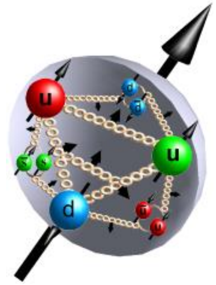


超子的自旋结构

Bo-Qiang Ma (马伯强)

? PKU (北京大学)

第一届超子物理研讨会

April 13, 2024

IMP@Huizhou, China

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

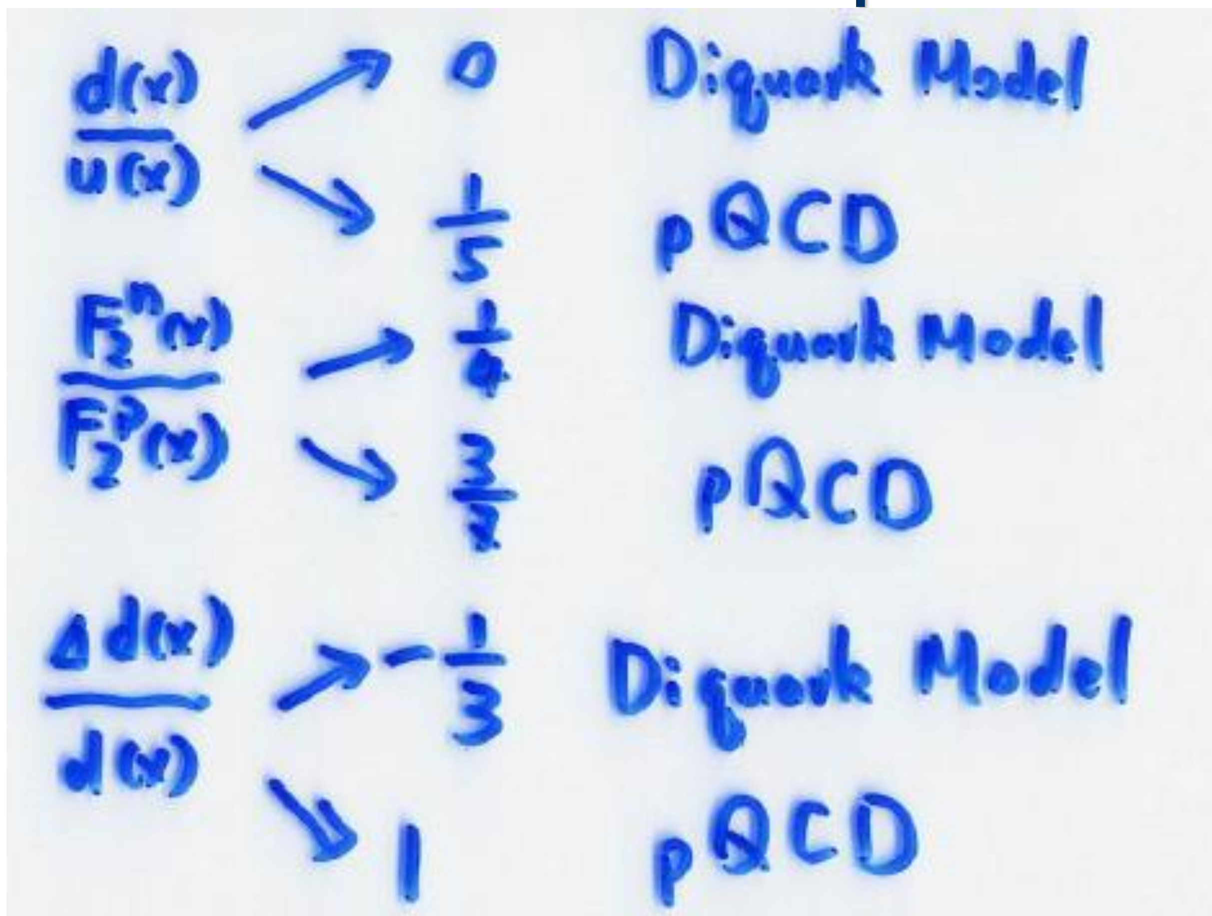
- **Isospin Symmetry Breaking** $\bar{u}_p \neq \bar{d}_n \quad \bar{d}_p \neq \bar{u}_n$

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

Unknown about the nucleon: valence

x→1 behaviors of flavor and spin

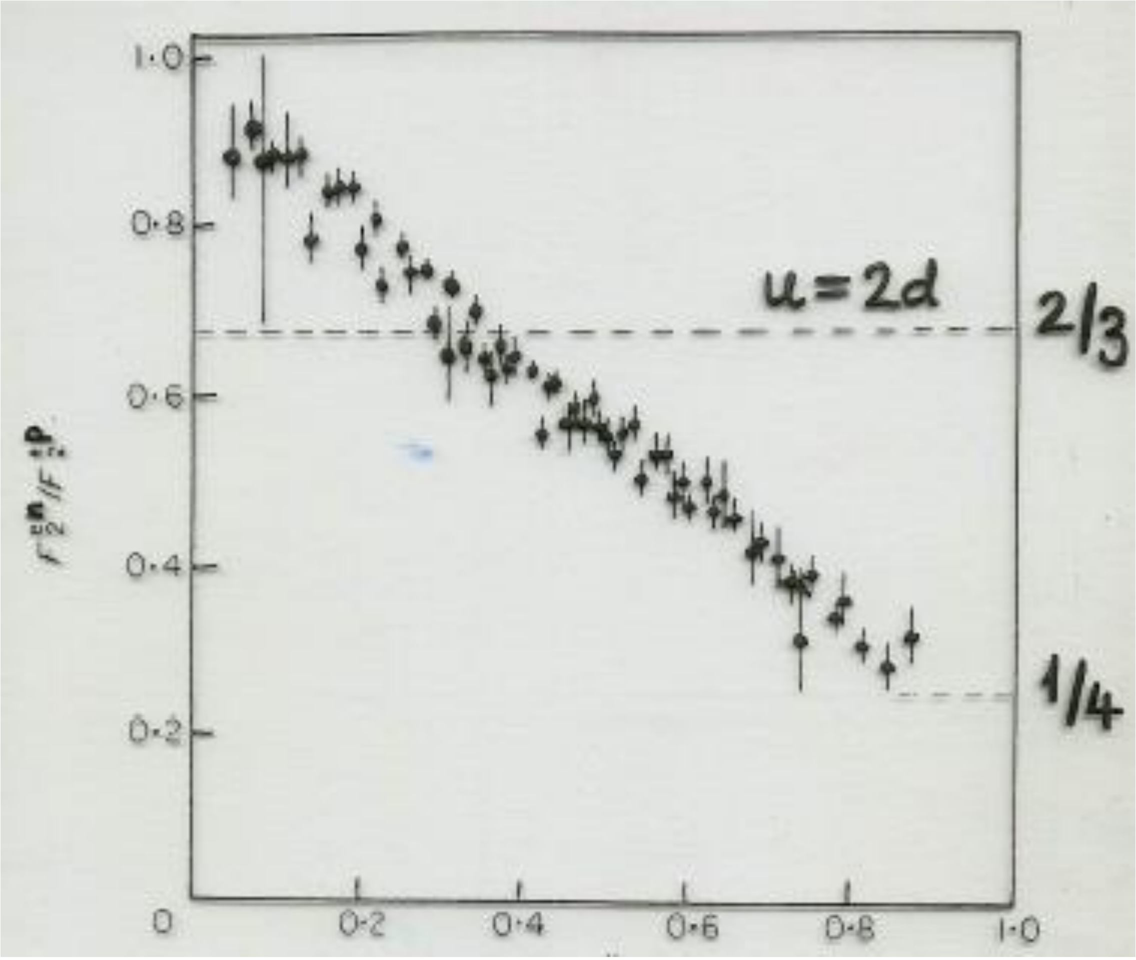
- **Flavor**



- **Spin**

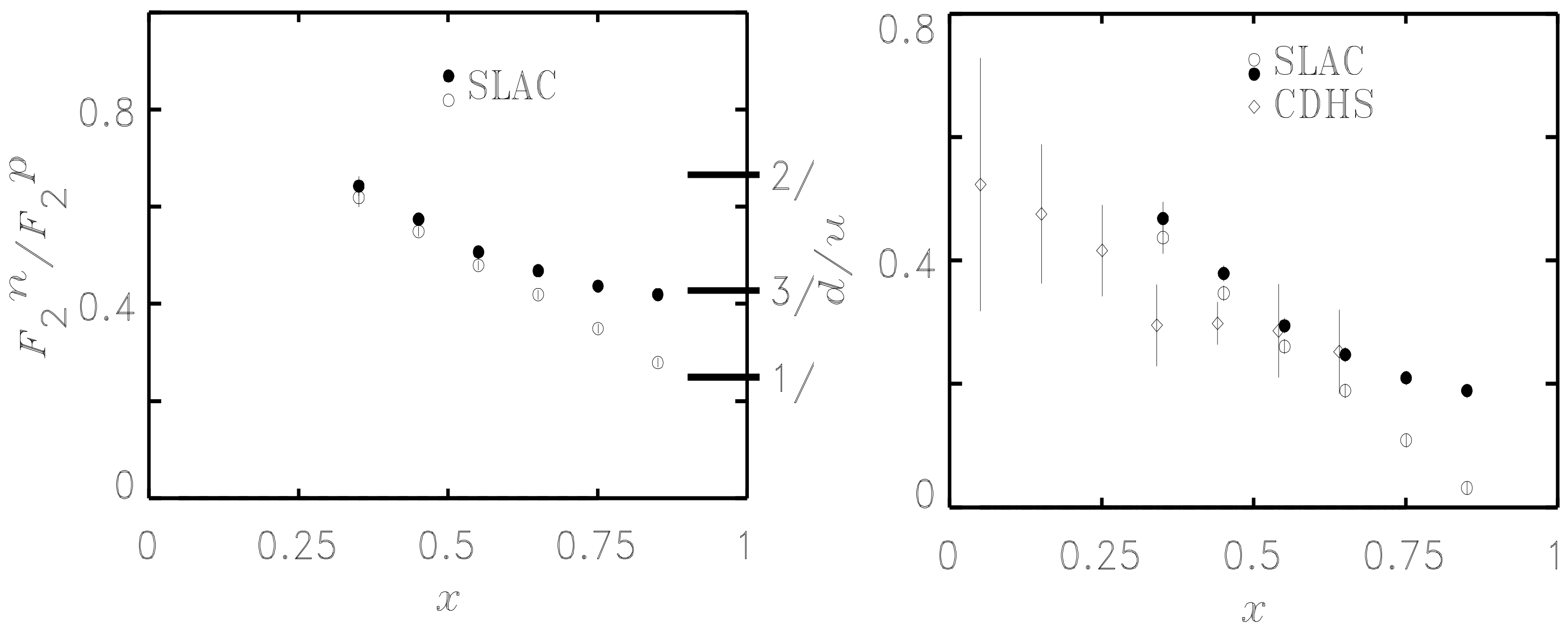
Ma, PLB 375 (96) 320

Ratio of Neutron/Proton Structure Functions



Flavor Content of the Proton

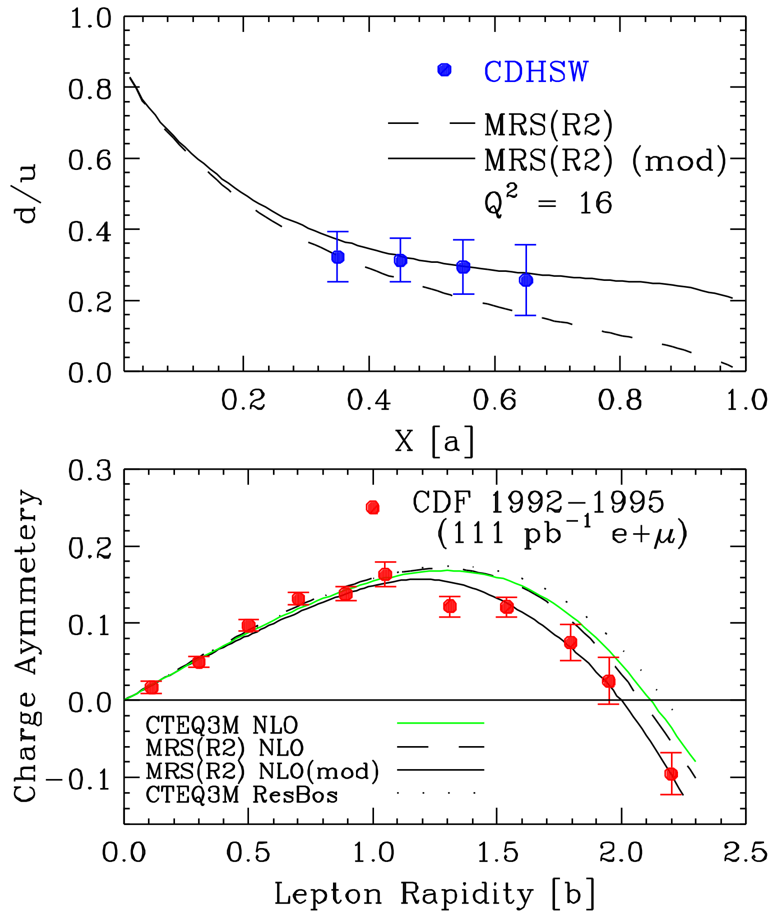
with nuclear binding correction



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

Flavor Content of the Proton

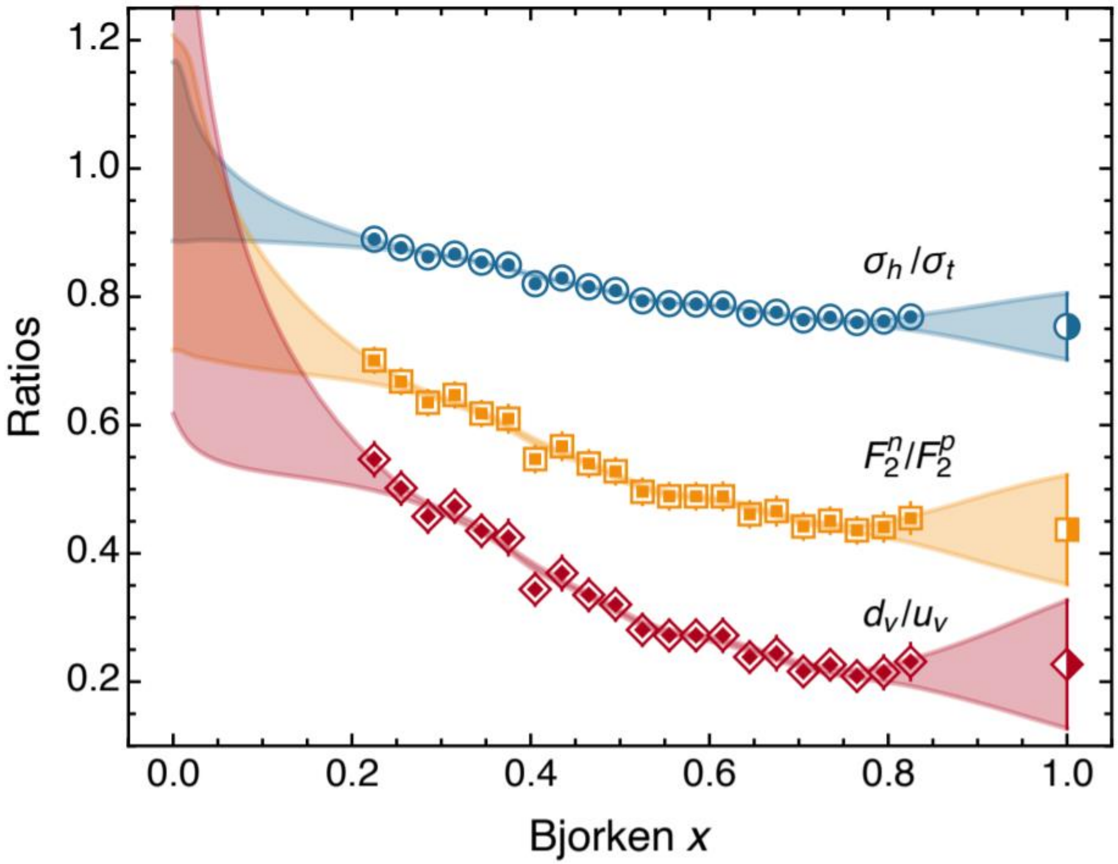
from DIS neutrino data analysis



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

Flavor Content of the Proton

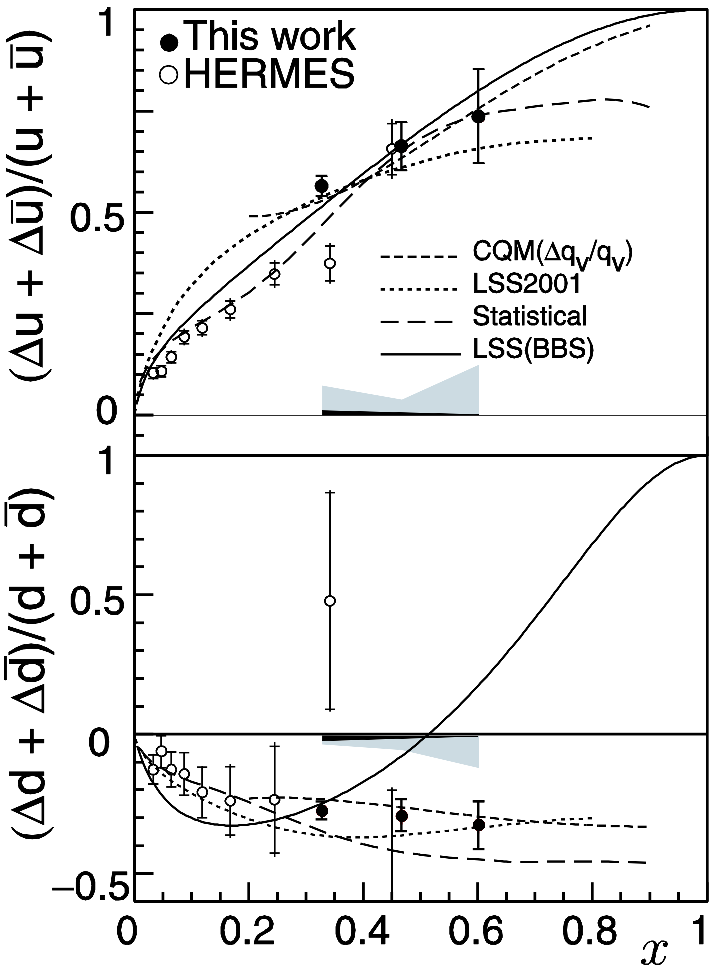
from DIS data of ^{3}He and ^{3}H



Z.-F.Cui, F.Cao, D.Bonosi, L.Chang, C.R.Roberts, S.M.Schmidt, arXiv2108.113

Quark Helicity Distributions of Proton

Measurements at JLAB and HERMES



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

Status

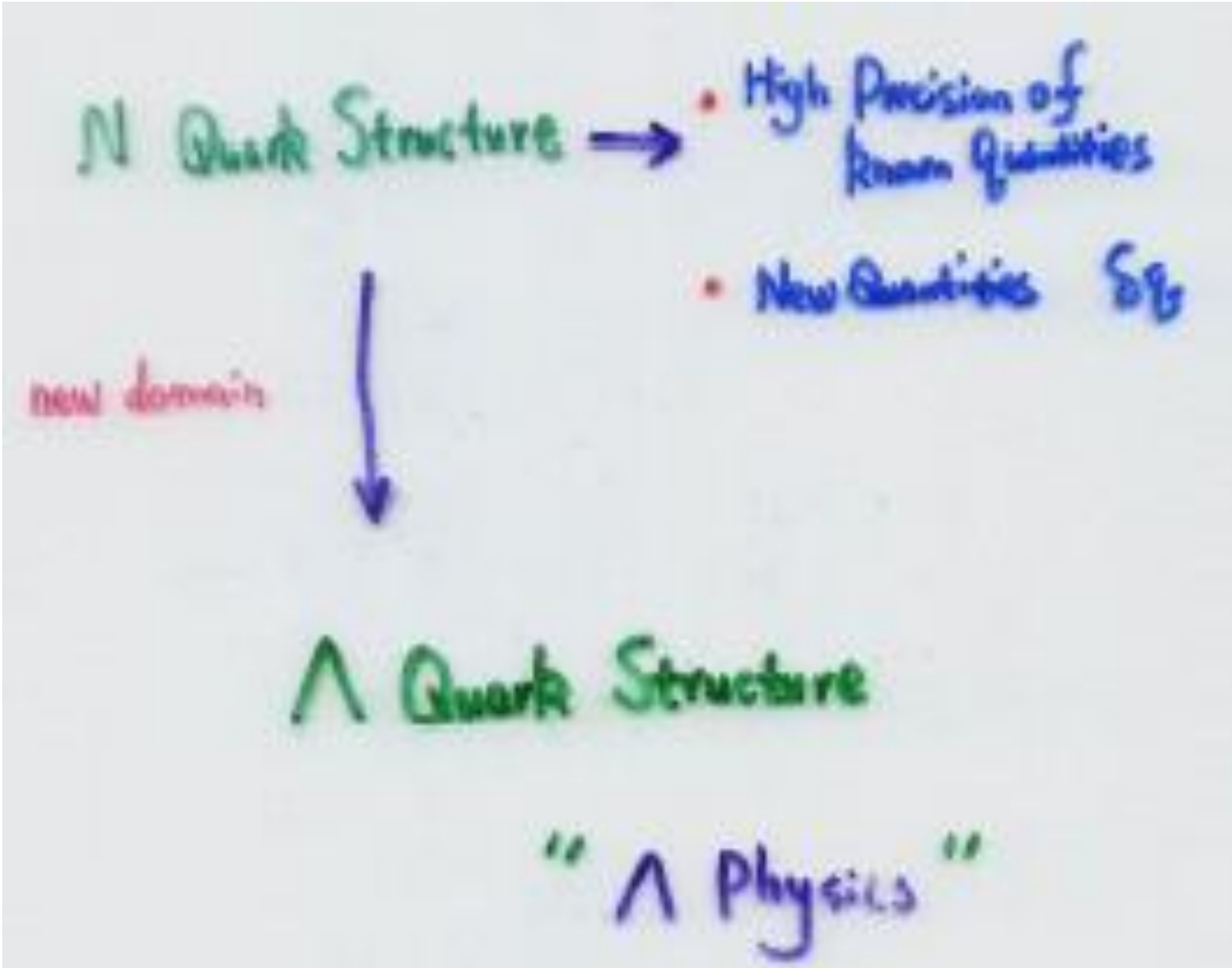
of the Flavor and Spin Contents of the Proton

- 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:

$$\int_0^1 dx\, g_1^{e\Lambda}(x) = \frac{1}{18}(2\Sigma - D)$$

$$= \int_0^1 dx\, g_1^{ep}(x) - \frac{1}{18}(2D + 3F)$$

$$= -0.042 \pm 0.019$$

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

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

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

- $p(uuds\bar{s}) \simeq \Lambda(uds)K^{+}(u\bar{s})$
- $\begin{cases} \Lambda(udsu\bar{u}) = p(uud)K^{-}(s\bar{u}) \\ \Lambda(udsd\bar{d}) = n(udd)K(s\bar{d}) \end{cases}$

Different flavor & spin structure in different models

Phys. Lett. B477 (2000) 107. hep-ph/9906424

Ma-Schmidt-Yang $\quad x \to 1$ behaviors

- Flavor

$$\frac{u(x)}{s(x)} \begin{cases} \nearrow 0 & \text{Diquark Model} \\ \searrow \frac{1}{2} & \text{pQCD} \end{cases}$$

- $$\frac{\Delta s(x)}{s(x)} \to 1$$

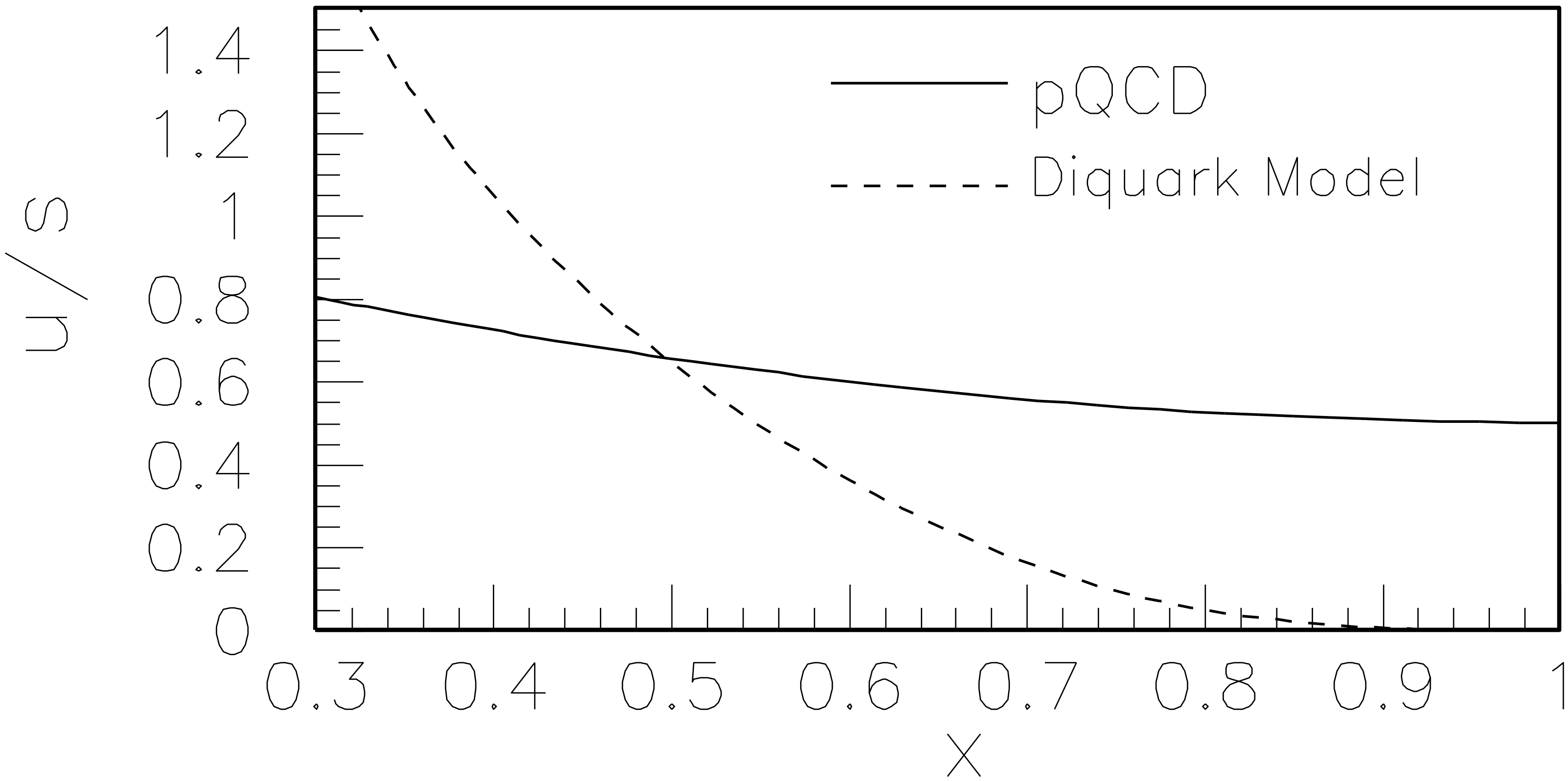
$$\frac{\Delta u(x)}{u(x)} \to 1$$

$\Delta u(x) = \Delta d(x) > 0$ at large x

$\int_0^1 dx\, \Delta u(x) = \int_0^1 dx\, \Delta d(x) \leqslant 0$

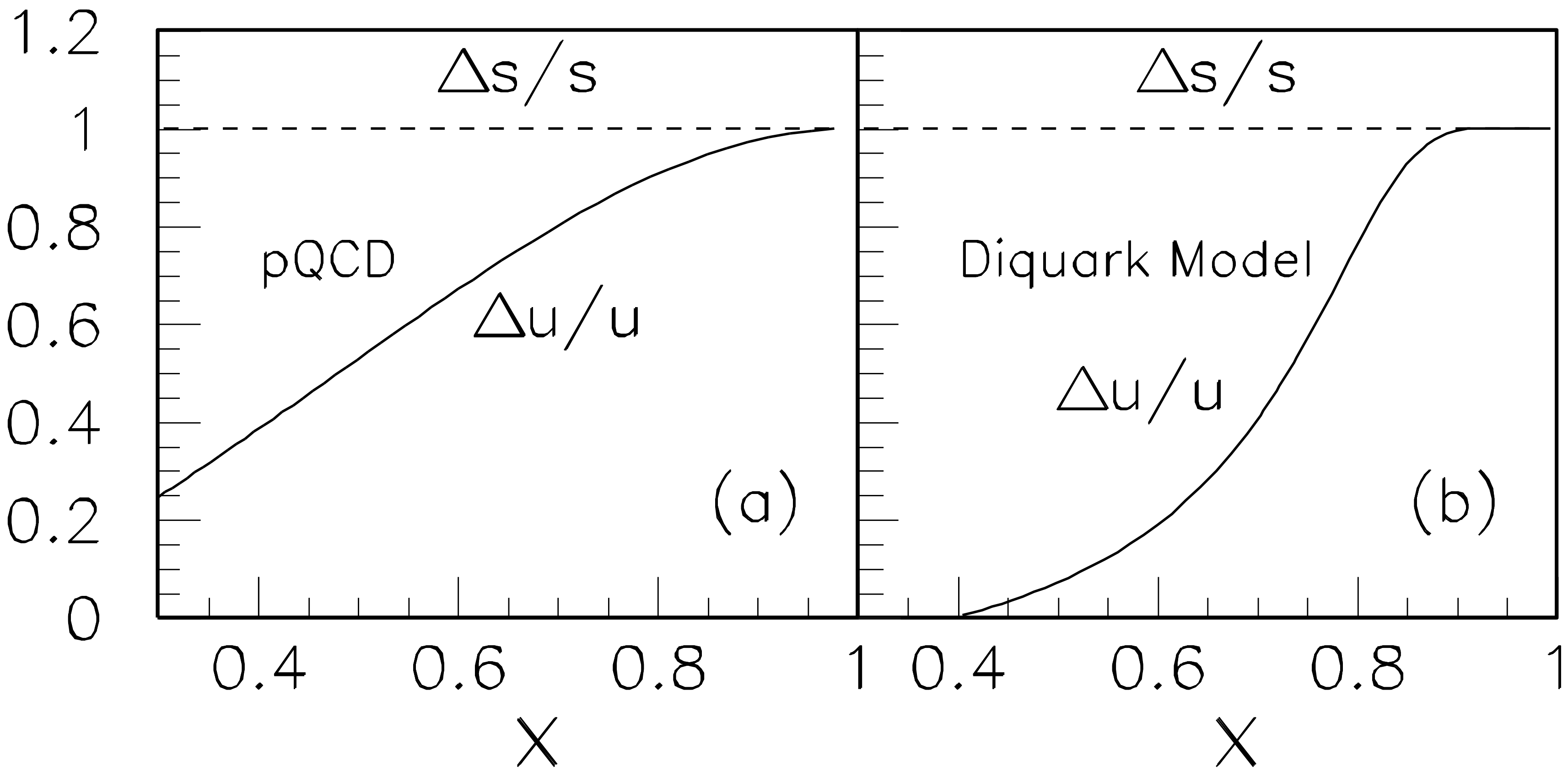
B.-Q. Ma, I. Schmidt, J.-J. Yang, Phys. Lett. B 477 (2000) 107

Flavor structure in two different models



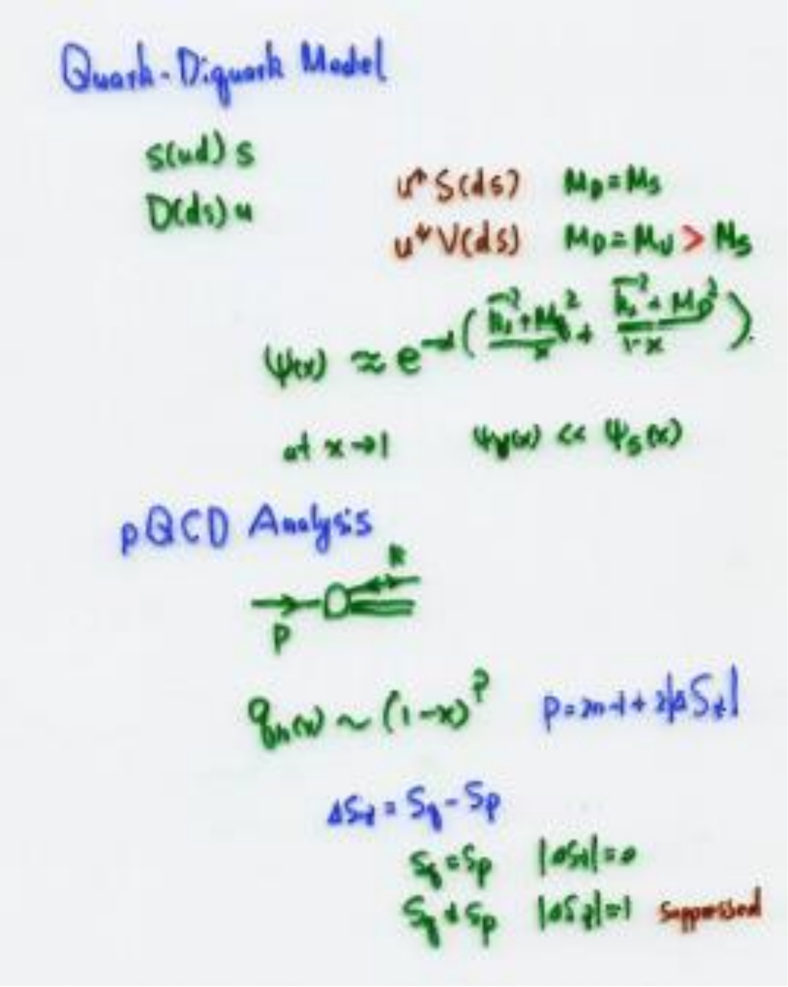
B.-Q. Ma, I. Schmidt, J.-J. Yang,
Phys. Lett. B 477 (2000) 107

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:

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

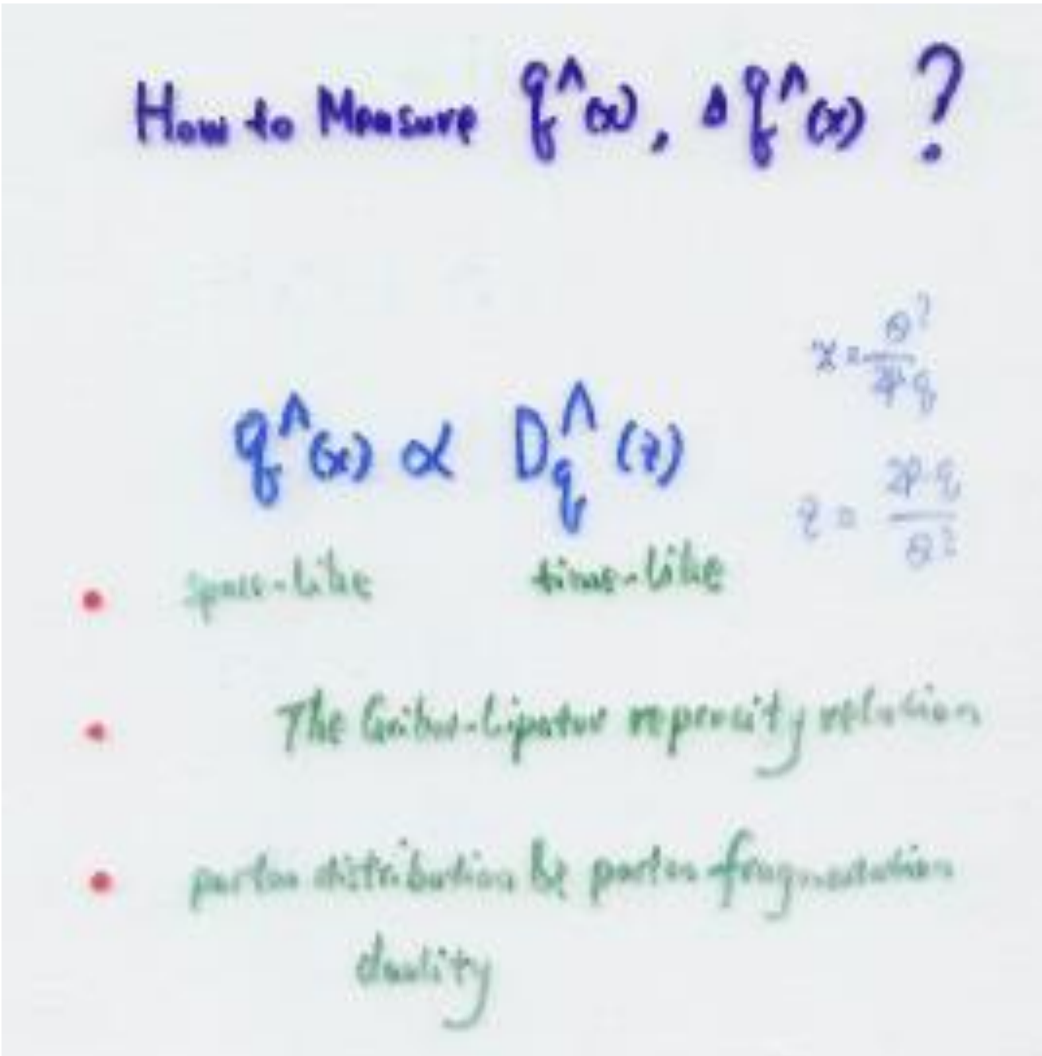
- We predict:

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

in both quark-diquark model and pQCD analysis

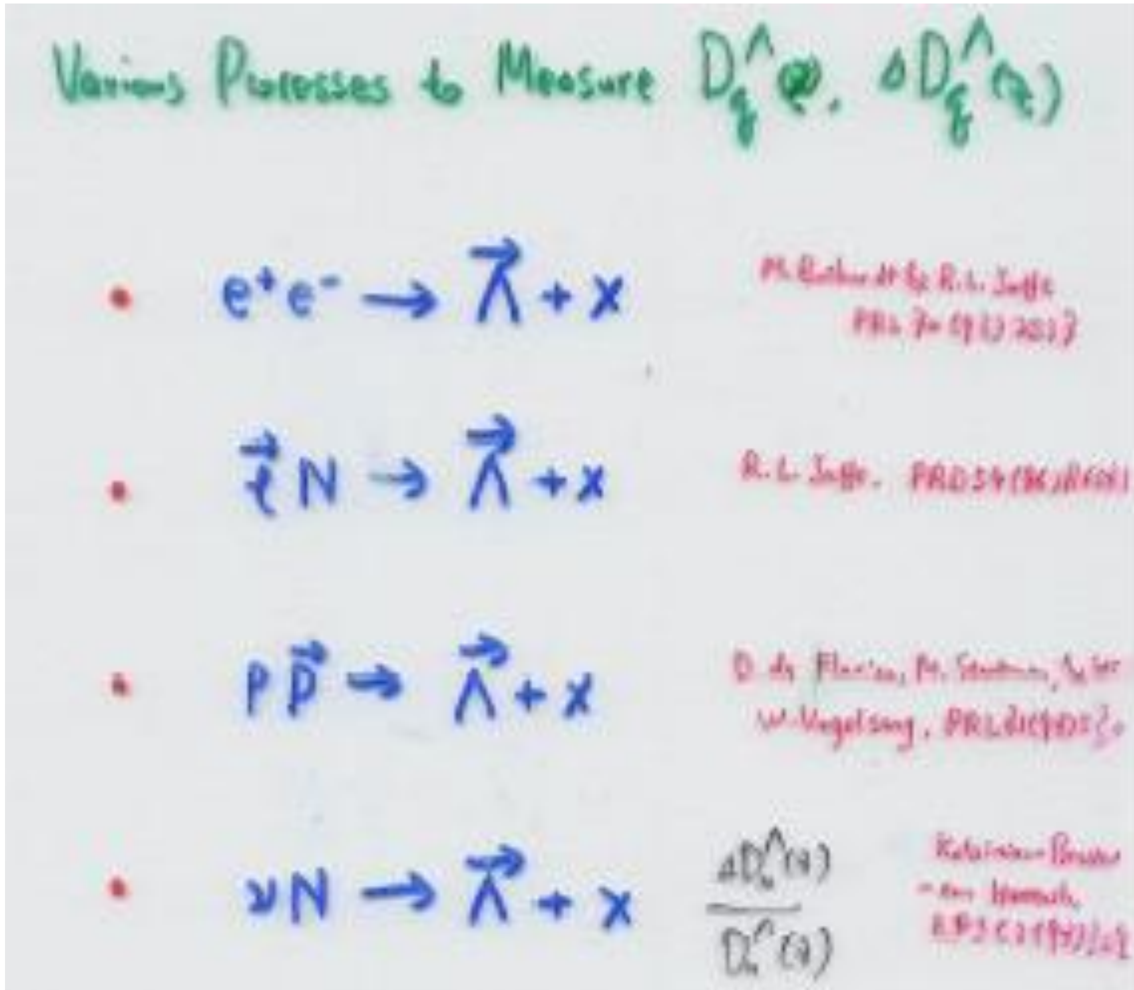
B.-Q. Ma, I. Schmidt, J.-J. Yang, Phys. Lett. B 477 (2000) 107

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 of fragmentation functions

B.-Q. Ma, J. Soffer, PRL 82 (1999) 2250

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

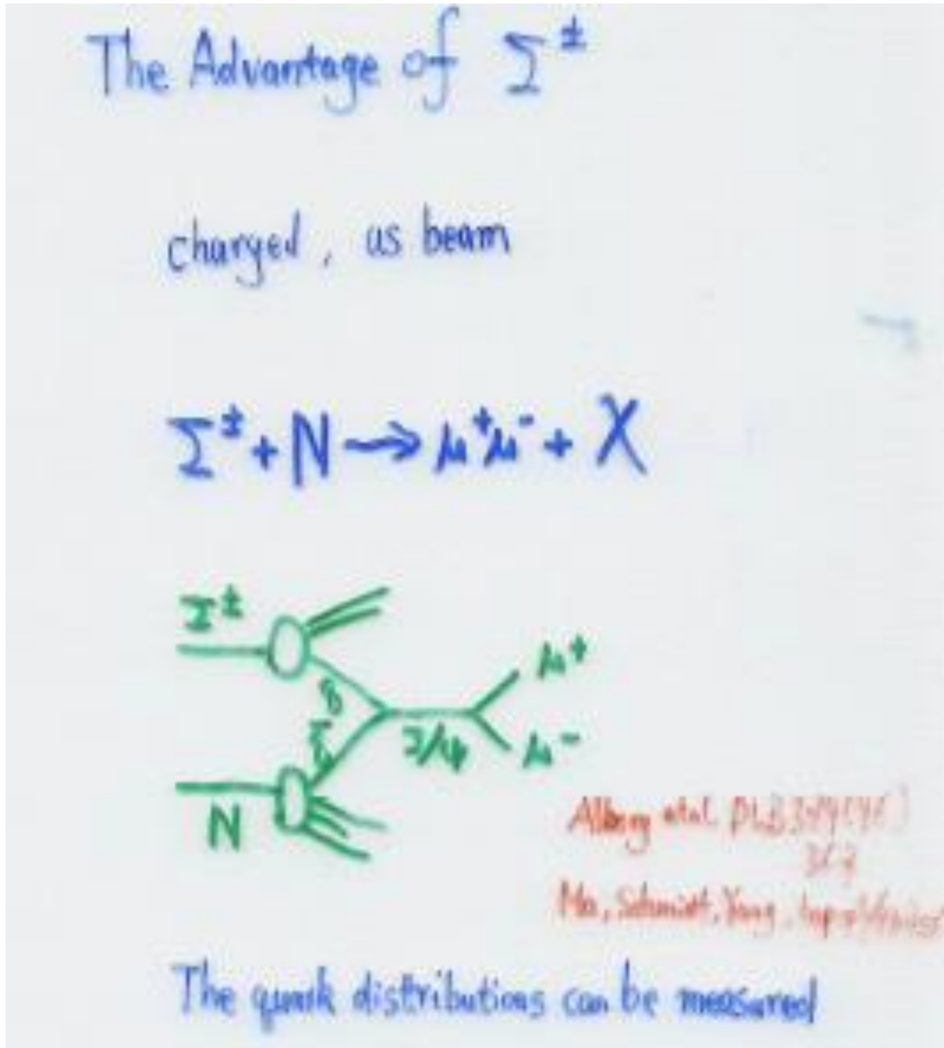
$\frac{\Delta s}{s} \to -\frac{1}{3}$ Diquark Model

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

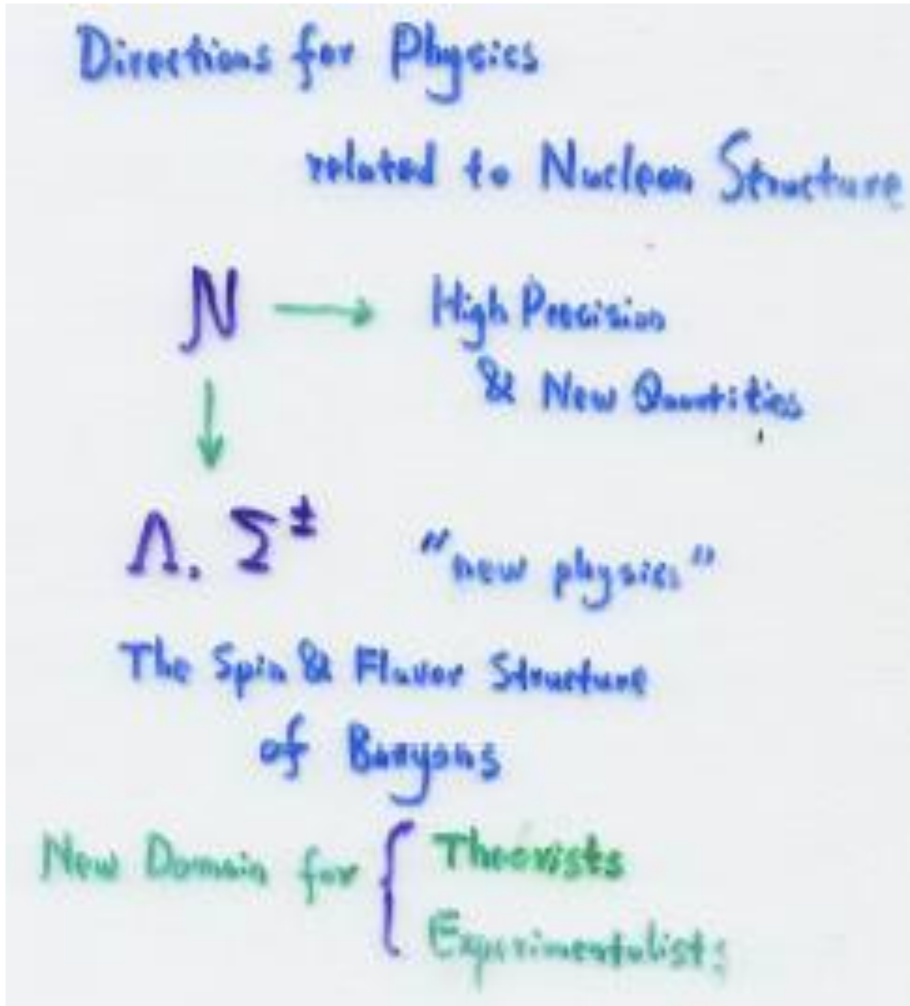
$\frac{\Delta u}{u} \to 1$

- Bigger difference at middle x

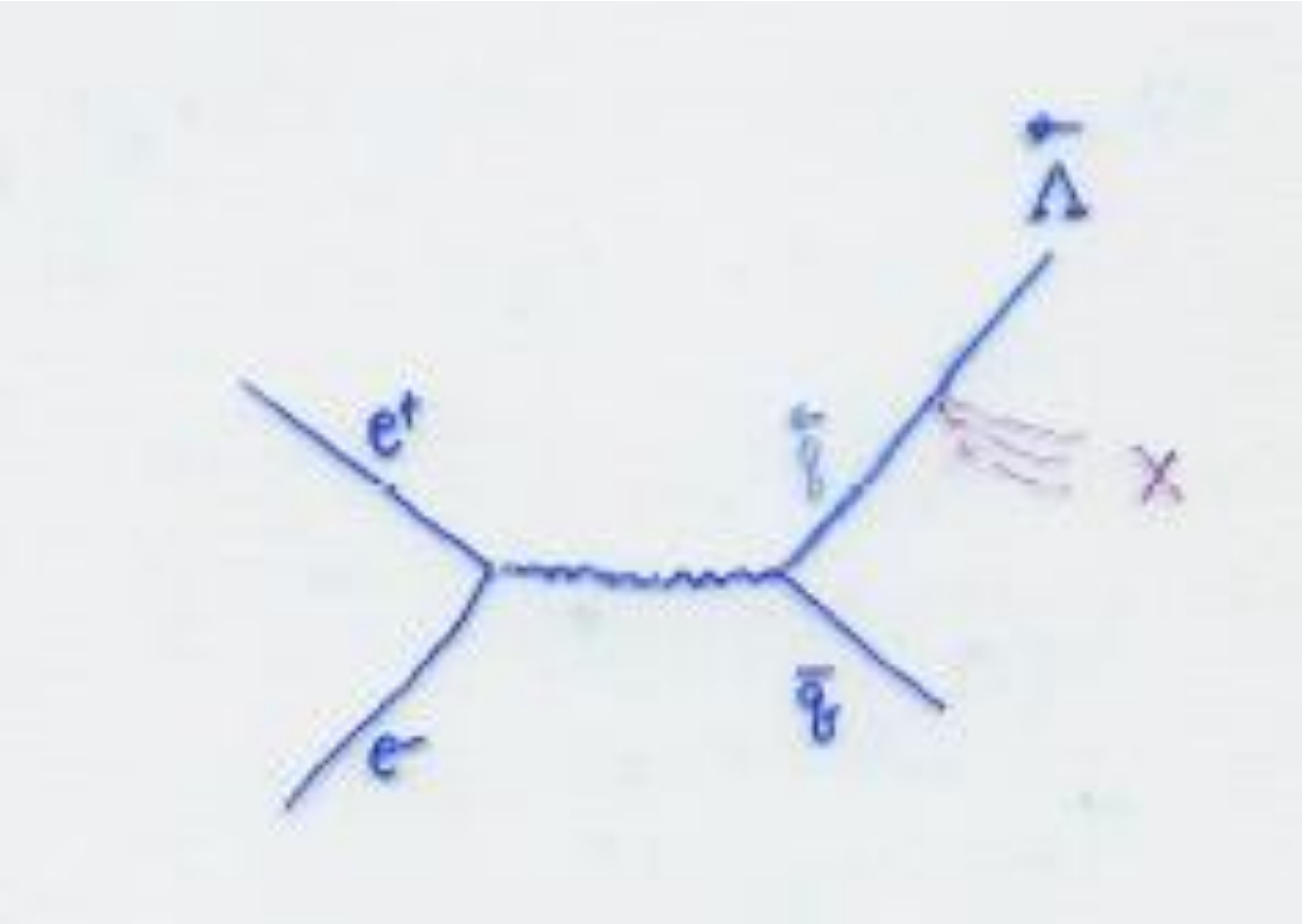
The advantage of using Sigma hyperons



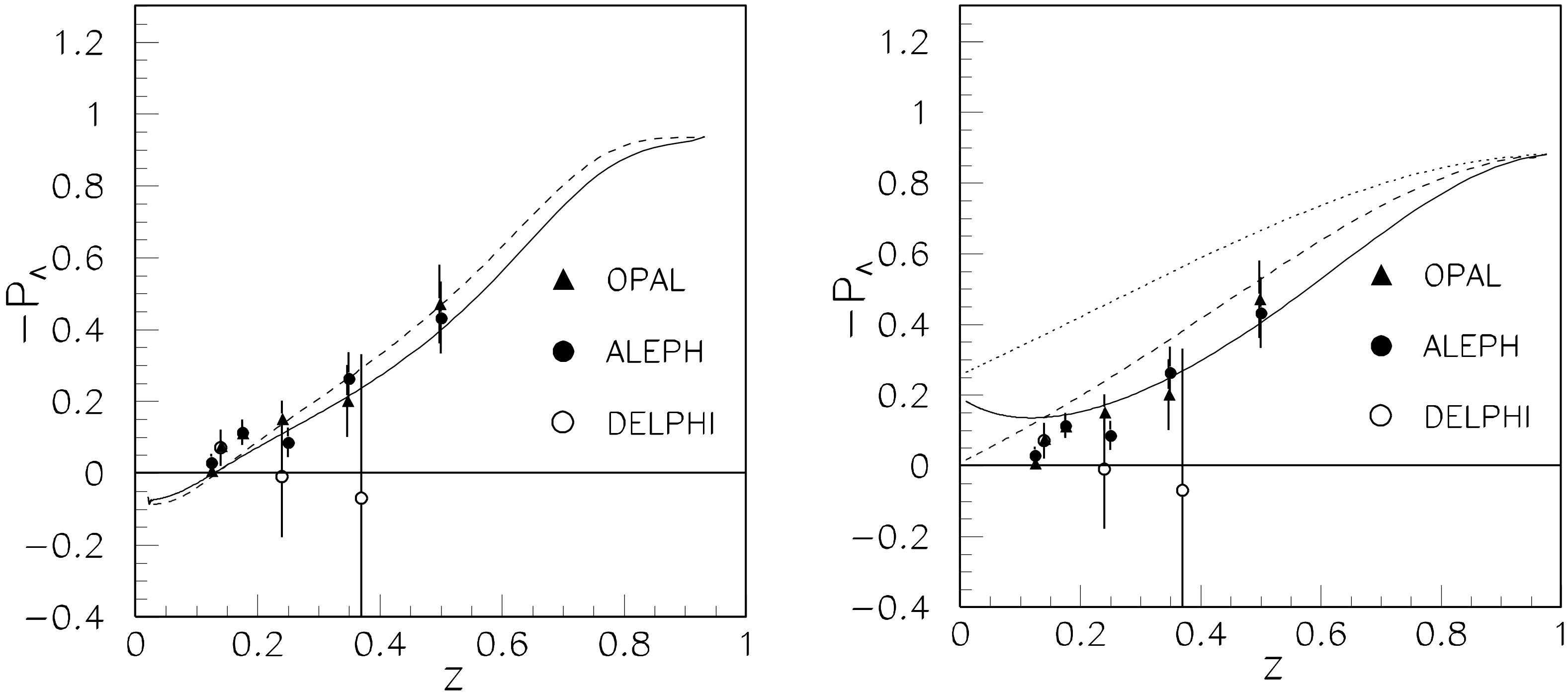
New Domain for Theorists and Experimenlists



Spin structure of Lambda from Lambda polarization in Zº decay

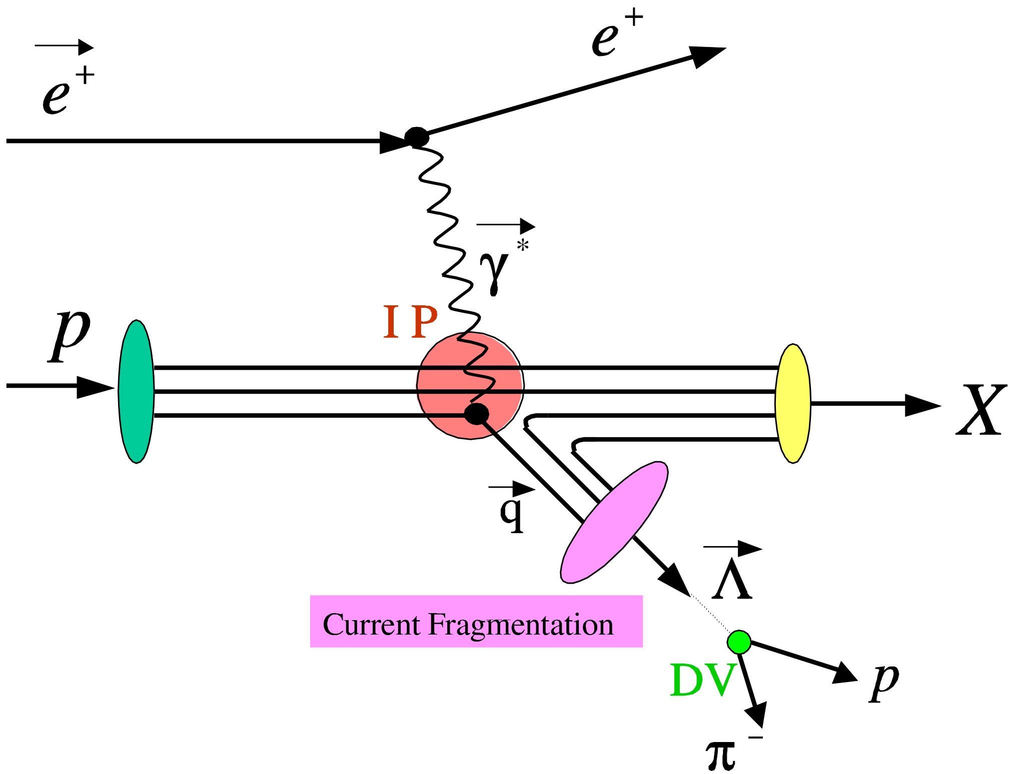


Diquark model and pQCD results

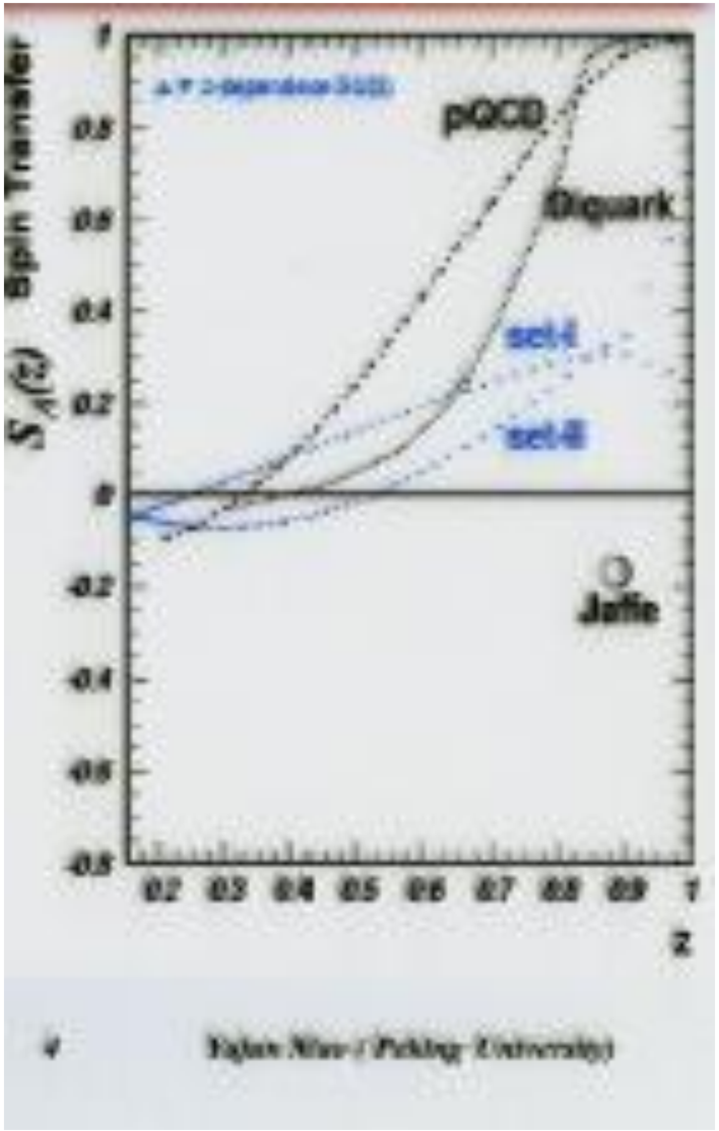


B.-Q. Ma, I. Schmidt, J.-J. Yang,
Phys. Rev. D 61 (2000) 034017

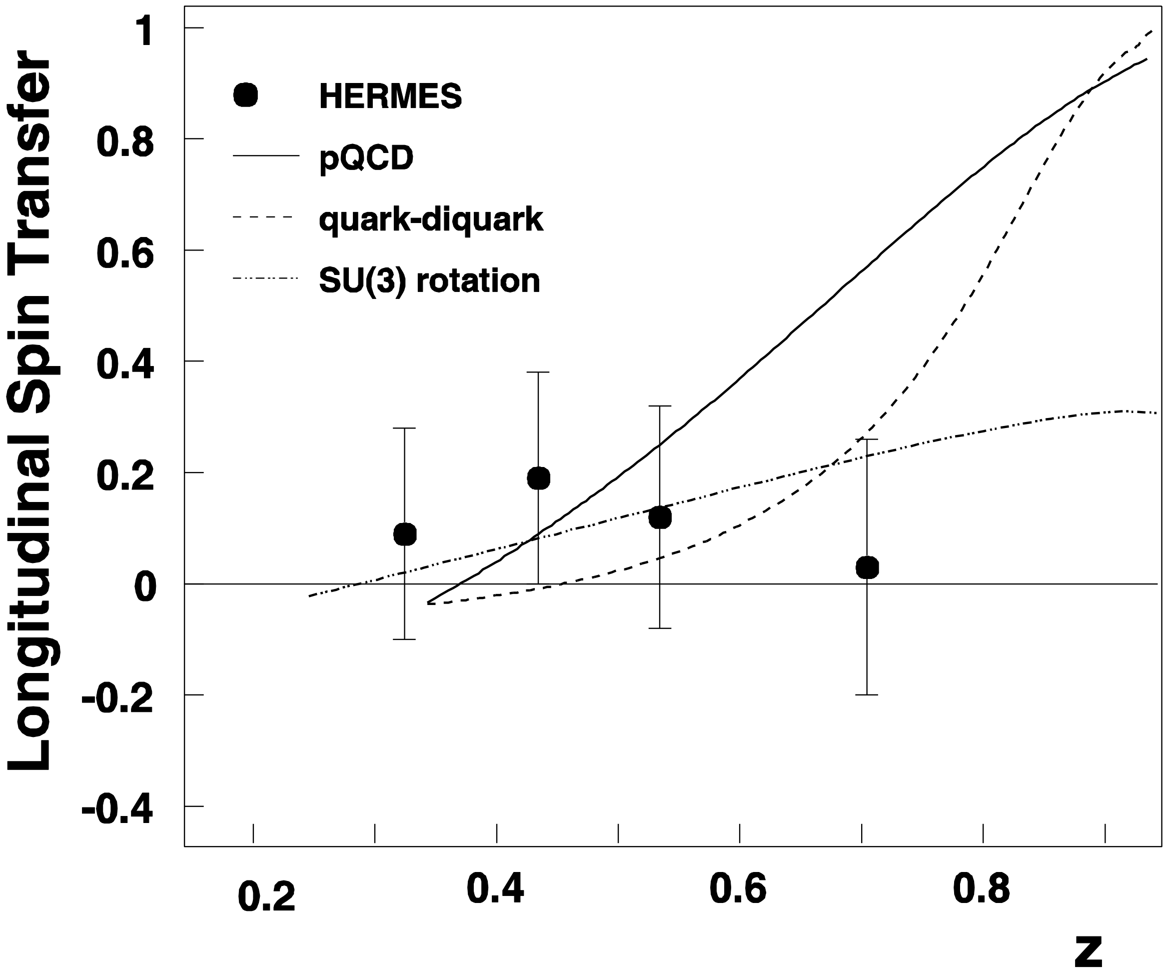
Spin Transfer to Λ in Semi-Inclusive DIS



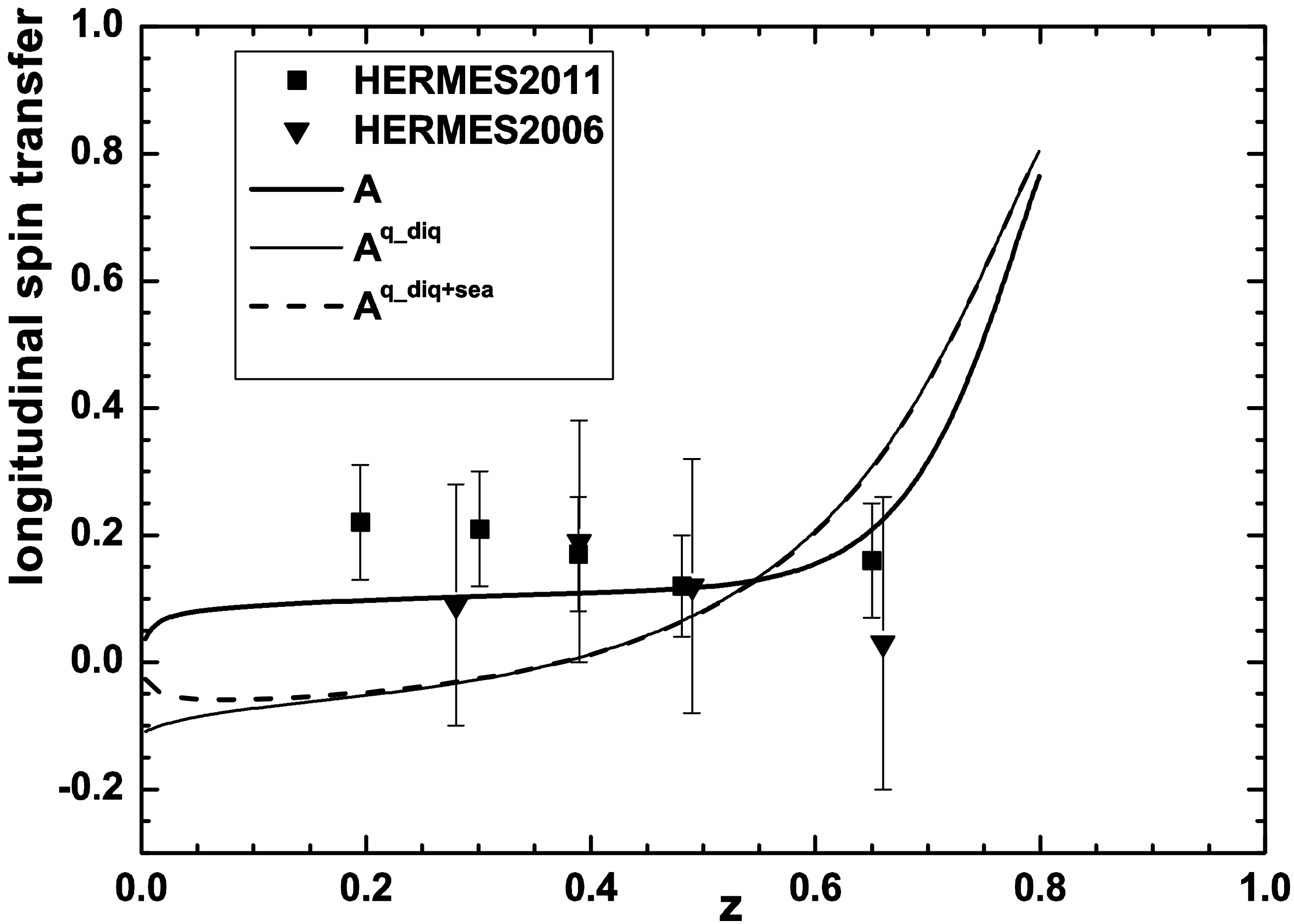
Different predictions



Comparison with data

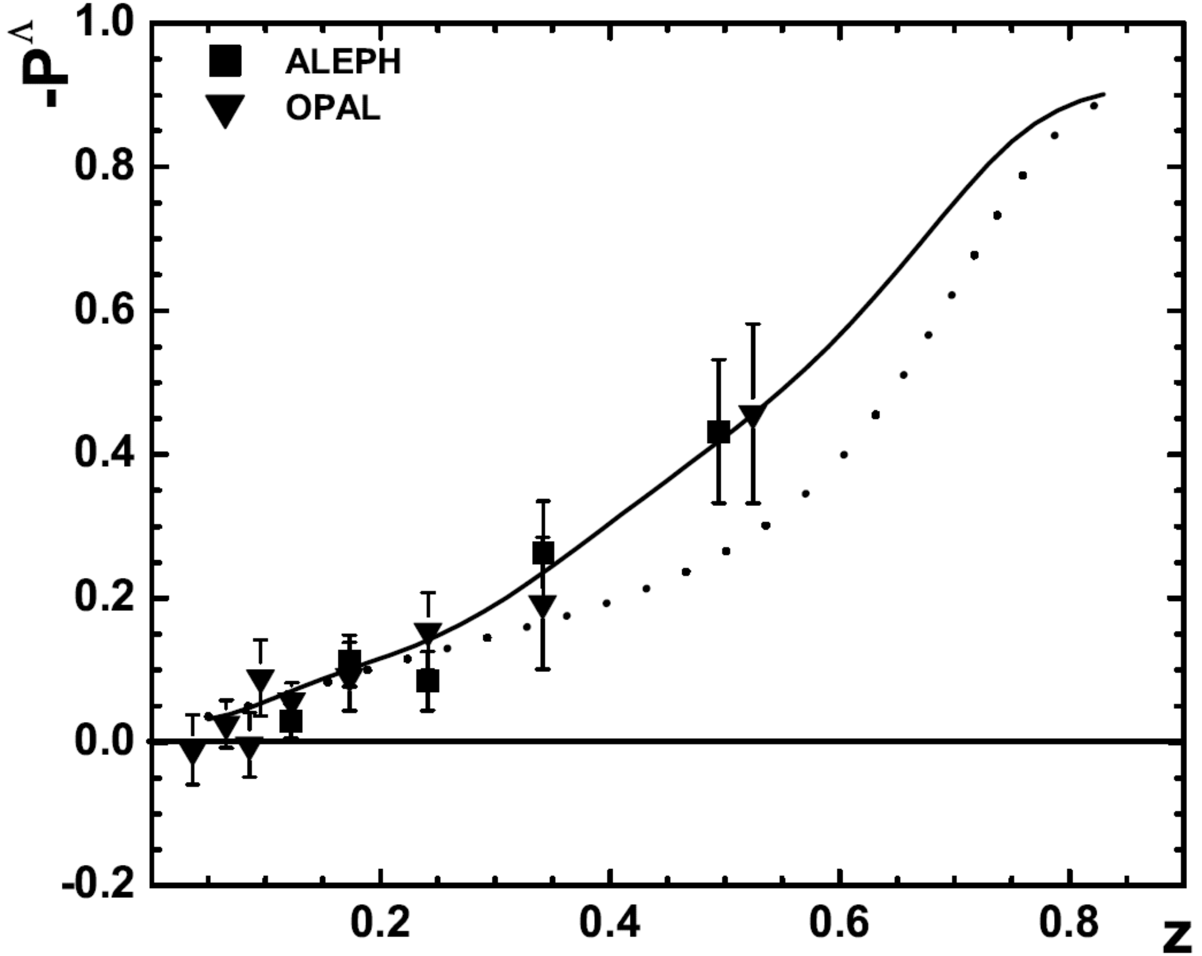


New results including both unfavored and indirect decays: SIDIS



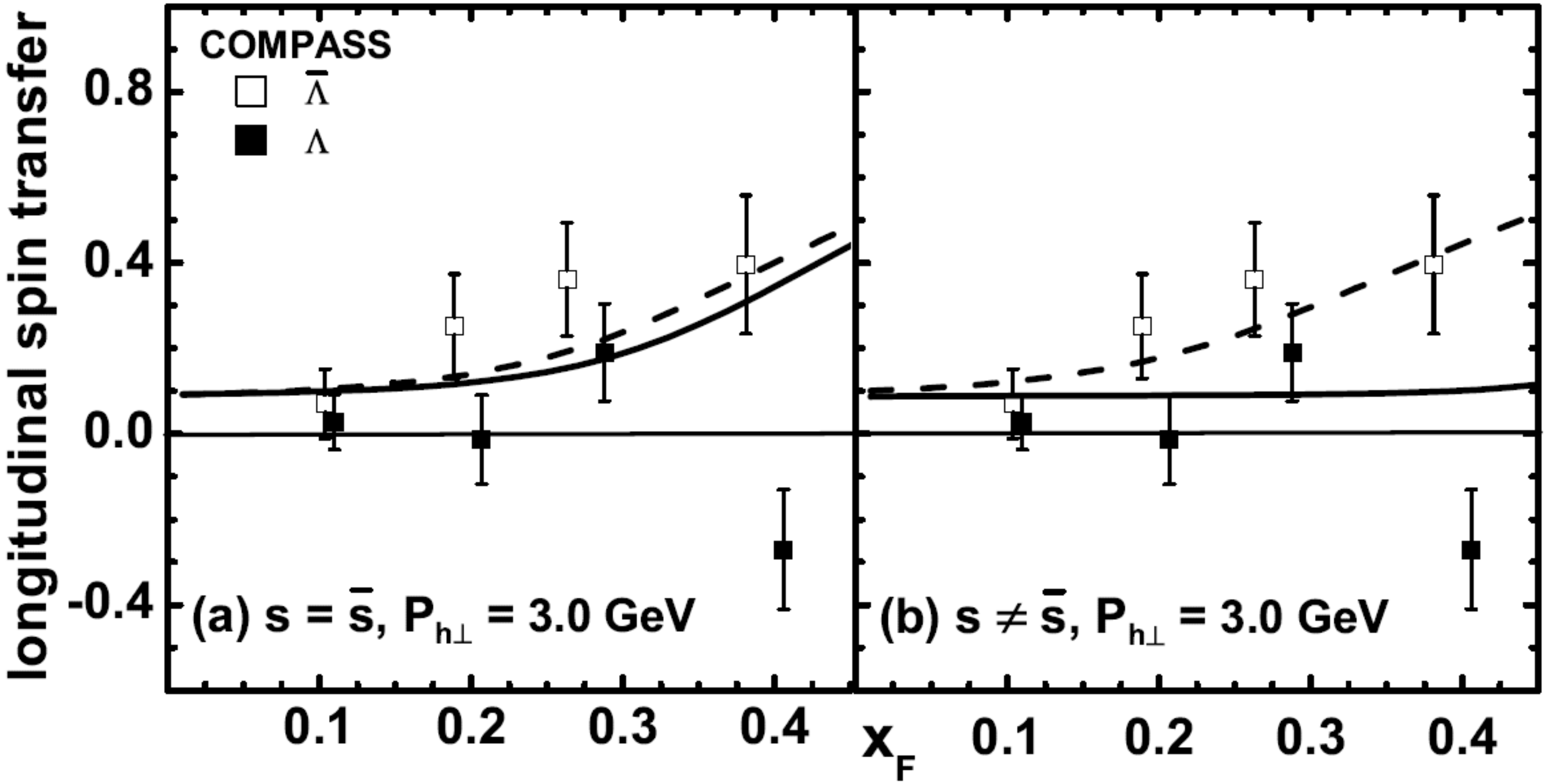
Y.Chi, B.-Q. Ma, Phys.Lett.B 726 (2013) 737

Results with new parametrization: Z-pole



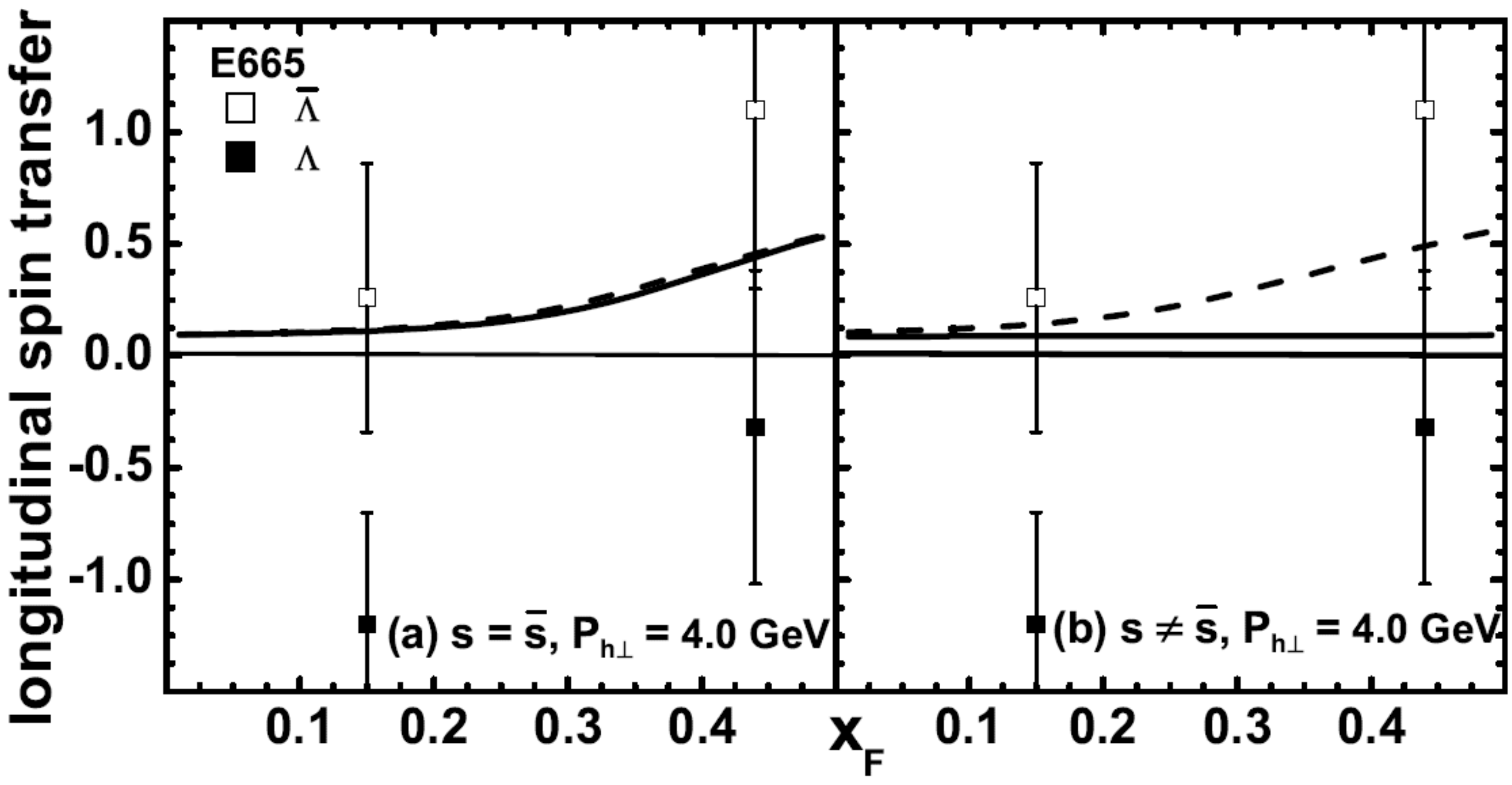
X.Du, B.-Q. Ma, PRD95 (2017) 014029

Difference between Lambda and anti-Lambda spin transfers with the COMPASS data



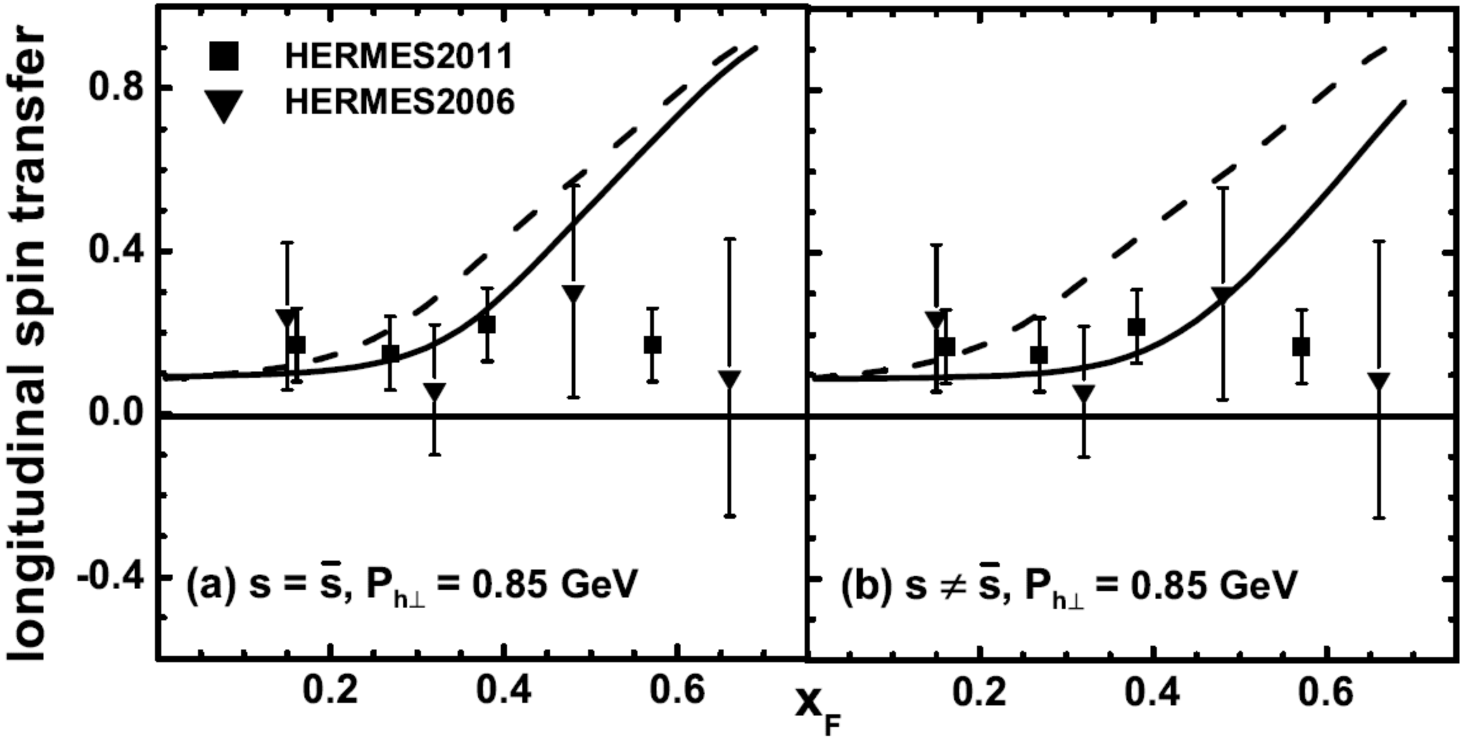
X.Du, B.-Q. Ma, PRD95 (2017) 014029

Difference between Lambda and anti-Lambda spin transfers with s-sbar asymmetry for E665



X.Du, B.-Q. Ma, PRD95 (2017) 014029

Difference between Lambda and anti-Lambda spin transfers with s-sbar asymmetry for HERMES



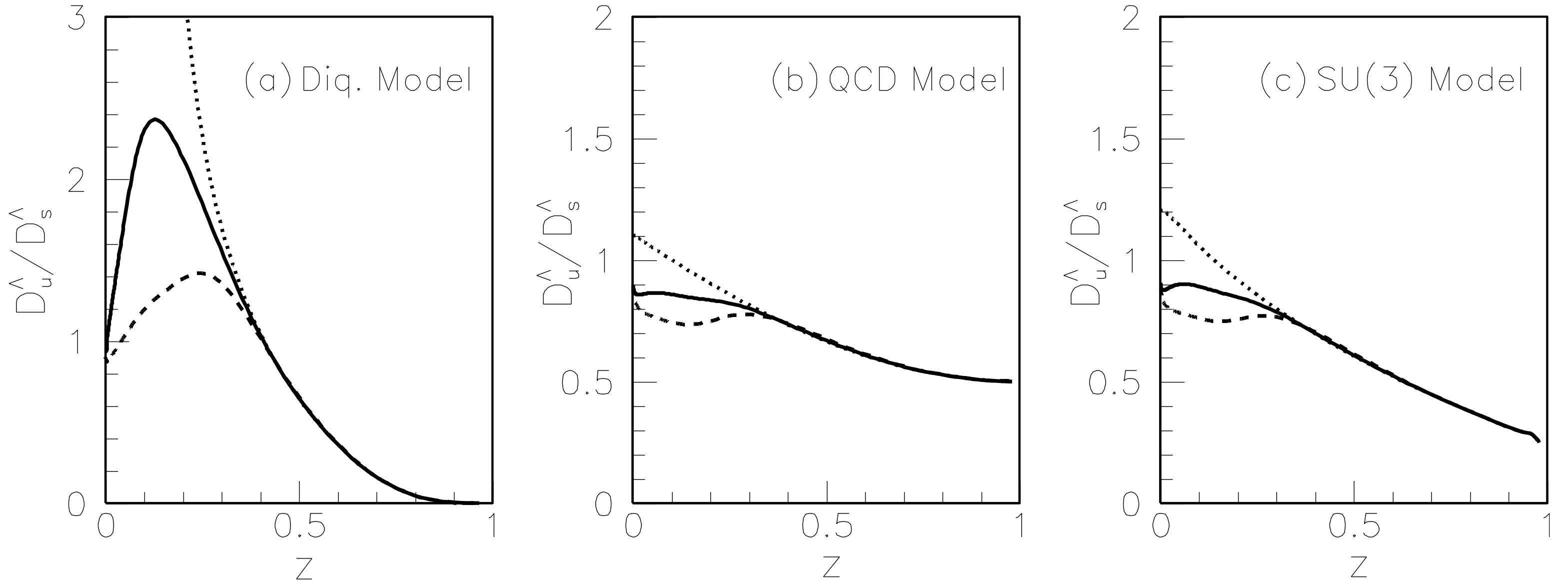
X.Du, B.-Q. Ma, PRD95 (2017) 014029

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

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

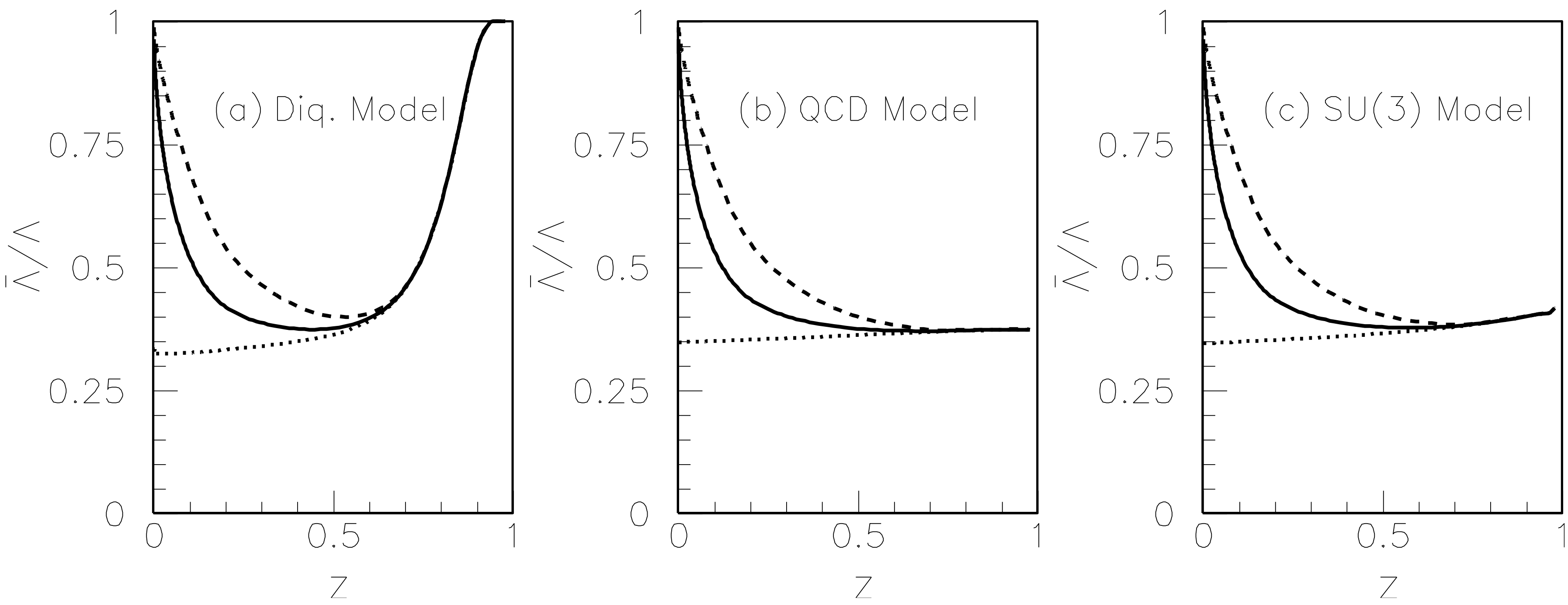
B.-Q. Ma, I. Schmidt, J.-J. Yang
Phys. Lett. B 574 (2003) 35

The flavor structure of Lambda
u/s ratio with x-dependence



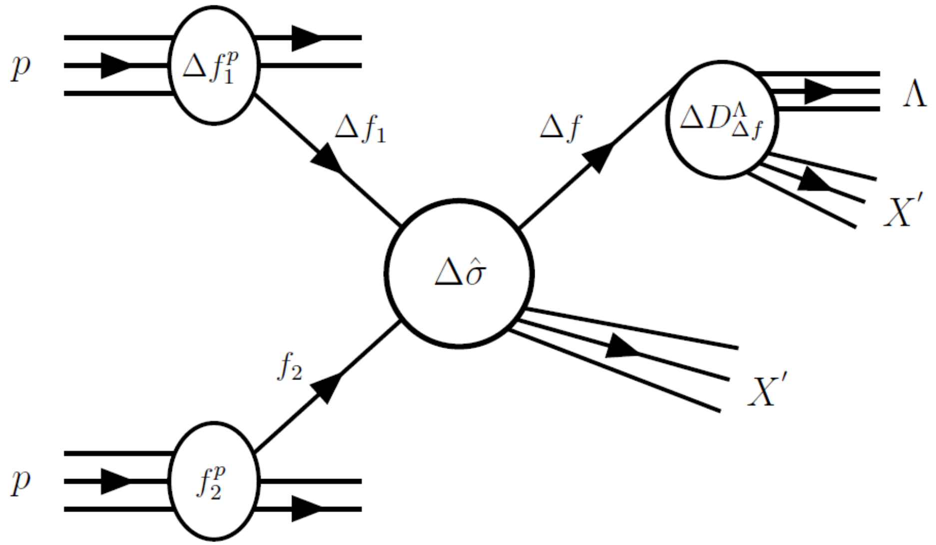
B.-Q. Ma, I. Schmidt, J.-J. Yang
Phys. Lett. B 574 (2003) 35

Different predictions



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

$$\vec{p}p \to \vec{\Lambda}X$$

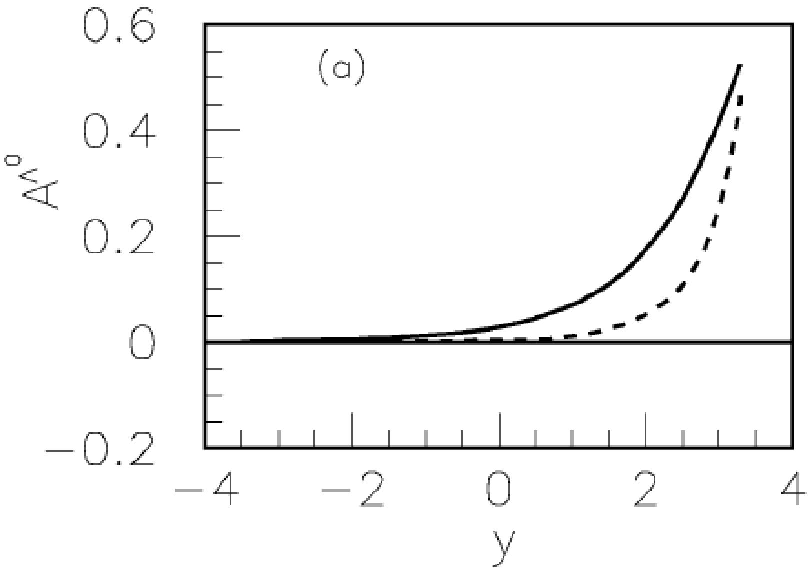


Providing information about

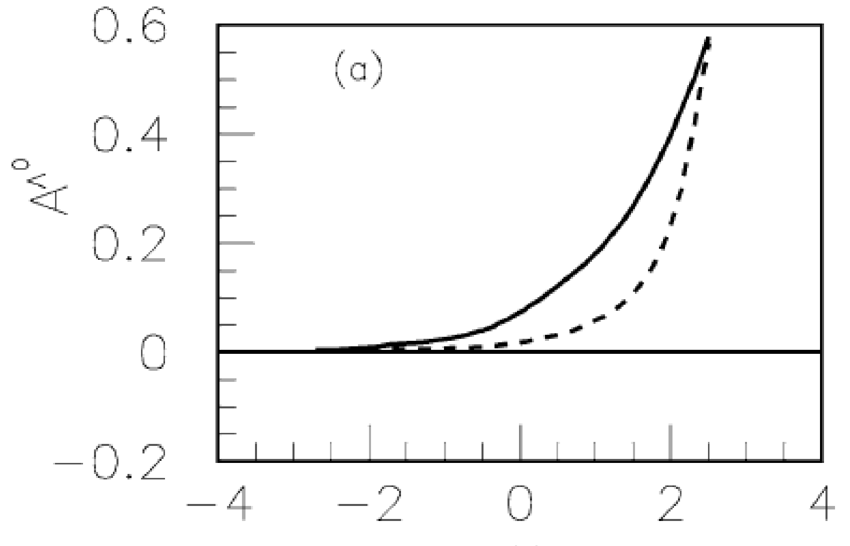
- the inclusive production of hadrons
- the strange and antistrange quark polarizations of the proton.

Spin transfer for

$$\vec{p}\,p \to \vec{\Lambda} X \text{ at RHIC-BNL}$$



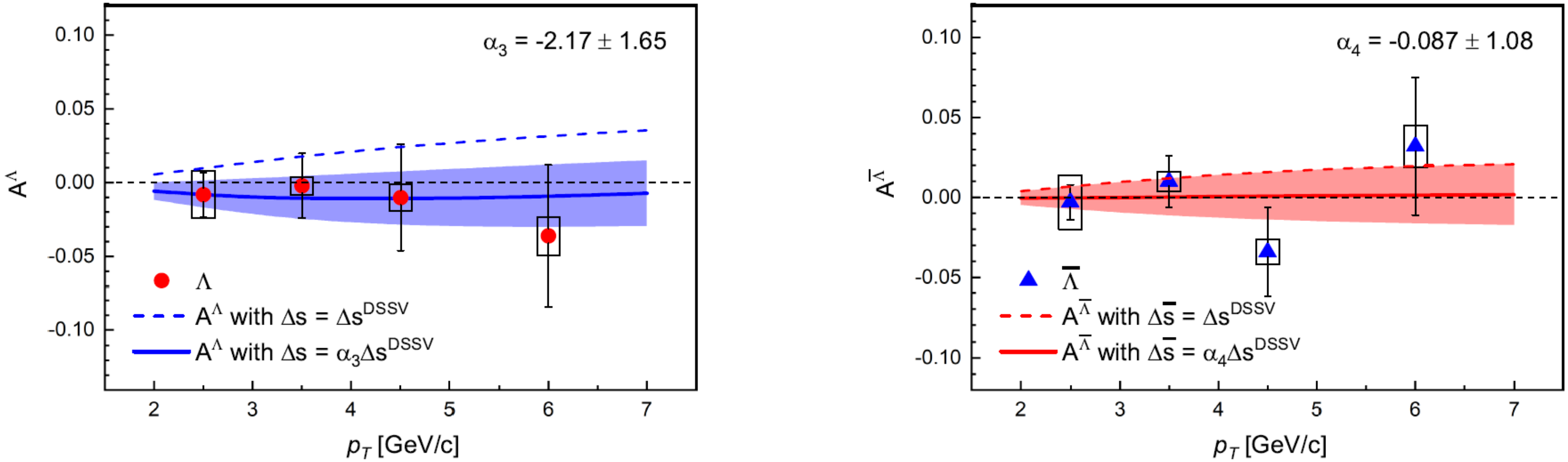
$\sqrt{s} = 500$ GeV



$\sqrt{s} = 200$ GeV

B.-Q. Ma, I. Schmidt, J.-J. Yang, J.Soffer, Nucl. Phys. A 703 (2002) 346

Fitting to STAR DATA



Xiaonan Liu, B.-Q. Ma, arXiv:1905.02360, EPJC 79 (2019) 409

Xiaonan Liu, B.-Q. Ma, arXiv:1905.02360, EPJC 79 (2019) 409

Results from fitting STAR data

Table: Fitting results of α_i and calculated results of Δs and $\Delta \bar{s}$.

	value	Δs	$\Delta \bar{s}$	χ^2_{min}
α_1	-1.20±1.31	-0.014±0.015		0.37
α_2	-0.24±0.49		-0.003±0.005	2.48
α_3	-2.17±1.65	-0.025±0.019		0.42
α_4	-0.087±1.08		-0.001±0.012	2.24

Two options: with/without gluon polarization

Xiaonan Liu, B.-Q. Ma, arXiv:1905.02360, EPJC 79 (2019) 409

Comparison with Predictions & Results

The central values of the fitting results are basically compatible with

- the light-cone meson-baryon fluctuation model[24] prediction $\Delta s(x) \approx -0.05$ to -0.01 and $\Delta \bar{s}(x) \approx 0$.
- the recent lattice QCD determination[25], $\Delta s^{+} = -0.02(1)$ at $Q^2 \approx 7\mathrm{GeV}^2$.
- the results from Jefferson Lab Angular Momentum (JAM) Collaboration[26] $\Delta s^{+}(Q_0^2) = -0.03(10)$.

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[24] S. J. Brodsky and B.-Q. Ma, Phys. Lett. B 381, 317 (1996).
[25] G. S. Bali et al. [QCDSF Collaboration], Phys. Rev. Lett. 108, 222001 (2012)
[26] J.J.Ethier, N.Sato and W.Melnitchouk, Phys. Rev. Lett. 119, 132001 (2017)

Relating Λ-production with nucleon strangeness

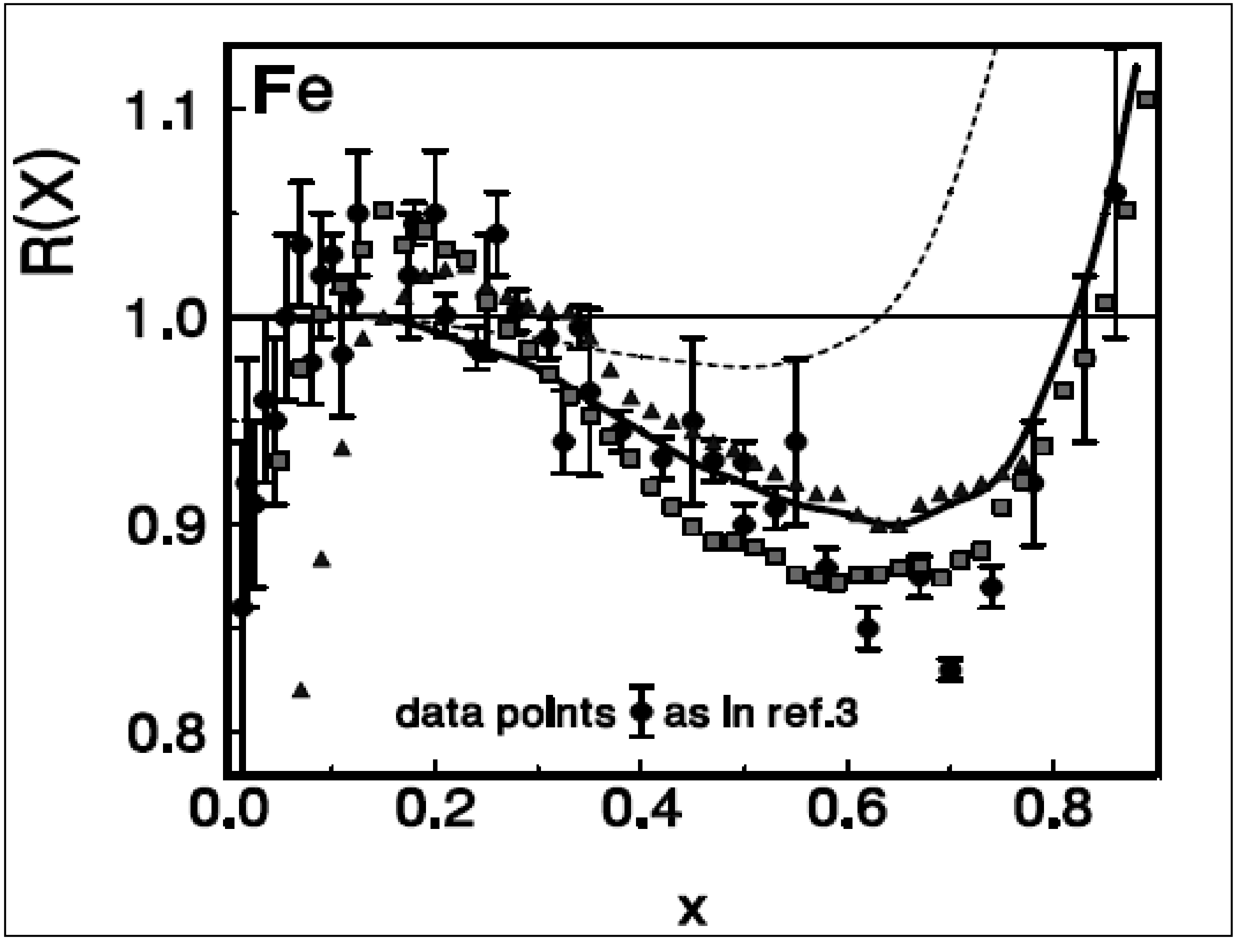
- **The spin transfer process of $\vec{p}p \to \vec{\Lambda}X$ is feasible to study strange-antistrange polarizations of the nucleon.**
- **The fitting to STAR data suggests:**

$$\Delta s \neq \Delta \bar{s}$$
$$\Delta s \approx -0.025 \pm 0.019$$
$$\Delta \bar{s} \approx -0.001 \pm 0.012$$

- **The results are compatible with the light-cone baryon-meson fluctuation model prediction.**

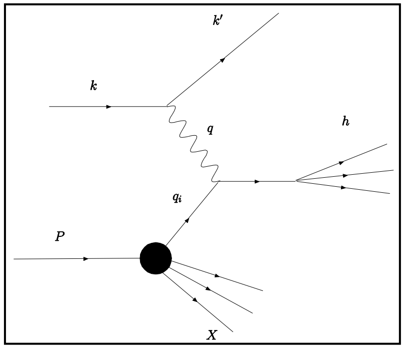
Xiaonan Liu, B.-Q. Ma, arXiv:1905.02360, EPJC 79 (2019) 409

Nuclear EMC Effect



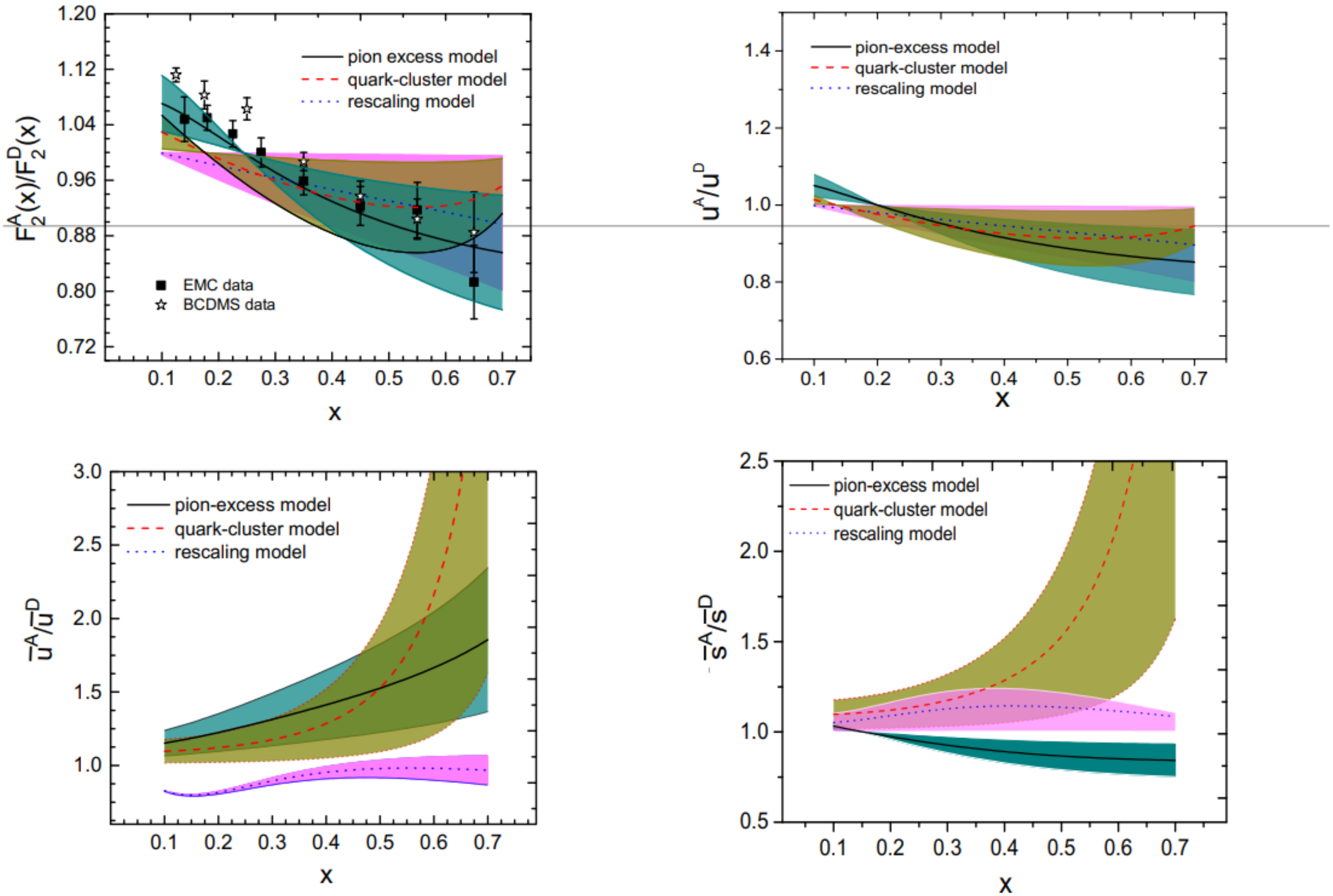
Anti-Lambda production as a probe of the nuclear sea structure?

- 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.



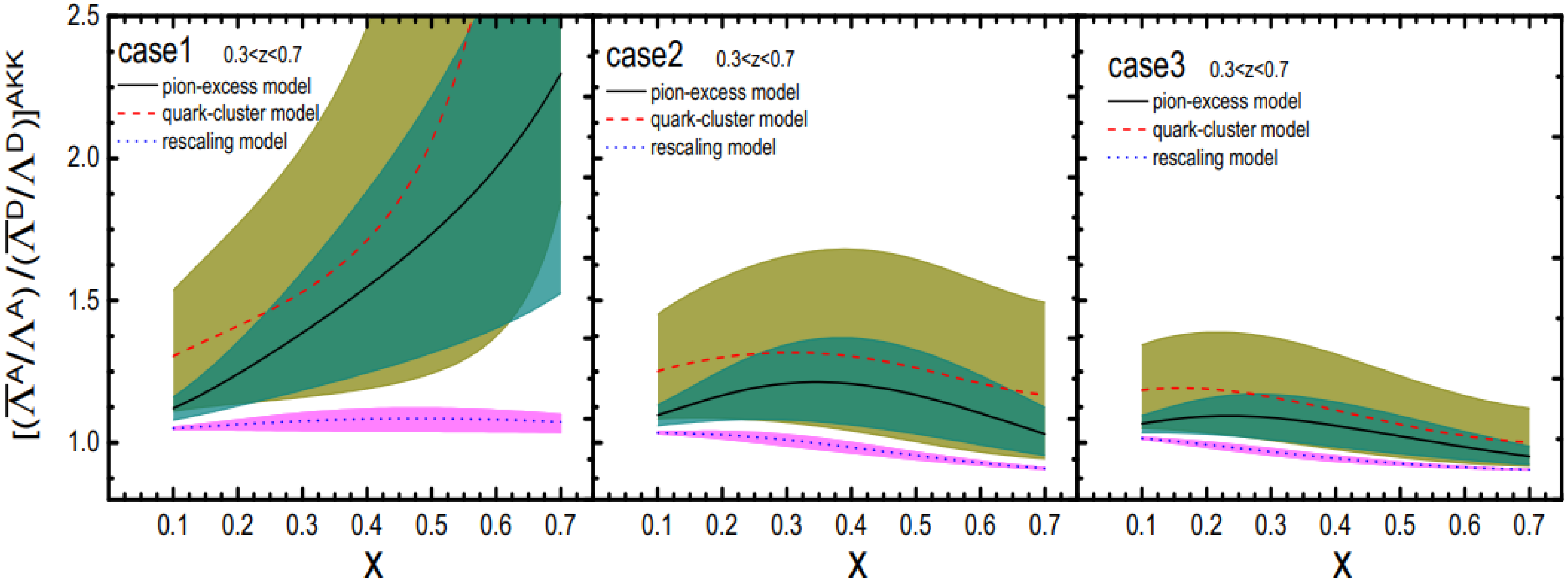
B.Lu, B.-Q. Ma, Phys.Rev.C74 (2006) 055202
C.Gong, B.-Q. Ma, Phys.Rev.C97 (2018) 065207

Different sea behaviors in nuclei



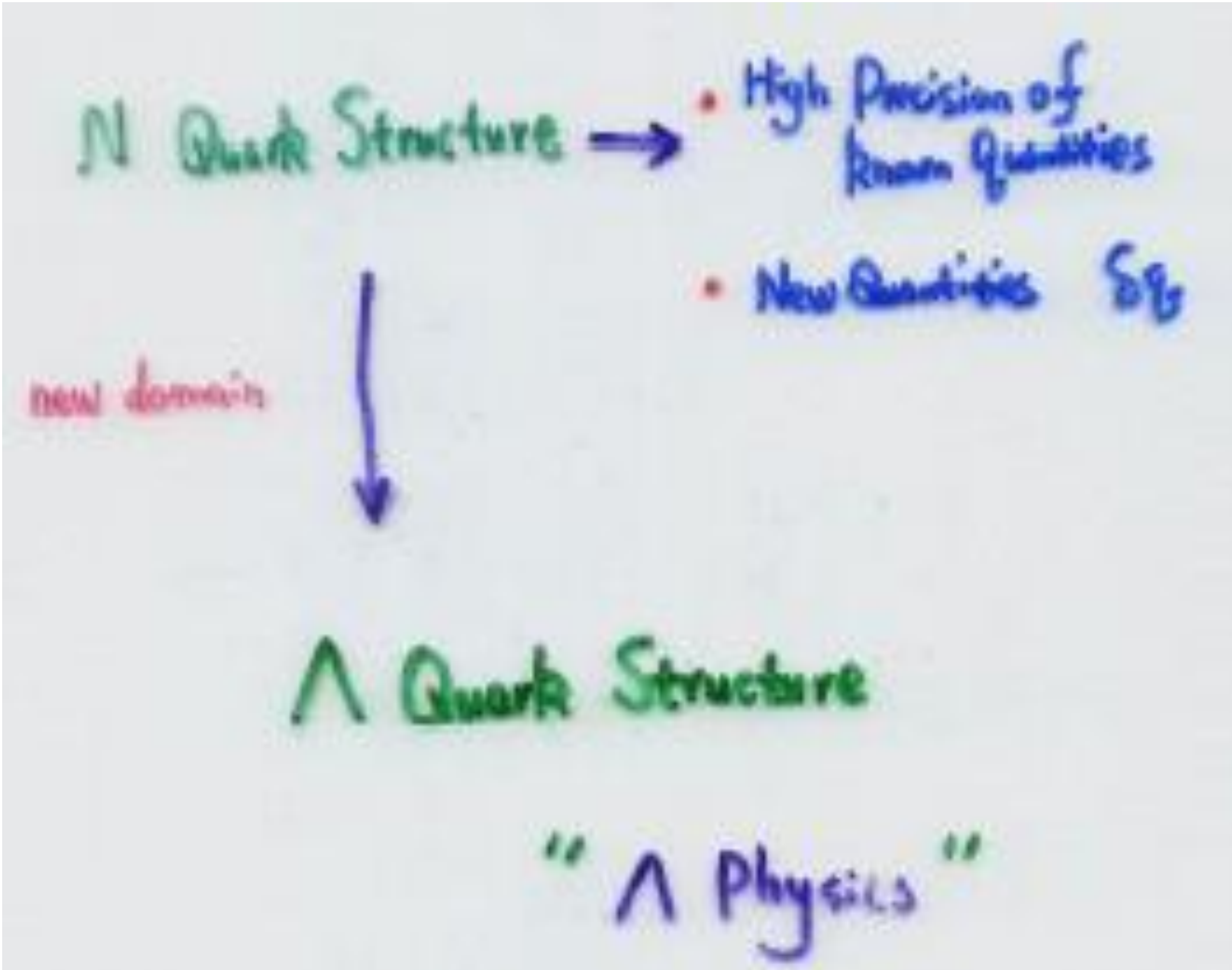
C.Gong, B.-Q. Ma, Phys.Rev.C97 (2018) 065207

Different predictions of anti-lambda production



C.Gong, B.-Q. Ma, Phys.Rev.C97 (2018) 065207

Conclusion 1: Lambda Physics



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$$\Delta s \approx -0.025 \pm 0.019$$

$$\Delta \bar{s} \approx -0.001 \pm 0.012$$

- **The results are compatible with the light-cone baryon-meson fluctuation model prediction.**

Xiaonan Liu, B.-Q. Ma, arXiv:1905.02360, EPJC 79 (2019) 409

Conclusion 3: 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.

B.Lu, B.-Q. Ma, Phys.Rev.C74 (2006) 055202
C.Gong, B.-Q. Ma, Phys.Rev.C97 (2018) 065207