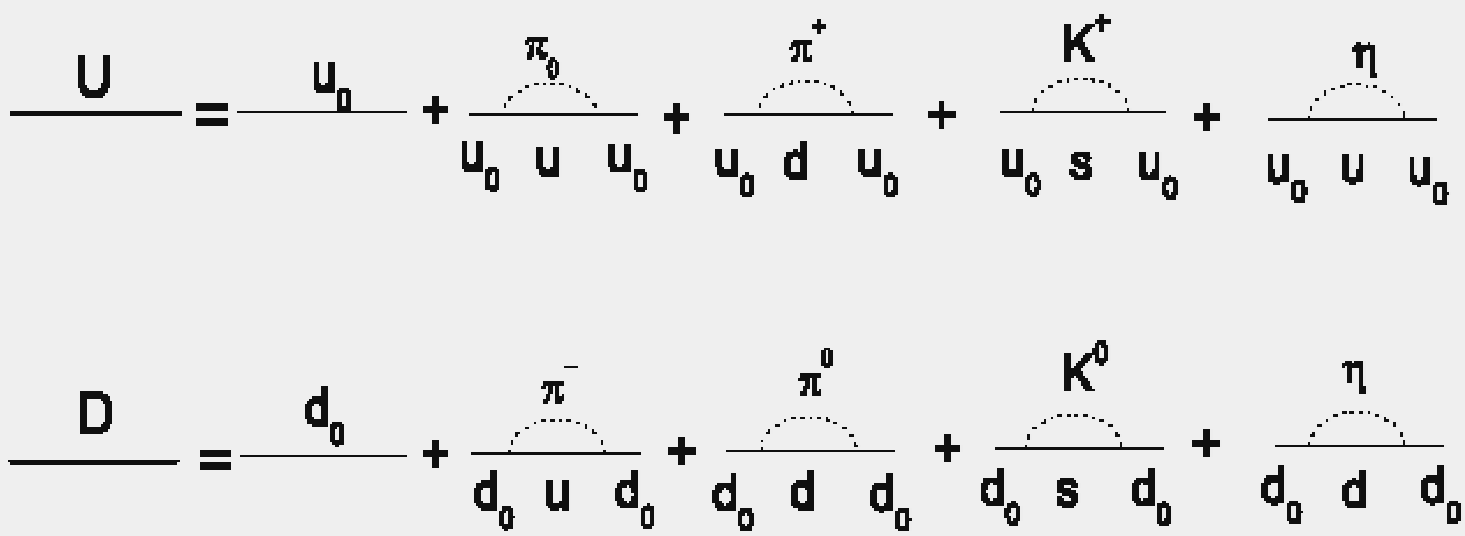
手征夸克模型下不对称奇异海的贡献

- 在手征夸克模型下，核子的组分夸克的波函数可写成：

$$|U\rangle = Z^{\frac{1}{2}}|u_0\rangle + a_\pi|u\pi^0\rangle + \frac{a_\pi}{\sqrt{2}}|d\pi^+\rangle + a_K|sK^+\rangle + \frac{a_\eta}{\sqrt{6}}|u\eta\rangle$$

$$|D\rangle = Z^{\frac{1}{2}}|d_0\rangle + a_\pi|d\pi^0\rangle + \frac{a_\pi}{\sqrt{2}}|u\pi^-\rangle + a_K|sK^0\rangle + \frac{a_\eta}{\sqrt{6}}|d\eta\rangle$$

- 机制：

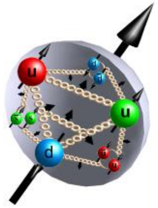


The baryon-meson fluctuation model

$$p(uud) \to \pi^+(u\bar{d})n(udd),$$

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

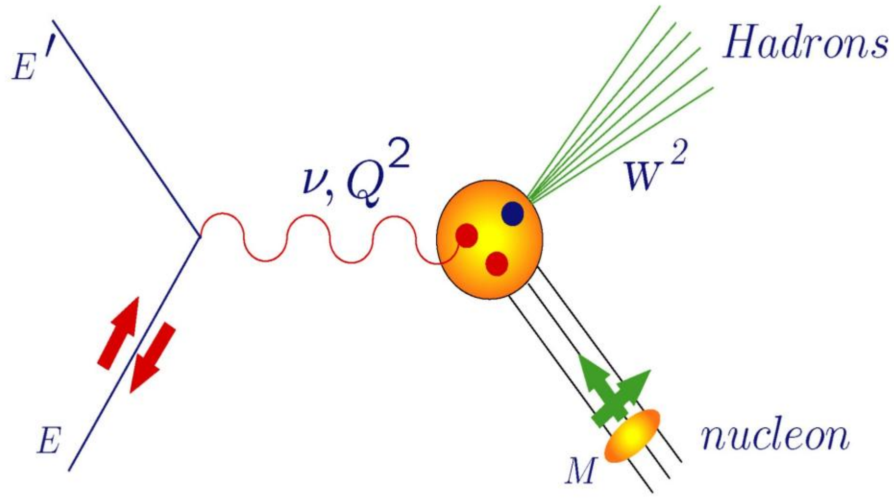
$$p(uud) \to p(uud)\pi^0(\frac{1}{\sqrt{2}}[u\bar{u} - d\bar{d}]),$$



Proton Spin Structure

?

Polarized Deep Inelastic Electron Scattering



$x = \dfrac{Q^2}{2M\nu}$ Fraction of nucleon momentum carried by the struck quark

Q^2 = 4-momentum transfer of the virtual photon, ν = energy transfer, θ = scattering angle

- All information about the nucleon vertex is contained in

F_2 and F_1 the unpolarized (spin averaged) structure functions,

and

g_1 and g_2 the spin dependent structure functions

Challenge: *Spin "Crisis"*

- 1980s

EMC at CERN + early SLAC (E80/E130)

quarks contribution to proton spin is only

$\Delta\Sigma$ = (12+-9+-14)% ! spin "crisis"

(Ellis-Jaffe sum rule violated)

- 1990s

SLAC (E142/E143/E154/E155), SMC at CERN, HERMES at DESY

$\Delta\Sigma$ = 20-30%

Bjorken Sum Rule verified to 5-10% level

20 years

of the proton spin crisis or spin puzzle

- **Spin Structure:**

$$\Sigma = \Delta u + \Delta d + \Delta s \approx 0.020$$

$$\downarrow$$

$$\Sigma = \Delta u + \Delta d + \Delta s \approx 0.3$$

spin "crisis" or "puzzle": where is the proton's missing spin?

The first stage of experiments

- **Non-zero strange spin constribution**

$$\Delta u = 0.750$$

$$\Delta d = -0.511$$

$$\Delta s = -0.218$$

$$\Sigma = \Delta u + \Delta d + \Delta s \approx 0.020$$

A large strange spin contribution?

The Ellis-Jaffe sum rule & Its violation

$$A_1^p = \int_0^1 dx g_1^p(x) = \frac{1}{2}\left[\frac{4}{9}\Delta u + \frac{1}{9}\Delta d + \frac{1}{9}\Delta s\right]$$

- **Neutron beta decay and isospin symmetry**

$$\Delta u - \Delta d = \frac{G_A}{G_V} = 1.261$$

- **Strangeness changing hyperon decay and SU(3) symmetry**

$$\Delta u + \Delta d - 2\Delta s = 0.675$$

- **The assumption of zero strange spin constribution** $\Delta s = 0$

The Ellis-Jaffe sum $A_1^p = \int_0^1 dx g_1^p(x) = 0.198$

However, what EMC measured $A_1^p = \int_0^1 dx g_1^p(x) = 0.126$

A previous global fit:

SU(3) symmetry+measured g_1^p g_1^n

$$\Delta u = 0.83 \pm 0.03$$

$$\Delta d = -0.43 \pm 0.03$$

$$\Delta s = -0.10 \pm 0.03$$

$$\Sigma = \Delta u + \Delta d + \Delta s \approx 0.3$$

The second stage of experiments.

The third stage of experiments:

g_1^p g_1^n +semi-inclusive DIS process

$$\Delta u = 0.599 \pm 0.022 \pm 0.065$$

$$\Delta d = -0.280 \pm 0.026 \pm 0.057$$

$$\Delta s = 0.028 \pm 0.033 \pm 0.009$$

$$\Sigma = \Delta u + \Delta d + \Delta s \approx 0.347 \pm 0.024 \pm 0.040$$

HERMES Collaboration, PRL92 (2004) 012005.

The Proton "Spin Crisis"

$$\Sigma = \Delta u + \Delta d + \Delta s \approx 0.3$$

In contradiction with the naïve quark model expectation:

Naive Quark Model:

$$\Delta u = \frac{4}{3}; \qquad \Delta d = -\frac{1}{3}; \qquad \Delta s = 0$$

$$\Sigma = \Delta u + \Delta d + \Delta s = 1$$

The Proton "Spin Crisis"

These results could be argued to imply that the sum of the spins carried by the quarks in a proton was consistent with zero, rather than with 1/2 as given in the quark model, suggesting a "Spin Crisis" in the parton model.

M.Anselmino, A.Efremov, E.Leader
Physics Reports 261 (1995) page 4

质子“自旋危机”

这表明质子中的夸克实际上对其自旋没有贡献， 这一事实即为人们所称的“自旋危机”。

《低能及中高能原子核物理》 415页

程檀生 钟毓树 编著

北京大学出版社 1997 年

Many Theoretical Explanantions

- The sea quarks of the proton are largely negatively polarized
- The gluons provide a significant contribution to the proton spin

It was though that the spin "crisis" cannot be understood within the quark model: " the lowest uud valence component of the proton is estimated to be of only a few percent." **R.L. Jaffe and Lipkin, PLB266(1991)158**

The proton spin crisis

& the Melosh-Wigner rotation

- It is shown that the proton "spin crisis" or "spin puzzle" can be understood by the relativistic effect of quark transversal motions due to the Melosh-Wigner rotation.
- The quark helicity Δq measured in polarized deep inelastic scattering is actually the quark spin in the infinite momentum frame or in the light-cone formalism, and it is different from the quark spin in the nucleon rest frame or in the quark model.

B.-Q. Ma, J.Phys. G 17 (1991) L53

B.-Q. Ma, Q.-R. Zhang, Z.Phys.C 58 (1993) 479-482

The Notion of Spin

- Related to the space-time symmetry of the Poincaré group
- Generators $P^{\mu} = (H, \vec{P})$, space-time translator

  $J^{\mu\nu}$ infinitesimal Lorentz transformation

  $\vec{J}$ $J^{k} = \frac{1}{2}\varepsilon_{ijk} J^{ij}$ angular momentum

  $\vec{K}$ $K^{k} = J^{k0}$ boost generator

  Pauli-Lubanski vertor $w_{\mu} = \frac{1}{2} J^{\rho\sigma} P^{\nu} \varepsilon_{\nu\rho\sigma\mu}$

  Casimir operators: $P^2 = P^{\mu} P_{\mu} = m^2$ mass

  $w^2 = w^{\mu} w_{\mu} = s^2$ spin

The Wigner Rotation

for a rest particle $(m,\vec{0}) = p^{\mu}$ $(0,\vec{s}) = \mathrm{w}^{\mu}$

for a moving particle $\mathrm{L}(p)p = (m,\vec{0})$ $(0,\vec{s}) = \mathrm{L}(p)w/m$

$\mathrm{L}(p) =$ ratationless Lorentz boost

Wigner Rotation

$\vec{s}, p_{\mu} \to \vec{s}', p'_{\mu}$

$\vec{s}' = R_w(\Lambda, p)\vec{s}$ $p' = \Lambda p$

$R_w(\Lambda, p) = \mathrm{L}(p')\Lambda \mathrm{L}^{-1}(p)$ a pure rotation

E.Wigner, Ann.Math.40(1939)149

Melosh Rotation for Spin-1/2 Particle

The connection between spin states in the rest frame and infinite momentum frame
Or between spin states in the conventional equal time dynamics and the light-front dynamics

$$\chi^{\uparrow}(T) = w[(q^{+} + m)\chi^{\uparrow}(F) - q^{R}\chi^{\downarrow}(F)];$$

$$\chi^{\downarrow}(T) = w[(q^{+} + m)\chi^{\downarrow}(F) + q^{L}\chi^{\uparrow}(F)].$$

What is Δq measured in DIS

- Δq is defined by $\Delta q\ s_\mu = \langle p,s|\bar{q}\gamma_\mu\gamma_5 q|p,s\rangle$

$$\Delta q = \langle p,s|\bar{q}\gamma^+\gamma_5 q|p,s\rangle$$

- Using light-cone Dirac spinors

$$\Delta q = \int_0^1 \mathrm{d}x \left[q^\uparrow(x) - q^\downarrow(x) \right]$$

- Using conventional Dirac spinors

$$\Delta q = \int \mathrm{d}^3\vec{p} M_q \left[q^\uparrow(\vec{p}) - q^\downarrow(\vec{p}) \right]$$

$$M_q = \frac{(p_0 + p_3 + m)^2 - \vec{p}_\perp^{\,2}}{2(p_0 + p_3)(p_0 + m)}$$

Thus Δq is the light-cone quark spin or quark spin in the infinite momentum frame, not that in the rest frame of the proton

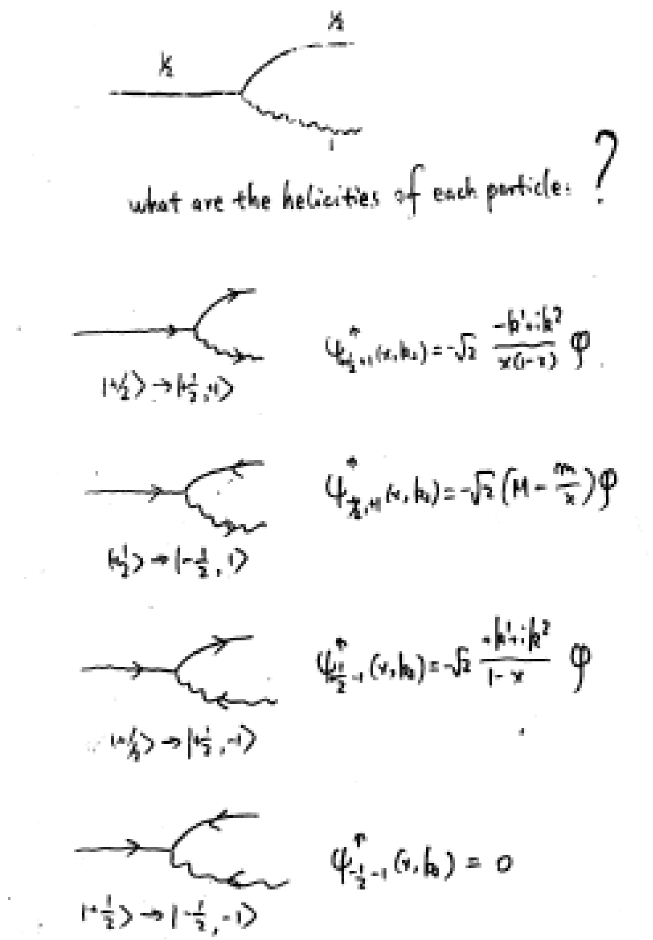
A general consensus

The quark helicity Δq defined in the infinite momentum frame is generally not the same as the constituent quark spin component in the proton rest frame, just like that it is not sensible to compare apple with orange.

H.-Y.Cheng, hep-ph/0002157，
Chin.J.Phys.38:753,2000

A QED Example of Relativistic Spin Effect

S.J. Brodsky, D.S. Hwang, B.-Q. Ma, I. Schmidt, Nucl. Phys. B 593 (2001) 311



The lowest spin states of a composite system must contain the orbital angular momentum contribution.

$$\Delta s_{\text{non-rel}} + L_{\text{non-rel}} = \Delta s_{\text{rel}} + L_{\text{rel}}$$

Other approaches with same conclusion

Contribution from the lower component of Dirac spinors in the rest frame:

D.Qing, X.-S.Chen, F.Wang, **Phys.Rev.D58:114032,1998**.

P.Zavada, **Phys.Rev.D65:054040,2002**.

B.-Q. Ma, Q.-R. Zhang, Z.Phys.C 58 (1993) 479-482

Quark spin sum is not a Lorentz invariant quantity

Thus the quark spin sum equals to the proton in the rest frame does not mean that it equals to the proton spin in the infinite momentum frame

$$\sum_q \vec{s}_q = \vec{S}_p \quad \text{in the rest frame}$$

does not mean that

$$\sum_q \vec{s}_q = \vec{S}_p \quad \text{in the infinite momentum frame}$$

Therefore it is not a surprise that the quark spin sum measured in DIS does not equal to the proton spin

The Spin Distributions in Quark Model

The spin distribution probabilities in the quark-diquark model

$$u_V^{\uparrow} = \frac{1}{18};\quad u_V^{\downarrow} = \frac{2}{18};\quad d_V^{\uparrow} = \frac{2}{18};\quad d_V^{\downarrow} = \frac{4}{18};$$

$$u_S^{\uparrow} = \frac{1}{2};\quad u_S^{\downarrow} = 0;\quad d_S^{\uparrow} = 0;\quad d_S^{\downarrow} = 0. \tag{7}$$

Naive Quark Model:

$$\Delta u = \frac{4}{3};\qquad \Delta d = -\frac{1}{3};\qquad \Delta s = 0$$

$$\Sigma = \Delta u + \Delta d + \Delta s = 1$$

Relativistic Effect due to Melosh-Rotation

$$\Delta u_v(x) = u_v^{\uparrow}(x) - u_v^{\downarrow}(x) = -\frac{1}{18}a_V(x)W_V(x) + \frac{1}{2}a_S(x)W_S(x);$$

$$\Delta d_v(x) = d_v^{\uparrow}(x) - d_v^{\downarrow}(x) = -\frac{1}{9}a_V(x)W_V(x).$$

from

$$a_S(x) = 2u_v(x) - d_v(x);$$

$$a_V(x) = 3d_v(x).$$

We obtain

$$\Delta u_v(x) = [u_v(x) - \frac{1}{2}d_v(x)]W_S(x) - \frac{1}{6}d_v(x)W_V(x);$$

$$\Delta d_v(x) = -\frac{1}{3}d_v(x)W_V(x).$$

Relativistic SU(6) Quark Model

Flavor Symmetric Case

Relativistic Correction: $M_q = 0.75$

$\Delta u = \frac{4}{3} M_q = 1; \qquad \Delta d = -\frac{1}{3} M_q = -0.25; \qquad \Delta s = 0$

$\Sigma = \Delta u + \Delta d + \Delta s = 0.75$

$F_2^n(x)/F_2^p(x) \geq \frac{2}{3}$ for all x

Relativistic SU(6) Quark Model

Flavor Asymmetric Case

Relativistic Correction: $M_u \approx 0.6$; $M_d \approx 0.9$

$\Delta u = \frac{4}{3} M_u = 0.8$; $\Delta d = -\frac{1}{3} M_d = -0.3$; $\Delta s = 0$

$\Sigma = \Delta u + \Delta d + \Delta s \approx 0.5$

$F_2^n(x)/F_2^p(x) \to \frac{1}{4}$ at large x

B.-Q.Ma, Phys. Lett. B **375** (1996) 320.

Relativistic SU(6) Quark Model

Flavor Asymmetric Case + Intrinsic Sea

For Intrinsic $d\bar{d}$ Sea ($\sim 15\%$): $\quad \Delta d_{\text{sea}} \approx -0.07$

For Intrinsic $s\bar{s}$ Sea ($\sim 5\%$): $\quad \Delta s_{\text{sea}} \approx -0.03$

Thus: $\quad \Sigma = \Delta u + \Delta d + \Delta s + \Delta d_{\text{sea}} + \Delta s_{\text{sea}} \approx 0.4$

S. J. Brodsky and B.-Q.Ma, Phys. Lett. B 381 (1996) 317.

More detailed discussions, see, B.-Q.Ma, J.-J.Yang, I.Schmidt, Eur.Phys.J.A12(2001)353

Understanding the Proton Spin "Puzzle" with a New "Minimal" Quark Model

Three quark valence component could be as large as 70% to account for the data

The Melosh-Wigner rotation

in pQCD based parametrization of quark helicity distributions

"The helicity distributions measured on the light-cone are related by a Wigner rotation (Melosh transformation) to the ordinary spin S_i^z of the quarks in an equal-time rest-frame wavefunction description. Thus, due to the non-collinearity of the quarks, one cannot expect that the quark helicities will sum simply to the proton spin."

S.J.Brodsky, M.Burkardt, and I.Schmidt,

Nucl.Phys.B441 (1995) 197-214, p.202

pQCD counting rule

$$q_{\mathrm{h}}^{\pm} \propto (1-x)^{p}$$

$$p = 2n - 1 + 2\,|\Delta s_z| \qquad \Delta s_z = s_q - s_N$$

- **Based on the minimum connected tree graph of hard gluon exchanges.**
- **"Helicity retention" is predicted -- The helicity of a valence quark will match that of the parent nucleon.**

Parameters in pQCD counting rule analysis

In leading term

$$q_{\mathrm{i}}^{+} = \frac{\tilde{A}_{q_i}}{B_3} x^{-\frac{1}{2}} (1-x)^3$$

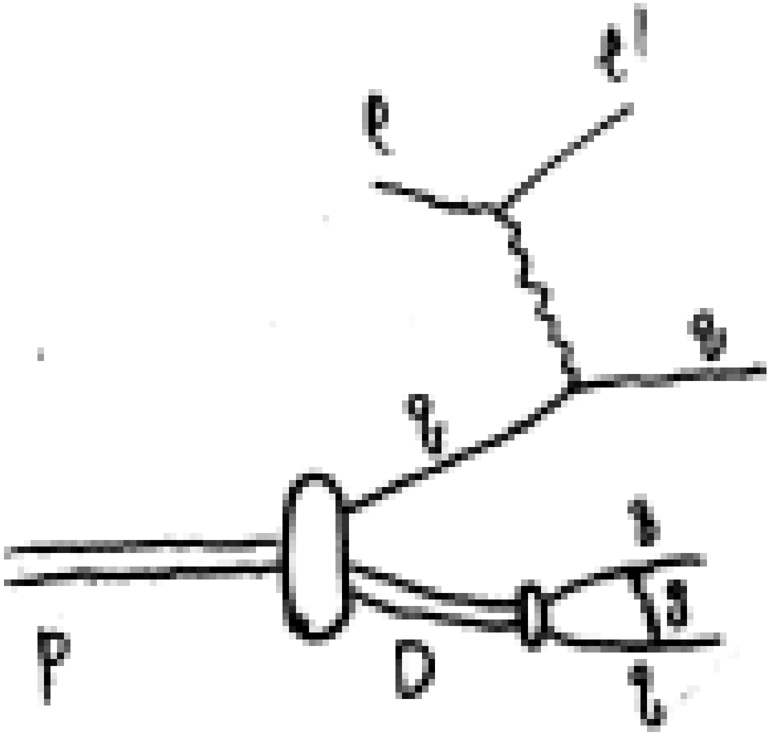
$$q_{\mathrm{i}}^{-} = \frac{\tilde{C}_{q_i}}{B_5} x^{-\frac{1}{2}} (1-x)^5$$

Baryon	q_1	q_2	$\tilde{A}_{q_1}$	$\tilde{C}_{q_1}$	$\tilde{A}_{q_2}$	$\tilde{C}_{q_2}$
p	u	d	1.375	0.625	0.275	0.725

B.-Q. Ma, I. Schmidt, J.-J. Yang, Phys.Rev.D63(2001) 037501.

New Development: H. Avakian, S.J.Brodsky, D.Boer, F.Yuan, Phys.Rev.Lett.99:082001,2007.

A relativistic quark-diquark model



A relativistic quark-diquark model

- The unpolarized distribution of quark q in hadron h can be written as

$$q(x) = c_q^S a_S(x) + c_q^V a_V(x),$$

where $a_D(x)$ is

$$a_D(x) \propto \int [\mathrm{d}^2 \mathbf{k}_\perp] |\phi(x, \mathbf{k}_\perp)|^2 \quad (D = S \text{ or } V),$$

- BHL prescription of the light-cone momentum space wave function for quark-diquark

$$\phi(x, \mathbf{k}_\perp) = A_D \exp\left\{-\frac{1}{8\alpha_D^2}\left[\frac{m_q^2 + \mathbf{k}_\perp^2}{x} + \frac{m_D^2 + \mathbf{k}_\perp^2}{1-x}\right]\right\},$$

B.-Q. Ma, Phys.Lett. B 375 (1996) 320-326.
B.-Q. Ma, I. Schmidt, J. Soffer, Phys.Lett. B 441 (1998) 461-467.

A relativistic quark-diquark model

- longitudinally polarized quark distribution

$$\Delta q(x) = \tilde{c}_q^S \tilde{a}_S(x) + \tilde{c}_q^V \tilde{a}_V(x)$$

where

$$\tilde{a}_D(x) = \int [\mathrm{d}^2 \mathbf{k}_\perp] W_D(x, \mathbf{k}_\perp) |\phi(x, \mathbf{k}_\perp)|^2 \quad (D = S \text{ or } V)$$

- Melosh-Winger rotation factor

Longitudinally polarized

$$W_D(x, \mathbf{k}_\perp) = \frac{(k^+ + m_q)^2 - \mathbf{k}_\perp^2}{(k^+ + m_q)^2 + \mathbf{k}_\perp^2}$$

where $k^+ = x\mathcal{M}$, $\mathcal{M}^2 = \frac{m_q^2 + \mathbf{k}_\perp^2}{x} + \frac{m_D^2 + \mathbf{k}_\perp^2}{1-x}$.

Two different sets of parton distributions

- SU(6) quark-diquark model

$$\Delta u_v(x) = [u_v(x) - \frac{1}{2} d_v(x)] W_S(x) - \frac{1}{6} d_v(x) W_V(x),$$
$$\Delta d_v(x) = -\frac{1}{3} d_v(x) W_V(x).$$

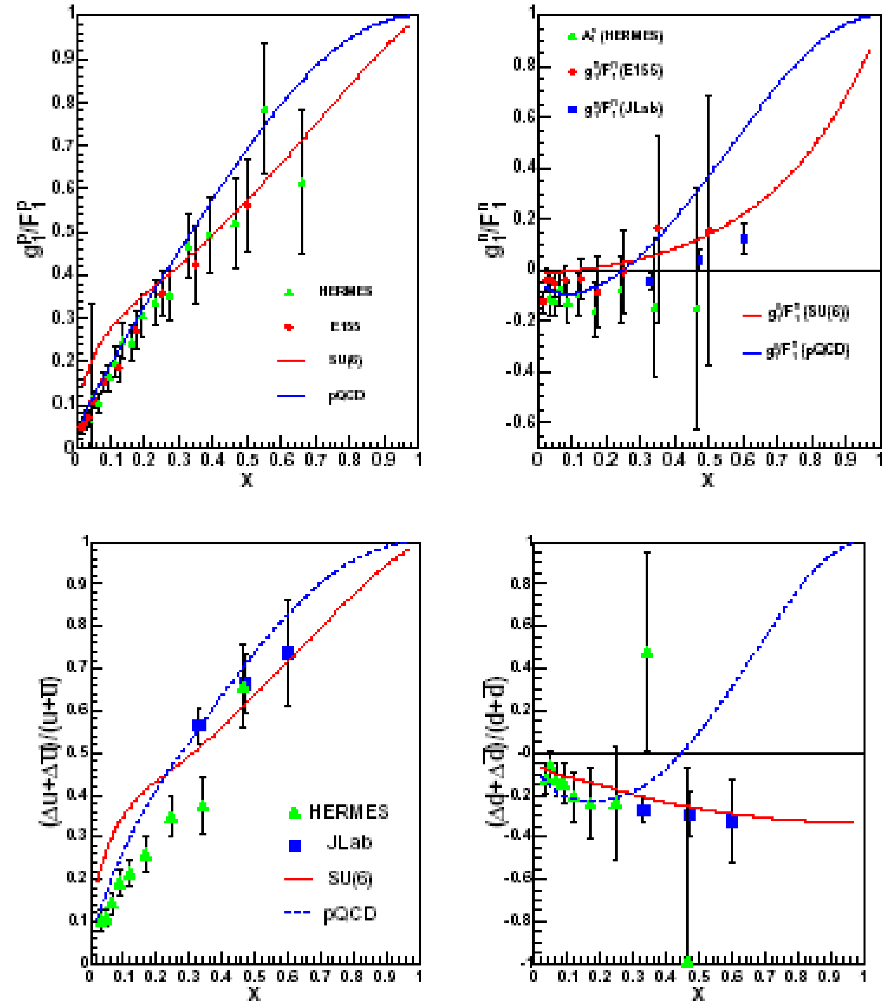
- pQCD based counting rule analysis

$$\begin{aligned}
u_v^{\text{pQCD}}(x) &= u_v^{\text{para}}(x), \\
d_v^{\text{pQCD}}(x) &= \frac{d_v^{\text{th}}(x)}{u_v^{\text{th}}(x)} u_v^{\text{para}}(x), \\
\Delta u_v^{\text{pQCD}}(x) &= \frac{\Delta u_v^{\text{th}}(x)}{u_v^{\text{th}}(x)} u_v^{\text{para}}(x), \\
\Delta d_v^{\text{pQCD}}(x) &= \frac{\Delta d_v^{\text{th}}(x)}{u_v^{\text{th}}(x)} u_v^{\text{para}}(x),
\end{aligned}$$

- CTEQ5 set 3 as input.

Different predictions in two models

- Helicity distribution
  - SU(6) quark-diquark model:
    $\Delta u(x)/u(x) \to 1$ as $x \to 1.$
    $\Delta d(x)/d(x) \to -\frac{1}{3}$ as $x \to 1.$
  - pQCD based counting rule analysis:
    $\Delta u(x)/u(x) \to 1$ as $x \to 1.$
    $\Delta d(x)/d(x) \to 1$ as $x \to 1.$



Some Applications of the Melosh-Wigner Rotation

- Magnetic Moment

  S.J. Brodsky and F.Schlumpf,

  Phys.Lett.B 329 (1994) 111.

- Axial Momemt

  F.Schlumpf and S.J. Brodsky,

  Phys.Lett.B 360 (1995) 1.

- Tensor Charge

  I. Schmidt and J. Soffer,

  Phys.Lett.B 407 (1997) 331

- Orbital Angular Momentum et al

  D. Qing, X-S.Chen, and F.Wang,

  Phys.Rev.C 57 (1998) R31; Phys.Rev.D 58 (1998) 114032.

Pion Spin Structure and Form Factor

Based on collaborated works with T.Huang and Q.-X.Shen

[1] T. Huang, B.Q. Ma, and Q.X. Shen, Phys. Rev. D **49**, 1490 (1994).

[2] B. Q. Ma, Z. Phys. A **345**, 321 (1993).

[3] B.Q. Ma and T.Huang, J. Phys. G **21**, (765) (1995).

Pion Spin-Space Wave Function in Rest Frame

In the pion rest frame, the instant-form spin space wave-function of pion is

$$\chi_T = (\chi_1^{\uparrow}\chi_2^{\downarrow} - \chi_2^{\uparrow}\chi_1^{\downarrow})/\sqrt{2},$$

in which $\chi_i^{\uparrow,\downarrow}$ are the two-component Pauli spinors.

The Lowest Valence State Wave Function in Light-Cone

$$|\psi^{\pi}_{q\overline{q}}> = \psi(x, \mathbf{k}\_, \uparrow, \downarrow)|\uparrow\downarrow> + \psi(x, \mathbf{k}\_, \downarrow, \uparrow)|\downarrow\uparrow>$$

$$+\psi(x, \mathbf{k}\_, \uparrow, \uparrow)|\uparrow\uparrow> + \psi(x, \mathbf{k}\_, \downarrow, \downarrow)|\downarrow\downarrow>,$$

where

$$\psi(x, \mathbf{k}\_, \lambda_1, \lambda_2) = C_0^F(x, \mathbf{k}\_, \lambda_1, \lambda_2)\varphi(x, \mathbf{k}\_).$$

Here $\varphi(x, \mathbf{k}\_)$ is the momentum space wave function in the light-cone formalism.

The Spin Component Coefficients

The spin component coefficients C_0^F have the forms,

$$C_0^F(x, q, \uparrow, \downarrow) = w_1 w_2[(q_1^- + m)(q_2^- + m) - \mathbf{q}_-^2]/\sqrt{2};$$

$$C_0^F(x, q, \downarrow, \uparrow) = -w_1 w_2[(q_1^- + m)(q_2^- + m) - \mathbf{q}_-^2]/\sqrt{2};$$

$$C_0^F(x, q, \uparrow, \uparrow) = w_1 w_2[(q_1^- + m)q_2^L - (q_2^- + m)q_1^L]/\sqrt{2};$$

$$C_0^F(x, q, \downarrow, \downarrow) = w_1 w_2[(q_1^- + m)q_2^R - (q_2^- + m)q_1^R]/\sqrt{2}.$$

C_0^F satisfy the relation

$$\Sigma_{\lambda_1,\lambda_2} C_0^F(x, \mathbf{k}_-, \lambda_1, \lambda_2) C_0^F(x, \mathbf{k}_-, \lambda_1, \lambda_2) = 1.$$

The general consensus

The so-called “proton spin crisis” is not pertinent since the proton helicity content explored in the DIS experiment is, strictly speaking, defined in the infinite momentum frame in terms of QCD current quarks and gluons, whereas the spin structure of the proton in the proton re[illegible]e is referred to the constituent quarks. That is, the quark [illegible] Δq defined in the infinite momentum frame is gene[illegible]t the same as the constituent quark spin component in the proton rest frame, just like that it is not sensible to compare apple with orange. What trigged by the EMC experiment is the “proton helicity decomposition puzzle” rather than the “proton spin crisis” .

H.-Y.Cheng, hep-ph/0002157，Chin.J.Phys.38:753,2000

The idea has been widely recongized by international colleagues

The significance of the Melosh rotation connecting the spin states in the light-front dynamics and the conventional instant form dynamics has been widely recognized.

J.P. Singh and A. Upadhyay, J.Phys.G30 (2004) 881.

The Melosh-Wigner rotation
is not the whole story

- **The role of sea is not addressed**
- **The role of gluon is not addressed**

It is important to study the roles played by the sea quarks and gluons. Thus more theoretical and experimental researches can provide us a more completed picture of the nucleon spin structure.

Chances： New Research Directions

- New quantities： Transversity, Generalized Parton Distributions, Collins Functions, Silver Functions, Boer-Mulders Functions, Pretzelosity

- Hyperon Physics： The spin structure of Lambda and Sigma hyperons

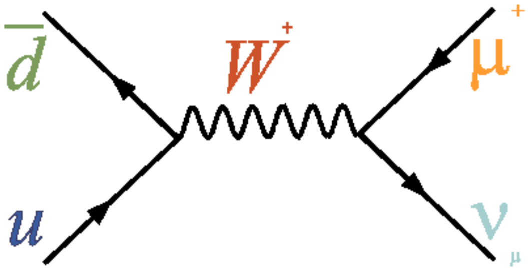
B.-Q. Ma, I. Schmidt, J.-J. Yang
Phys. Lett. B 477 (2000) 107
Phys. Rev. D 61 (2000) 034017

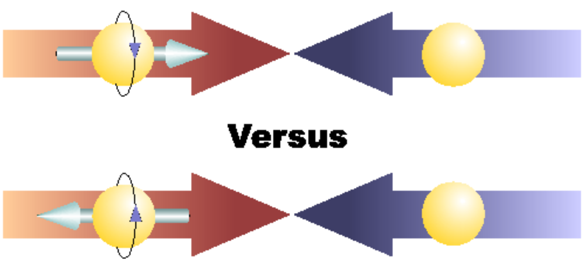
Prospects of Spin Physics at RHIC

- Gluon spin from jet, photon and charm productions
- Transversity from Drell-Yan process
- Azimuthal asymmetries of hadron productions
- Flavor decomposition of valence quark helicities through W productions
- ……

W Production in pp Collisions

- *W* is produced through pure V-A
  - Chirality is fixed → ideal for spin structure studies
- *W* couples to weak charge ~ flavor
  - Flavor is (almost) fixed → ideal for flavor structure studies
- Parity Violating Asymmetry A_L :





J. Soffer et al.

$$A_L^{W^+} = \frac{\Delta u(x_a)\bar{d}(x_b) - \Delta\bar{d}(x_a)u(x_b)}{u(x_a)\bar{d}(x_b) + \bar{d}(x_a)u(x_b)}$$

$W^{\pm}$ production at RHIC

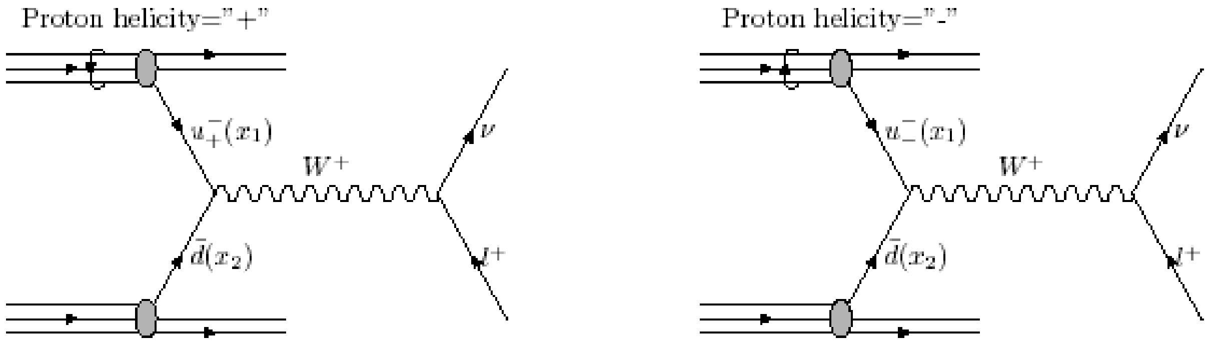
- Parity-violating asymmetry

$$A_L = -\frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}, \quad A_L = -\frac{1}{P} \times \frac{N'_+ - N'_-}{N'_+ + N'_-},$$

- The maximum parity violation of W bosons.
- $u\bar{d} \to W^+$ and $\bar{u}d \to W^-$.
- At LO, the parity-violating asymmetry will approach $\Delta q(x)/q(x)$ when the rapidity of $W^{\pm}$, y_W, is large.

C. Bourrely, J. Soffer, Nucl. Phys. B423(1994) 329

One of the possible leading order production of W^+ production.



$$A_L^{W^+} = \frac{u_-^-(x_1)\bar{d}(x_2) - u_+^-(x_1)\bar{d}(x_2)}{u_-^-(x_1)\bar{d}(x_2) + u_+^-(x_1)\bar{d}(x_2)} = \frac{\Delta u(x_1)}{u(x_1)}$$

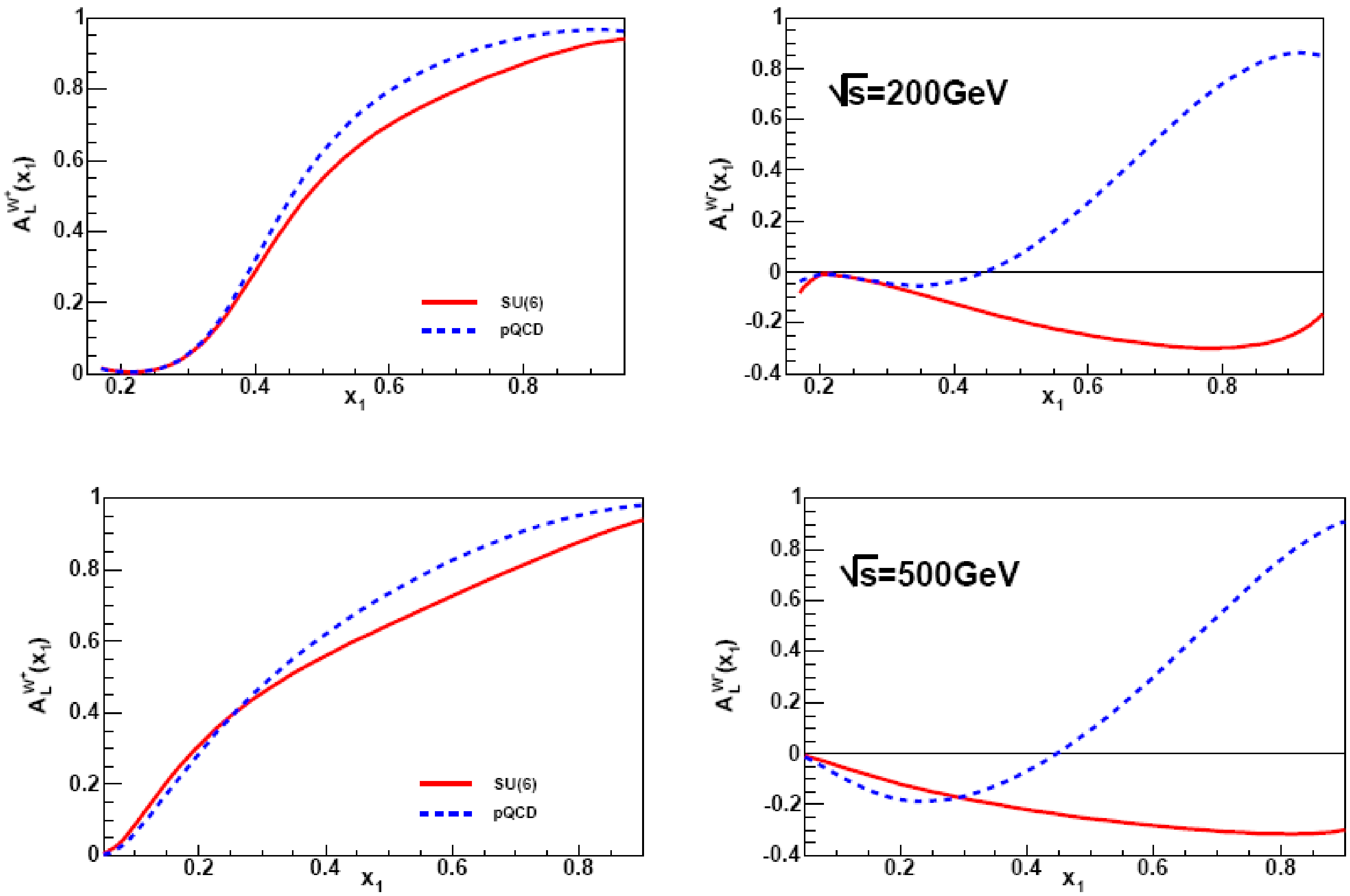
$$A_L^{W^+} = \frac{\Delta u(x_1)\bar{d}(x_2) - \Delta\bar{d}(x_1)u(x_2)}{u(x_1)\bar{d}(x_2) + \bar{d}(x_1)u(x_2)}$$

$$A_L^{W^-} = \frac{\Delta d(x_1)\bar{u}(x_2) - \Delta\bar{u}(x_1)d(x_2)}{d(x_1)\bar{u}(x_2) + \bar{u}(x_1)d(x_2)}$$

$$x_1 = \frac{M_W}{\sqrt{s}} e^{y_W}$$

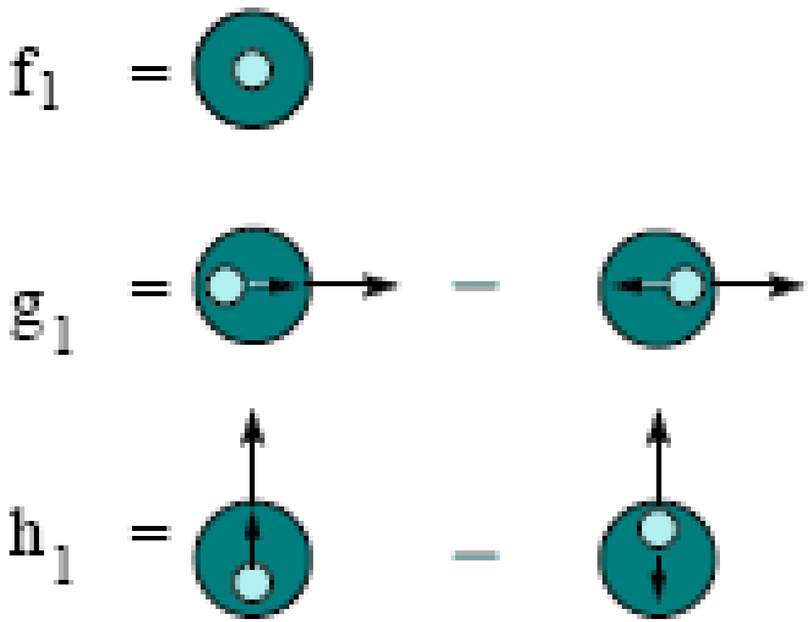
$$x_2 = \frac{M_W}{\sqrt{s}} e^{-y_W}$$

X. Chen, Y. Mao, B.-Q. Ma, NPA **A759(2008)188**



What is transversity?

Three fundamental quantities of quark distributions



The Melosh-Wigner Rotation in Transversity

$$2\,\delta q = \langle p, \uparrow | \bar{q}_{\lambda} \gamma^{\perp} \gamma^{+} q_{-\lambda} | p, \downarrow \rangle$$

$$\delta q(x) = \int [\mathrm{d}^2 \boldsymbol{k}_{\perp}] \tilde{M}_q(x, \boldsymbol{k}_{\perp}) \Delta q_{\mathrm{RF}}(x, \boldsymbol{k}_{\perp})$$

$$\tilde{M}_q(x, \boldsymbol{k}_{\perp}) = \frac{(k^{+} + m)^2}{(k^{+} + m)^2 + \boldsymbol{k}_{\perp}^2}$$

I.Schmidt&J.Soffer, Phys.Lett.B 407 (1997) 331

Transversity with Melosh-Wigner rotation in the quark-diquark model

$$\delta u_v(x) = \left[u_v(x) - \frac{1}{2} d_v(x) \right] \hat{W}_S(x) - \frac{1}{6} d_v(x) \hat{W}_V(x),$$

$$\delta d_v(x) = -\frac{1}{3} d_v(x) \hat{W}_V(x),$$

B.-Q. Ma, I. Schmidt, J. Soffer, Phys.Lett. B 441 (1998) 461-467.

The transversity in pQCD, in similar to helicity distributions

$$\delta q(x) = \frac{\tilde{A}_q}{B_3} x^{(-1/2)} (1-x)^3 - \frac{\tilde{C}_q}{B_5} x^{(-1/2)} (1-x)^5$$

Baryon	q_1	q_2	$\tilde{A}_{q1}$	$\tilde{C}_{q1}$	$\tilde{A}_{q2}$	$\tilde{C}_{q2}$	$\hat{A}_{q1}$	$\hat{C}_{q1}$	$\hat{A}_{q2}$	$\hat{C}_{q2}$
p	u	d	1.375	0.625	0.275	0.725	1.52	0.48	0.305	0.695

B.-Q. Ma, I. Schmidt, J.-J. Yang, Phys.Rev.D63(2001) 037501.

Transversity in two models

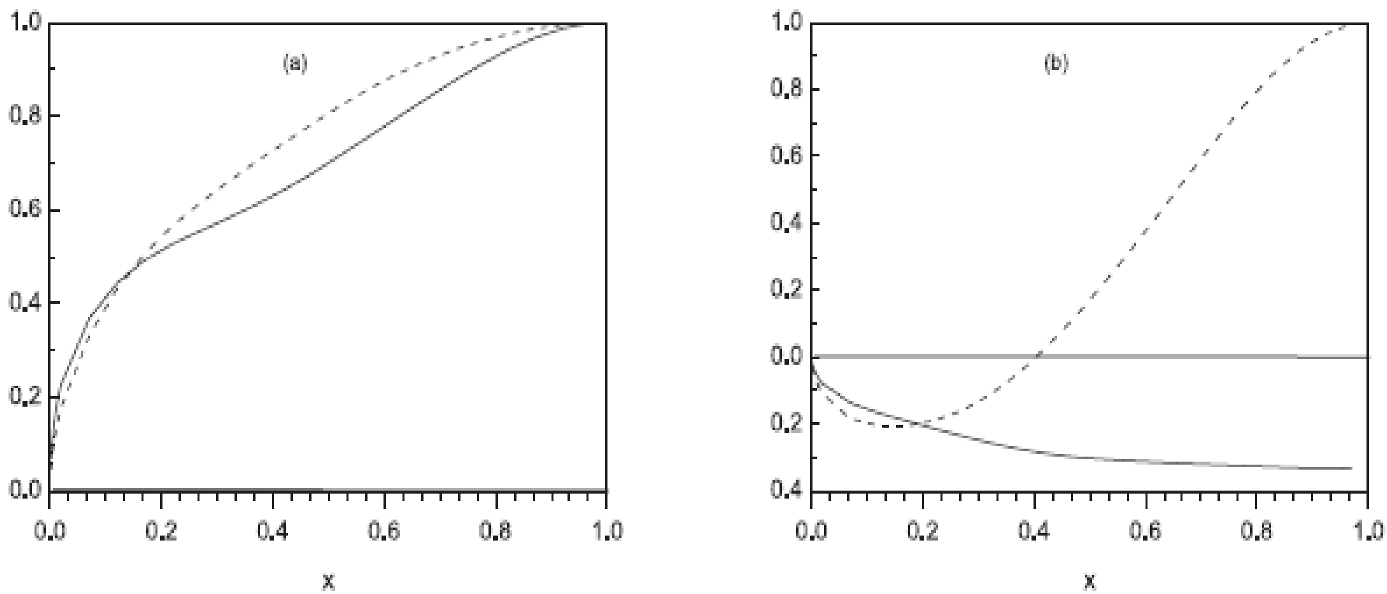
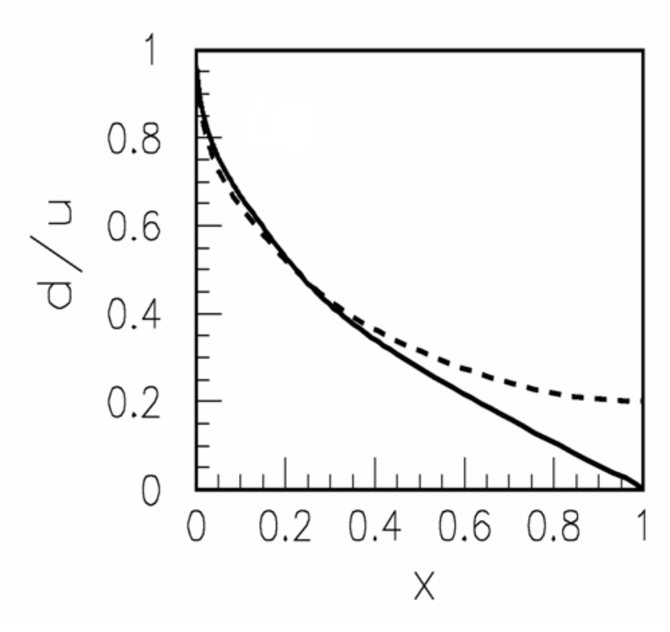
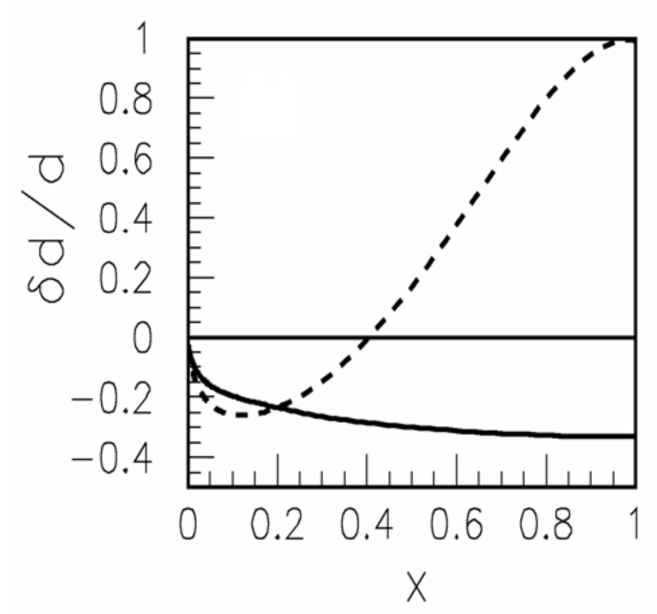


图 3.1　$\delta u/u$ (a) 和$\delta d/d$ (b) 的曲线示意图，$Q^2 = 2$ GeV^2, 实线代表的是quark-diquark 模型，虚线代表的是pQCD 理论.

SU(6) quark-diquark model VS pQCD based analysis

Ma, Schmidt and Yang, PRD 65, 034010 (2002)





solid curve for SU(6) and dashed curve for pQCD

Collins asymmetry in semi-inclusive production

$$A_{UT}^{Collins} = \frac{1}{|S_\perp|}\frac{d\sigma_{UT}^{Collins}}{d\sigma_{UU}}$$ After integration over specific weighting functions

$$A_T(x,y,z) = -\frac{(1-y)\sum_q e_q^2 \delta q(x) H_1^{\perp(1)q}(z)}{(1-y+y^2/2)\sum_q e_q^2 q(x) D_1^q(z)}$$

$q(x)$ unpolarized quark distrtion

$\delta q(x)$ transversity

$D_1(x)$ unpolarized fragmentation function

$H_1^{\perp(1)q}(x)$ Collins function

Two sets of Collins functions

Set I

$$\delta\hat{q}_{fav}^{\pi(1/2)}(z) = C_f z(1-z)\hat{u}^{\pi^+}(z) \quad \delta\hat{q}_{unfav}^{\pi(1/2)}(z) = C_u z(1-z)\hat{u}^{\pi^+}(z)$$

$$C_f = -0.29 \pm 0.04 \qquad C_u = 0.33 \pm 0.04$$

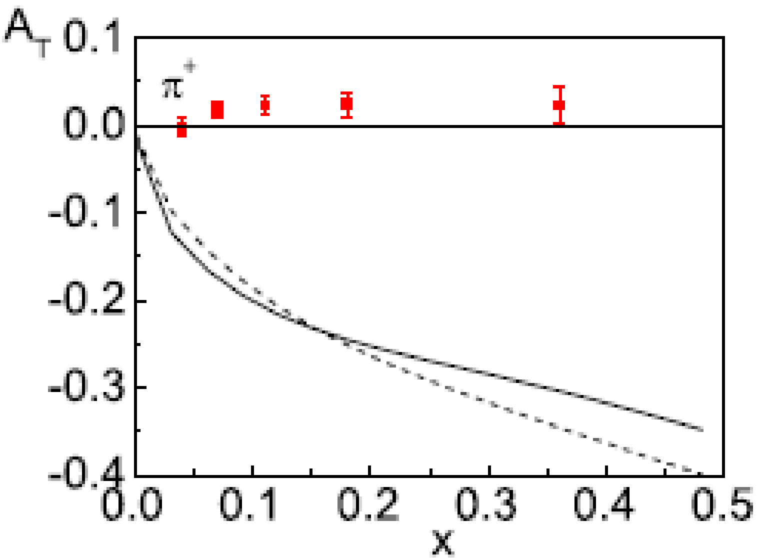
Set II

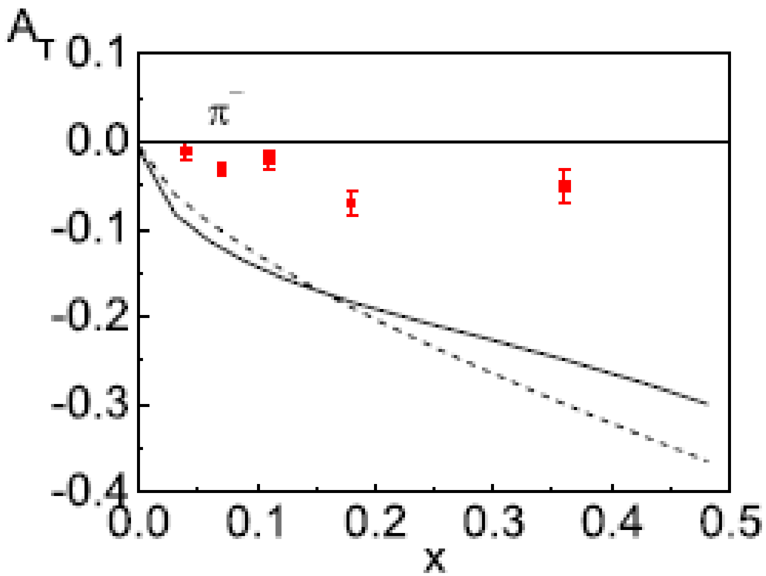
$$\delta\hat{q}_{fav}^{\pi(1/2)}(z) = C_f z(1-z)\hat{u}^{\pi^+}(z) \quad \delta\hat{q}_{unfav}^{\pi(1/2)}(z) = C_u z(1-z)\hat{d}^{\pi^+}(z)$$

$$C_f = -0.29 \pm 0.02 \qquad C_u = 0.56 \pm 0.07$$

W. Vogelsang and F. Yuan, Phys. Rev. D72 (2005).

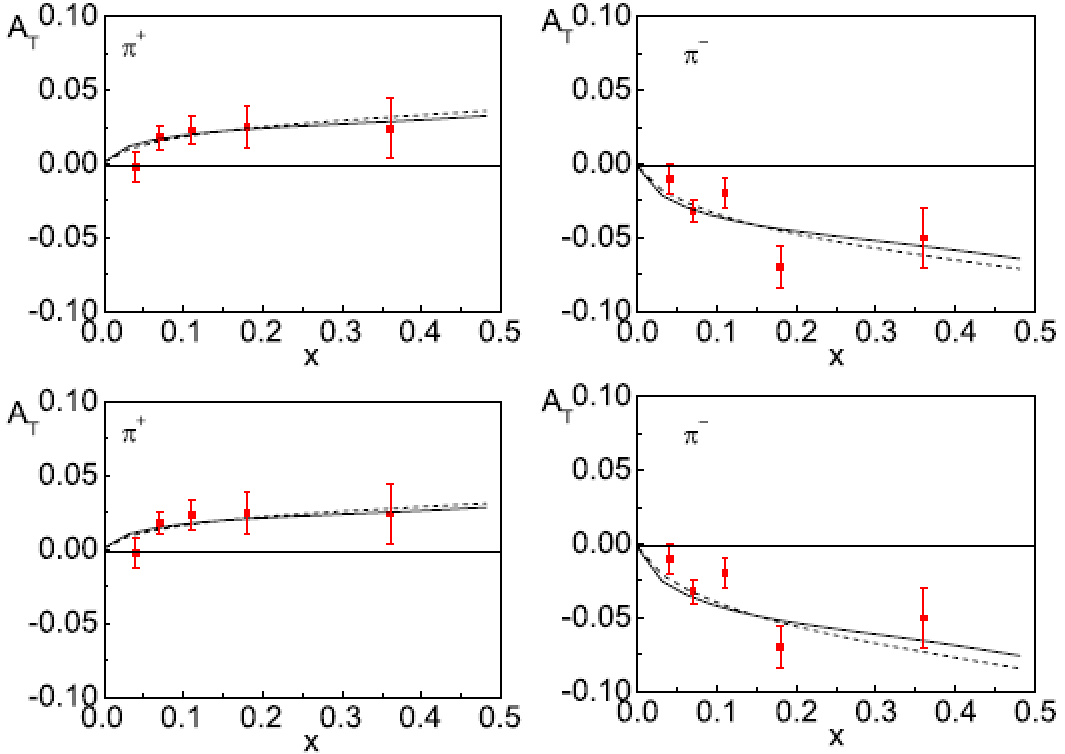
Prediction for HERMES with only favored fragmentation





Y. Huang, J. She, and B.-Q. Ma, Phys. Rev. D76 (2007) 034004.

Including unfavored fragmentation in HERMES condition



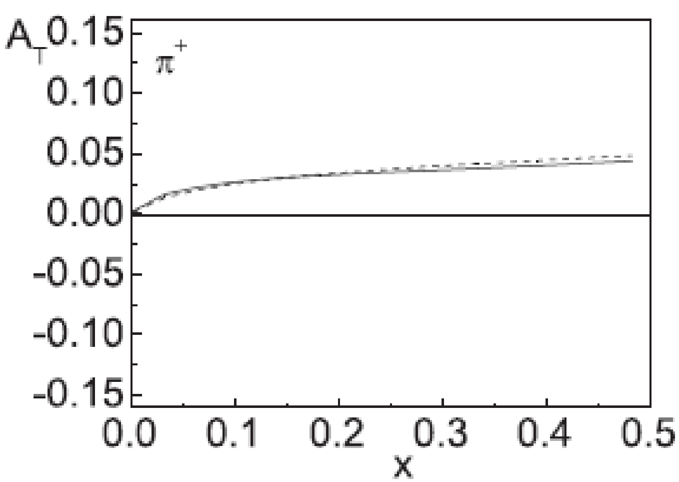
set I

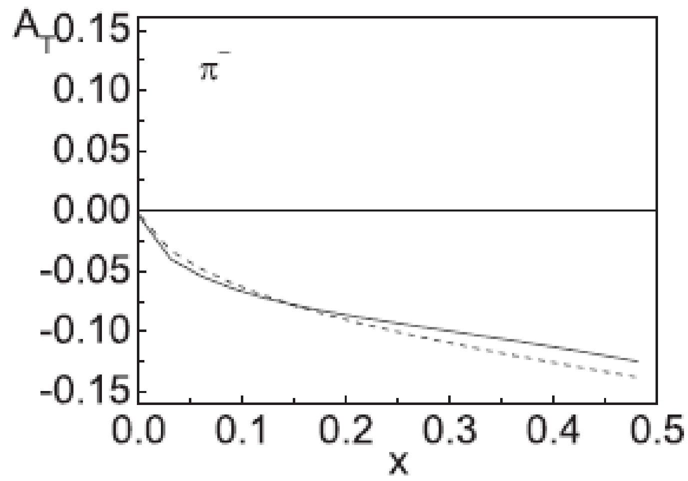
set II

Y. Huang, J. She, and B.-Q. Ma, Phys. Rev. D76 (2007) 034004.

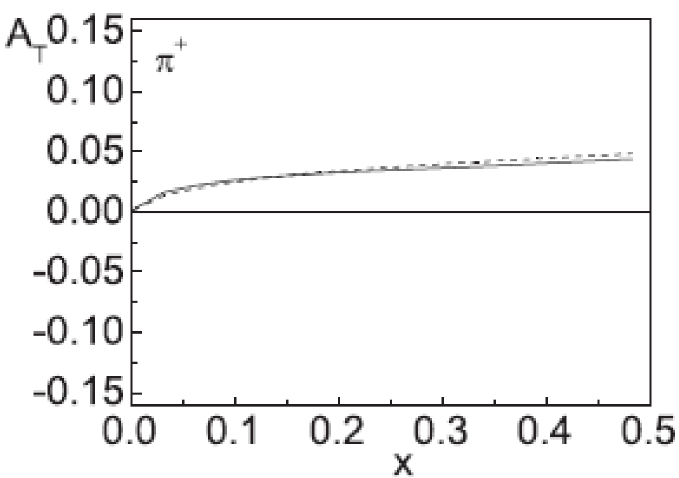
Prediction in JLab condition (proton target)

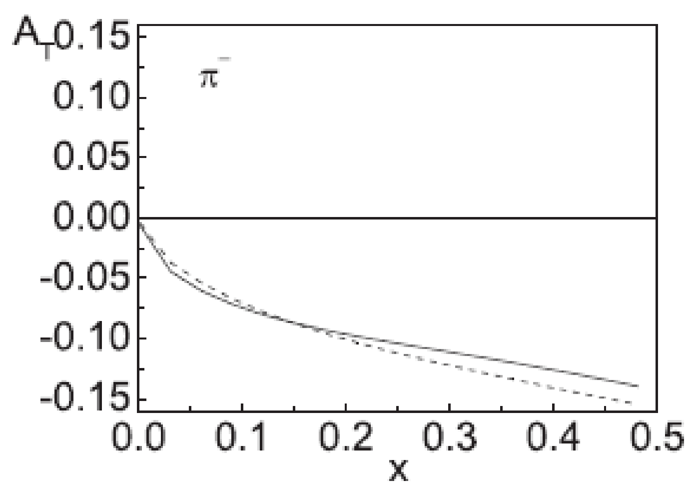
Set I





Set II

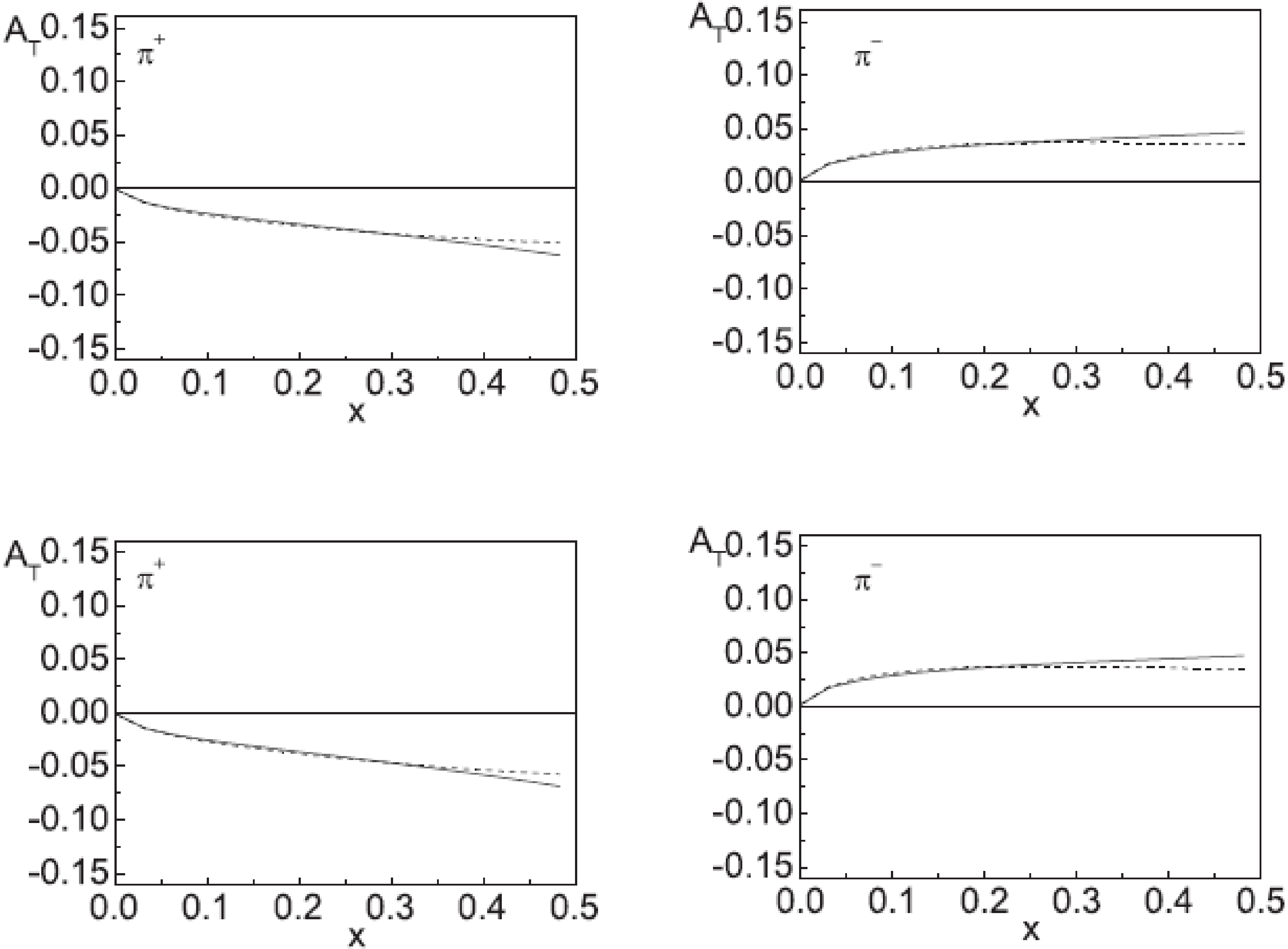




Prediction in JLab condition (neutron target)

Set I

Set II



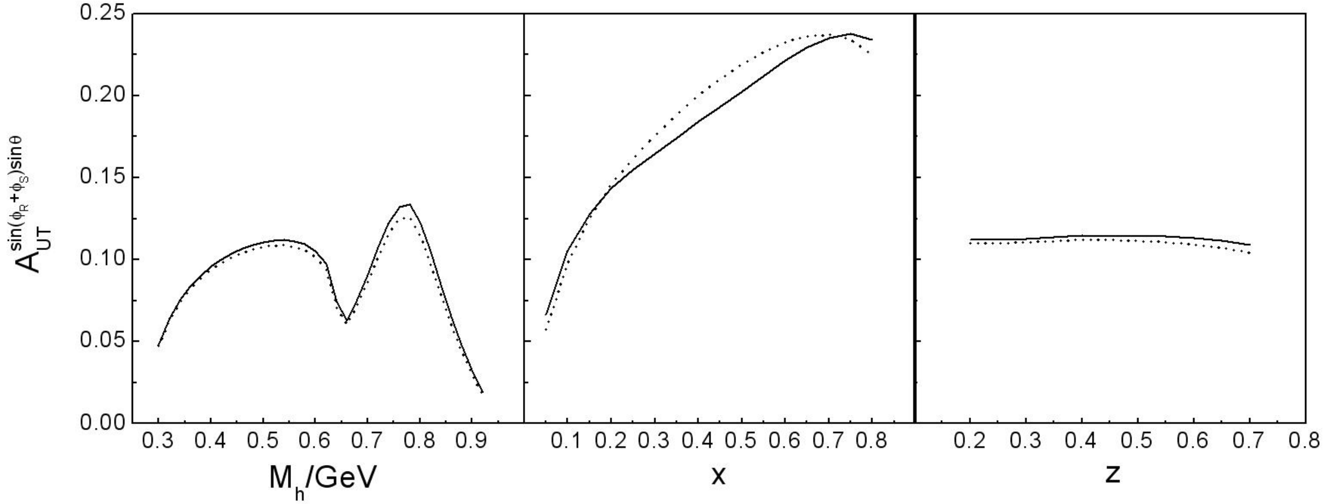
Transversity
from two pion interference fragmentation

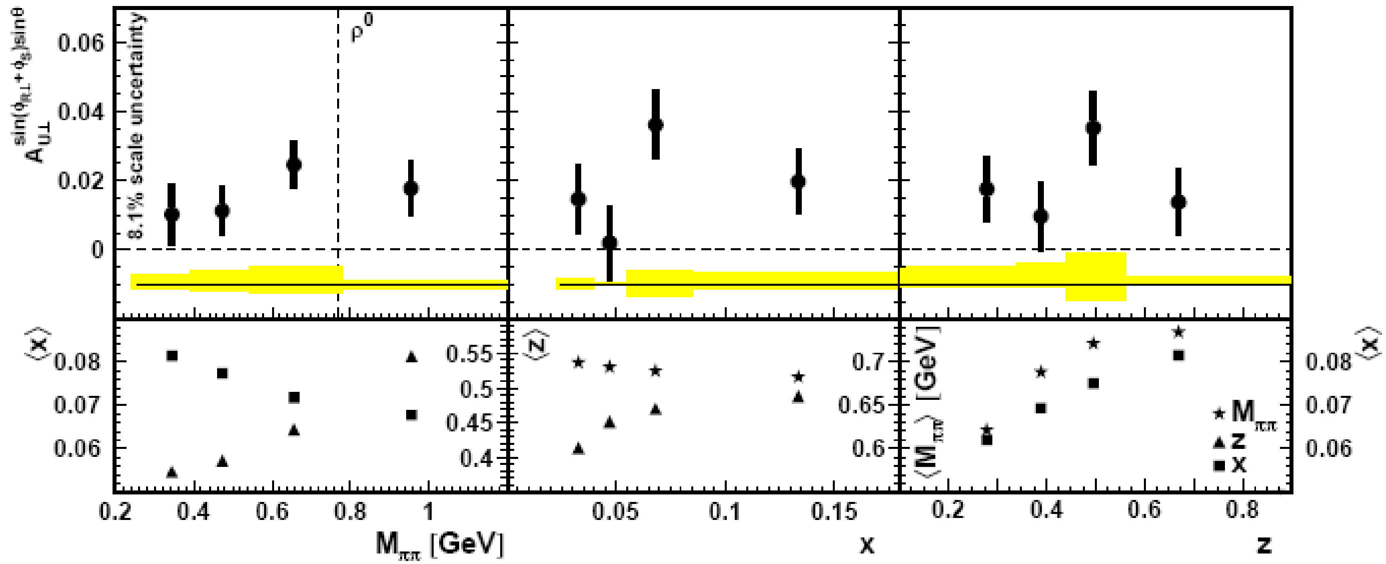
$$A_{UT}^{\langle 2\sin(\phi_R+\phi_S)/\sin\theta\rangle} \simeq -\frac{\sum_a e_a^2 \delta f^a(x) \int d\zeta \frac{|\vec{R}|}{M_h} H_1^{\sphericalangle a}(z,\zeta,M_h^2)}{\sum_a e_a^2 f^a(x) \int d\zeta D_1^a(z,\zeta,M_h^2)}$$

New fragmentation functions are introduced: the dihadron FFs, including the chiral odd interference FF.

- Jaffe, Jin and Tang, PRL 80, 1166 (1998)
- Radici, Jakob and Bianconi, PRD, 65, 074031 (2002)
- Bacchetta and Radici, PRD 74, 114007 (2006)

Prediction on the proton target

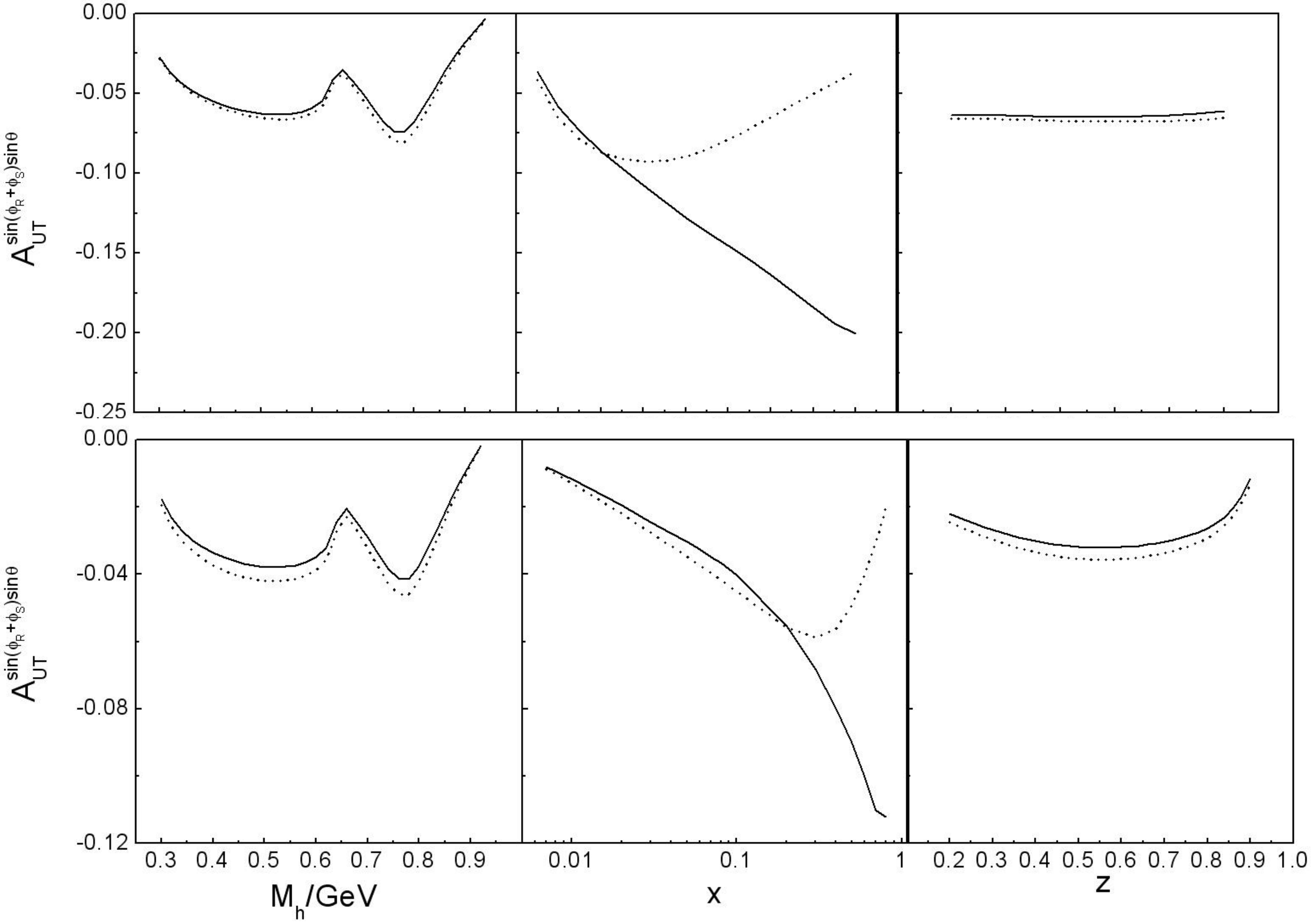




Prediction on neutron target

HERMES

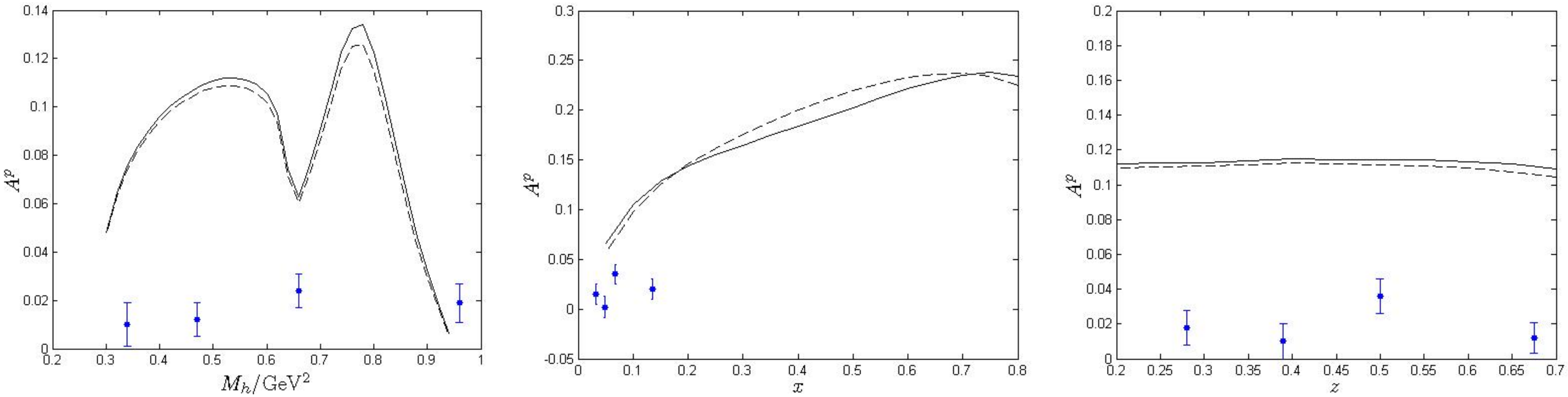
COMPASS



J. She, Y.Huang, and B.-Q. Ma, Phys. Rev. D77 (2008) 014035.

Comparison with HERMES Data

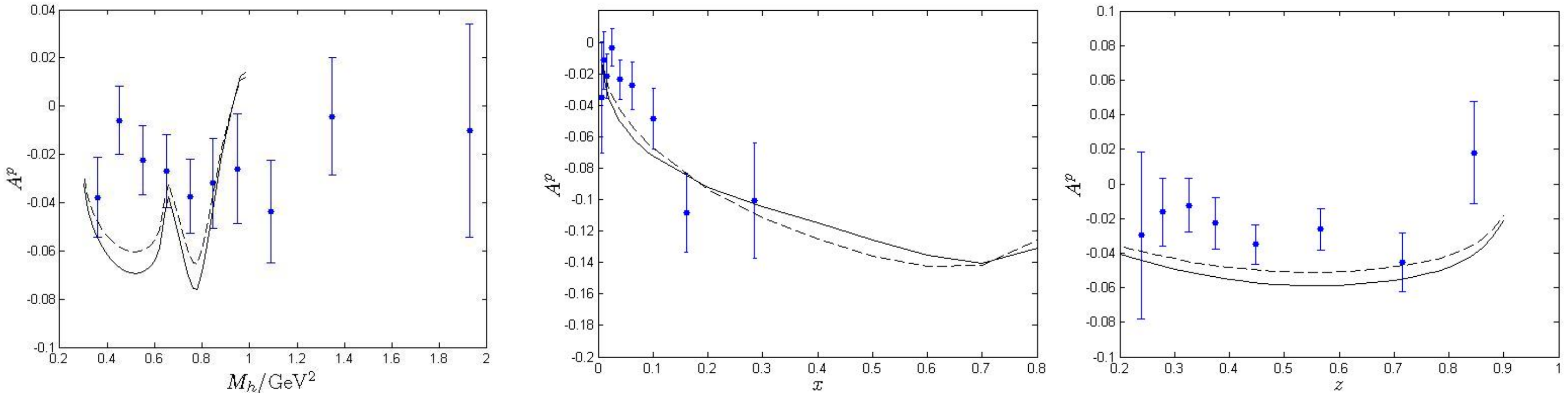
HERMES, JHEP 0806:017,2008



J. She, Y.Huang, and B.-Q. Ma, Phys. Rev. D77 (2008) 014035.

Comparison with COMPASS Data

COMPASS Preliminary, arXiv:0907.0961



J. She, Y.Huang, and B.-Q. Ma, Phys. Rev. D77 (2008) 014035.

The Melosh-Wigner Rotation in Quark Orbital Angular Moment

$$\hat{L}_q = -i\left(k_1 \frac{\partial}{\partial k_2} - k_2 \frac{\partial}{\partial k_1} \right).$$

$$L_q(x) = \int [d^2 k_\perp] M_L(x, k_\perp) \Delta q_{QM}(x, k_\perp)$$

$$M_L(x, k_\perp) = \frac{k_\perp^2}{(k^+ + m)^2 + k_\perp^2}$$

Ma&Schmidt, Phys.Rev.D 58 (1998) 096008

Three QCD spin sums for the proton spin

$$\vec{J}_{QCD} = \int d^3x\psi^\dagger \frac{\vec{\Sigma}}{2}\psi + \int d^3x\psi^\dagger \vec{x} \times (-i\nabla)\psi + \int d^3x\vec{E}^a \times \vec{A}^a + \int d^3x E^{ai}\vec{x} \times \nabla A^{ai} \equiv \vec{S}_q + \vec{L}_q + \vec{S}_g + \vec{L}_g,$$

$$\vec{J}_{QCD} = \int d^3x\psi^\dagger \frac{\vec{\Sigma}}{2}\psi + \int d^3x\psi^\dagger \vec{x} \times (-i\vec{D})\psi + \int d^3x\vec{x} \times (\vec{E} \times \vec{B}) \equiv \vec{S}_q + \vec{L}_q + \vec{J}_g,$$

$$\vec{J}_{QCD} = \int d^3x\psi^\dagger \frac{\vec{\Sigma}}{2}\psi + \int d^3x\psi^\dagger \vec{x} \times (-i\vec{D}_{pure})\psi + \int d^3x\vec{E}^a \times \vec{A}^a_{phys} + \int d^3x E^{ai}\vec{x} \times \nabla A^{ai}_{phys} \equiv \vec{S}_q + \vec{L}_q + \vec{S}_g + \vec{L}_g,$$

X.-S.Chen, X.-F.Lu, W.-M.Sun, F.Wang, T.Goldman, PRL100(2008)232002

Spin and orbital sum in light-cone formalism

$$\frac{1}{2}M_q + M_L = \frac{1}{2}$$

$$M_q(x,k_\perp) = \frac{(k^+ + m)^2 - k_\perp^2}{(k^+ + m)^2 + k_\perp^2} \qquad M_L(x,k_\perp) = \frac{k_\perp^2}{(k^+ + m)^2 + k_\perp^2}$$

$$\frac{1}{2}\Delta q(x) + L_q(x) = \frac{1}{2}\Delta q_{QM}(x)$$

Ma&Schmidt, Phys.Rev.D 58 (1998) 096008

Relations of quark distributions

$$\Delta q_{QM}(x) + \Delta q(x) = 2\,\delta q(x)$$

B.-Q. Ma, I. Schmidt, J. Soffer, Phys.Lett. B 441 (1998) 461-467.

$$\frac{1}{2}\Delta q(x) + L_q(x) = \frac{1}{2}\Delta q_{QM}(x),$$

$$\Delta q(x) + L_q(x) = \delta q(x),$$

Ma&Schmidt, Phys.Rev.D 58 (1998) 096008

The Melosh-Wigner Rotation in "Pretzelosity"

$$g_1^q(x, k_\perp) - h_1^q(x, k_\perp) = h_{1T}^{\perp(1)q}(x, k_\perp) \ .$$

$$\frac{(k^+ + m)^2 - \mathbf{k}_\perp^2}{(k^+ + m)^2 + \mathbf{k}_\perp^2} - \frac{(k^+ + m)^2}{(k^+ + m)^2 + \mathbf{k}_\perp^2} = -\frac{\mathbf{k}_\perp^2}{(k^+ + m)^2 + \mathbf{k}_\perp^2}$$

$$\mathrm{Pretrelocity} = \Delta \mathrm{q} - \delta \mathrm{q} = -\mathrm{L_q}$$

$$\mathrm{Pretrelocity} = -\int [\mathrm{d}^2\mathbf{k}_\perp] \frac{\mathbf{k}_\perp^2}{(\mathrm{k}^+ + \mathrm{m})^2 + \mathbf{k}_\perp^2} \Delta \mathrm{q}_{\mathrm{QM}}(\mathrm{x}, \mathbf{k}_\perp)$$

"Pretrel" or "Brezel"

“Pretrel” or “Brezel”

"Mahua(麻花)": the Chinese Preztel

What is "Pretzelosity" ?

- Pretzelosity: one of the eight leading twist transverse dependent parton distributions (TMDs).
- The quark-quark correlator up to the leading twist

$$\Phi(x,\mathbf{p}_\perp) = \frac{1}{2}\{f_1 \not{n}_+ - f_{1T}^\perp \frac{\epsilon_\perp^{ij} p_\perp^i S_\perp^j}{M_N} \not{n}_+ + (S_\| g_{1L} + \frac{\mathbf{p}_\perp \cdot \mathbf{S}_\perp}{M_N} g_{1T})\gamma_5 \not{n}_+ + h_{1T} \frac{[\not{S}_\perp, \not{n}_+]\gamma_5}{2} + (S_\| h_{1L}^\perp + \frac{\mathbf{p}_\perp \cdot \mathbf{S}_\perp}{M_N} h_{1T}^\perp)\frac{[\not{p}_\perp, \not{n}_+]\gamma_5}{2M_N} + i h_1^\perp \frac{[\not{p}_\perp, \not{n}_+]}{2M_N}\}. \quad (7)$$

P.J. Mulders and R.D. Tangerman, Nucl. Phys. **B 461**, 197 (1996), Erratum-ibid. **B 484**, 538 (1997). K. Goeke, A. Metz, and M. Schlegel, Phys. Lett. **B 618**, 90 (2005).

What is "Pretzelosity"?

$$\frac{p_\perp^x p_\perp^y}{M_N^2} h_{1T}^\perp(x, p_\perp^2) = \int \frac{d\xi^- d^2\boldsymbol{\xi}_\perp}{16\pi^3} e^{i(xP^+\xi^- - \mathbf{p}_\perp \cdot \boldsymbol{\xi}_\perp)} \times \langle PS^y | \bar{\psi}(0) i\sigma^{1+}\gamma_5 \psi(0, \xi^-, \xi_\perp) | PS^y \rangle, \quad (12)$$

$|PS^y\rangle$: the hadronic state with a polarization in the y direction.

- Some properties of pretzelosity:
  1. It is chiral-odd, and needs a chiral-odd partner in the SIDIS.
  2. There is no gluon analog of pretzelosity.
  3. In a large class of models, it is the difference of helicity and transversity, and hence a measure for relativistic effects.

H. Avakian, A.V. Efremov, P. Schweitzer, and F. Yuan, arXiv:0805.3355.

A Simple Relation

- The difference of helicity and transversity is the first moment of pretzelosity.

$$h_{1T}^{\perp(1)qv}(x, \mathbf{p}_\perp) \equiv \frac{p_\perp^2}{2M_N^2} h_{1T}^{\perp qv}(x, \mathbf{p}_\perp) = g_1^{qv}(x, \mathbf{p}_\perp) - h_1^{qv}(x, \mathbf{p}_\perp),$$

- This relation has already been obtained in
H. Avakian, A.V. Efremov, P. Schweitzer, and F. Yuan, arXiv:0805.3355. B. Pasquini, S. Cazzaniga and S. Boffi, Phys. Rev. **D 78**, 034025 (2008).
- But this relation is not fully satisfied in
A. Bacchetta, F. Conti, and M. Radici, Phys. Rev. **D 78**, 074010 (2008).

Connection with Quark Orbital Angular Momentum

- The rotation factor for $\vec{x} \times -i\nabla$ is $\frac{p_\perp^2}{(x\mathcal{M}_D+m_q)^2+p_\perp^2}$
  B.-Q. Ma, I. Schmidt, Phys. Rev. **D 58**, 096008 (1998).
- a simple relation between the pretzelosity and the quark orbital angular momentum

$$L^{qv}(x,\mathbf{p}_\perp) = -h_{1T}^{\perp(1)qv}(x,\mathbf{p}_\perp) = h_1^{qv}(x,\mathbf{p}_\perp) - g_1^{qv}(x,\mathbf{p}_\perp), (21)$$

or at the integration level

$$L^{qv}(x) = \int d^2\mathbf{p}_\perp L^{qv}(x,\mathbf{p}_\perp) = -h_{1T}^{\perp(1)qv}(x) = h_1^{qv}(x) - g_1^{qv}(x).$$

- A measurement of pretzelosity may reveal the information on the quark orbital angular momentum.

Pretzelosity in SIDIS

- Pretzelosity can be measured through $\sin(3\phi_h - \phi_S)$ asymmetry in the SIDIS process, where the cross section can be written as

$$\frac{d^6\sigma_{UT}}{dxdyd\phi_S dzd^2\mathbf{P}_{h\perp}} = \frac{2\alpha^2}{sxy^2}\{(1-y+\frac{1}{2}y^2)F_{UU} + S_\perp \sin(3\phi_h - \phi_S)(1-y)F_{UT}^{\sin(3\phi_h-\phi_S)} + \ldots\}, \quad (23)$$

with $F_{UU} = \mathcal{F}[\omega_1 f_1 D_1]$, $F_{UT}^{\sin(3\phi_h-\phi_S)} = \mathcal{F}[\omega_2 h_{1T}^\perp H_1^\perp]$

- The $\sin(3\phi_h - \phi_S)$ asymmetry

$$A_{UT}^{\sin(3\phi_h-\phi_S)} = \frac{\frac{2\alpha^2}{sxy^2}(1-y)F_{UT}^{\sin(3\phi_h-\phi_S)}}{\frac{2\alpha^2}{sxy^2}(1-y+\frac{1}{2}y^2)F_{UU}}. \quad (24)$$

Quantities in Calculation

- DFs and FFs to be parametrized:

	x dependence	z dependence	TM dependence
f_1	well known	—	not so clear
$h_{1T}^{\perp}$	not known	—	not known
D_1	—	known	not so clear
$H_1^{\perp}$	—	a little known	not clear

- Theoretical understanding: non-perturbative, model calculation, cannot give the exact value so far.
- Transverse momentum dependence: not so clearly yet, usually parametrized in a Gaussian form.
- D_1 and $H_1^{\perp}$: Gaussian parametrization given by
  S. Kretzer, *et al.*, Eur. Phys. J. **C 22**, 269 (2001).
  M. Anselmino, *et al.*, arXiv:0807.0173.

Approach 0 to TMDs

- Starting with the equation

$$
\begin{aligned}
h_{1T}^{\perp(uv)}(x) &= \left[f_1^{(uv)}(x) - \frac{1}{2} f_1^{(dv)}(x)\right] \hat{W}_S(x) - \frac{1}{6} f_1^{(dv)}(x) \hat{W}_V(x), \\
h_{1T}^{\perp(dv)}(x) &= -\frac{1}{3} f_1^{(dv)}(x) \hat{W}_V(x),
\end{aligned}
\tag{25}
$$

  where $\hat{W}_D(x) = \int d^2\mathbf{p}_\perp \varphi^2(x,\mathbf{p}_\perp) W_D(x,\mathbf{p}_\perp) / \int d^2\mathbf{p}_\perp \varphi^2(x,\mathbf{p}_\perp)$
- $f_1(x)$: CTEQ6L as an input. $h_{1T}^{\perp}(x)$: from Eq. 25
- Transverse momentum dependence: Gaussian form.
- How to fit the Gaussian width? $p_{av}/k_{av} \approx 2$?
  H. Avakian, A.V. Efremov, P. Schweitzer, and F. Yuan, arXiv:0805.3355.

Approach 1 to TMDs

- Model calculation.

$$f_1^{(uv)}(x, \mathbf{p}_\perp) = \frac{1}{16\pi^3} \times (\frac{1}{3}\sin^2\theta\varphi_V^2 + \cos^2\theta\varphi_S^2),$$
$$f_1^{(dv)}(x, \mathbf{p}_\perp) = \frac{1}{8\pi^3} \times \frac{1}{3}\sin^2\theta\varphi_V^2.$$

$$h_{1T}^{\perp(uv)}(x, \mathbf{p}_\perp) = -\frac{1}{16\pi^3} \times (\frac{1}{9}\sin^2\theta\varphi_V^2 W_V - \cos^2\theta\varphi_S^2 W_S),$$
$$h_{1T}^{\perp(dv)}(x, \mathbf{p}_\perp) = -\frac{1}{8\pi^3} \times \frac{1}{9}\sin^2\theta\varphi_V^2 W_V.$$

- $\varphi_D(x, \mathbf{p}_\perp)$: adopting the BHL form:

$$\varphi_D(x, \mathbf{p}_\perp) = A_D \exp\{-\frac{1}{8\alpha_D^2}[\frac{m_q^2 + p_\perp^2}{x} + \frac{m_D^2 + p_\perp^2}{1-x}]\},$$

J.She, J.Zhu, B.-Q.Ma, Phys.Rev.D79 (2009) 054008

Approach 2 to TMDs

- Staring with the equation (an unintegrated version)

$$\begin{aligned} h_{1T}^{\perp(uv)}(x,\mathbf{p}_\perp) &= \left[f_1^{(uv)}(x,\mathbf{p}_\perp)-\frac{1}{2}f_1^{(dv)}(x,\mathbf{p}_\perp)\right]W_S(x,\mathbf{p}_\perp) \\ &\quad -\frac{1}{6}f_1^{(dv)}(x,\mathbf{p}_\perp)W_V(x,\mathbf{p}_\perp), \\ h_{1T}^{\perp(dv)}(x,\mathbf{p}_\perp) &= -\frac{1}{3}f_1^{(dv)}(x,\mathbf{p}_\perp)W_V(x,\mathbf{p}_\perp). \end{aligned} \tag{27}$$

- $f_1(x,\mathbf{p}_\perp)$: a Gaussian form

$$f_1(x,\mathbf{p}_\perp)=f_1(x)\frac{\exp(-p_\perp^2/p_{av}^2)}{\pi p_{av}^2}, \tag{28}$$

with CTEQ6L parametrization for $f_1(x)$.

J.She, J.Zhu, B.-Q.Ma, Phys.Rev.D79 (2009) 054008

$h_{1T}^{\perp(1)}(x)$ and $f_1(x)$

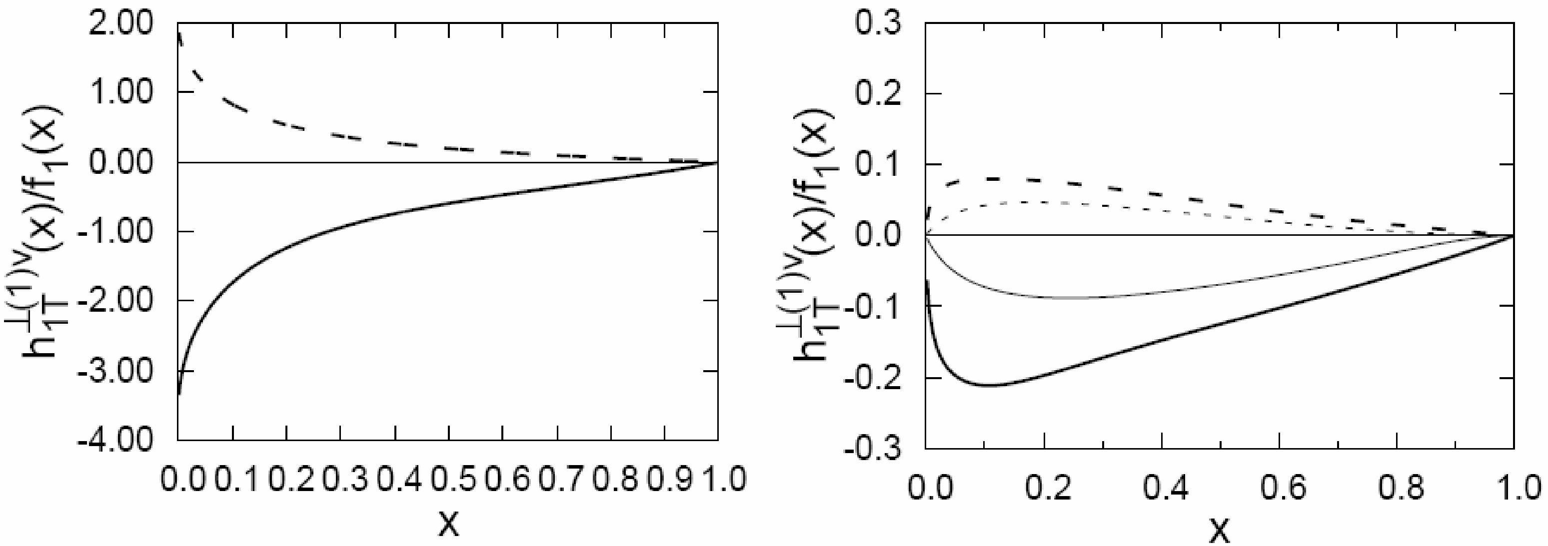


Figure: The ratio $h_{1T}^{\perp(1)(x)}/f_1(x)$. Left panel for approach 0 and right panel for approach 1 (thin curves) and approach 2 (thick curves). Solid curves for the u quark, and dashed curves for the d quark. Only valence quarks are considered.

J.She, J.Zhu, B.-Q.Ma, Phys.Rev.D79 (2009) 054008

Results at HERMES kinematics.

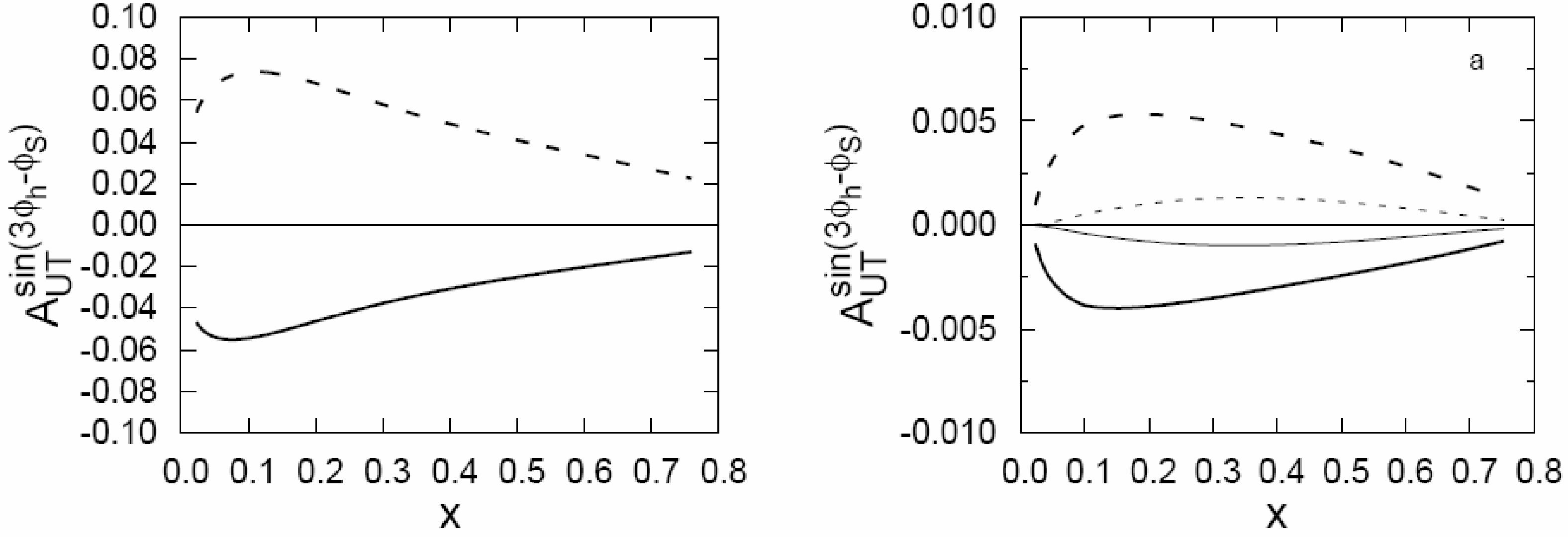


Figure: The results for HERMES kinematics with a proton target. Left panel for approach 0 and right panel for approach 1 (thin curves) and approach 2 (thick curves). Solid curves for the π^+ production, and dashed curves for the π^- production.

Results at COMPASS kinematics.

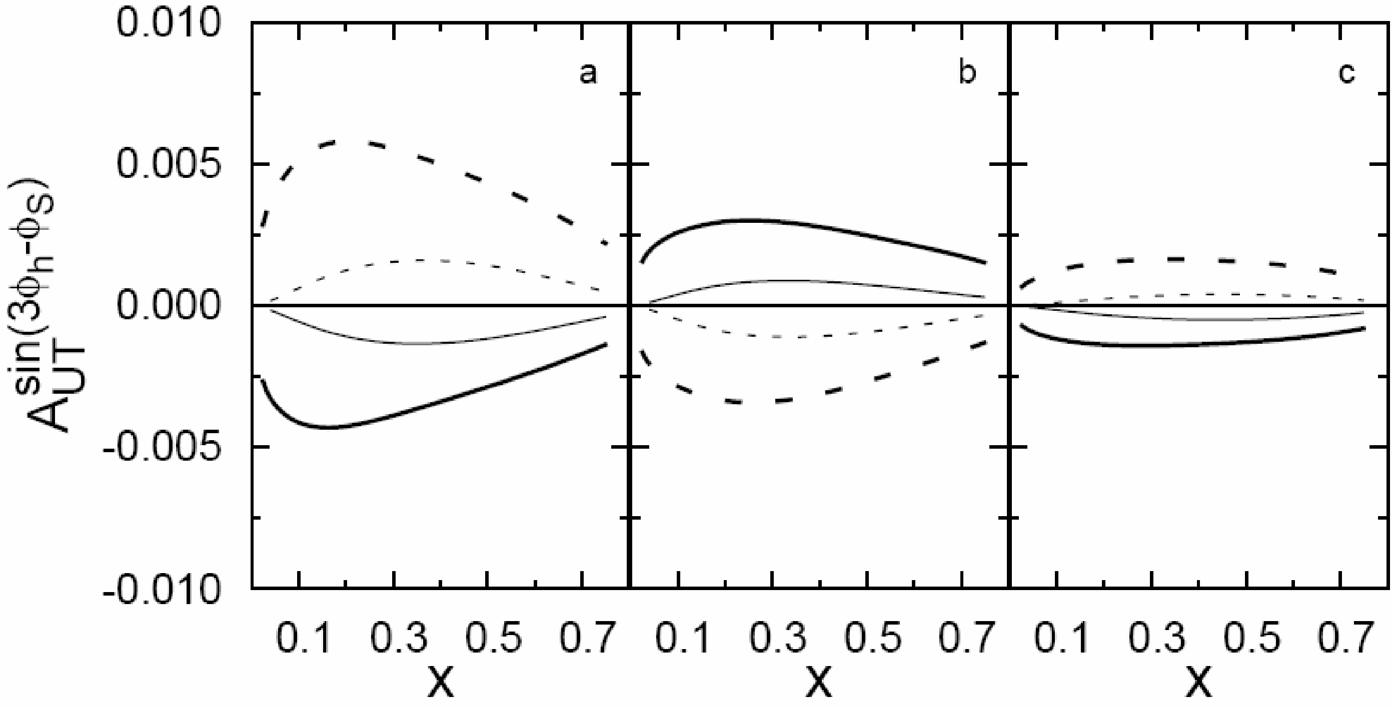


Figure: The results for COMPASS kinematics. a) proton target, b) neutron target, and c) deuteron target.

Results at JLab kinematics.

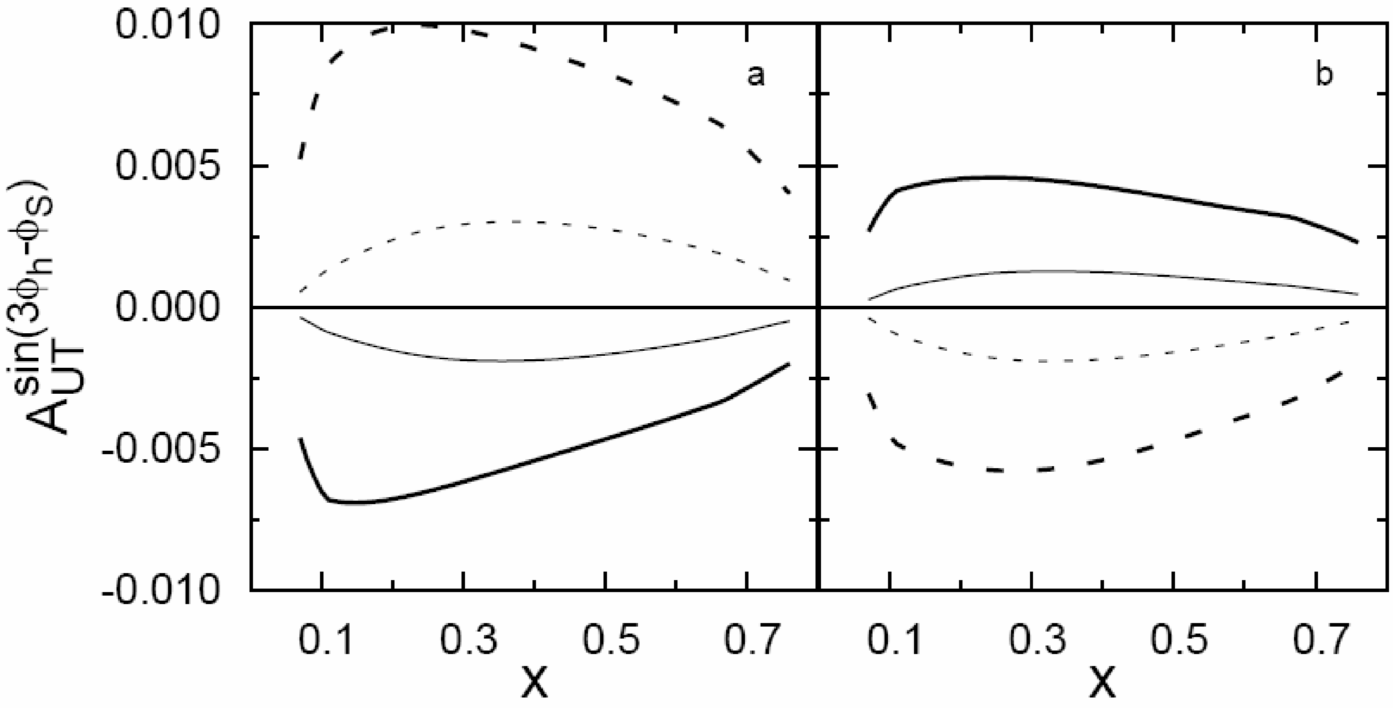


Figure: The results for JLab kinematics. a) proton target and b) neutron target.

Avakian's work

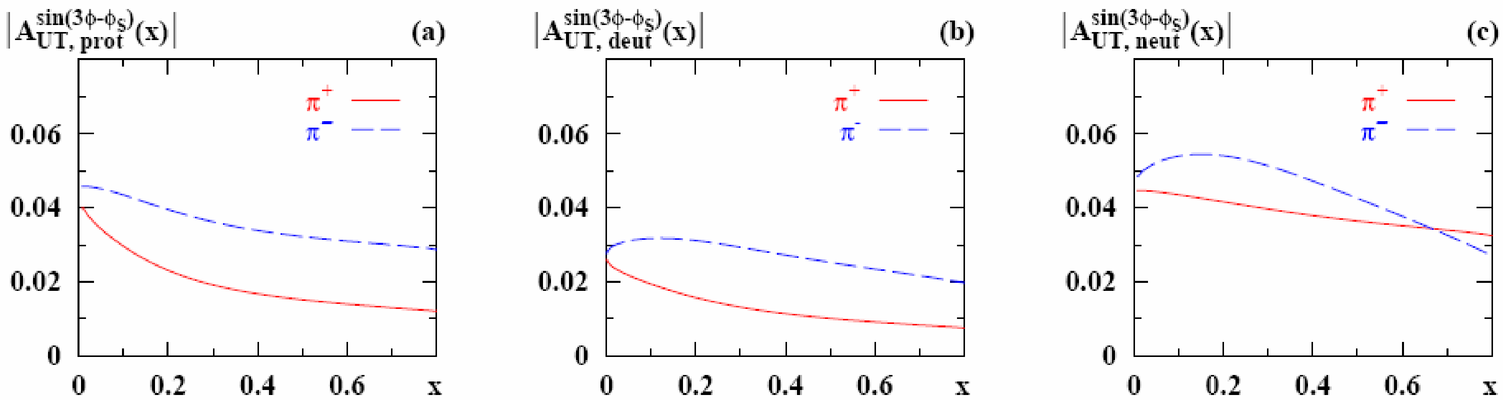


Figure: The predictions on the $\sin(3\phi_h - \phi_S)$ asymmetry at JLab kinematics. a) proton target, b) deuteron target and c) neutron target.

Much larger than our result!

H. Avakian, A.V. Efremov, P. Schweitzer, and F. Yuan, PRD 78, 114024 (2008) .

Boffi's work

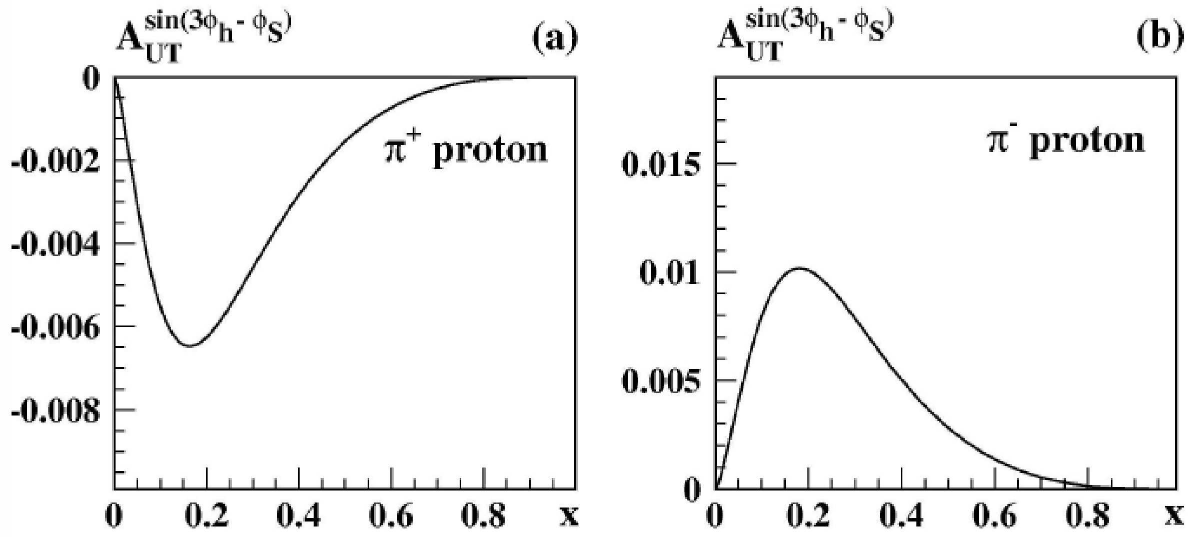


Figure: The $\sin(3\phi_h - \phi_S)$ asymmetry on a proton target.

Much smaller than Aviank's result, but a little larger than ours.

S. Boffi, A. V. Efremov, B. Pasquini, and P. Schweitzer, arXiv:0903.1271.

A short summary

- Results are sensitive to different transverse momentum approaches.
- The asymmetry is not an increasing function of x.
- The asymmetry is too small, up to a maximum less than 1%. A great challenge for a direct measurement.
- Can we enhance the asymmetry? We observe that the asymmetry is an increasing function of $\mathbf{p}_\perp^2$, but $\mathbf{p}_\perp^2$ cannot be manipulated directly.
- A compromise method is to select large $P_{h\perp}$ events instead, $\mathbf{P}_{h\perp} = z(\mathbf{p}_\perp - \mathbf{k}_\perp)$. We can exclude most small $p_\perp$ events.
- We will recalculate our results with a cutoff $P_{h\perp} > 1.0\mathrm{GeV}$.

HERMES results with a cutoff.

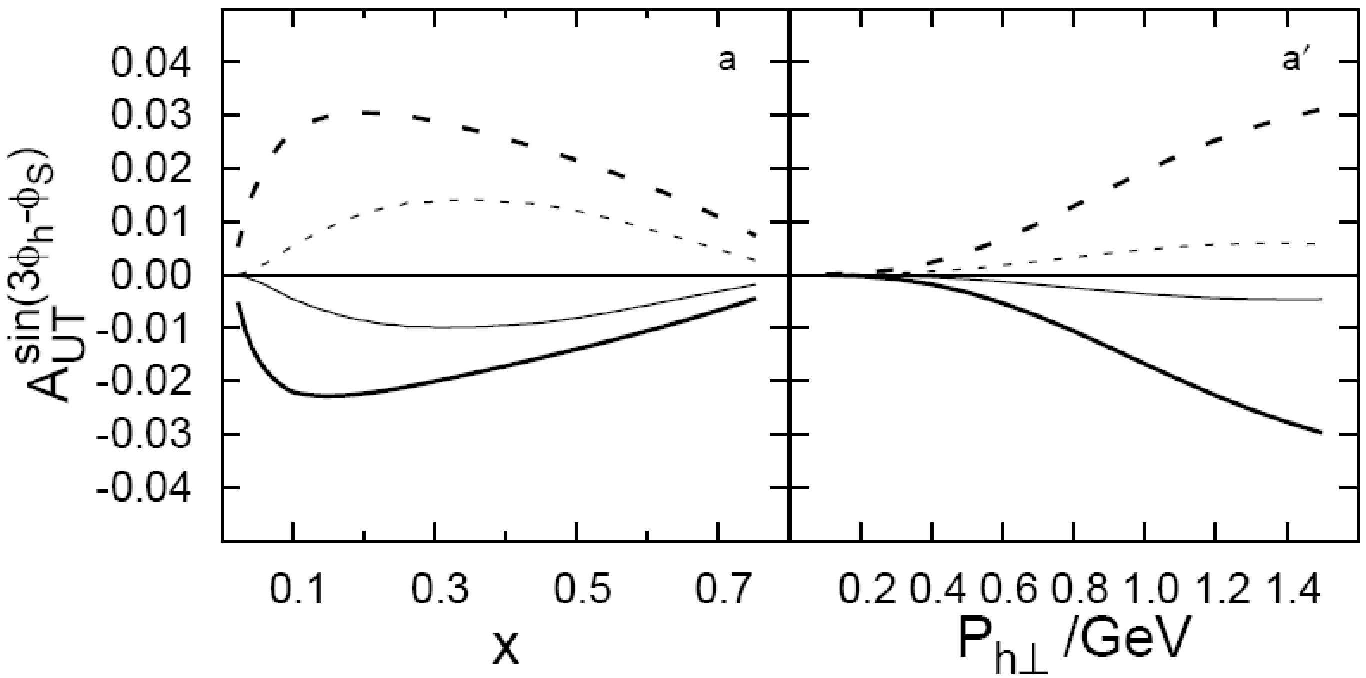


Figure: The results for HERMES kinematics on a proton target with a cutoff $P_{h\perp} > 1.0\,\mathrm{GeV}$, while the right panel shows the $P_{h\perp}$ dependence of the asymmetry after integrating all the other kinematic variables.

COMPASS results with a cutoff.

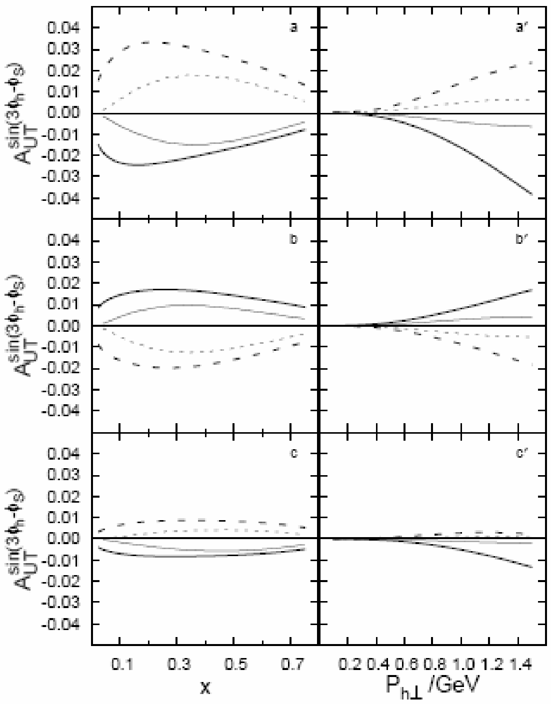


Figure: The results for COMPASS kinematics with a cutoff $P_{h\perp} > 1.0\,\mathrm{GeV}$. The upper, middle, and lower panels correspond to the proton, neutron, and deuteron target, respectively.

JLab results with a cutoff.

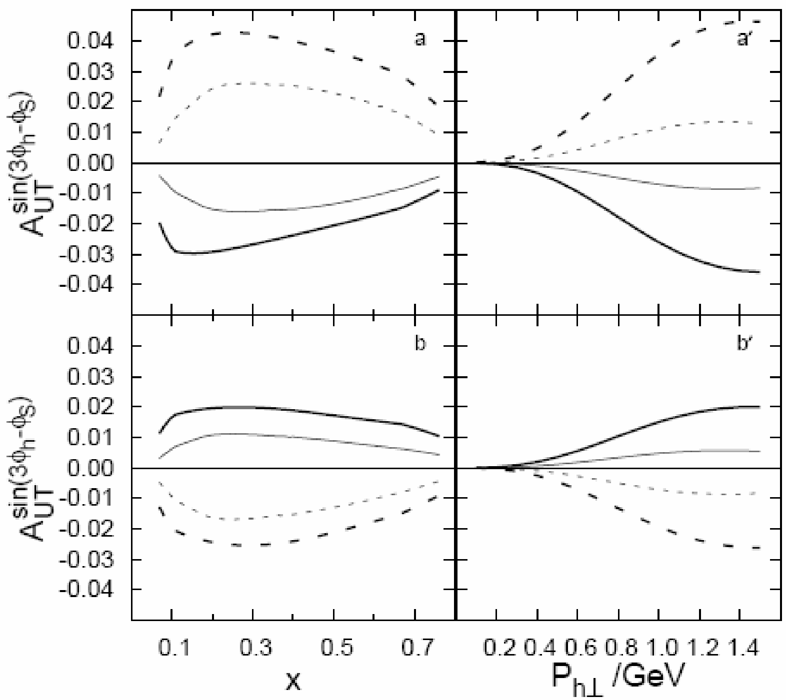


Figure: The results for JLab kinematics with a cutoff $P_{h\perp} > 1.0\,\mathrm{GeV}$. The upper and lower panels correspond to the proton and neutron target, respectively.

Caution

- The TMD factorization was proved to be valid only in the region $\Lambda_{\mathrm{QCD}} \ll P_{h\perp} \ll Q$.
- If $P_{h\perp} \sim \Lambda_{\mathrm{QCD}}$ and Q^2 is too large, a higher order pQCD correction (the gluon radiation) will be important.
- This transition point is around $P_{h\perp} \approx 1\mathrm{GeV}$.
- We must be careful and we assume that our results at a little larger $P_{h\perp}$ but not too larger than 1GeV are still acceptable.
- Another problem: the events will be exponentially suppressed at $P_{h\perp} \gg \Lambda_{\mathrm{QCD}}$, a challenge for the experiments to collect more data.

Conclusions

- **Relativistic effect of Melosh-Winger rotation is important in hadron spin physics.**
- **Transversity is being accessed in SIDIS and two pion inteference fragmentation processes**
- **The unfavored Collins fragmentation plays a surprising role to reproduce the data, than naively expected.**
- **The pretzelosity is an important quantity for the spin-orbital correlation.**
- **New way to access quark orbital angular momentum is suggested.**

The Nucleon Strangeness Asymmetry

?

Outline

- **The nucleon strangeness asymmetry versus NuTeV anomaly**

- **Influence of Heavy Quark Recombination to the Measurement of the Nucleon Strangeness Asymmetry**

The Strange-Antistrange Asymmetry

The strange quark and antiquark distributions are

symmetric at leading-orders of perturbative QCD

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

However, it has been argued that there is strange-antistrange distribution asymmetry in pQCD evolution at three-loops from non-vanishing up and down quark valence densities.

S.Catani et al. PRL93(2004)152003

Strange-Antistrange Asymmetry

from Non-Perturbative Sources

- **Meson Cloud Model** $s(x) < \bar{s}(x)$ at large x

  A.I. Signal and A.W. Thomas, PLB191(87)205

- **Chiral Field** $s(x) > \bar{s}(x)$ at large x

  M. Burkardt and J. Warr, PRD45(92)958

- **Baryon-Meson Fluctuation** $s(x) > \bar{s}(x)$ at large x

  S.J. Brodsky and B.-Q. Ma, PLB381(96)317

The strange-antistrange asymmetry in a microscopic model

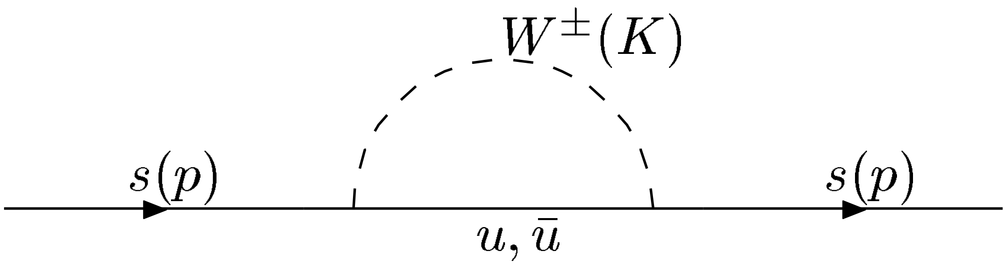
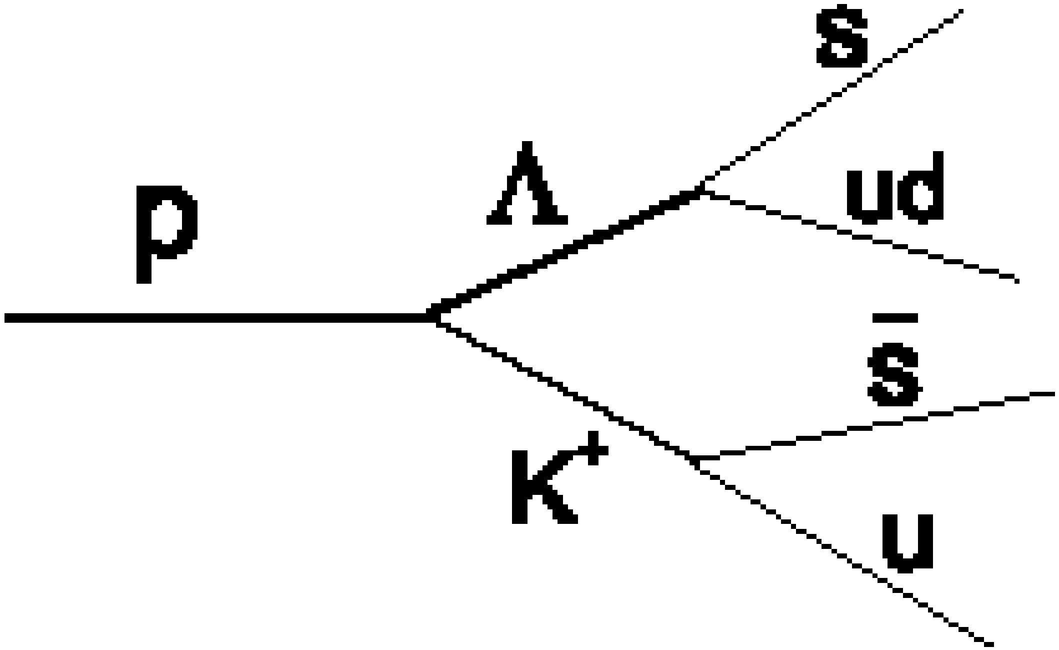


Fig. 1(a)

X.Q.Li, X.B.Zhang, B.Q.Ma (PRD65 (01) 014003)

there exists an obvious mass difference due to medium effect between strange and anti-strange quarks, as large as 10-100 MeV, which can produce more sbar at small x and more s at large x.

Mechanism for s-sbar asymmetry



$s(x) \neq \bar{s}(x)$

Strange-Antistrange Asymmetry
in phenomenological analyses

- **V. Barone et al. Global Analysis, EPJC12(00)243**

$$\int x[s(x)-\bar{s}(x)]dx \approx 0.002$$

- **NuTeV dimuon analysis, hep-ex/0405037, PRL99(07)192001**

$$\int x[s(x)-\bar{s}(x)]dx \approx -0.0013 \to 0.00196$$

- **CTEQ Global Analysis,** F. Olness *et. al* (hep-ph/0312323),

$$\int x[s(x)-\bar{s}(x)]dx \approx -0.001 \to 0.004$$

With large uncertainties

Weinberg (weak) Angle from Nuetrino DIS:
NuTeV Anamoly

- **NuTeV Collaboration reported result,** PRL88(02)091802

$$\sin^2\theta_w = 0.2277 \pm 0.0013(\text{stat}) \pm 0.0009(\text{syst})$$

- **Other electroweak processes**

$$\sin^2\theta_w = 0.2227 \pm 0.0004$$

- **The three standard deviations could be an indication of**
  new physics beyond standard model
  if it cannot be explained in conventional physics

- **The Paschos-Wolfenstein relation**

$$R^- = \frac{\sigma_{NC}^{\nu N} - \sigma_{NC}^{\overline{\nu} N}}{\sigma_{CC}^{\nu N} - \sigma_{CC}^{\overline{\nu} N}} = \frac{1}{2} - \sin^2 \theta_w$$

- **The assumptions for the P-W relationship**

a isoscalar target

b charge symmetry or isospin symmetry between p and n

$$u^p(x) = d^n(x) \quad d^p(x) = u^n(x)$$

$$\overline{u}^p(x) = \overline{d}^n(x) \quad \overline{d}^p(x) = \overline{u}^n(x)$$

c symmetric strange and antistrange distributions

$$s^p(x) = \overline{s}^p(x) = s^n(x) = \overline{s}^n(x)$$

Modified P-W relationship

- **The cross section for neutrino-nucleon DIS**

  a for neutral current interaction

$$\frac{\mathrm{d}^2\sigma_{NC}^{\nu(\overline{\nu})}}{\mathrm{d}x\mathrm{d}y} = \pi s \left(\frac{\alpha}{2\sin^2\theta_w \cos^2\theta_w M_Z^2} \right)^2 \left(\frac{M_Z^2}{M_Z^2+Q^2}\right)^2 [xyF_1^Z(x,Q^2) + (1 - y - \frac{xym_N^2}{s})F_2^Z(x,Q^2) \pm (y - \frac{y^2}{2})xF_3^Z(x,Q^2)],$$

b for charged current interaction

$$\frac{\mathrm{d}^2\sigma_{CC}^{\nu(\overline{\nu})}}{\mathrm{d}x\mathrm{d}y} = \pi s \left(\frac{\alpha}{2\sin^2\theta_w M_W^2}\right)^2 \left(\frac{M_W^2}{M_W^2+Q^2}\right)^2 \Big[xyF_1^{W^\pm}(x,Q^2) + \left(1-y-\frac{xym_N^2}{s}\right)F_2^{W^\pm}(x,Q^2) \pm \left(y-\frac{y^2}{2}\right)xF_3^{W^\pm}(x,Q^2)\Big],$$

- The structure functions of neutral current

$$\lim_{Q^2\to\infty} F_1^{Zp}(x,Q^2) = \frac{1}{2}\big[(u_V^2+u_A^2)(u^p(x)+\overline{u}^p(x)+c^p(x)+\overline{c}^p(x)) + (d_V^2+d_A^2)(d^p(x)+\overline{d}^p(x)+s^p(x)+\overline{s}^p(x))\big],$$

$$\lim_{Q^2\to\infty} F_3^{Zp}(x,Q^2) = 2\big[u_V u_A(u^p(x)-\overline{u}^p(x)+c^p(x)-\overline{c}^p(x)) + d_V d_A(d^p(x)-\overline{d}^p(x)+s^p(x)-\overline{s}^p(x))\big],$$

$$F_2^{Zp}(x,Q^2) = 2xF_1^{Zp}(x,Q^2),$$

- The structure functions of charged current

$$\lim_{Q^2\to\infty} F_1^{W^+p}(x,Q^2) = d^p(x) + \overline{u}^p(x) + s^p(x) + \overline{c}^p(x),$$

$$\lim_{Q^2\to\infty} F_1^{W^-p}(x,Q^2) = u^p(x) + \overline{d}^p(x) + \overline{s}^p(x) + c^p(x),$$

$$\frac{1}{2}\lim_{Q^2\to\infty} F_3^{W^+p}(x,Q^2) = d^p(x) - \overline{u}^p(x) + s^p(x) - \overline{c}^p(x),$$

$$\frac{1}{2}\lim_{Q^2\to\infty} F_3^{W^-p}(x,Q^2) = u^p(x) - \overline{d}^p(x) - \overline{s}^p(x) + c^p(x),$$

$$F_2^{W^\pm p}(x,Q^2) = 2xF_1^{W^\pm p}(x,Q^2).$$

$$u_V = \frac{1}{2} - \frac{4}{3}\sin^2\theta_w, \quad u_A = \frac{1}{2},$$

$$d_V = -\frac{1}{2} + \frac{2}{3}\sin^2\theta_w, \quad d_A = -\frac{1}{2}.$$

$$d^n(x) = u^p(x),$$
$$u^n(x) = d^p(x),$$
$$s^n(x) = s^p(x) = s(x),$$
$$c^n(x) = c^p(x) = c(x).$$

- **The modified P-W relation**

$$R_N^- = \frac{\sigma_{NC}^{\nu N} - \sigma_{NC}^{\overline{\nu} N}}{\sigma_{CC}^{\nu N} - \sigma_{CC}^{\overline{\nu} N}} = R^- + \delta R_s^- .$$

$$\delta R_s^- = -(-1 + \frac{7}{3}\sin^2\theta_w)\frac{S^-}{Q_V + 3S^-},$$

$Q_V \equiv \int_0^1 x[u_V(x) + d_V(x)]\mathrm{d}x$ and $S^- \equiv \int_0^1 x[s(x) - \overline{s}(x)]\mathrm{d}x$.

strange-antistrange asymmetry

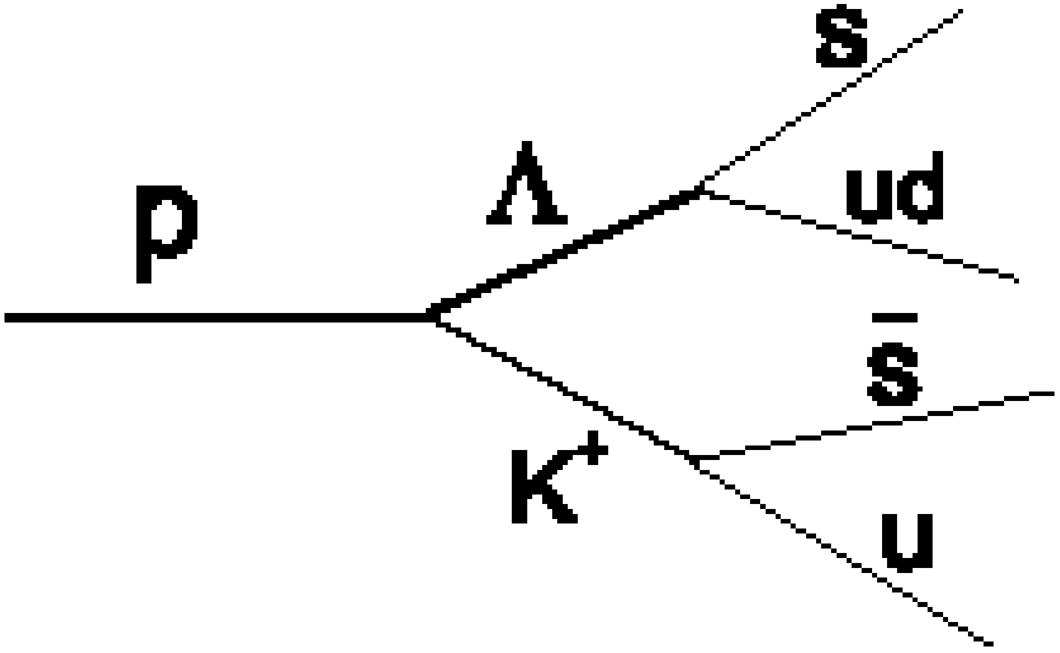
- **In light-cone baryon-meson fluctuation model**

$$|p\rangle = |uud\rangle\,\Psi_{uud/p} + |uudg\rangle\,\Psi_{uudg/p} + \sum_{q\overline{q}} |uudq\overline{q}\rangle\,\Psi_{uudq\overline{q}/p} + \cdots$$

- **The dominant baryon-meson configuration for s-sbar**

$$P(uuds\overline{s}) = K^{+}(u\overline{s}) + \Lambda(uds)$$

Mechanism for s-sbar asymmetry



$s(x) \neq \bar{s}(x)$

- **Proton wave functions**

$$\Psi_D(x, \mathbf{k}_\perp) = A_D \exp(-M^2/8\alpha_D^2),$$

$$\Psi_D(x, \mathbf{k}_\perp) = A_D(1 + M^2/\alpha_D^2)^{-P},$$

$$M^2 = \frac{m_1^2 + \mathbf{k}_\perp^2}{x} + \frac{m_2^2 + \mathbf{k}_\perp^2}{1-x},$$

- **The momentum distributions**

$$s(x) = \int_x^1 \frac{\mathrm{d}y}{y} f_{\Lambda/K^+\Lambda}(y) q_{s/\Lambda}(x/y),$$

$$\overline{s}(x) = \int_x^1 \frac{\mathrm{d}y}{y} f_{K^+/K^+\Lambda}(y) q_{\overline{s}/K^+}(x/y),$$

- **The probabilities**

$$f_{\Lambda/K^+\Lambda}(y) = \int_{-\infty}^{+\infty} \mathrm{d}\mathbf{k}_\perp \left| A_D \exp[-\frac{1}{8\alpha_D^2}(\frac{m_\Lambda^2+\mathbf{k}_\perp^2}{y} + \frac{m_{K^+}^2+\mathbf{k}_\perp^2}{1-y})] \right|^2,$$

$$f_{K^+/K^+\Lambda}(y) = \int_{-\infty}^{+\infty} \mathrm{d}\mathbf{k}_\perp \left| A_D \exp[-\frac{1}{8\alpha_D^2}(\frac{m_{K^+}^2+\mathbf{k}_\perp^2}{y} + \frac{m_\Lambda^2+\mathbf{k}_\perp^2}{1-y})] \right|^2,$$

$$q_{s/\Lambda}(x/y) = \int_{-\infty}^{+\infty} \mathrm{d}\mathbf{k}_\perp \left| A_D \exp[-\frac{1}{8\alpha_D^2}(\frac{m_s^2+\mathbf{k}_\perp^2}{x/y} + \frac{m_D^2+\mathbf{k}_\perp^2}{1-x/y})] \right|^2,$$

$$q_{\bar{s}/K^+}(x/y) = \int_{-\infty}^{+\infty} \mathrm{d}\mathbf{k}_\perp \left| A_D \exp[-\frac{1}{8\alpha_D^2}(\frac{m_{\bar{s}}^2+\mathbf{k}_\perp^2}{x/y} + \frac{m_q^2+\mathbf{k}_\perp^2}{1-x/y})] \right|^2.$$

The probabilities for meson-baryon fluctuation

- General case

$$P_{(K^+\Lambda)} = 3\% - 6\%$$

Brodsky & Ma, PLB381(96)317

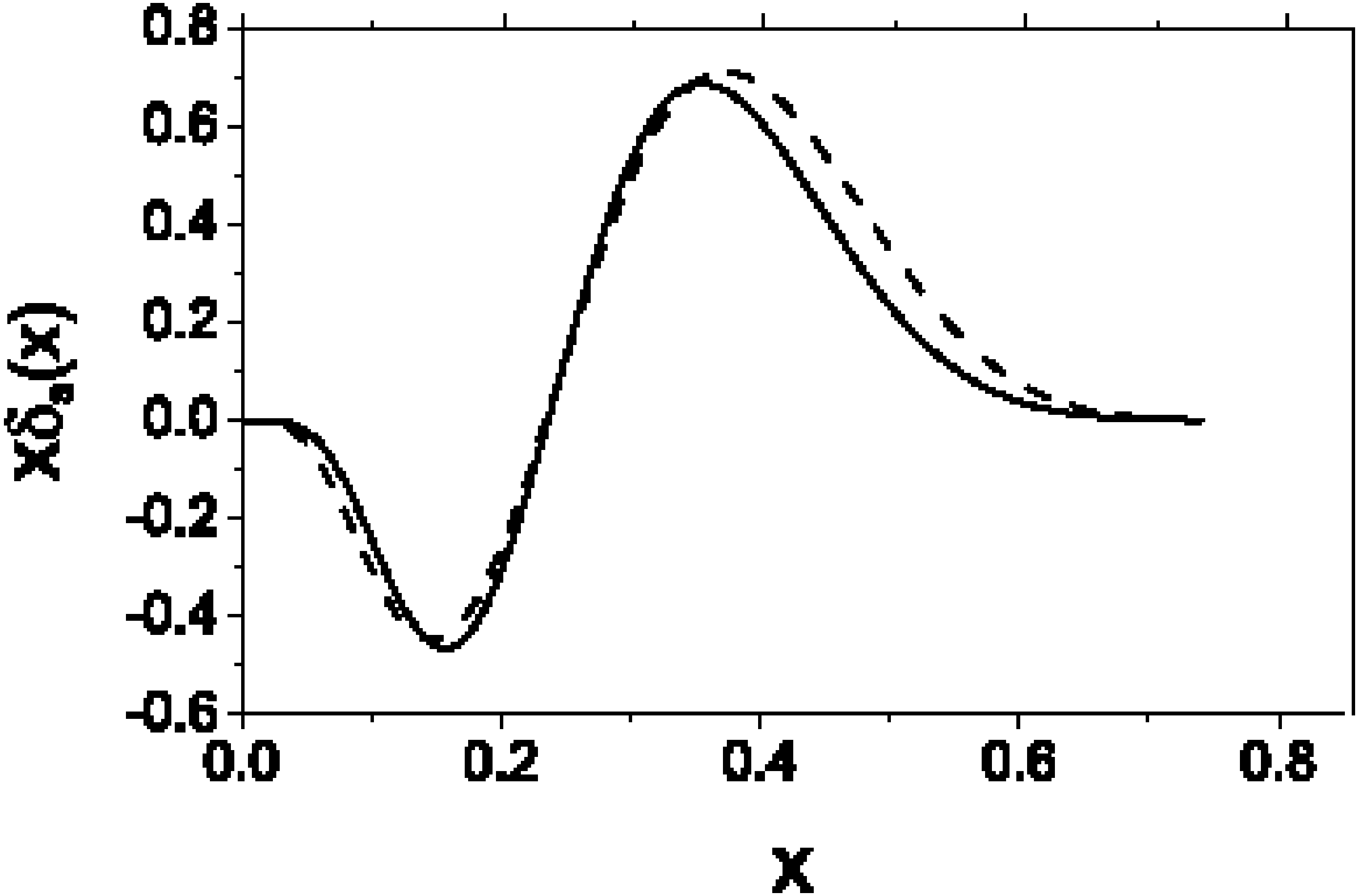
Ma, Schmidt, Yang, EPJA12(01)353

- Our case

$$P_{(K^+\Lambda)} = 4\% - 10\%$$

- **The distributions for** $x\delta_s(x)$

$$\text{with } \delta_s(x) = s(x) - \overline{s}(x)$$



The results for S^-

$Q_V \equiv \int_0^1 x[u_V(x) + d_V(x)]\mathrm{d}x$ and $S^- \equiv \int_0^1 x[s(x) - \overline{s}(x)]\mathrm{d}x$.

- For Gaussian wave function

$$0.0042 < S^- < 0.0106$$

- For power law wave function

$$0.0035 < S^- < 0.0087$$

However, we have also very large Qv (around a factor of 3 larger) in our model calculation, so the ratio of S⁻/Qv is reasonable

The results

- **For Gaussian wave function**

$$0.0017 < \delta R_S^- < 0.0041$$

the discrepancy from 0.005 to 0.0033(0.0009)

- **For power law wave function**

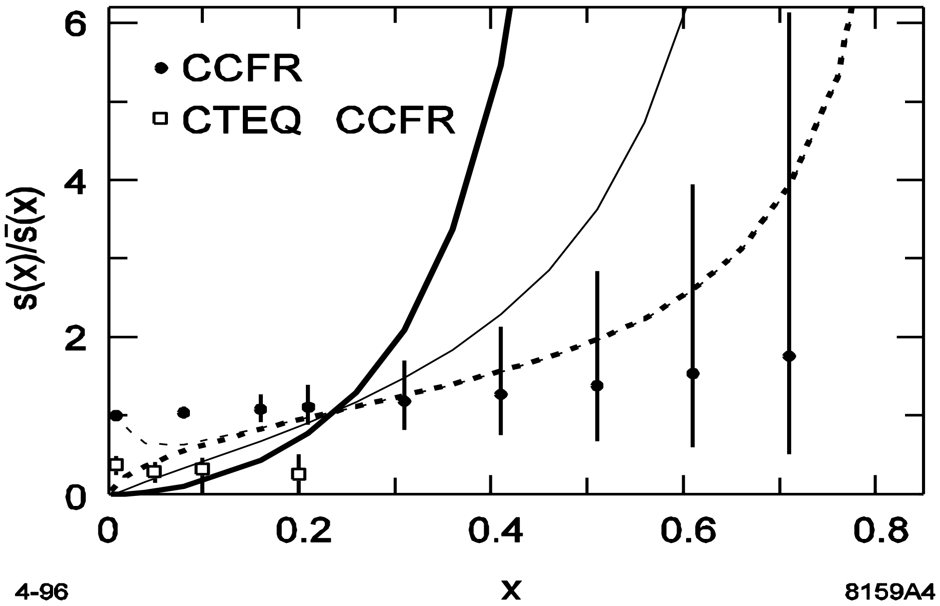
$$0.0014 < \delta R_S^- < 0.0034$$

the discrepancy from 0.005 to 0.0036(0.0016)

Remove the discrepancy 30%-80%

between NuTev and other values of Weinberg angle

s(x)/sbar(x) asymmetry



s(x)/sbar(x) could be compatible with data by by including some intrinsic strange sea contributions

CCFR and NuTeV experimental analyses break net zero strangeness

$$\int s(x)dx = \int \bar{s}(x)dx$$

A Further Chiral Quark Model Study

- A further study by using chiral quark model also shows that this strange-antistrange asymmetry has a significant contribution to the Paschos-Wolfenstein relation and can explain the anomaly without sensitivity to input parameters.

Y.Ding, R.-G.Xu, B.-Q.Ma, PLB607 (2005) 101

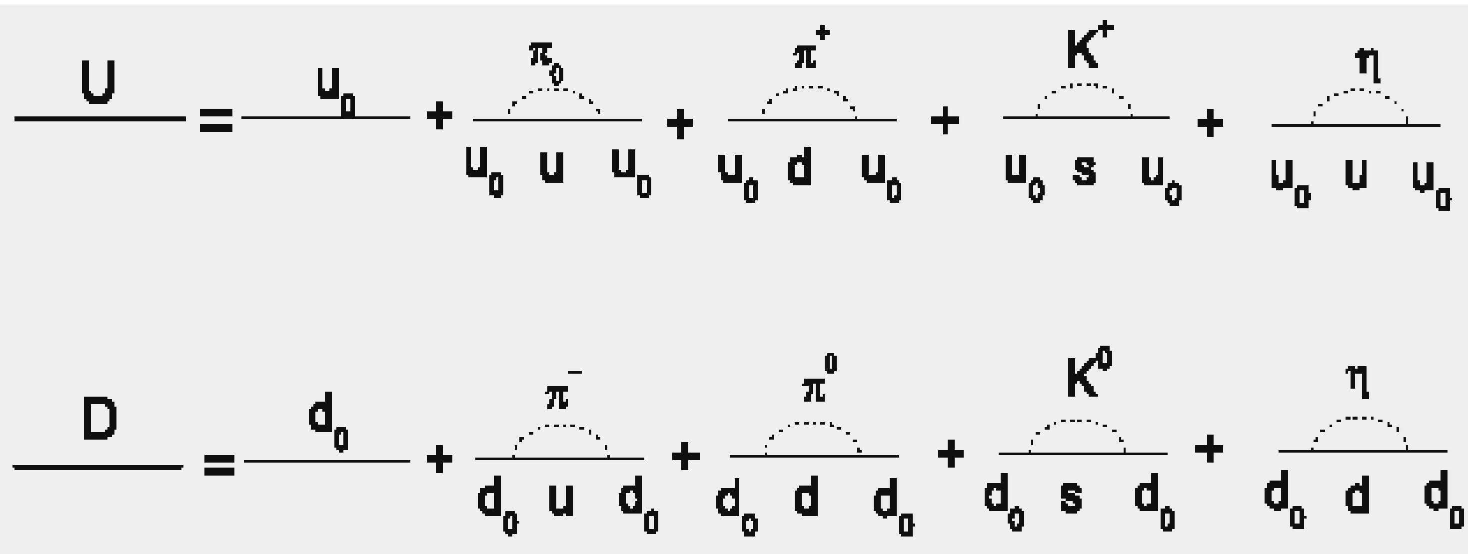
The Effective Chiral Quark Model

- Established by Weinberg, and developed by Manohar and Georgi, has been widely adopted by the hadron physics society as an effective theory of QCD at low energy scale.
- Applied to explain the Gottfried sum rule violation by Eichten, Hinchliffe and Quigg, PRD 45 (92) 2269.
- Applied to explain the proton spin puzzle by Cheng and Li, PRL 74 (95) 2872.

The Effective Chiral Quark Model

$$|U\rangle = Z^{\frac{1}{2}}|u_0\rangle + a_\pi |u\pi^0\rangle + \frac{a_\pi}{\sqrt{2}}|d\pi^+\rangle + a_K |sK^+\rangle + \frac{a_\eta}{\sqrt{6}}|u\eta\rangle$$

$$|D\rangle = Z^{\frac{1}{2}}|d_0\rangle + a_\pi |d\pi^0\rangle + \frac{a_\pi}{\sqrt{2}}|u\pi^-\rangle + a_K |sK^0\rangle + \frac{a_\eta}{\sqrt{6}}|d\eta\rangle$$



Two different inputs of valence quark distributions

1、Constituent Quark Model:

$$u_0(x) = \frac{2}{B[c_1+1, c_1+c_2+1]} x^{c_1} (1-x)^{c_1+c_2+1},$$

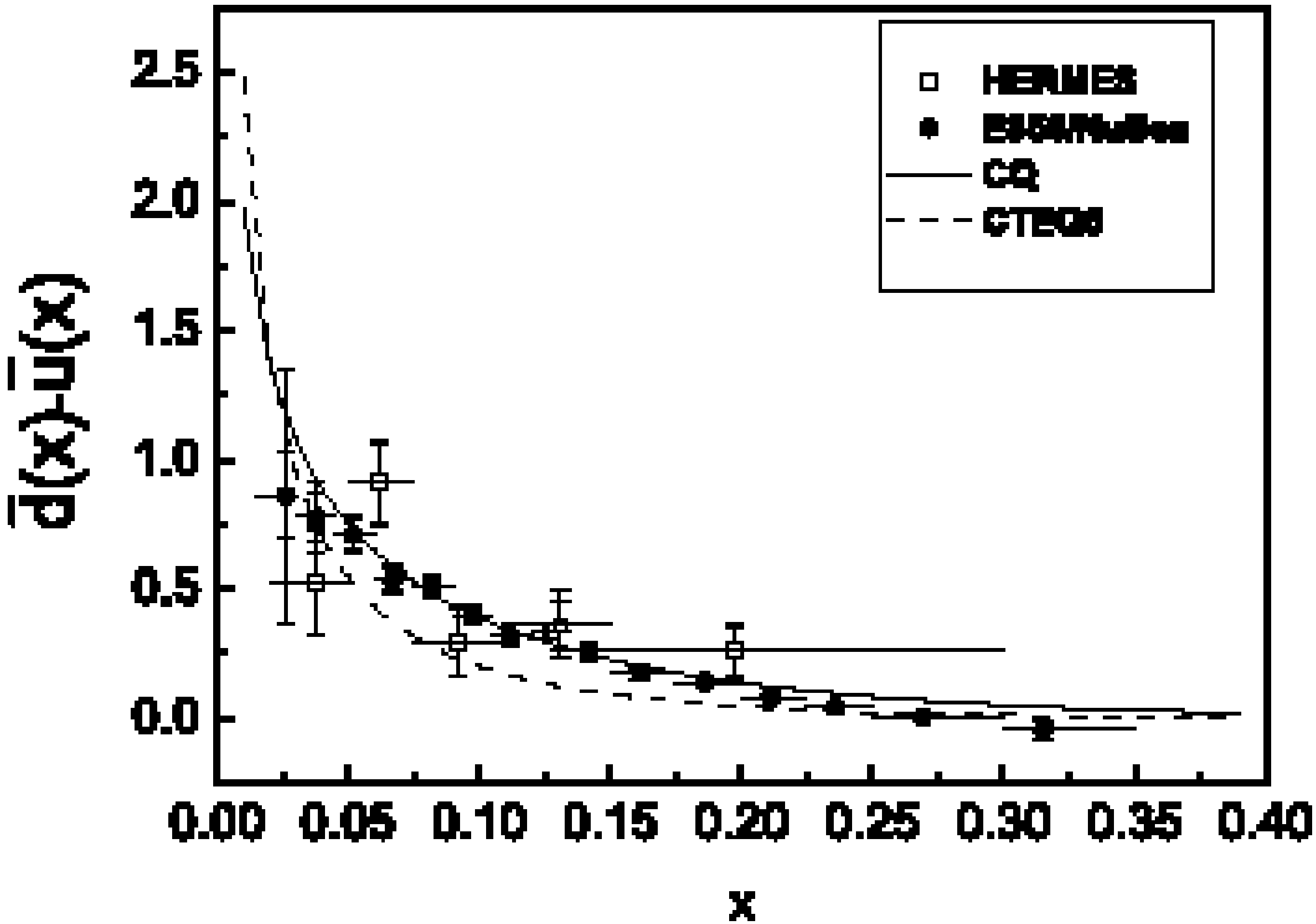
$$d_0(x) = \frac{2}{B[c_2+1, 2c_1+1]} x^{c_2} (1-x)^{2c_1+1}.$$

2、CTEQ6 parametrization

$$u_0(x) = 1.7199 x^{-0.4474} (1-x)^{2.9009} \exp(-2.3502x)(1+\exp(1.6123)x)^{1.5917},$$

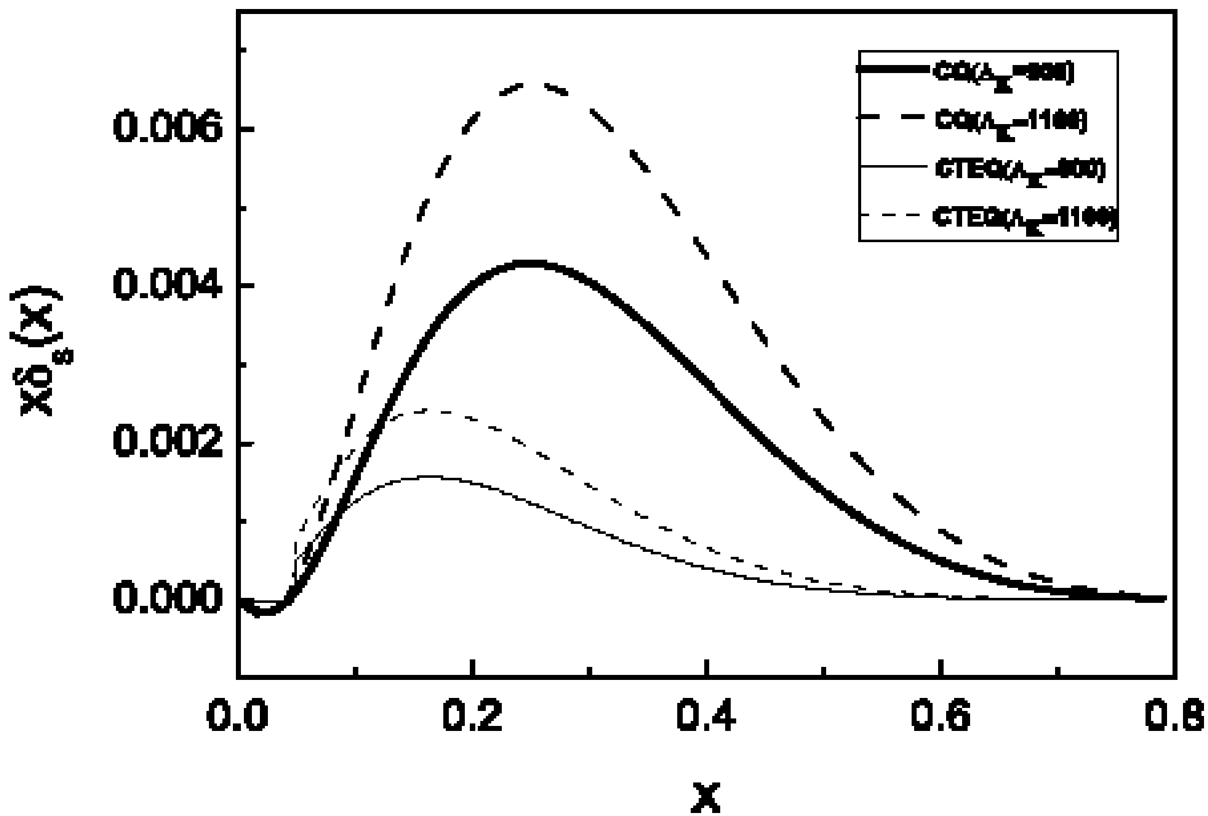
$$d_0(x) = 1.4473 x^{-0.3840} (1-x)^{4.9670} \exp(-0.8408x)(1+\exp(0.4031)x)^{3.0000}.$$

The distributions of $\bar{d}(x) - \bar{u}(x)$ within the chiral quark model



The distributions for

$$x\delta_s(x) = x(s(x) - \bar{s}(x))$$



Y.Ding, R.-G.Xu, B.-Q.Ma, PLB607(2005)101

The results for different inputs within the effective chiral quark model

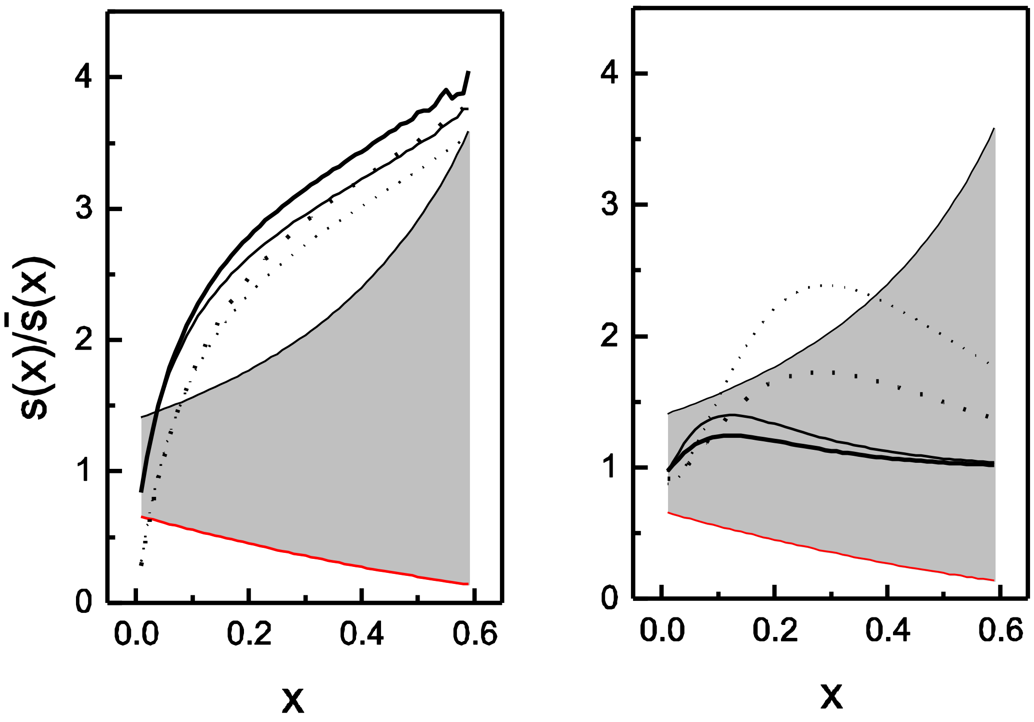
Λ_k	Z	Q_v	S^-	δR_s^-
900	0.74888	0.86376	0.00558	0.00297
1000	0.73996	0.85484	0.007183	0.00384
1100	0.73063	0.84551	0.00879	0.00473

Λ_k	Z	Q_v	S^-	δR_s^-
900	0.74888	0.37089	0.00252	0.00312
1000	0.73996	0.36686	0.00322	0.00402
1100	0.73063	0.36247	0.00398	0.00498

- The results can remove the deviation at least 60%

Y.Ding, R.-G.Xu, B.-Q.Ma, PRD71(2005) 094014

The comparison for $s(x)/\bar{s}(x)$ between the model calculation and experiment data



The shadowing area is the range of NuTeV Collaboration, the left side is the result of the chiral quark model only, and the right side is with an additional symmetric strange sea contribution.

Several works with similar conclusion

- Ding-Ma, 30-80% correction

  PLB590 (2004) 216

- Alwall-Ingelman, 30% correction

  PRD70 (2004) 111505(R)

- Ding-Xu-Ma, 60-100% correction

  PLB607 (2005) 101, PRD71 (2005) 094014

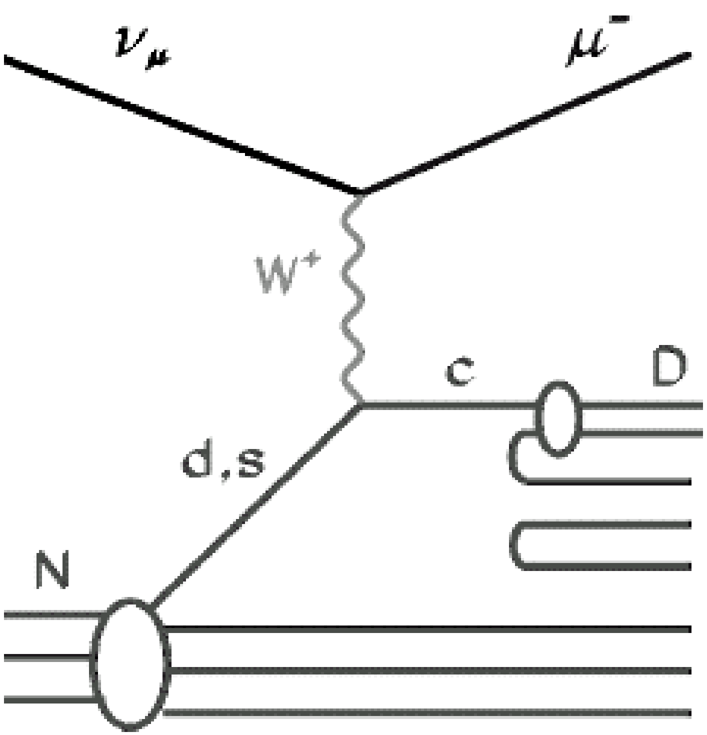
- Wakamatsu, 70-110% correction

  PRD71 (2005) 057504

NuTeV anomaly versus s-sbar asymmetry

- The effect due to strange-antistrange asymmetry might be important to explain the NuTeV anomoly or the NuTeV anomaly could be served as an evidence for the s-sbar asymmetry.
- The calculated s-sbar asymmetry are compatible with the data by including some additional symmetric strange quark contribution.
- Reliable precision measurements are needed to make a crucial test of s-sbar asymmetry.

Strangeness Measurment
via dimuon events by CCFR and NuTeV



50%

$$\nu_\mu + s(d) \rightarrow \mu^- + c$$

90%

$$\bar{\nu}_\mu + \bar{s}(\bar{d}) \rightarrow \mu^+ + \bar{c}$$

- Different charged dimuon signal:

$$c \rightarrow \mu^+ \qquad \bar{c} \rightarrow \mu^-$$

Dimuon measurement of strangeness asymmetry:

$$\frac{d^2\sigma_{\nu_\mu N\to\mu^-\mu^+X}}{d\xi dy} - \frac{d^2\sigma_{\overline{\nu}_\mu N\to\mu^+\mu^-X}}{d\xi dy} = \frac{G_F^2 S}{\pi r_w^2} f_c B_c$$
$$\times \left\{ \xi[s(\xi) - \overline{s}(\xi)]|V_{cs}|^2 + \frac{1}{2}\xi[d_v(\xi) + u_v(\xi)]|V_{cd}|^2 \right\};$$

$$\xi = x(1 + m_c^2/Q^2) \qquad y = \nu/E_\nu$$

$$f_c \equiv 1 - m_c^2/2ME_\nu\xi, \qquad r_w \equiv 1 + Q^2/M_W^2$$

Strangeness asymmetry: $S^-(\xi) \equiv \xi[s(\xi) - \overline{s}(\xi)]$

Early analysis shows no indication of strangeness asymmetry.

•Mason, hep-ex/0405037

•**CCFR & NuTeV LO fit:** $S^- = -0.0027 \pm 0.0013$

•**NuTeV LO fit:** $S^- = -0.0003 \pm 0.0011$

•**NuTeV NLO fit:** $S^- = -0.0011 \pm 0.0014$

Recent NLO analysis of NuTeV data with improved method shows support of positive S^-

$$S^- = +0.00196 \pm 0.00046(stat) \pm 0.00045(syst) \pm 0.00128(external)$$

•Mason, FERMILAB-THESIS-2006-01,
•NuTeV, PRL99(07)192001

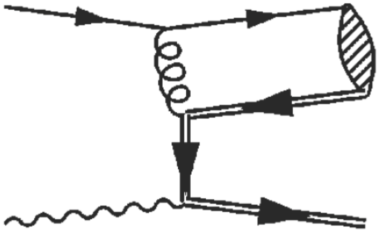
Influence of Heavy Quark Recombination

- Heavy Quark Recombination

Heavy quark recombination combines a heavy quark with a light Anti-quark of small relative momentum, e.g. ($c\bar{q}$), and then Hadronize into a D meson.

- **Can explain the following through simple QCD picture**

A. Charm photoproduction asymmetry



Braaten, Jia, Mehen,PRD66,012003(2002)

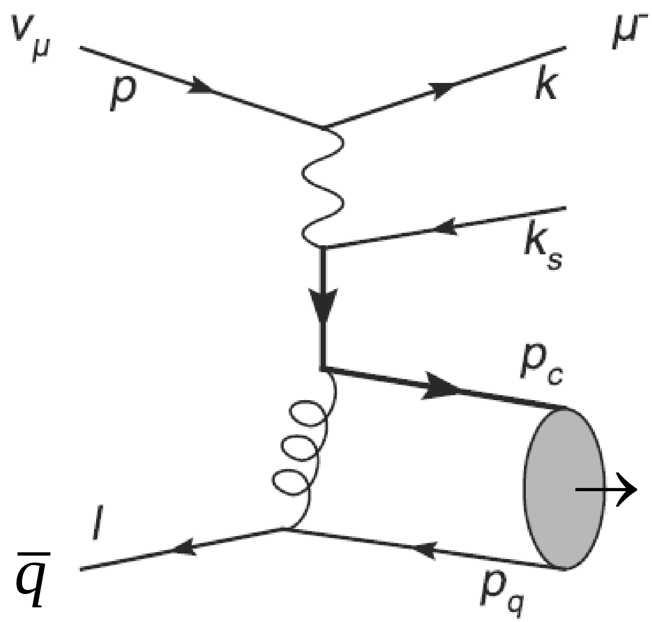
B. Leading particle effect in pi-N scattering
Braaten, Jia, Mehen,PRL89,122002(2002)

Influence on Strangeness Asymmetry Measurement

Heavy Quark Rocombination

$$\nu_\mu + \overline{q} \to \mu^- + \overline{s}(\overline{d}) + D(c\overline{q})$$

$$\overline{\nu}_\mu + q \to \mu^+ + s(d) + \overline{D}(\overline{c}q)$$



HR has an additional contribution

$q = u, d$

$D: {}^1S_0, {}^3S_1$

$$\left[\frac{d^2\sigma_{\nu_\mu N\to\mu^-\mu^+X}}{d\xi dy} - \frac{d^2\sigma_{\overline{\nu}_\mu N\to\mu^+\mu^-X}}{d\xi dy}\right]_{HR}$$

$$= \sum_{q,D}\int dx[\overline{q}(x) - q(x)]\frac{d^2\hat{\sigma}_{D(c\overline{q})}}{d\xi dy}B_{D(c\overline{q})},$$

Influence on Strangeness Asymmetry Measurement

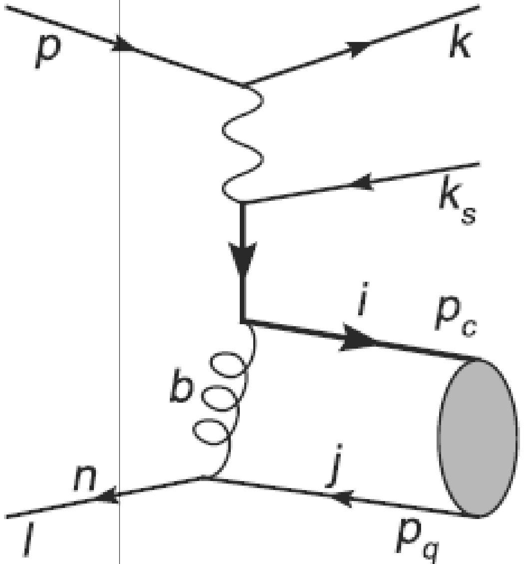
$$S^-_{\rm real}(\xi) = S^-_{\rm analy}(\xi) + \delta S^-_{\rm HR}(\xi)$$

$$\delta S^-_{\rm HR}(\xi) \approx \frac{\pi r_w^2}{G_F^2 S f_c B_c |V_{cs}|^2} \times \sum_{q,D} \int dx [q(x) - \overline{q}(x)] \frac{d^2\hat{\sigma}_{D(c\overline{q})}}{d\xi dy} \cdot B_{D(c\overline{q})}$$

$$\delta S^-_{\rm HR}(\xi) > 0 \qquad\qquad S^-_{\rm real} \equiv \int d\xi S^-_{\rm real}(\xi)$$

Calculation on HR Contribution

$$\nu_\mu + \overline{q} \to \mu^- + \overline{s}(d) + D(c\overline{q})$$



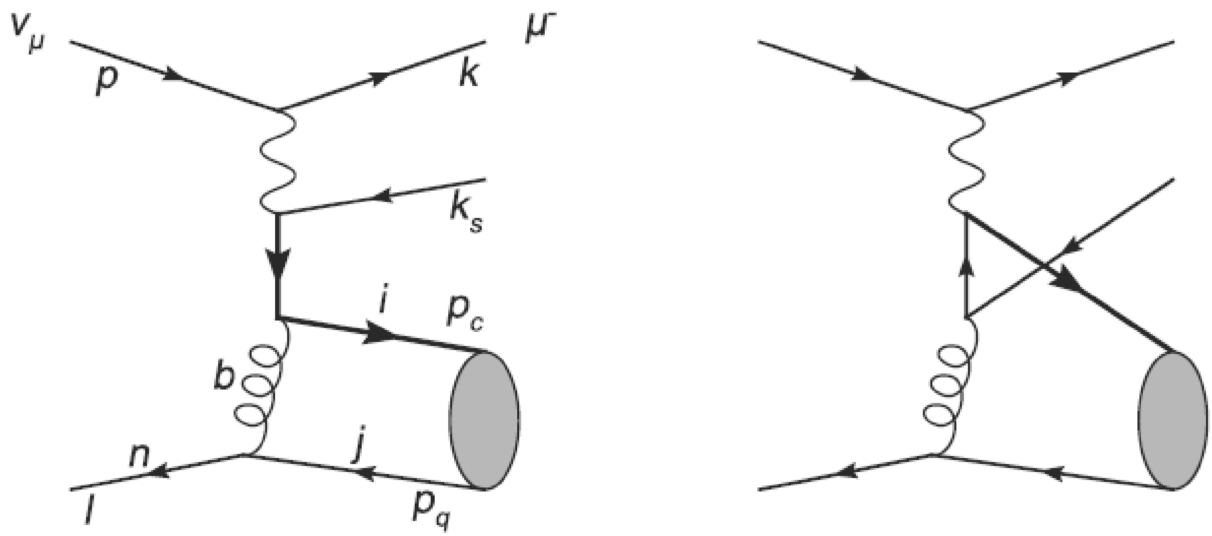
color singlet $^1S_0$

$$v_j(p_q)\overline{u}_i(p_c) \to x_q \frac{\delta_{ij}}{N_c} m_c f_+ (\not{p}_c - m_c)\gamma_5 .$$

For color octet $\delta_{ij} \to \sqrt{6} T^a_{ij}$

For $^3S_1$ state $\gamma_5 \to \not{\epsilon}$

Then set $p_q = x_q p_c$ and take the limit $x_q \to 0$



color singlet $^1S_0$

$$M_{in} = \frac{16\pi G_F \alpha_s m_c \delta_{in} f_+}{9\sqrt{2} r_w (2l \cdot p_c)} L^\mu \overline{u}(l)\gamma^\nu (\not{p}_c - m_c)\gamma_5$$
$$\times [\gamma_\nu \frac{\not{p} - \not{k} - \not{k}_s + m_c}{(p-k-k_s)^2 - m_c^2}\gamma_\mu(1-\gamma_5)$$
$$+\gamma_\mu(1-\gamma_5)\frac{\not{l} - \not{k}_s}{(l-k_s)^2}\gamma_\nu] v(k_s),$$

P.Gao&B.-Q.Ma, , PRD77(08)054002.

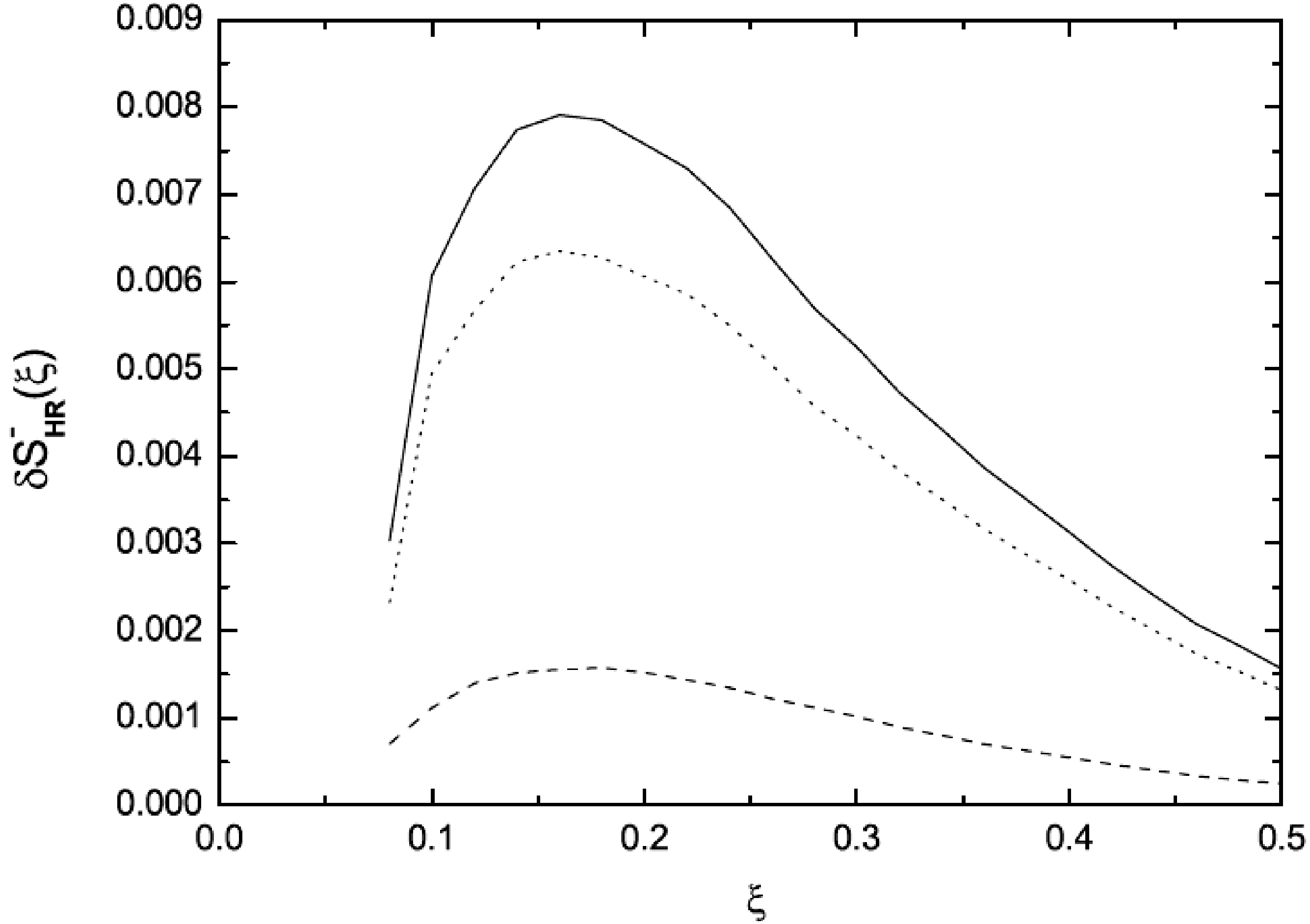


FIG. 2: $\delta S^{-}_{\rm HR}(\xi)$ for $E_\nu = 160$ GeV, $Q^2 = 20$ GeV and $\rho_{\rm sm} = 0.15$. The dashed curve is the contribution from ${}^1S_0$ state; the dotted curve is the contribution from ${}^3S_1$ state; and the solid curve is their sum, the $\delta S^{-}_{\rm HR}(\xi)$.

$\delta S^-_{\mathrm{HR}} \approx 0.0023$ for $\rho_{\mathrm{sm}} = 0.15$.

$$S^-_{\mathrm{real}} = S^-_{\mathrm{analy}} + \delta S^-_{\mathrm{HR}}$$

- **NuTeV NLO fit:**
- **Mason, FERMILAB-THESIS-2006-01**

$$S^- = +0.00196 \pm 0.00046(stat) \pm 0.00045(syst) \pm 0.00128(external)$$

the central value of the realistic strangeness asymmetry should be $S^-_{\mathrm{real}} \approx 0.0043$.

Such a value of the strangeness asymmetry can explain the NuTeV anomaly to a large extent.

NuTeV central value $\sin^2\theta_W^{(\text{on shell})} = 0.2277$

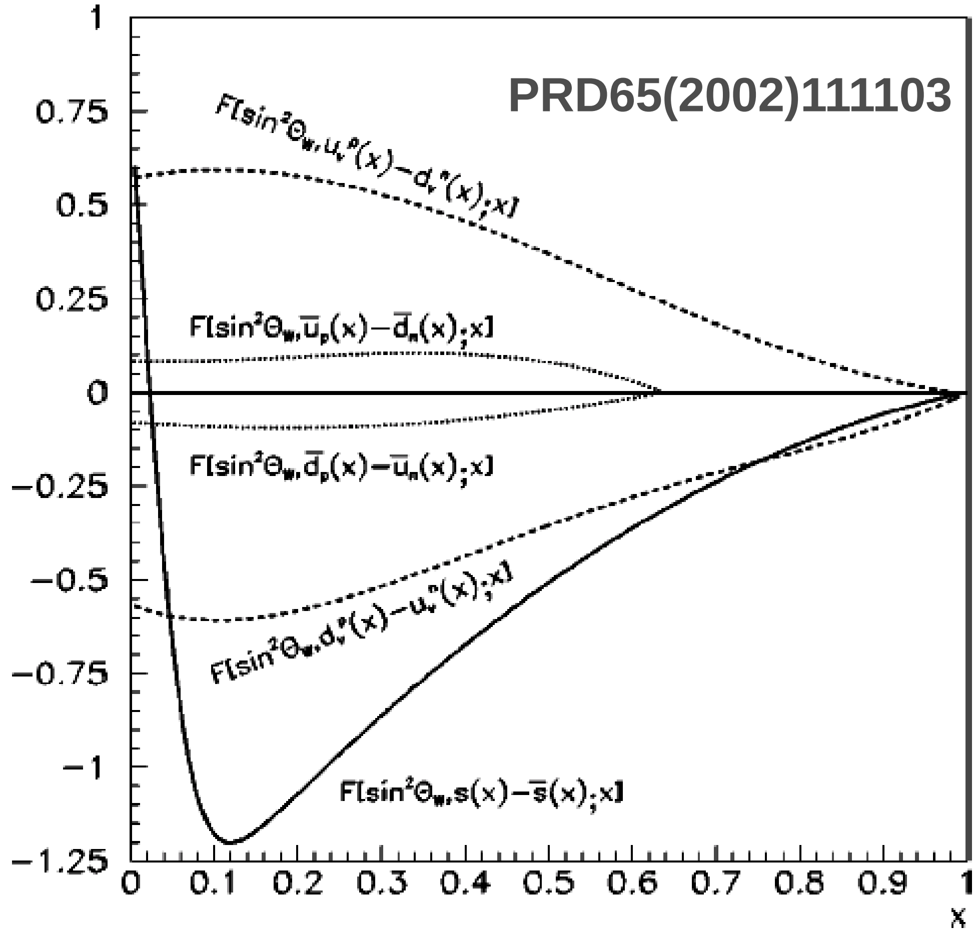
3 standard deviations above the expected value of 0.2227 ± 0.0004

nonzero $S^-(\xi)$ to the result of $\sin\theta_w$ is most sensitive in the range $\xi = 0.06 - 0.3$

S^- of the order 0.005 large enough to explain NuTeV anomaly

$\delta S^-_{\text{HR}} \approx 0.0023$

alone can provide nearly half



The functionals describing the shift in the NuTeV $\sin^2\theta_W$

Some uncertainties

$\rho_{\rm sm} = 0.15$, From charm photoproduction asymmetry

at least 30% uncertainty due to finite heavy quark mass, SU(3) breaking and $1/N_c$ corrections

should be multiplied by a K factor if NLO corrections in photo-gluon fusion are incorporated

$\rho_{\rm sm}$ could well be as large as 0.3. $\delta S^-_{\rm HR} \approx 0.0046$

This alone is enough to explain the NuTeV anomaly

$\rho_{\rm sm}$ could also be smaller than 0.15, $\rho_1 = 0.06$ from the leading particle effect, if take $\rho_{\rm sm} = 0.06$, we get $\delta S^-_{\rm HR} \approx 0.0009$.

This $\delta S^-_{\rm HR}$ alone is not enough to explain NuTeV anomaly, however, could still shift the measured value S^- to a entirely positive range.

Summary

- **Heavy quark recombination can give a sizable influence on the measurement of the nucleon strangeness asymmetry in CCFR and NuTeV dimuon measurements.**
- **Our studies show that the nucleon strangeness asymmetry should be positive and could be large enough to explain the NuTeV anomaly.**

Λ Hyperon Production

in High Energy Processes

Outline

- **The Motivation**
- **Distribution and Fragmentation Functions**
- **Case Study:** $e^+ + e^- \rightarrow \vec{\Lambda} + X$
- **Case Study:** $\vec{l} + N \rightarrow \vec{\Lambda} + X$
- **Case Study:** $\bar{\Lambda} / \Lambda$ **Ratio in** $l + N \rightarrow l' + \Lambda(\bar{\Lambda}) + X$
- **Case Study:** $\bar{\Lambda}$ **Production in l+A Process**
- **Conclusions**

Our View of the Proton

with history

• **Point-Like**	1919
• **Finite Size with Radius**	1930s-1950s
• **Quark Model**	1960s
• **QCD and Gluons**	1970s
• **Puzzles and Anomalies**	1980s-present

- **Quark Sea of the Nucleon**
- **Baryon-Meson Fluctuations**
- **Statistical Features**
- **……**

Our View of the Proton

with history

- **Point-Like** 1919
- **Finite Size with Radius** 1930s-1950s
- **Quark Model** 1960s
- **QCD and Gluons** 1970s
- **Puzzles and Anomalies** 1980s-present
  - **Quark Sea of the Nucleon**
  - **Baryon-Meson Fluctuations**
  - **Statistical Features**
  - **……**

Surprises & Unknown

about the Quark Structure of Nucleon: Sea

- **Spin Structure:**

$$\Sigma = \Delta u + \Delta d + \Delta s \approx 0.3$$

"puzzle": where is the proton's missing spin

- **Strange Content**

$$\Delta s \neq 0 \quad s(x) \neq \bar{s}(x)$$

Brodsky & Ma, PLB381(96)317

- **Flavor Asymmetry** $\bar{u} \neq \bar{d}$

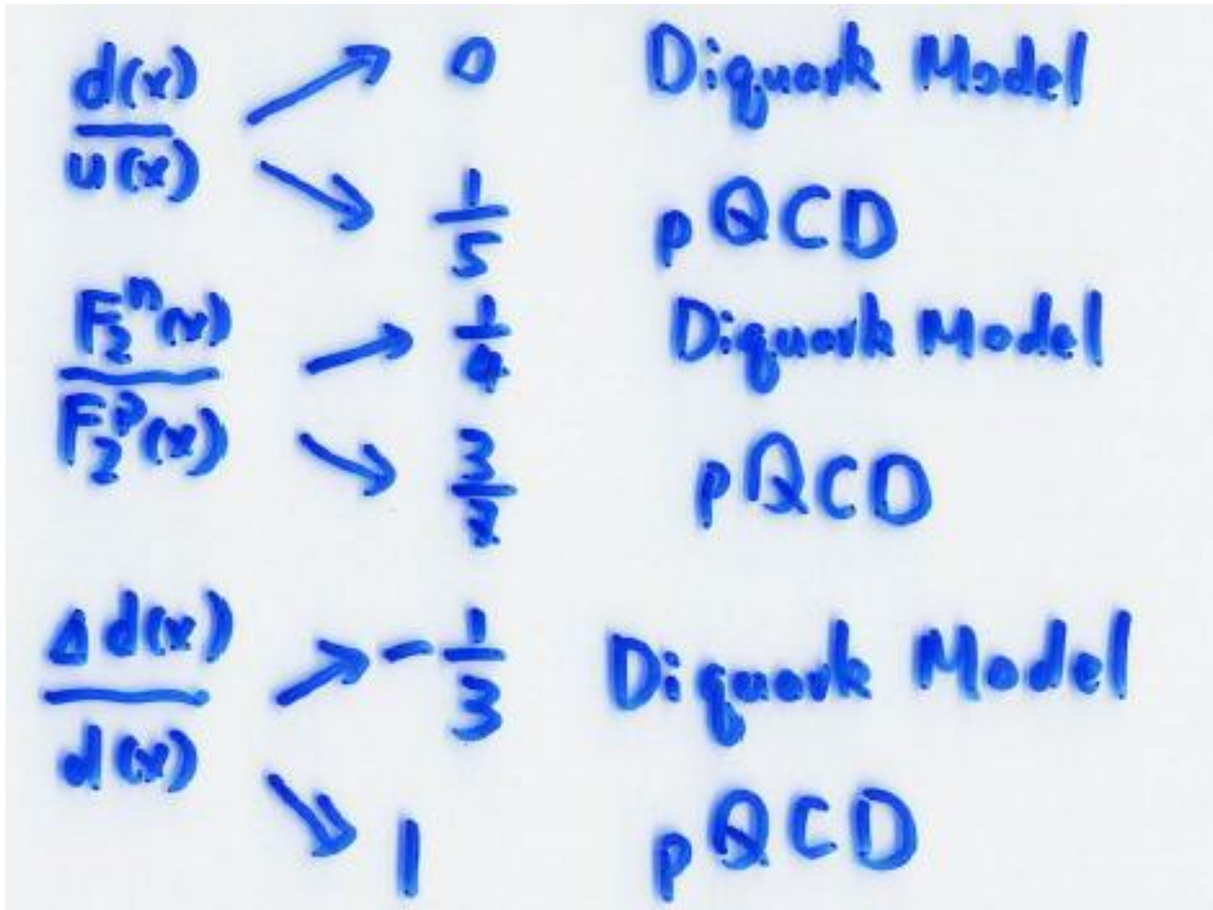
- **Isospin Symmetry Breaking** $\bar{u}_p \neq \bar{d}_n \quad \bar{d}_p \neq \bar{u}_n$

Ma, PLB 274 (92) 111
Boros, Londergan, Thomas, PRL81(98)4075

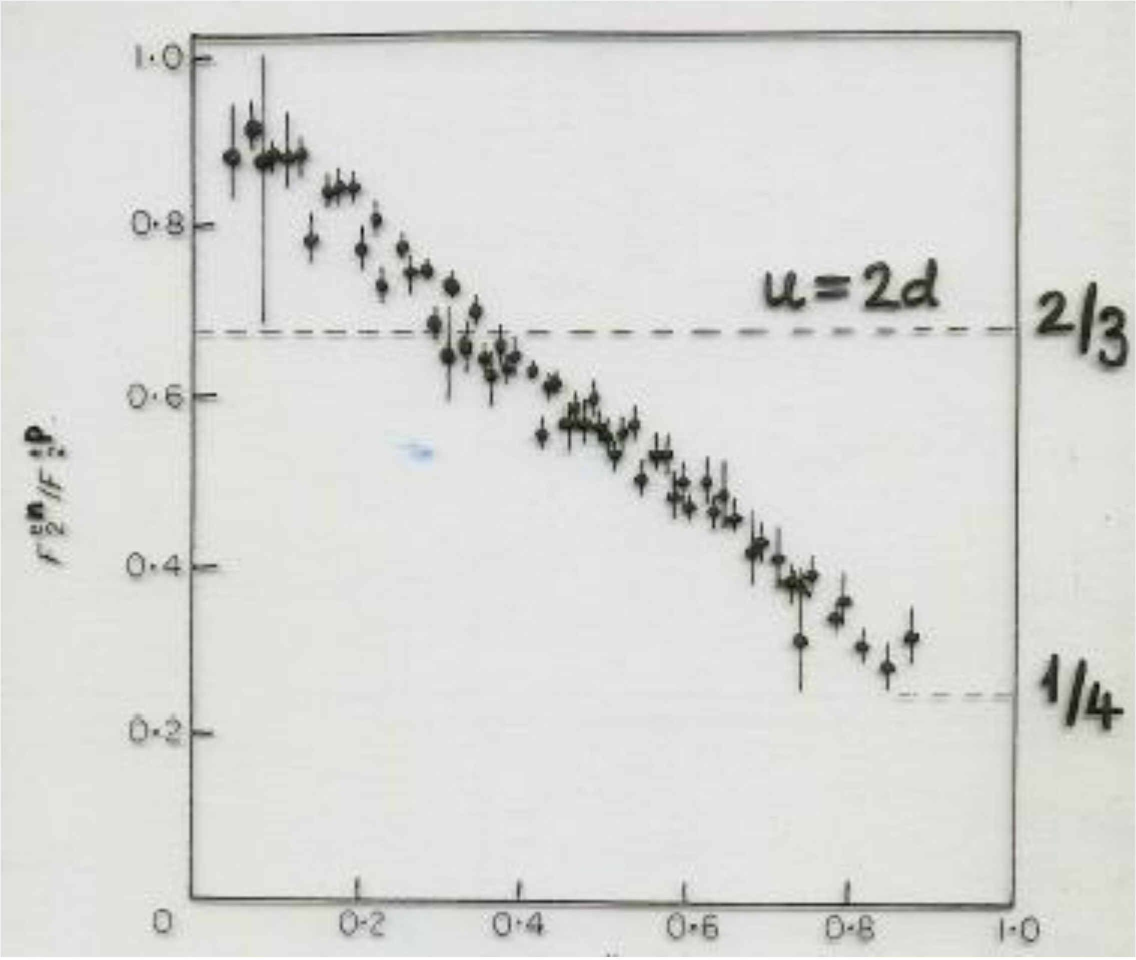
Unknown about the nucleon: valence

x→1 behaviors of flavor and spin

- **Flavor**
- **Spin**

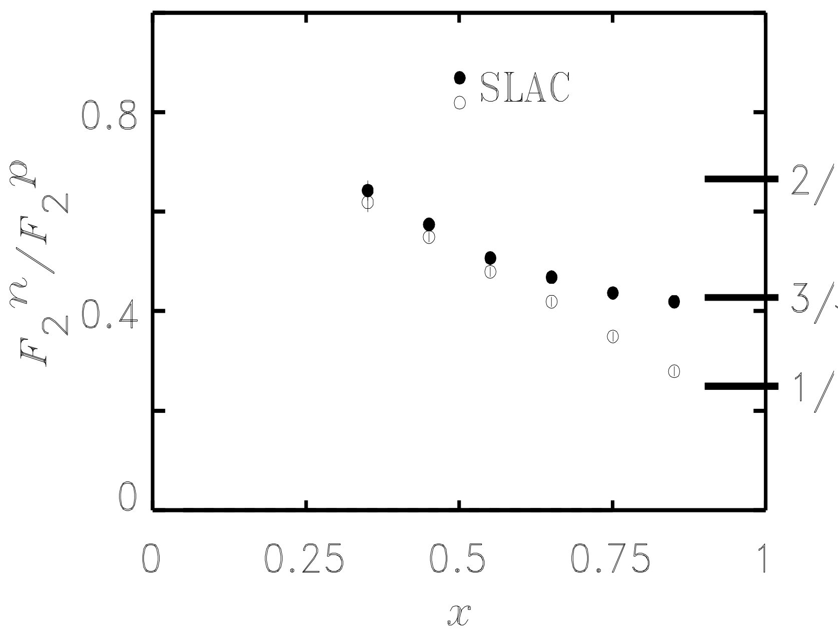


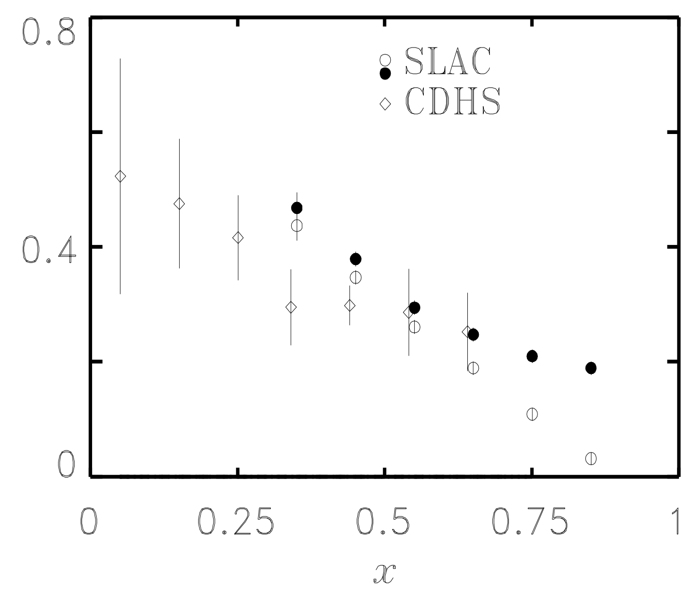
Ratio of Neutron/Proton Structure Functions



Flavor Content of the Proton

with nuclear binding correction

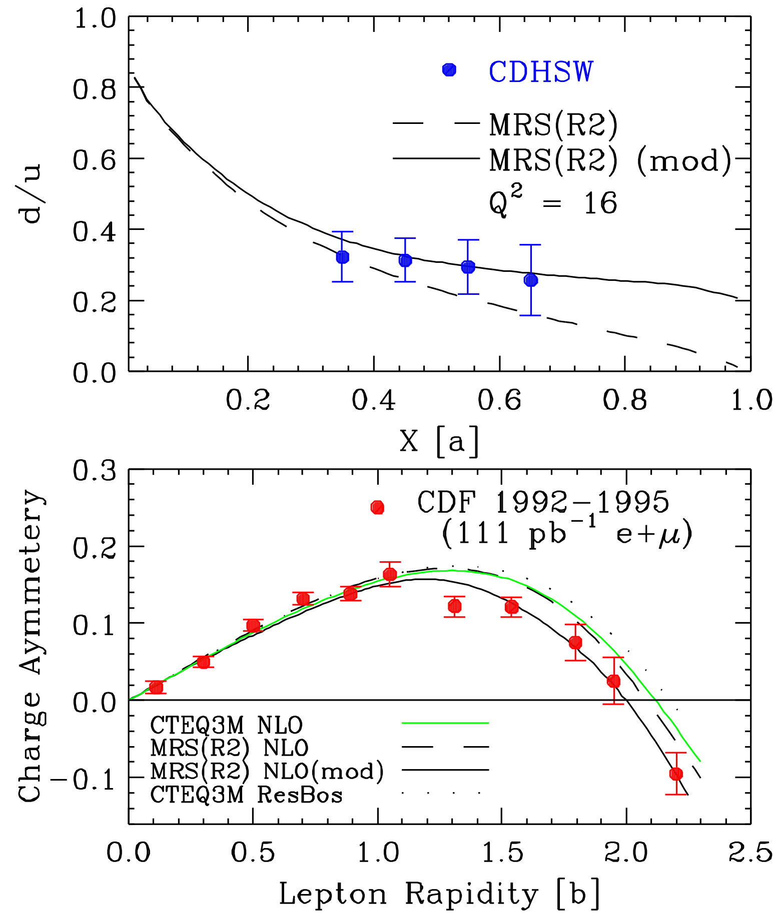




W.Melnitchouk & A.W. Thomas
PLB 377(1996) 11

Flavor Content of the Proton

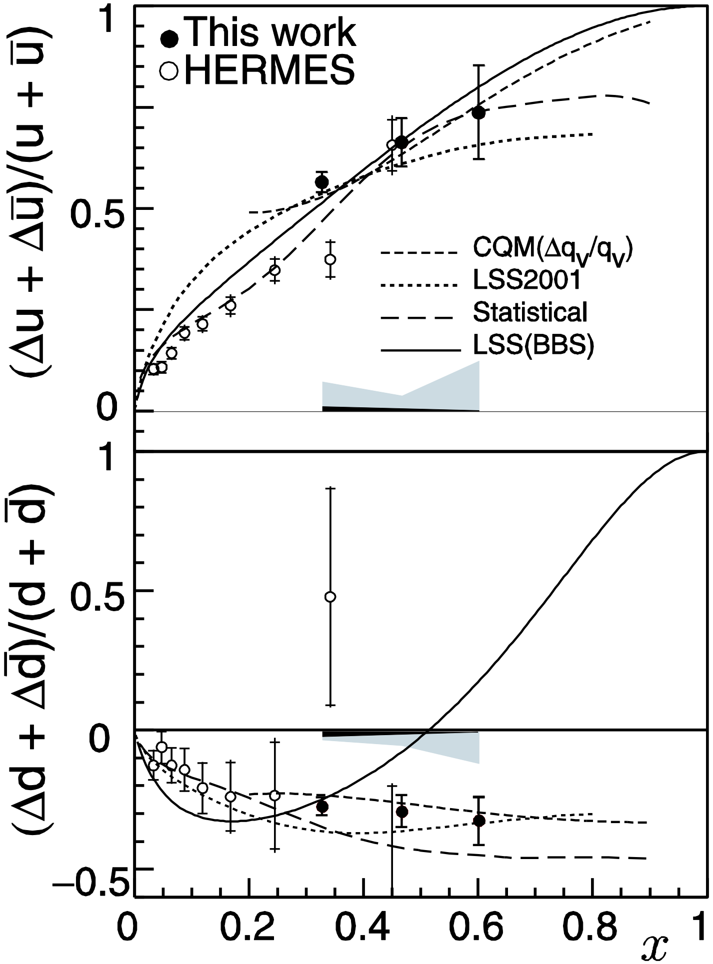
from DIS neutrino data analysis



U.K. Yang & A. Bodek
PRL 82 (1999) 2467.

Quark Helicity Distributions of Proton

Measurements at JLAB and HERMES



X. Zheng et al, JLAb Hall A Collaboration
nucl-ex/0308011
PRL92 (2004) 012004.

Present Status

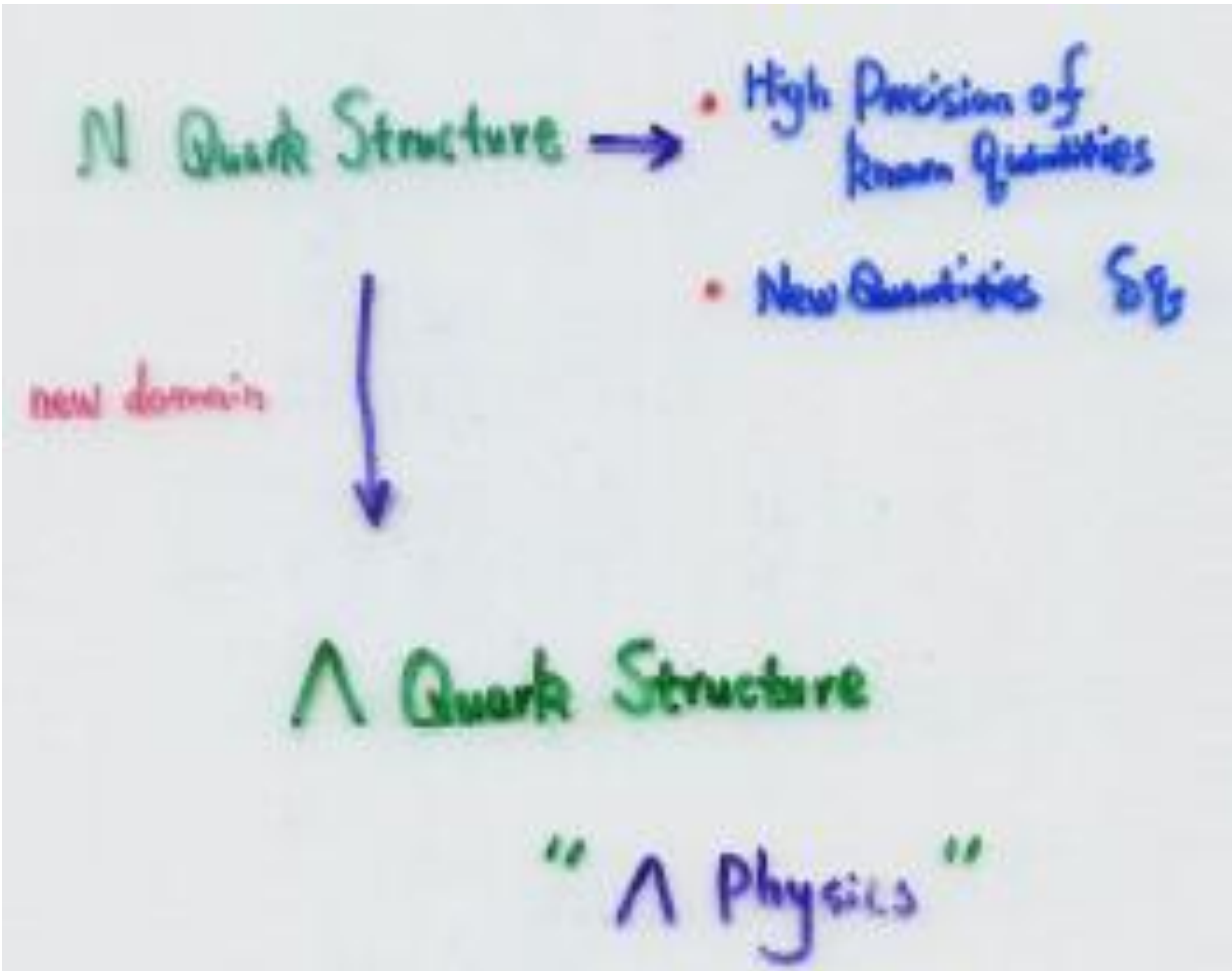
of the Flavor and Spin Contents of the Proton

- Flavor favors pQCD

- Spin favors diquark model

Unclear & In Contradiction!

How to Test Various Theories?



SU(3) Symmetry together with Proton Spin Problem

PRL 70(93) 2537

Burkardt-Jaffe SU(3) Argument:

$$\int_0^1 dx\, g_1^{e\Lambda}(x) = \frac{1}{12}(2\Sigma - D)$$

$$= \int_0^1 dx\, g_1^{ep}(x) - \frac{1}{12}(2D+3F)$$

$$= -0.042 \pm 0.019$$

$$\Delta u^\Lambda = \Delta d^\Lambda = \frac{1}{3}(\Sigma - D) = -0.23 \pm 0.06$$

$$\Delta s^\Lambda = \frac{1}{3}(\Sigma + 2D) = 0.58 \pm 0.07$$

whereas the Quark Model predicts

$$\Delta u^\Lambda = \Delta d^\Lambda = 0$$

$$\Delta s^\Lambda = 1$$

The u,d sea of Lambda versus s sea of Nucleon

PRL 82(99) 2250

Ma - Soffer

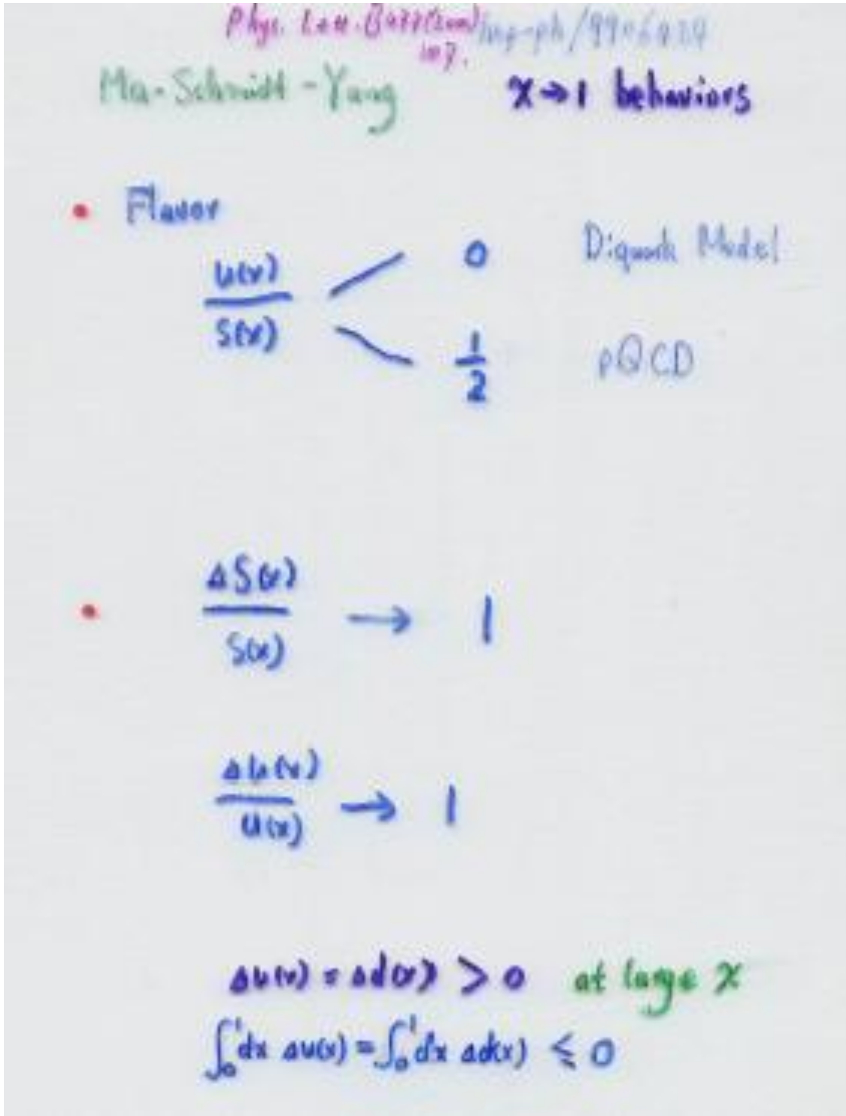
u, d polarizations in Λ

is related to s polarization in N

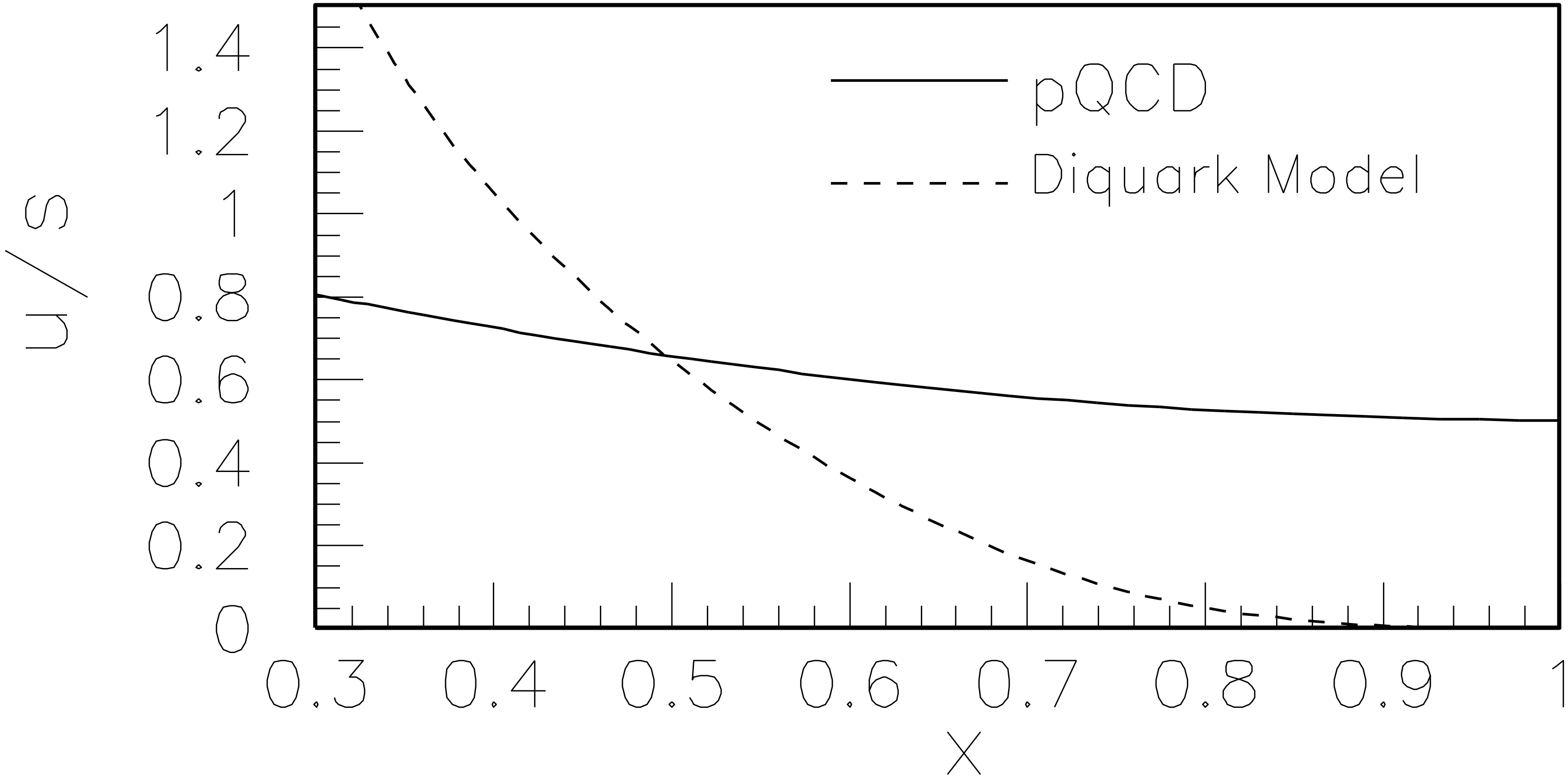
- $P(uud\,s\bar{s}) = \Lambda(uds)\,K^{+}(u\bar{s})$

- $\begin{cases} \Lambda(uds\,u\bar{u}) = P(uud)\,K^{-}(s\bar{u}) \\ \Lambda(uds\,d\bar{d}) = n(udd)\,K(s\bar{d}) \end{cases}$

Different flavor & spin structure in different models

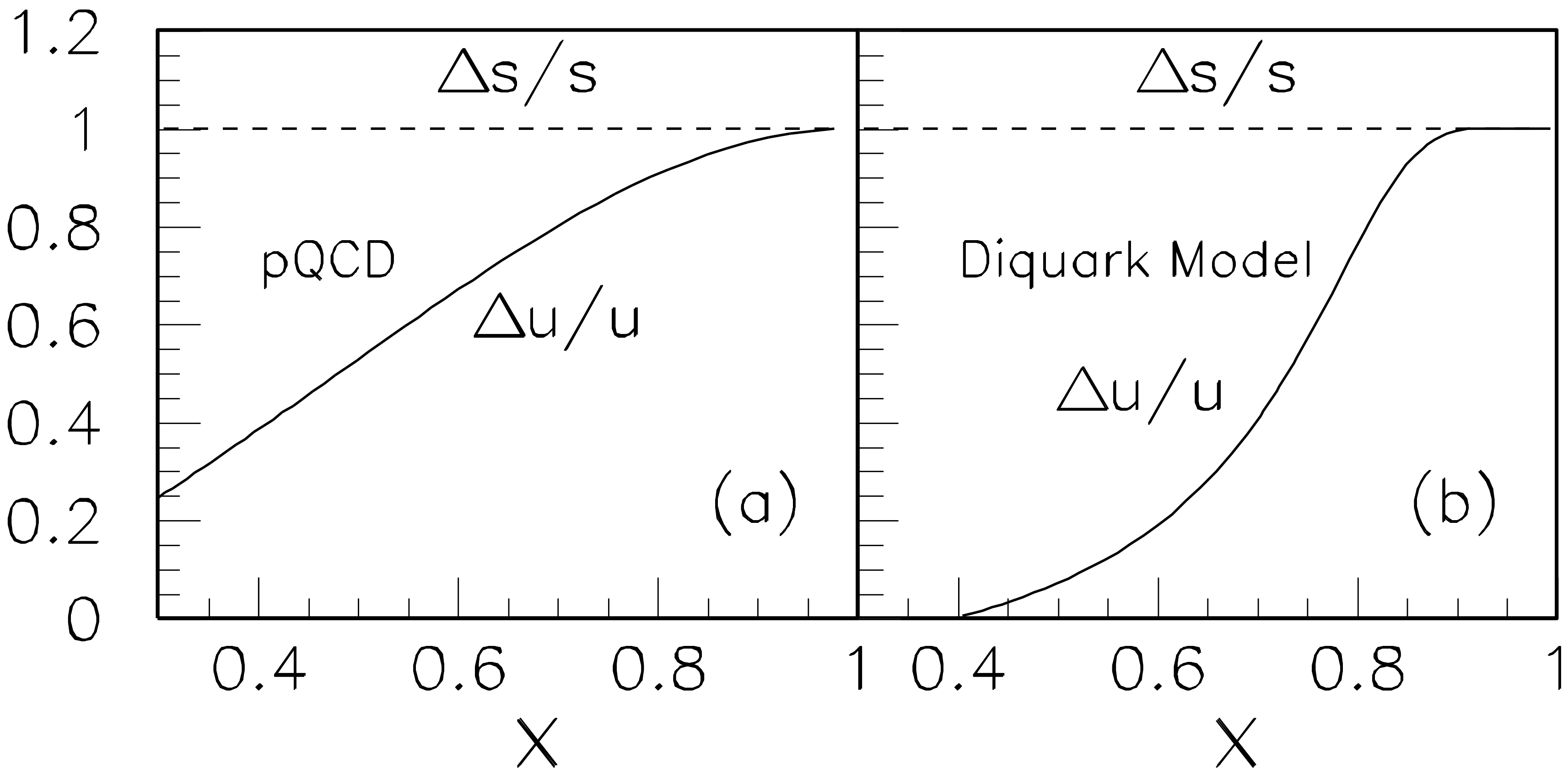


Flavor structure in two different models



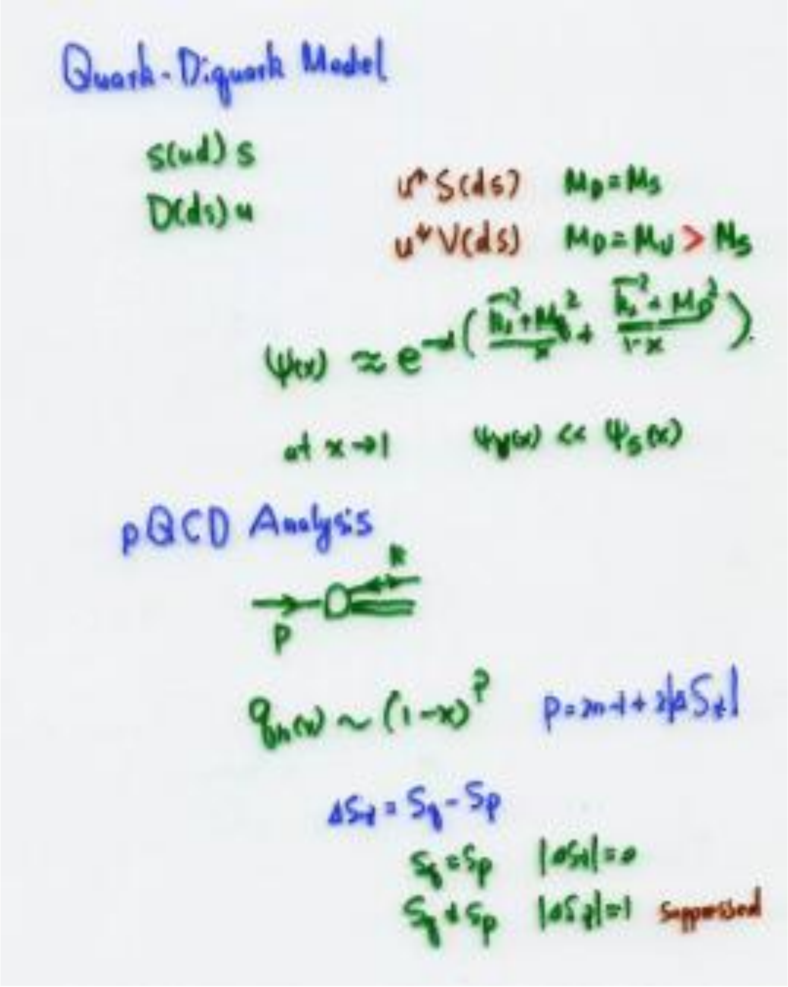
B.-Q. Ma, I. Schmidt, J.-J. Yang,
Phys. Lett. B 477 (2000) 107

Spin structure in two different models



B.-Q. Ma, I. Schmidt, J.-J. Yang,
Phys. Lett. B 477 (2000) 107

An intuitive argument



Significantly different predictions of Lambda Structure

- naive quark model predicts:

$$\Delta u = \Delta d = 0 , \quad \Delta s = 1$$

- Jaffe-Burkardt predict:

$$\Delta u = \Delta d = -0.2 \quad \Delta s = 0.6$$

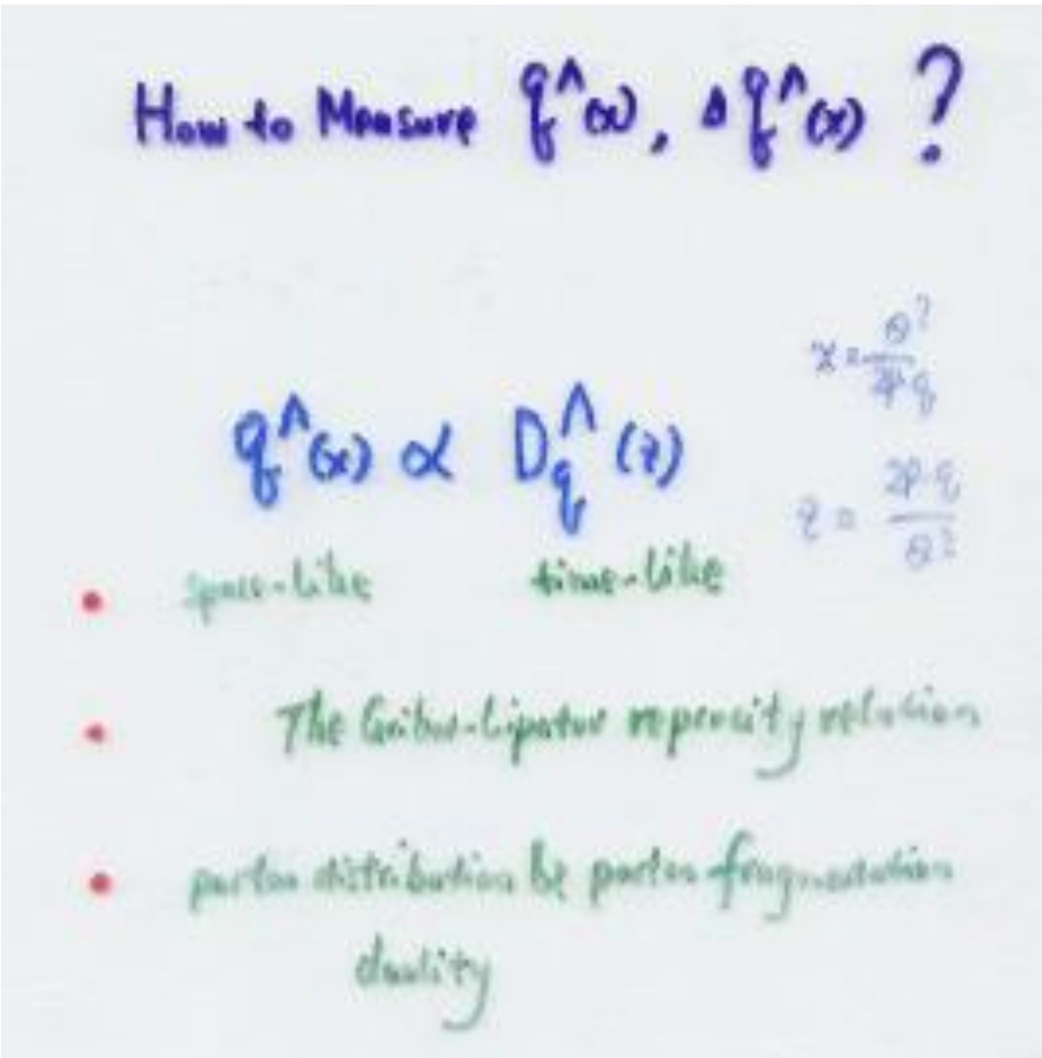
- We predict:

$$\frac{\Delta u}{u} = \frac{\Delta d}{d} \to 1 \quad \text{at } x \to 1$$

in Both quark-diquark model

and pQCD analysis

Connections between structure functions and fragmentation functions

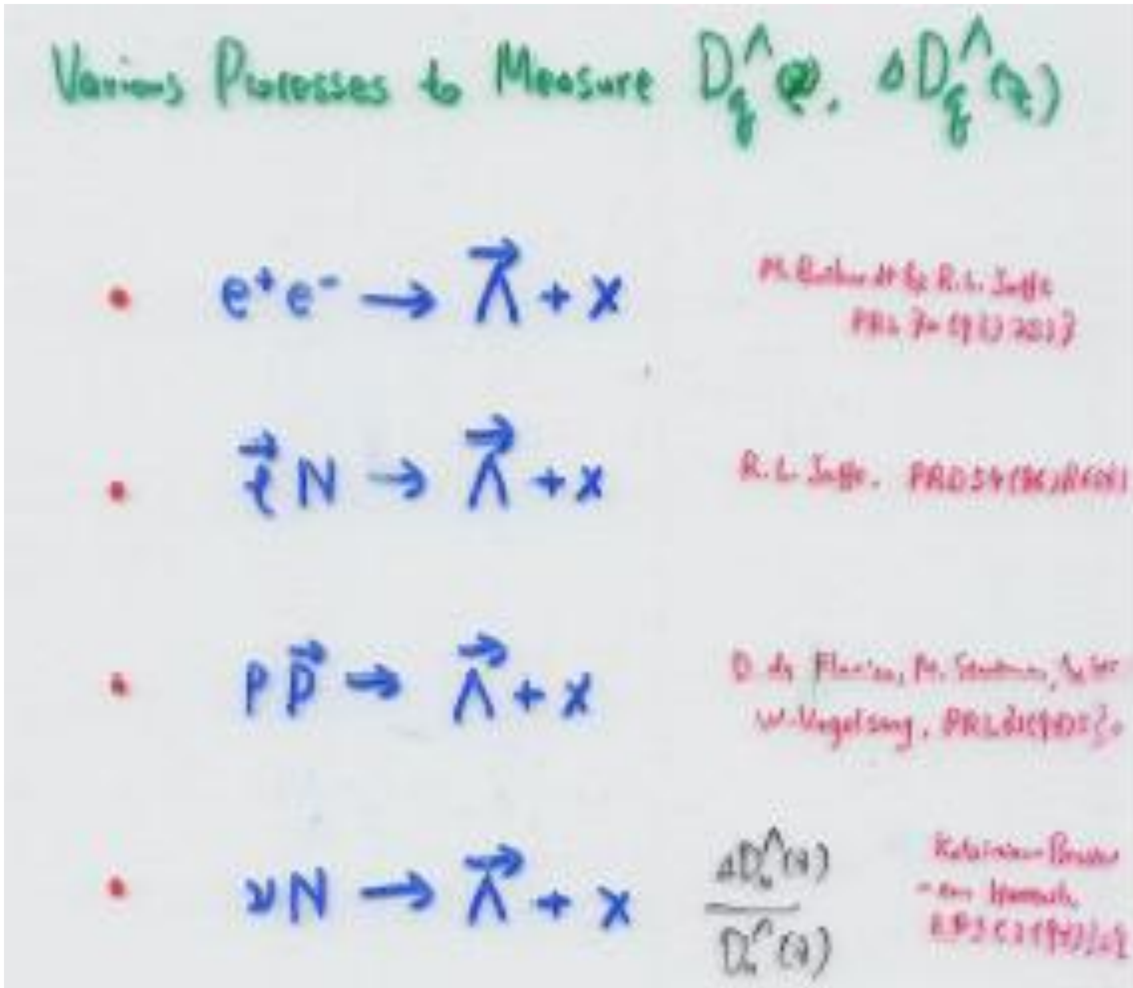


•S.J. Brodsky, B.-Q. Ma,
PLB 392 (1997) 452.

•V. Barone, A. Drago, B.-Q. Ma,
PRC 62 (2000) 062201 (R).

•B.-Q. Ma, I. Schmidt, J. Soffer,
J.-J. Yang,
PLB 547 (2002) 245.

Various Processes of Polarized Fragmentation



Flavor separation

Ma-Soffer Proposal: PRL82 (99) 2467

Complete flavor separation of

$D_q^{\Lambda}(z)$, $\Delta D_q^{\Lambda}(z)$, $D_{\bar{q}}^{\Lambda}(z)$, $\Delta D_{\bar{q}}^{\Lambda}(z)$

- $\nu N \to \mu^- \vec{\Lambda} X$
- $\bar{\nu} N \to \mu^+ \vec{\Lambda} X$
- $\nu N \to \mu^- \vec{\bar{\Lambda}} X$
- $\bar{\nu} N \to \mu^+ \vec{\bar{\Lambda}} X$

Extension to Sigma Hyperon

Ma-Schmidt-Yang hep-ph/9907556

Nucl. Phys. B 574 (2000) 331

Σ^+ Valence: $x \to 1$

$\frac{s}{u} \to 0$ Diquark Model

$\phantom{\frac{s}{u}} \to \frac{1}{5}$ pQCD

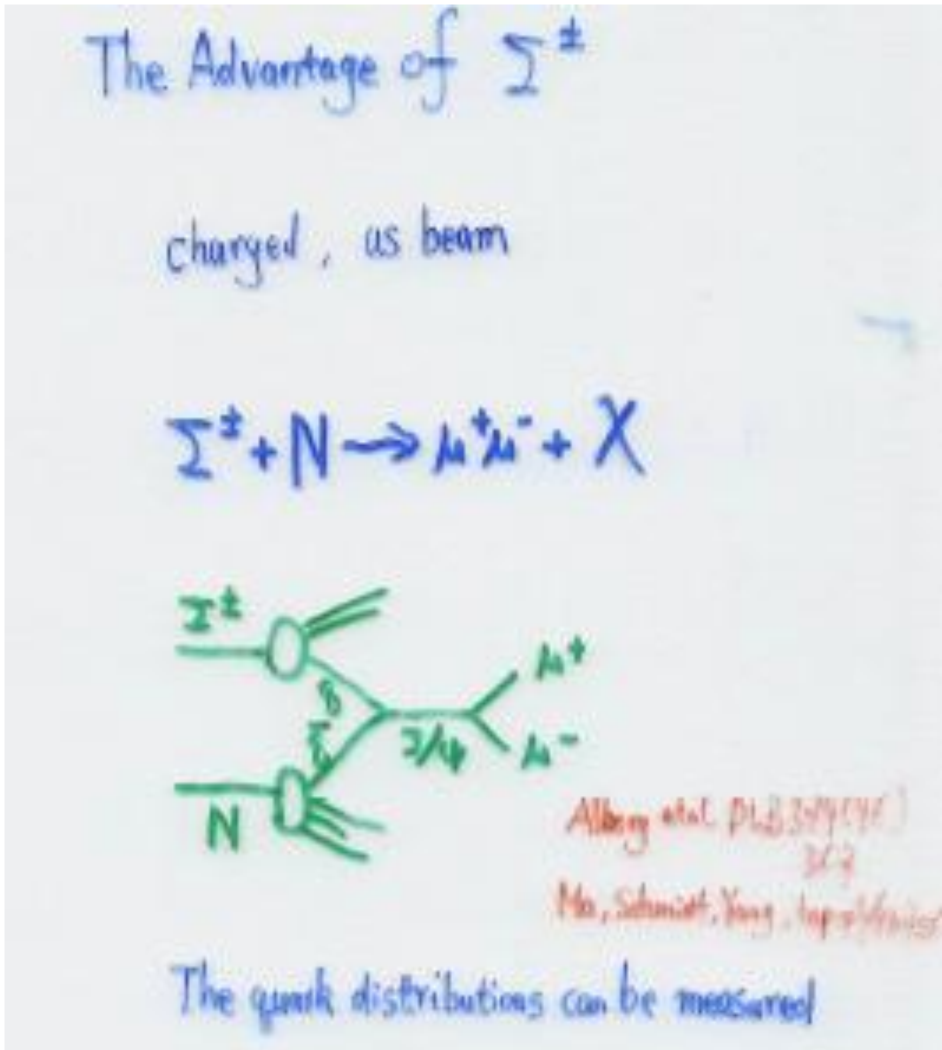
$\frac{\Delta s}{s} \to -\frac{1}{3}$ Diquark Model

$\phantom{\frac{\Delta s}{s}} \to 1$ pQCD

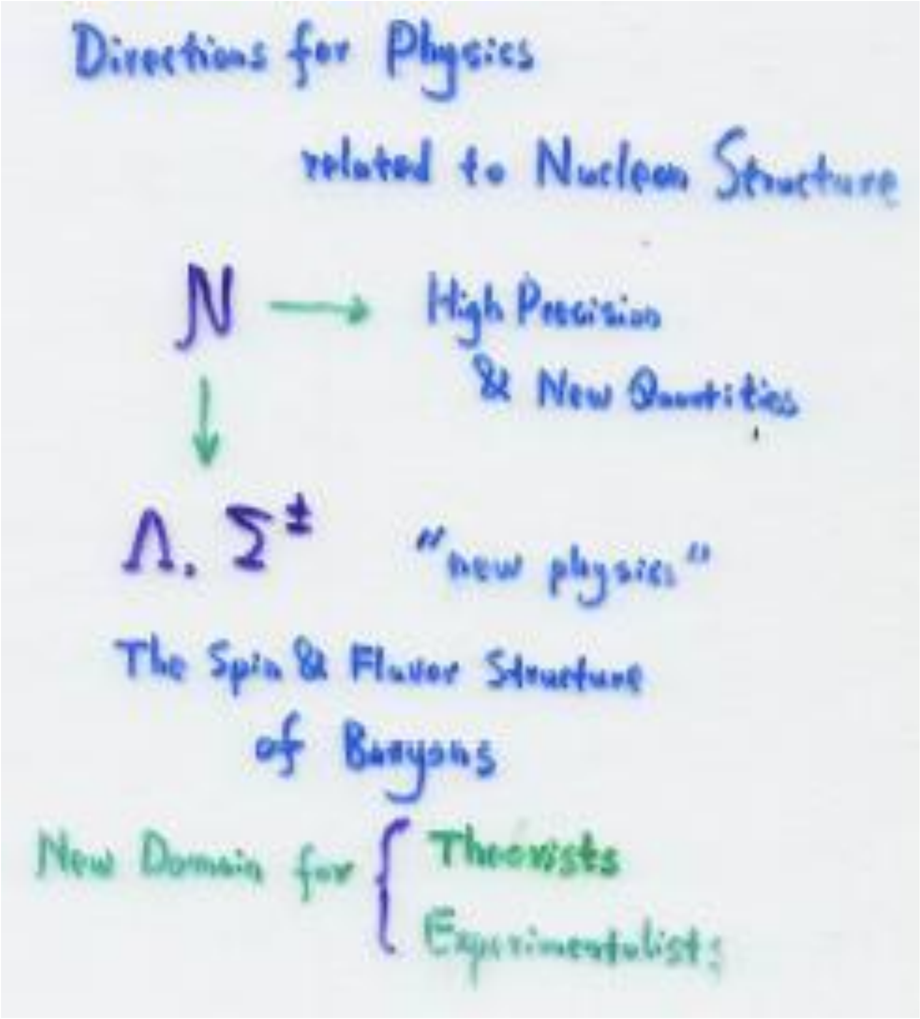
$\frac{\Delta u}{u} \to 1$

- Bigger difference at middle x

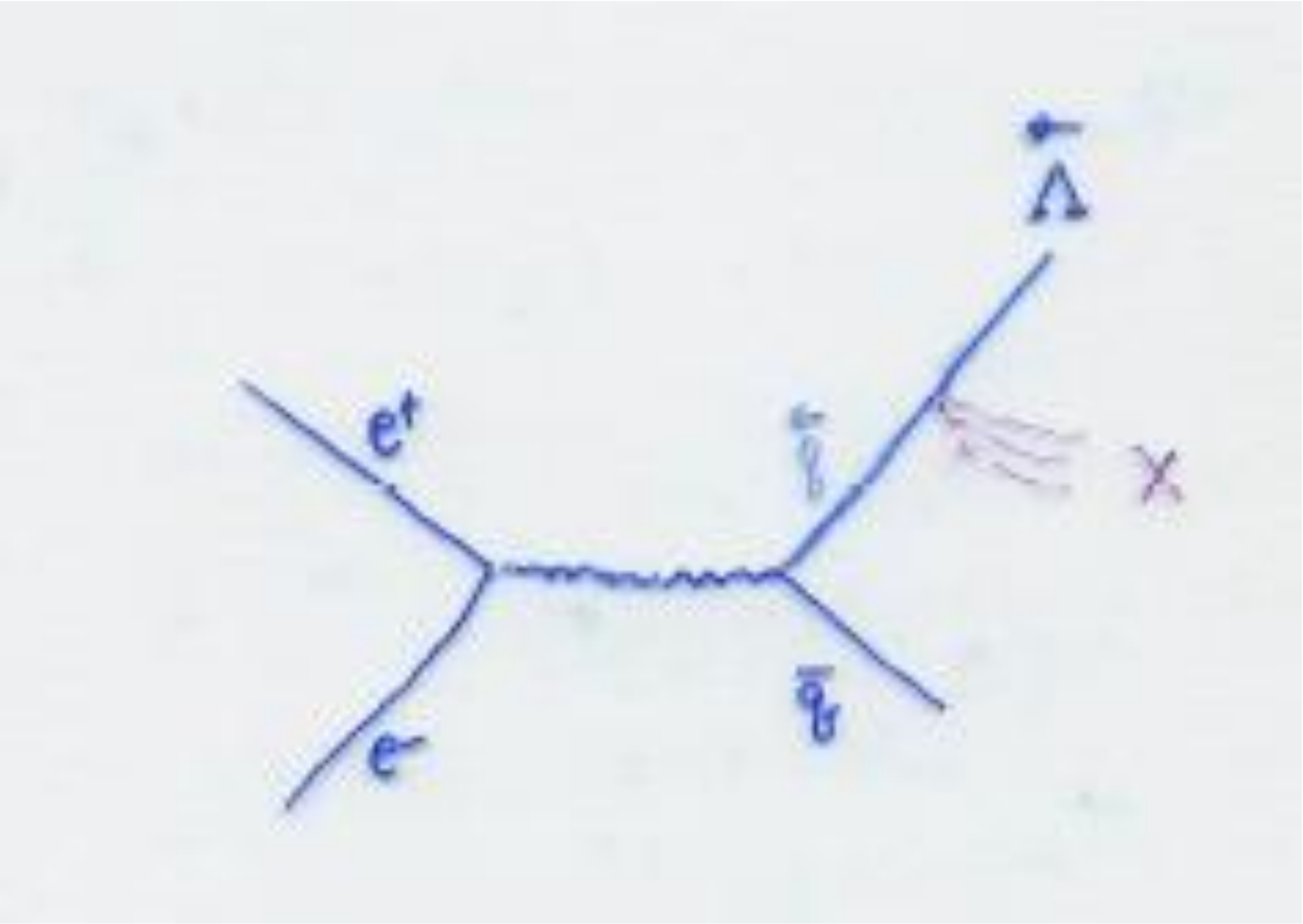
The advantage of using Sigma hyperons



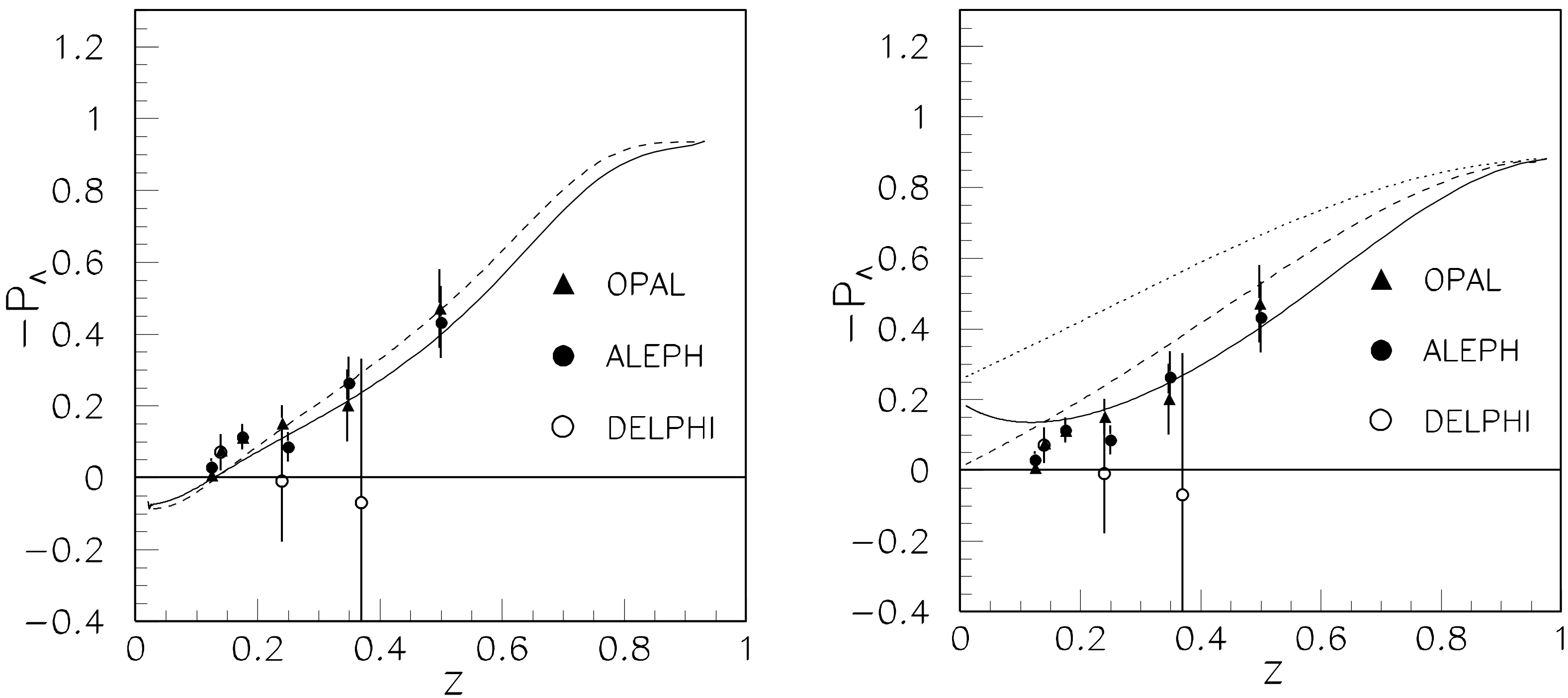
New Domain for Theorists and Experimenlists



Spin structure of Lambda from Lambda polarization in Z^o decay

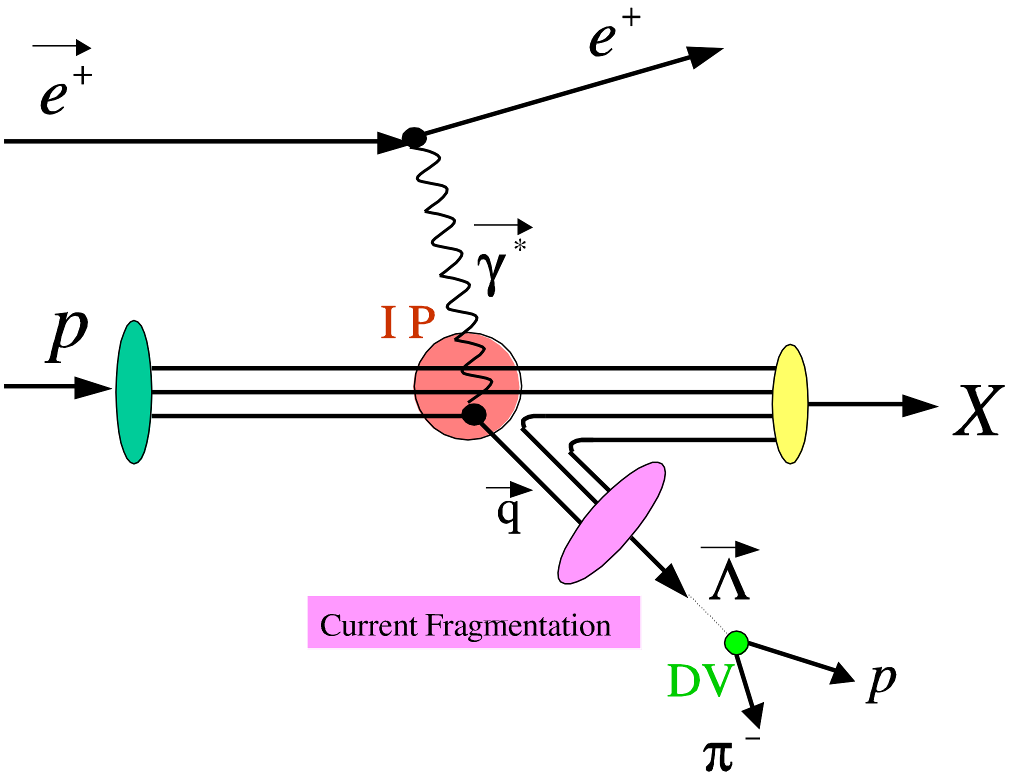


Diquark model and pQCD results

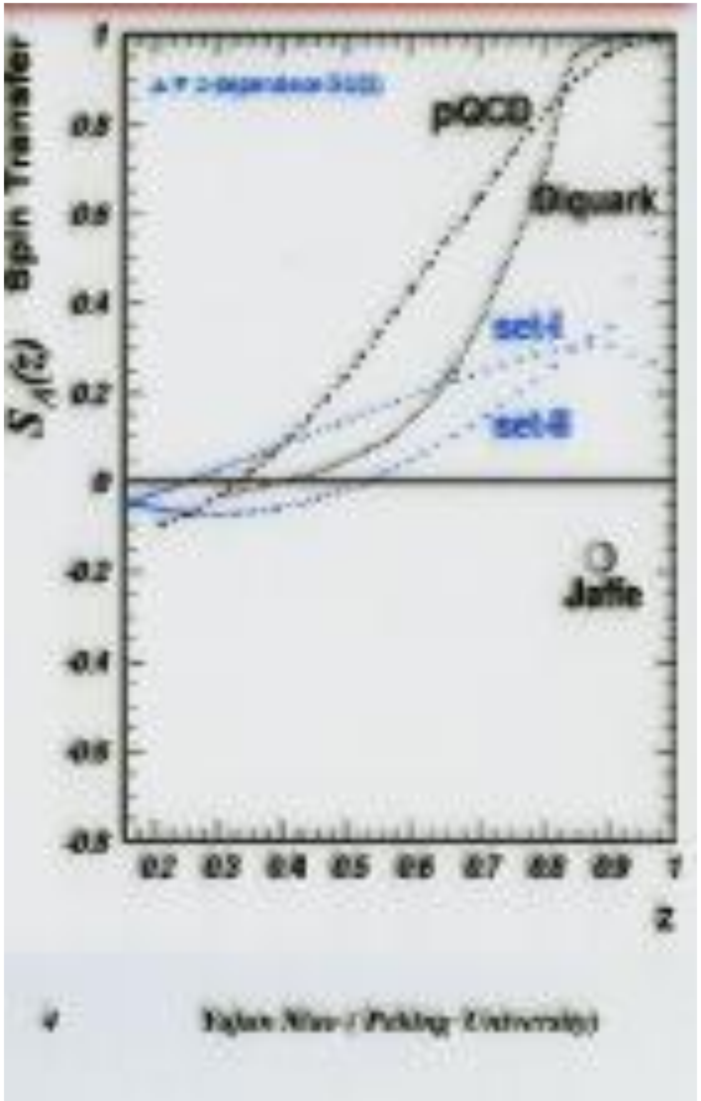


B.-Q. Ma, I. Schmidt, J.-J. Yang,
Phys. Rev. D 61 (2000) 034017

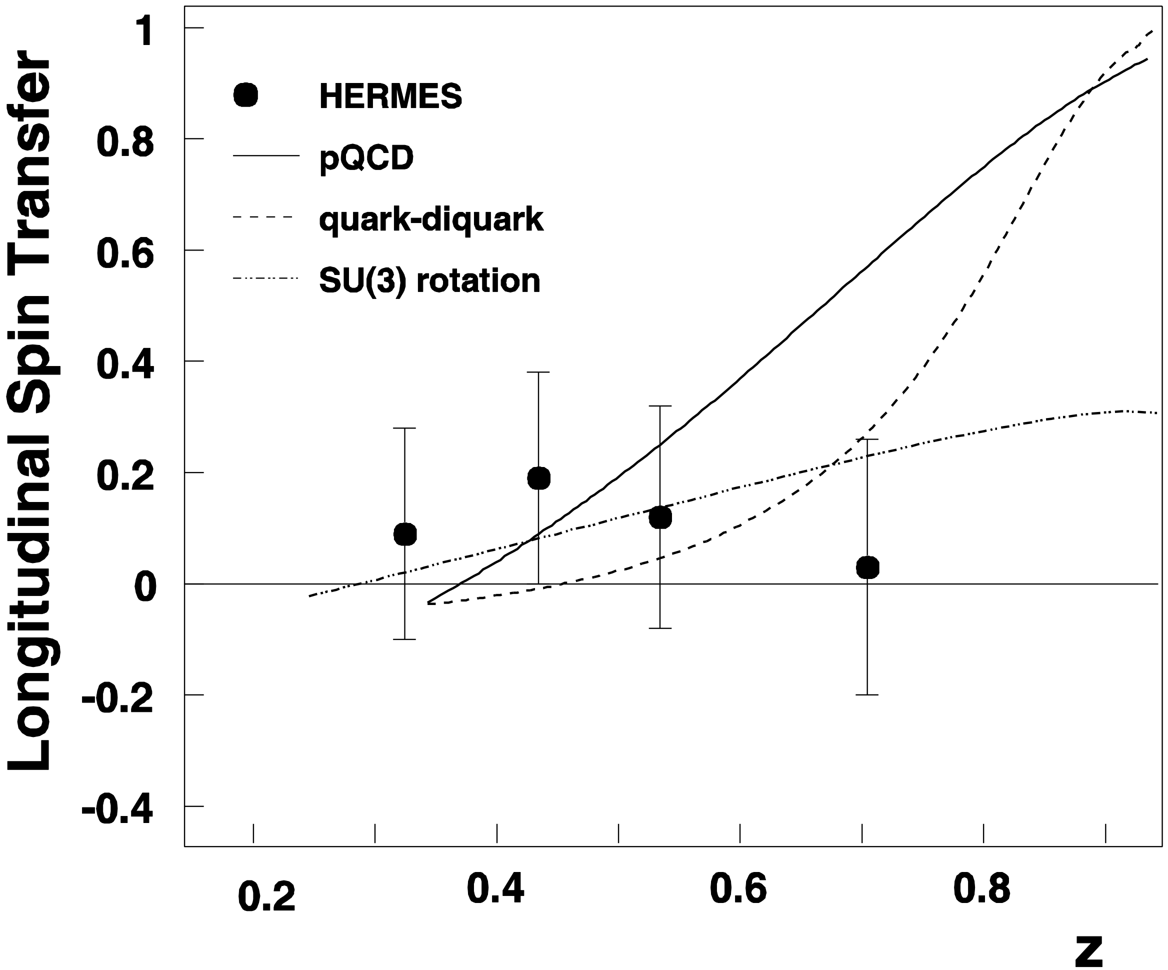
Spin Transfer to Λ in Semi-Inclusive DIS



Different predictions



Comparison with data



High Energy Spin Physics Experiment

@ HERMES by China Group

- Yajun Mao @ PKU
- Yunxiu Ye @ USTC
- Bo-Qiang Ma @ PKU
- & students

HERMES Collaboration，Airapetian et al., LONGITUDINAL SPIN TRANSFER TO THE LAMBDA HYPERON IN SEMI-INCLUSIVE DEEP-INELASTIC SCATTERING. Phys.Rev.D74:072004,2006.

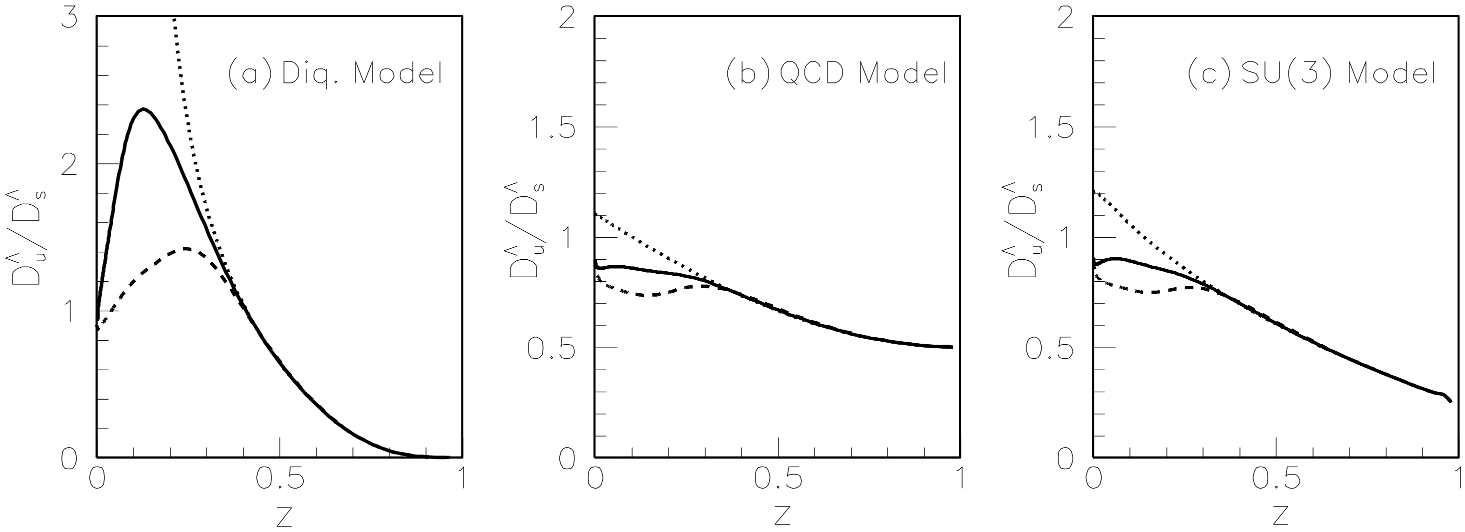
$\bar{\Lambda}/\Lambda$ Ratio in DIS Production

- A sensitive quantity that can provides information about the flavor structure of Λ hyperon.

B.-Q. Ma, I. Schmidt, J.-J. Yang
Phys. Lett. B 574 (2003) 35

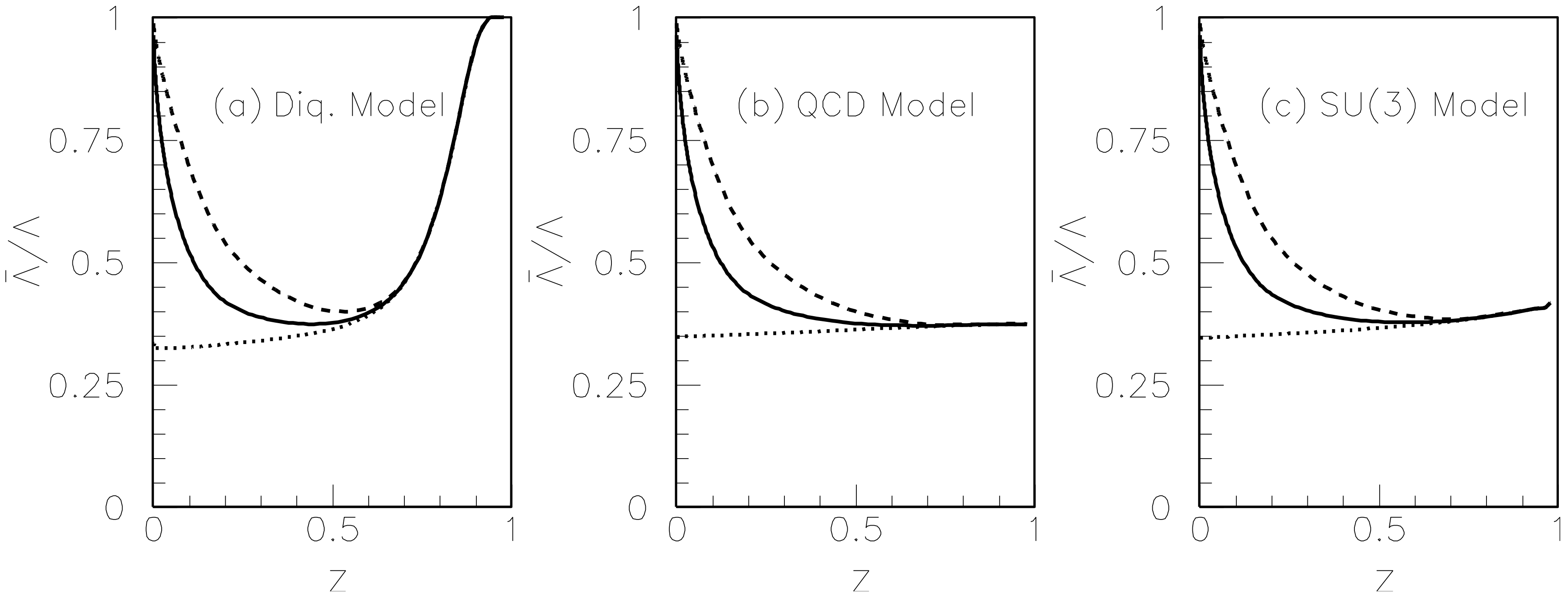
The flavor structure of Lambda

u/s ratio with x-dependence



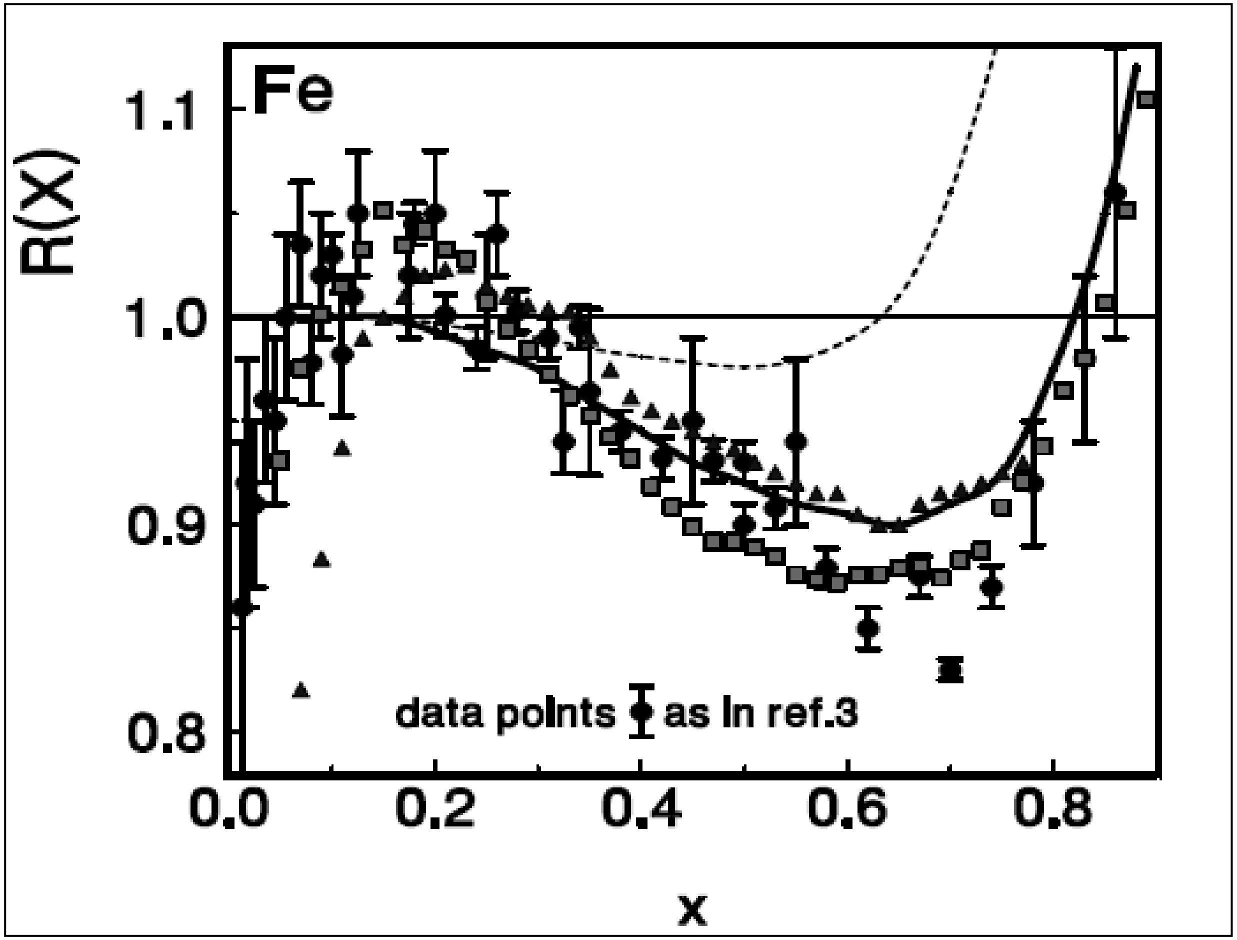
B.-Q. Ma, I. Schmidt, J.-J. Yang
Phys. Lett. B 574 (2003) 35

Different predictions



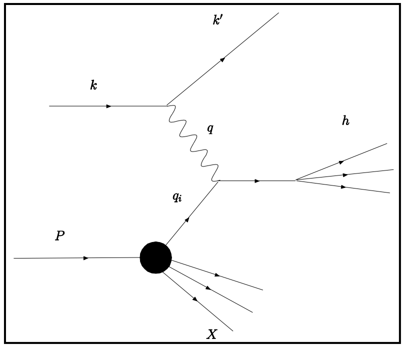
B.-Q. Ma, I. Schmidt, J.-J. Yang
Phys. Lett. B 574 (2003) 35

Nuclear EMC Effect

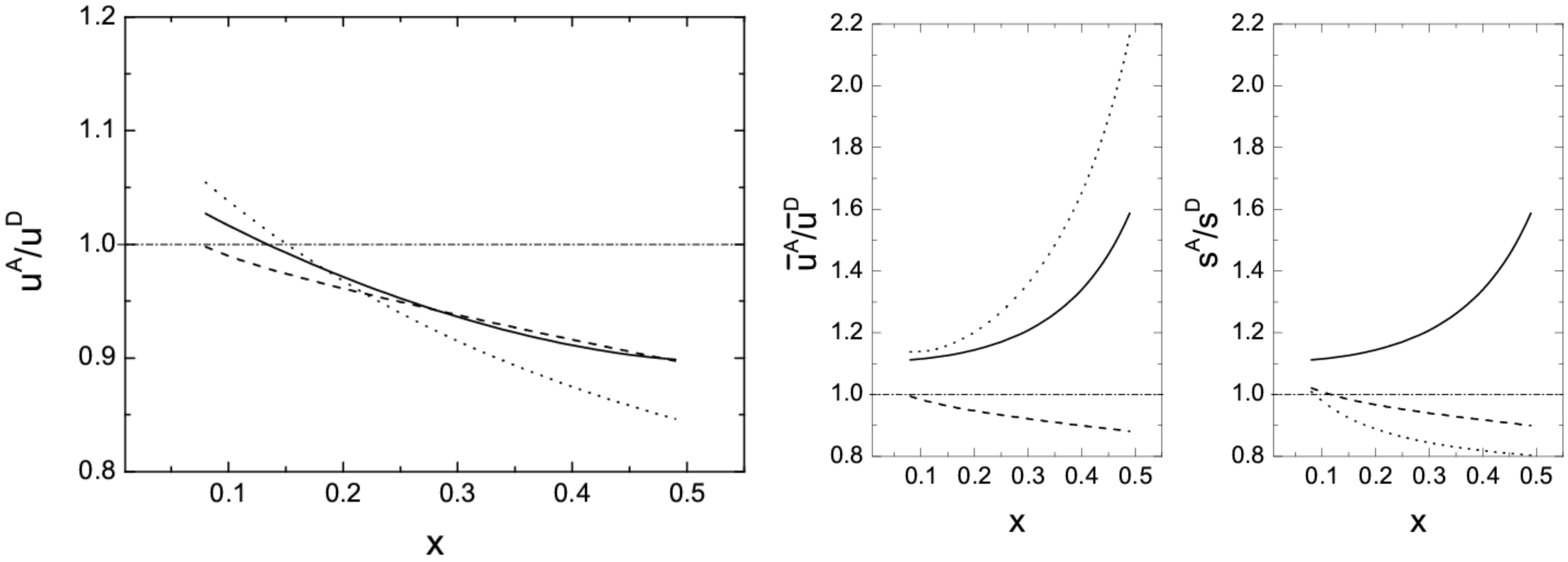


Anti-Lambda production as a probe of the nuclear sea structure?

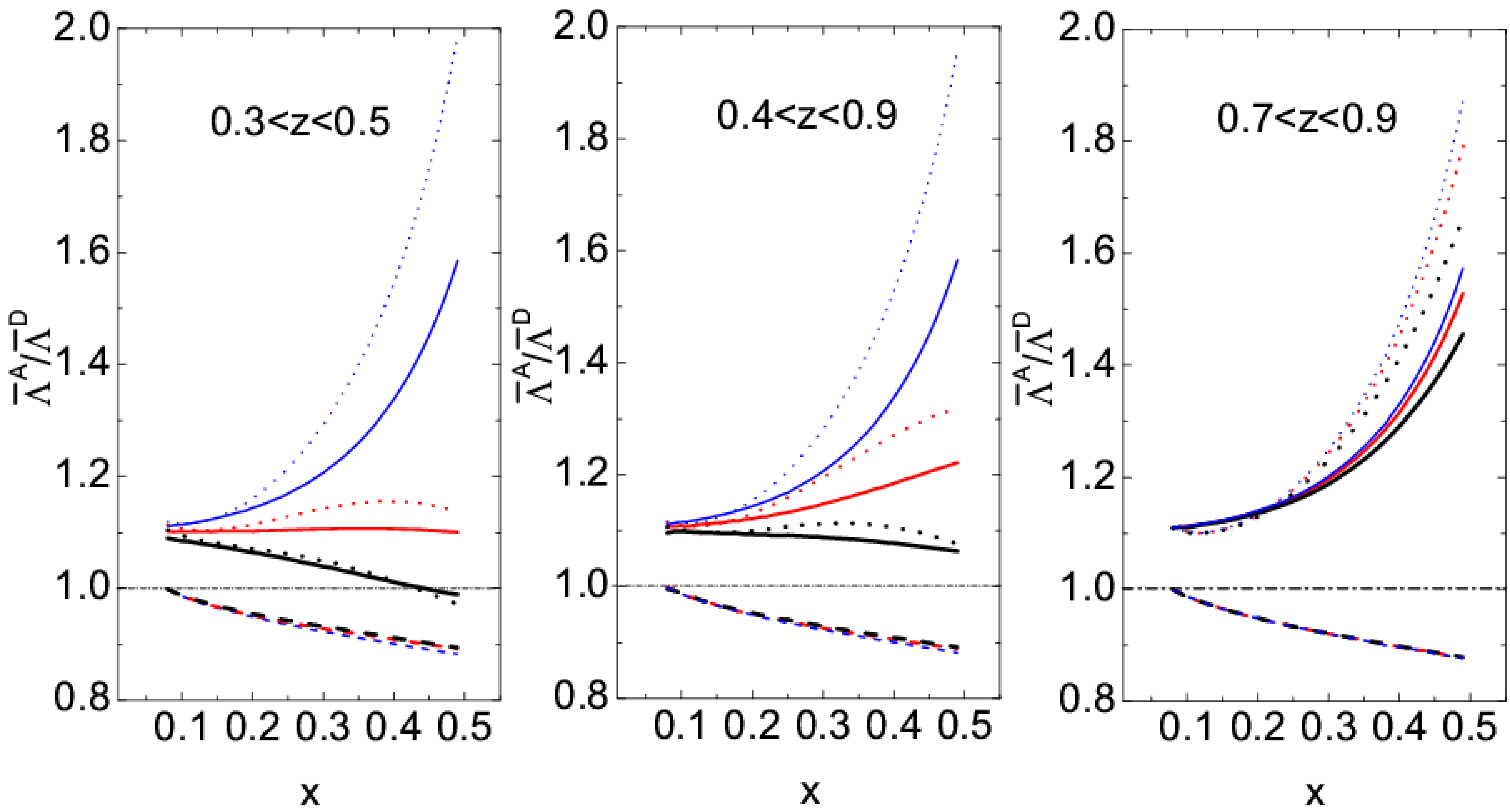
- 有三类原子核模型可以解释EMC效应: 团簇模型,Pi盈余模型, 重新标度模型.
- 通过考察原子核与核子荷电轻子半单举过程中末态强子anti-Lambda的产率比对x的依赖性，我们发现 anti-Lambda 能够区分定性描述原子核EMC效应的三类不同原子核结构模型.



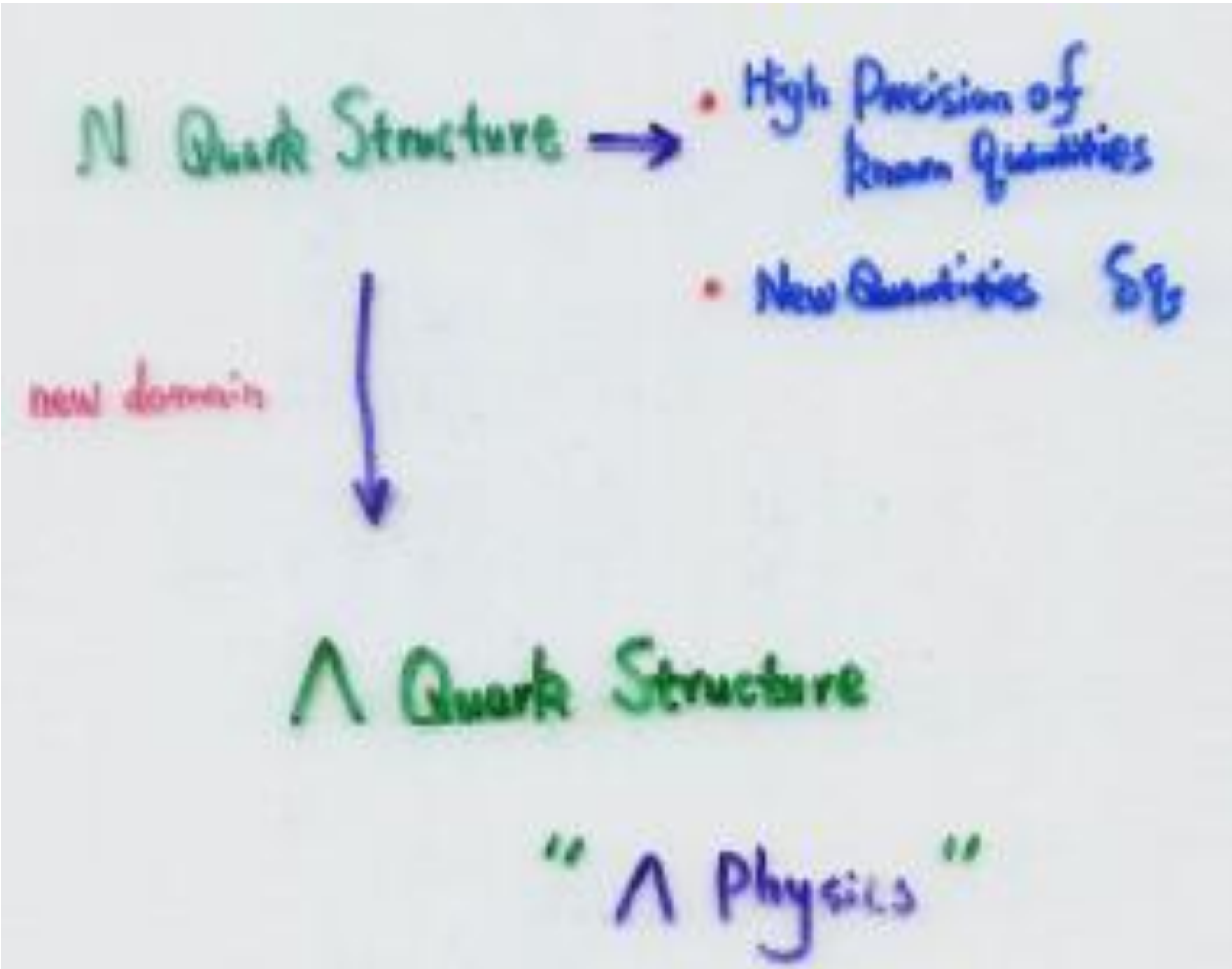
Different sea behaviors in nuclei



Different predictions of anti-lambda production



Conclusion 1: Lambda Physics



Conclusion 2: Anti-Lambda Production for Nuclear Physics

Anti-Lambda production charged lepton semi-inclusive deep inelastic scattering off nuclear target is ideal to figure out the nuclear sea content, which is differently predicted by different models accounting for the nuclear EMC effect.