The Quark-Antiquark Asymmetry of the Nucleon Strange Sea

M. Wakamatsu (February, 2002 / Trieste)

1. Introduction

- A **frustrating aspect** of **DIS analysis** is that **perturbative QCD** can predict only the Q^2**-dependence** of PDF, and it can say nothing about **PDF at a prescribed energy scale**
- To predict PDF themselves need to solve **nonperturbative QCD**, which is an extremely difficult theoretical problem
- At present, we cannot be too much **ambitious**, but still we can do **qualitatively interesting investigations** !

This is main objective of my present talk !

key observation

- In their semi-phenomenological fit, Glück, Reya and Vogt prepared the **initial PDF** at pretty **low energy scale** of $Q^2 \simeq (600\,\mathrm{MeV})^2$ in contrast to the common sense of perturbative QCD, and concluded that
- **sea-quark (or antiquark) components** are **absolutely necessary even at this low energy scale** !

- Even the **isospin asymetry** of the **sea-quark distributions** are established by the **NMC measurement**
- The origin of this **sea-quark asymmetry** is definitely **nonperturbative**, and it **cannot be radiatively generated** through the perturbative QCD evolution processes

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need **low energy (nonperturbative) mechanism**

generating sea-quark distributions

best candidate

- **Chiral Quark Soliton Model** (CQSM) is the **simplest** and **most powerful** effective model of QCD which fulfills the above requirement
- Although it is still a **toy model** in the sense that the **gluon degrees of freedom** are only **implicitly** treated, it has several nice features that are not possessed by other effective models like MIT bag model
- **field theoretical nature** of the model (i.e. proper account of **Dirac sea quarks**) enables

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reasonable estimation of **antiquark distributions**

2. Fundamentals of Chiral Quark Soliton Model

milestone in the history of CQSM

[1988] D. Diakonov, V. Petrov and P. Pobylitsa

- **proposal of the model** based on

  instanton picture of QCD vacuum

  ($\Leftrightarrow$ **Skyrme model**, Hybrid chiral bag model, $\cdots$)

[1991] M. W and H. Yoshiki

- **numerical basis** for **nonperturbative evaluation** of nucleon observables including **vacuum polarization**
- **spin contents of the nucleon**

[1993] M. W and T. Watabe

- discovery of **novel $1/N_c$ correction**

  — **resolution of g_A-problem** —

[1996,1997] D. Diakonov et al.

- application to **PDF** of the nucleon

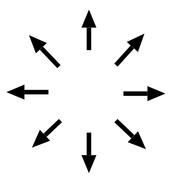
basic lagrangian of flavor SU(2) CQSM

$$\mathcal{L}_{CQM} = \bar{\psi} \left(i \not\partial - M \, e^{i \gamma_5 \boldsymbol{\tau} \cdot \boldsymbol{\pi}(x) / f_\pi} \right) \psi$$

no kinetic term for $\boldsymbol{\pi}(x)$

Soliton construction

1st step : start with static $\boldsymbol{\pi}(\boldsymbol{x})$ of **hedgehog shape**



$$\boldsymbol{\pi}(\boldsymbol{x}) = \hat{\boldsymbol{r}} \, F(r)$$

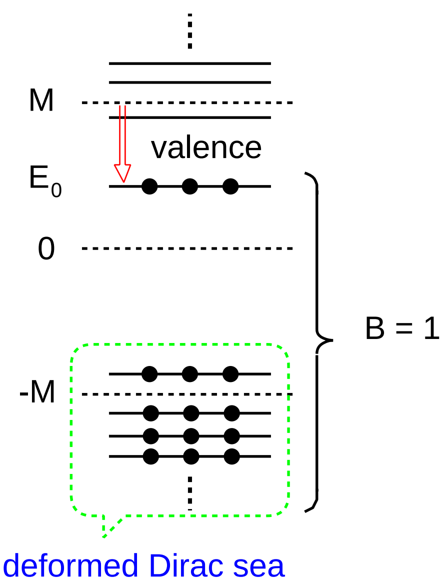
M.F. for quarks

Dirac eq.

$$H \, | \, m \rangle = E_m \, | \, m \rangle$$

$$H = \frac{\boldsymbol{\alpha} \cdot \nabla}{i} + M \beta \left(\cos F(r) + i \gamma_5 \, \boldsymbol{\tau} \cdot \hat{\mathbf{r}} \sin F(r) \right)$$

breaks "rotational" invariance



- The problem is reduced to a **self-consistent Hatree one** including all the **negative energy Dirac-sea** orbitals

2nd step : quantize **collective rotational motion**

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physical N and Δ

model need regularization

Pauli-Villars regularization with

physical cutoff mass M_{PV}

— M_{PV} is uniquely fixed to reproduce f_π —

quark distribution functions : $(-1 < x < 1)$

$$q(x) = \frac{1}{4\pi} \int_{-\infty}^{\infty} dz^0 \, e^{i\,x\,M_N\,z^0}$$

$$\times \underbrace{\langle N(\boldsymbol{P}) \,|\, \psi^\dagger(\boldsymbol{0})\, O\, \psi(\boldsymbol{z}) \,|\, N(\boldsymbol{P}) \rangle}\, |_{z^3=-z^0,\, z_\perp=0}$$

nucleon matrix element of **bilocal operator**

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path integral formulation of the model enables us to take full account of this **nonlocality in time** !

3. Comparison with High Energy Data

- **only 1 parameter** of the CQSM (dynamical quark mass M) is fixed from the analyses of **nucleon LE observables**

$$M = 375\,\mathrm{MeV} \quad (\text{ this fixes } M_{PV} \simeq 562\,\mathrm{MeV})$$

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parameter free predictions for **PDF**

- use predictions of CQSM as **initial-scale distributions**

$$u(x),\ \bar{u}(x),\ d(x),\ \bar{d}(x),\ \ \Delta u(x),\ \Delta\bar{u}(x),\ \Delta d(x),\ \Delta\bar{d}(x)$$

$$s(x) = \bar{s}(x) = \mathbf{0},\ g(x) = \mathbf{0},\ \Delta s(x) = \Delta\bar{s}(x) = \mathbf{0},\ \Delta g(x) = \mathbf{0}$$

- **scale dependence of PDF** : (setting $N_c = 3$)

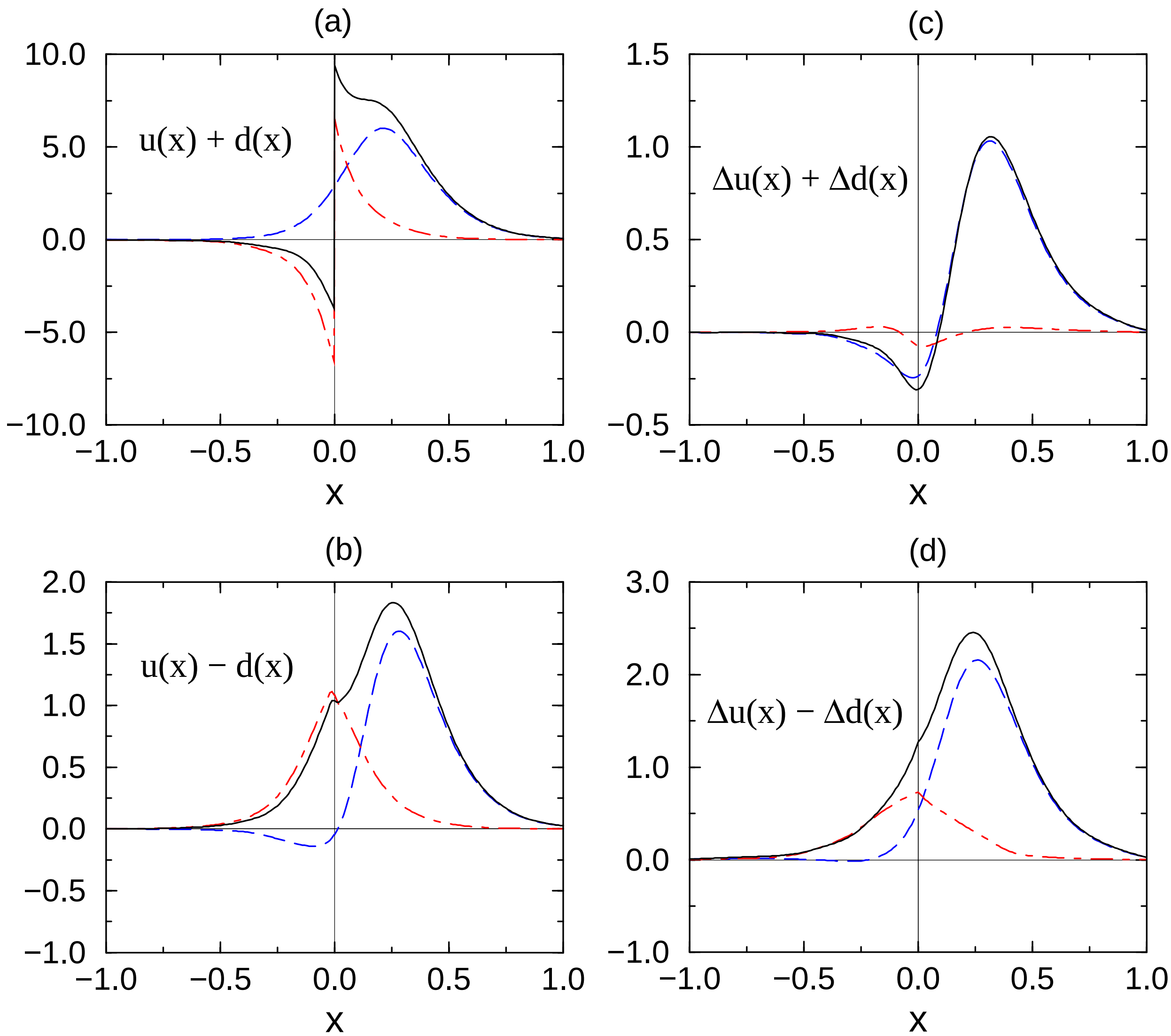
Fortran Program of **DGLAP** eqs. at **NLO**

provided by Saga group

initial energy scale is fixed to be

$$Q^2_{ini} = 0.30\,\mathrm{GeV}^2 \quad \simeq \quad (550\,\mathrm{MeV})^2$$

Parameter-free model predictions for twist-2 PDF



$$\begin{cases} u(-x) \ \pm \ d(-x) \ = \ -\left[\bar{u}(x) \ \pm \bar{d}(x)\right] & (0 < x < 1) \\ \Delta u(-x) \ \pm \ \Delta d(-x) \ = \ \Delta \bar{u}(x) \ \pm \ \Delta \bar{d}(x) & (0 < x < 1) \end{cases}$$

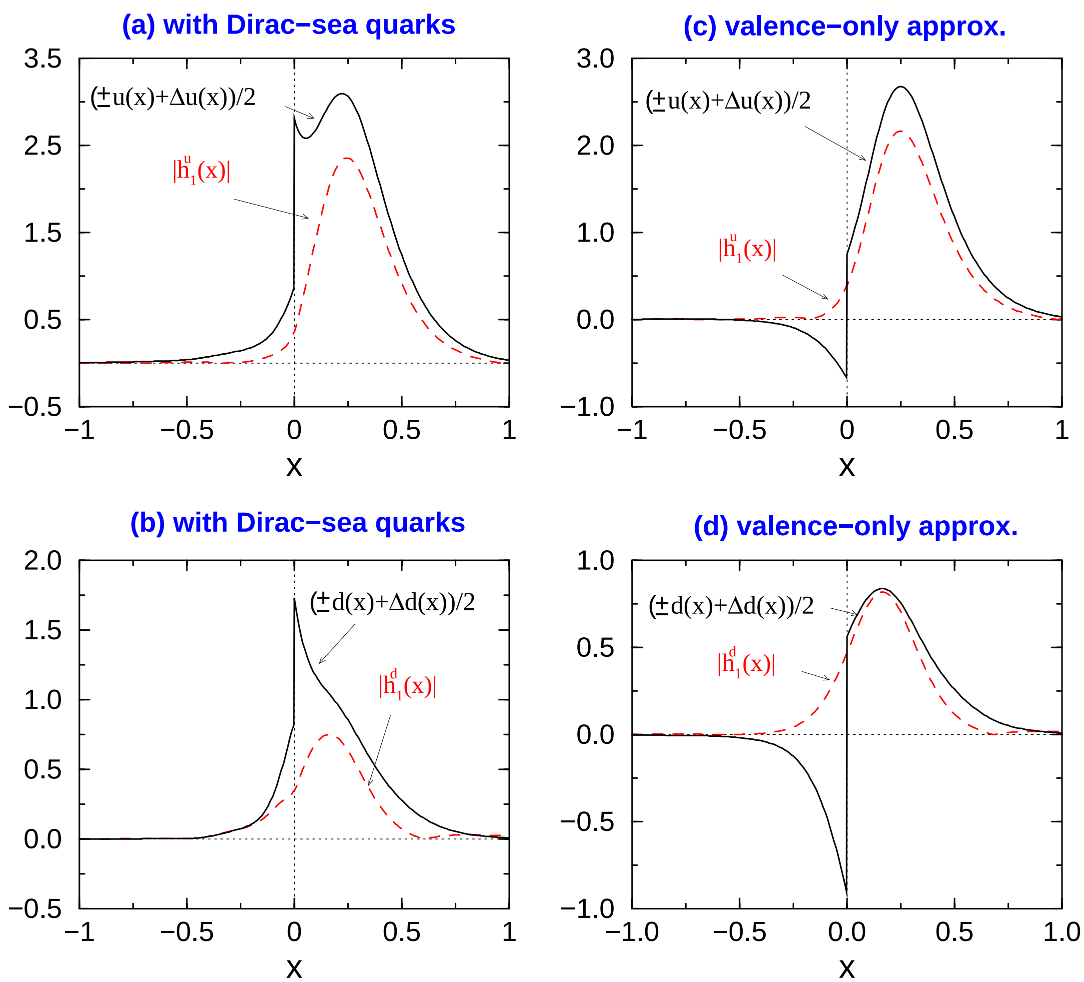
Soffer inequality for twist-2 PDF

$q(x)$: unpolarized distribution

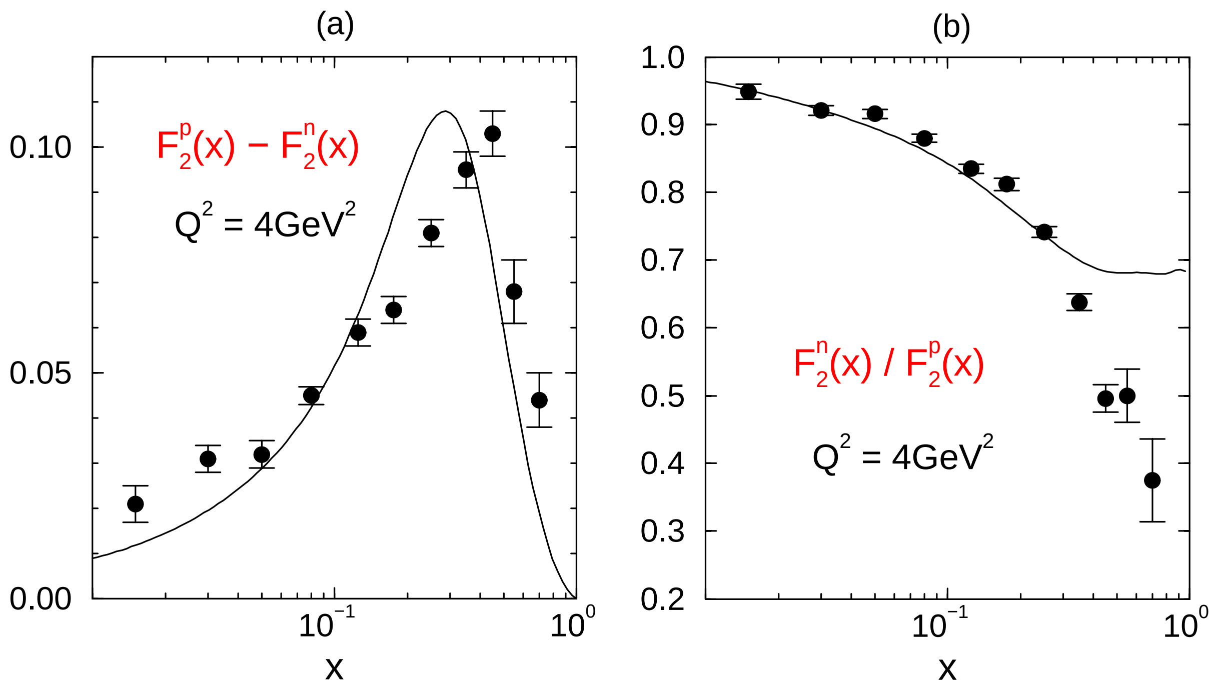
$\Delta q(x)$: longitudinally polarized distribution

$\delta q(x)$: **transversity distribution**

$$|\pm\,\delta q(x)| \;\leq\; \frac{1}{2}\,(\pm\, q(x) \;+\; \Delta q(x)) \qquad \begin{cases} x > 0 \\ x < 0 \end{cases}$$



direct comparison with **NMC data**



Gottfried sum

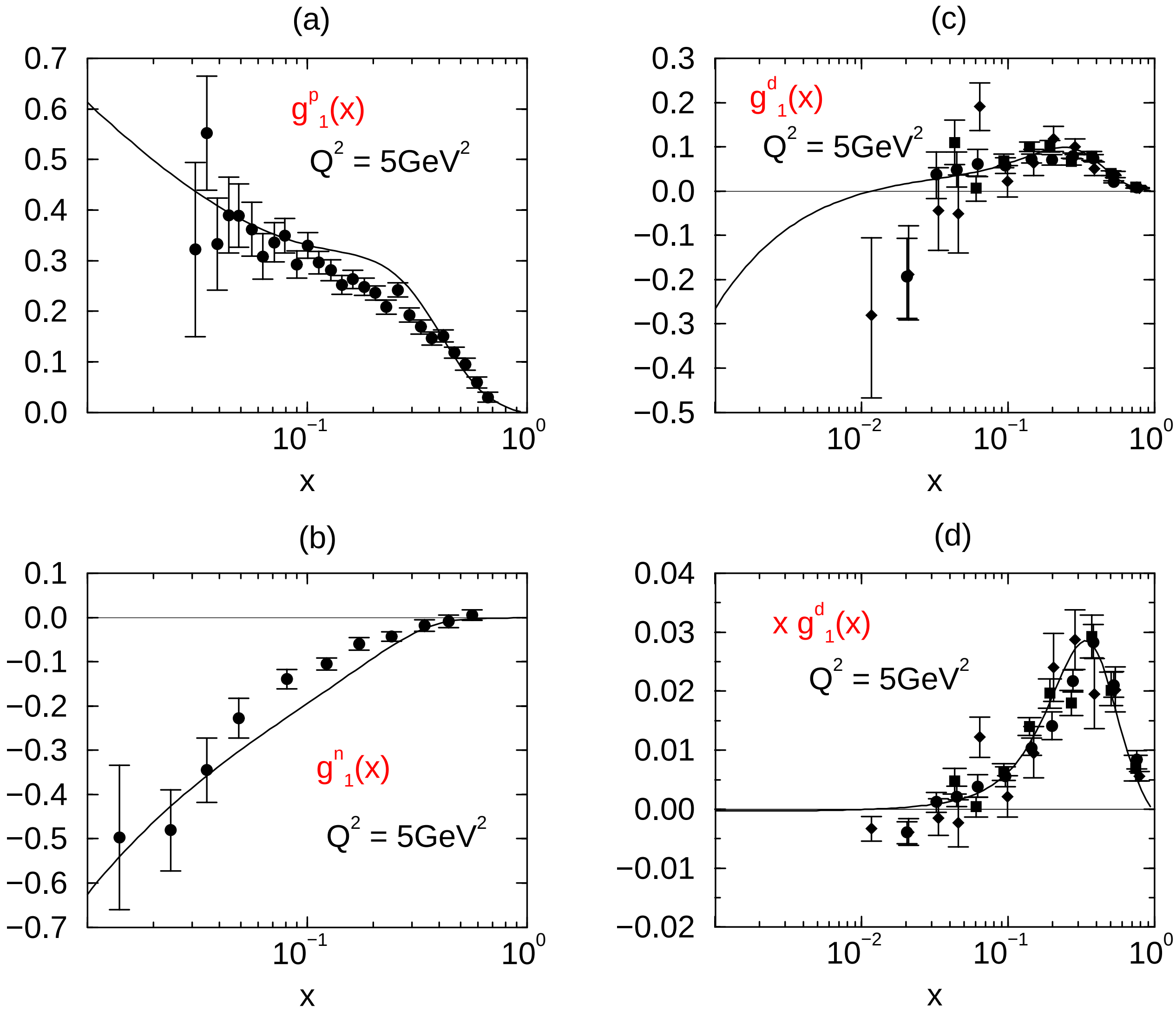
$$S_G = \int_0^1 \frac{F_2^p(x) - F_2^n(x)}{x}\, dx = \frac{1}{3} + \int_0^1 \{\, \bar{u}(x) - \bar{d}(x) \,\}$$

$$S_G^{th}(Q^2 = 4\,\mathrm{GeV}^2) \simeq \mathbf{0.204} < \frac{1}{3}$$

$$\Updownarrow$$

$$S_G^{exp}(Q^2 = 4\,\mathrm{GeV}^2) = \mathbf{0.228} \pm 0.007$$

comparison with **EMC** and **SMC** data



- good reproduction of **neutron data** !

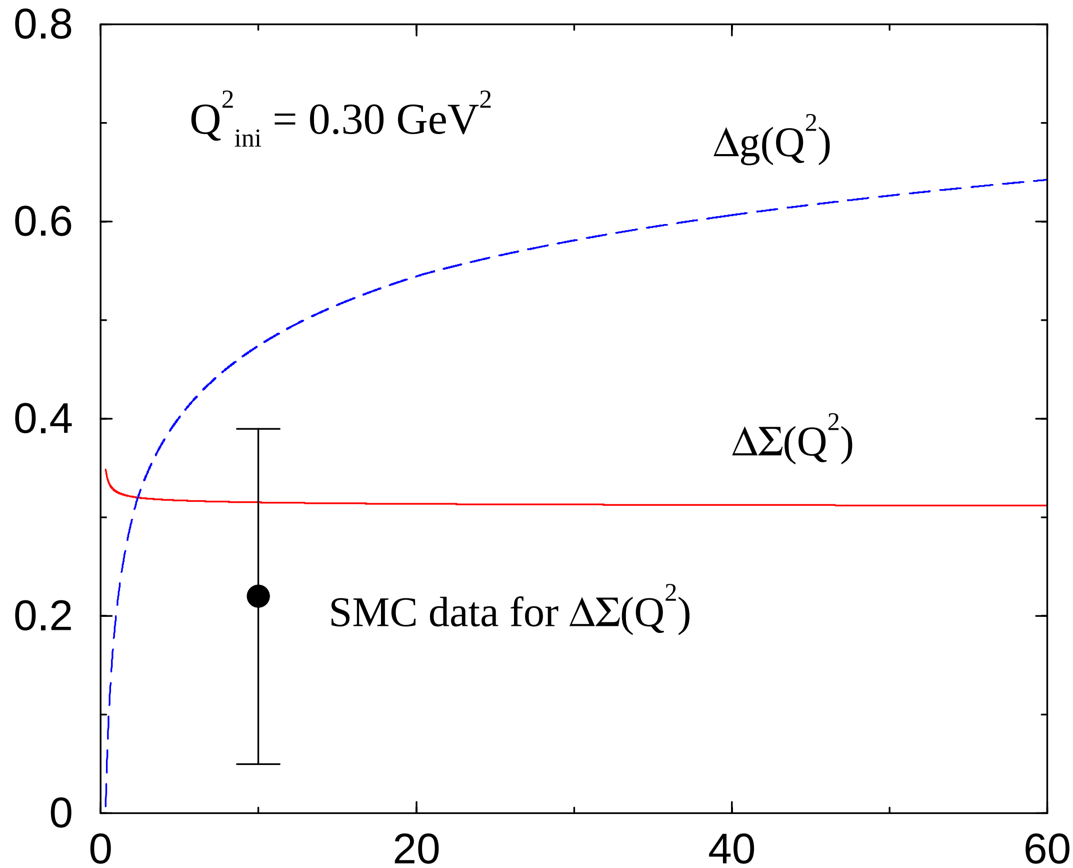
— manifestation of **chiral symmetry** —

- **sign change** of $g_1^d(x)$ at **small** x !

NLO evolution of $\mathbf{\Delta\Sigma}$ and $\mathbf{\Delta g}$

- $\Delta\Sigma \;=\; \mathbf{0.35}$
- $\Delta g \;=\; \mathbf{0}$

$\Big\}$ at $Q^2_{ini} \;=\; 0.30\,\mathrm{GeV}^2$



comparison with SMC analysis

$$\Delta\Sigma\,(Q^2 = 10\,\mathrm{GeV}^2) \;=\; \mathbf{0.31} \quad\Longleftrightarrow\quad \Delta\Sigma_{SMC} \;=\; \mathbf{0.22 \pm 0.17}$$

natural question after NMC observation

Do we expect **light flavor sea-quark asymmetry** also for the **spin dependent PDF** ?

answer of CQSM is Yes !

$$\Delta\bar{u}(x) - \Delta\bar{d}(x) \ > \ 0 \quad \text{with} \quad \Delta\bar{u}(x) > 0, \ \Delta\bar{d}(x) < 0$$

which seems **consistent** with some semi-phenomenological analyses using **semi-inclusive data** by

- T. Morii, T. Yamanishi, Phys. Rev. D61 (2000) 057501
- R.S. Bhalerao, Phys. Rev. C63 (2001) 025208

but it **contradicts** the predictions of the **meson cloud convolution model** which predicts

$$\Delta\bar{u}(x) \ - \ \Delta\bar{d}(x) \quad : \quad \textbf{small or negative}$$

- R.J. Fries, A. Schäfer, Phys. Lett. B443 (1998) 40
- S. Kumano, M. Miyama, hep-ph / 0110097

Summary of SU(2) CQSM

without any adjustable parameter, the model reproduces

- **NMC data** for $F_2^p(x) - F_2^n(x), F_2^n(x)/F_2^p(x)$
- qualitative behavior of experimentally measured longitudinally **polarized** structure functions $g_1^p(x), g_1^n(x), g_1^d(x)$

- **small quark spin fraction of the nucleon**

$$\Delta\Sigma^{th}(Q^2 = 10\,\mathrm{GeV}^2) \;=\; 0.31 \;\;\Leftrightarrow\;\; \Delta\Sigma_{SMC}(Q^2 = 10\,\mathrm{GeV}^2) \;=\; 0.22 \pm 0.17$$

in **no need of large gluon polarization**
at **low energy scale**

a unique prediction

- **large isospin asymmetry** of **spin-dependent sea**

$$\Delta\bar{u}(x) \;>\; 0 \;>\; \Delta\bar{d}(x)$$

$$\Updownarrow$$

contradicts the prediction of **Meson Cloud Model**

4. Strange quark distributions in the nucleon

flavor SU(2) CQSM ignores interesting possibility of

hidden strangeness excitations in nucleon

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flavor SU(3) generalization of CQSM

which is constructed on the basis of SU(2) CQSM with

some **additional dynamical assumptions**

model lagrangian

$$\mathcal{L} \;=\; \bar{\psi}(x)\,(\,i\;\partial\!\!\!/ \;-\; M\,U^{\gamma_5}(x) \;-\; \Delta m_s\,P_s\,)\;\psi(x)$$

with

$$U^{\gamma_5}(x) \;=\; e^{\,i\,\gamma_5\,\pi(x)/f_\pi}, \qquad \pi(x) \;=\; \pi_a(x)\,\lambda_a \quad (a = 1, \cdots, 8)$$

$$\Delta m_s\,P_s \;=\; \begin{pmatrix} 0 & & \\ & 0 & \\ & & \Delta m_s \end{pmatrix} \qquad : \qquad \textbf{SU(3) breaking term}$$

basic dynamical assumptions

(1) **lowest energy classical solution** is obtained by

embedding of SU(2) hedgehog solution

$$U_0^{\gamma_5}(\boldsymbol{x}) \;=\; \begin{pmatrix} e^{\,i\,\gamma_5\,\boldsymbol{\tau}\cdot\hat{\boldsymbol{r}}\,F(r)} & 0 \\ 0 & 1 \end{pmatrix}$$

(2) **quantization** of **symmetry restoring rotation**

in **SU(3) collective coordinate space**

$$U^{\gamma_5}(\boldsymbol{x},t) \;=\; A(t)\,U_0^{\gamma_5}(\boldsymbol{x})\;A^\dagger(t)$$

with

$$A(t) \;=\; e^{-\,i\,\Omega\,t}, \quad \Omega \;=\; \frac{1}{2}\,\Omega_a\,\lambda_a \;\in\; \mathrm{SU(3)}$$

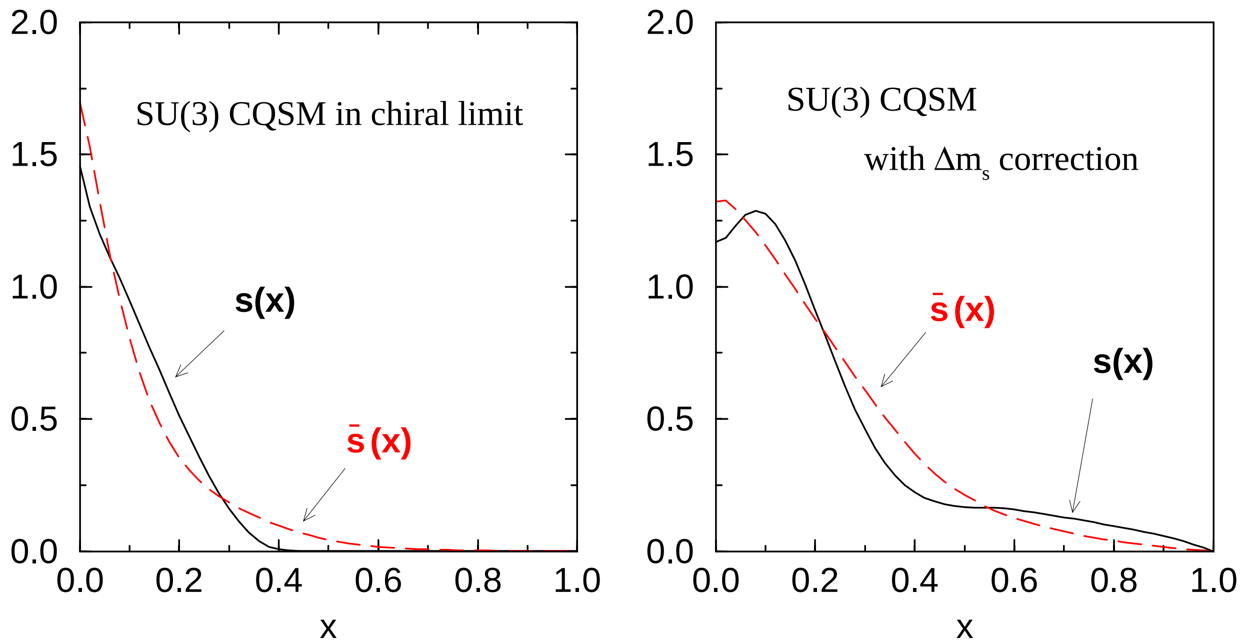
(3) **perturbative treatment** of **SU(3) breaking term**

$$\Delta\tilde{H} \;=\; \Delta m_s \cdot \gamma^0\,A^\dagger(t)\left(\frac{1}{3} \;-\; \frac{1}{\sqrt{3}}\,\lambda_8\right)A(t)$$

$$\Delta m_s \;=\; 150\,\mathrm{MeV}$$

theoretical strange quark distributions

(A) **unpolarized distribution**



- $\boldsymbol{s - \bar{s}}$ **asymmetry** of the **unpolarized** distribution functions certainly exists

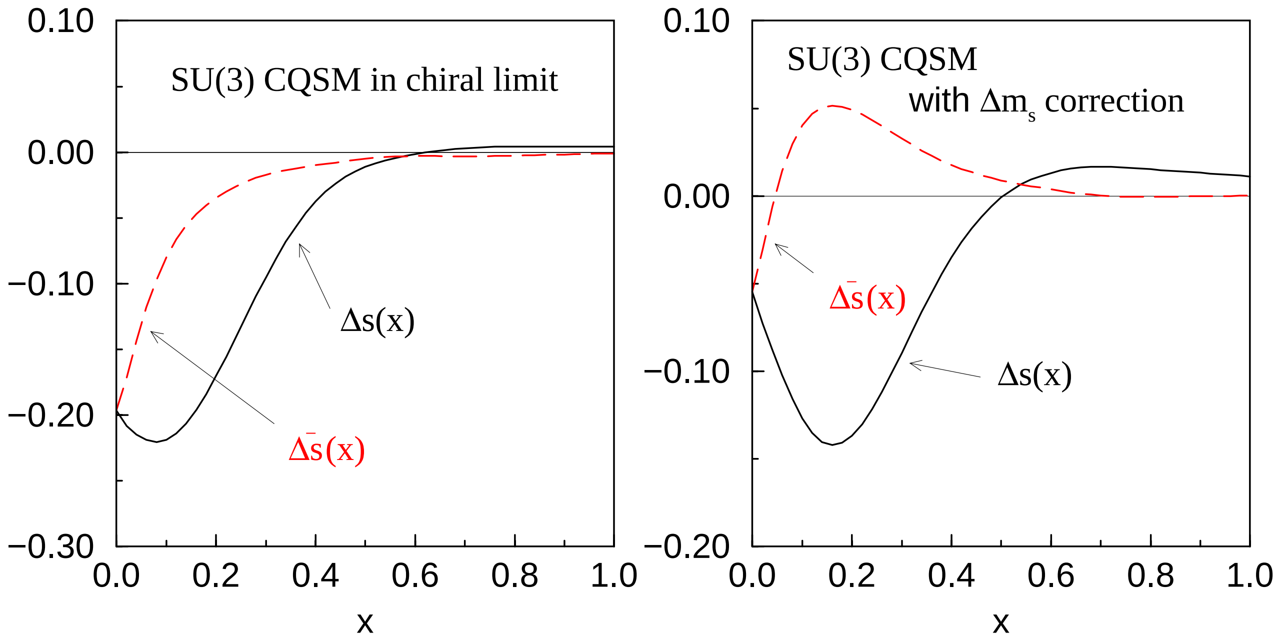
- difference $s(x) - \bar{s}(x)$ has **complicated** $\boldsymbol{x}$ **dependence** with several **zeros**, due to the **restrictions** :

$$s(x) > 0, \quad \bar{s}(x) > 0 \quad : \quad \text{positivity constraint}$$

$$\int [\, s(x) - \bar{s}(x) \,]\, dx = 0 \quad : \quad \text{strangeness conservation}$$

- $\boldsymbol{s(x) - \bar{s}(x)}$ is very **sensitive to SU(3) breaking**

(B) **longitudinally polarized distributions**



- $\Delta s(x)$ is **large and negative**
- $\Delta \bar{s}(x)$ is very sensitive to SU(3) breaking effect

  - **slightly negative** without Δm_s correction
  - **slightly positive** with Δm_s correction

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- $\boldsymbol{s - \bar{s}}$ **asymmetry** of the **longitudinally polarized** distribution is **more profound** than the **unpolarized one**
- there exists **large asymmetry** between $\boldsymbol{\Delta s(x)}$ and $\boldsymbol{\Delta \bar{s}(x)}$

simple argument of Brodsky and Ma

— light-cone meson-baryon fluctuation model —

$$p(1/2^+) \quad \longleftrightarrow \quad \overbrace{K^+(0^-)\ \Lambda(1/2^+)}^{L\,=\,odd}$$

virtual $K^+\,\Lambda$ state : (L=1)

$$|K^+\,\Lambda\,(J=\frac{1}{2}, J_z=\frac{1}{2})\rangle \;=\; \sqrt{\frac{2}{3}}\,|L=1, L_z=1\,\rangle\,|S=\frac{1}{2}, S_z=-\frac{1}{2}\,\rangle$$
$$-\;\sqrt{\frac{1}{3}}\,|L=1, L_z=0\,\rangle\,|S=\frac{1}{2}, S_z=+\frac{1}{2}\,\rangle$$

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- $P(S_\Lambda = \downarrow) \;=\; \mathbf{2}\,P(S_\Lambda = \uparrow)$ in $K^+\Lambda$ state $\quad\Rightarrow\quad \boldsymbol{S_\Lambda < 0}$
- since $\boldsymbol{\Lambda}\,[uds]$ **spin** comes from ***s*-quark**

$$\boldsymbol{\Delta s \;<\; 0}$$

- since **$\bar{s}$-quark** is contained in $K^+[u\bar{s}]$ with **0 spin**

$$\boldsymbol{\Delta \bar{s} \;=\; 0}$$

♣ **Note** that the simular argument on **pion clouds** lead to

$$\boldsymbol{\Delta \bar{d}(x) \;=\; \Delta \bar{u}(x) \;=\; 0}$$

because $\bar{d}$ and $\bar{u}$ are in **spin 0 pions**, in sharp contrast to the prediction of the **CQSM** such that $\boldsymbol{\Delta \bar{u}(x) \;>\; 0 \;>\; \Delta \bar{d}(x)}$!

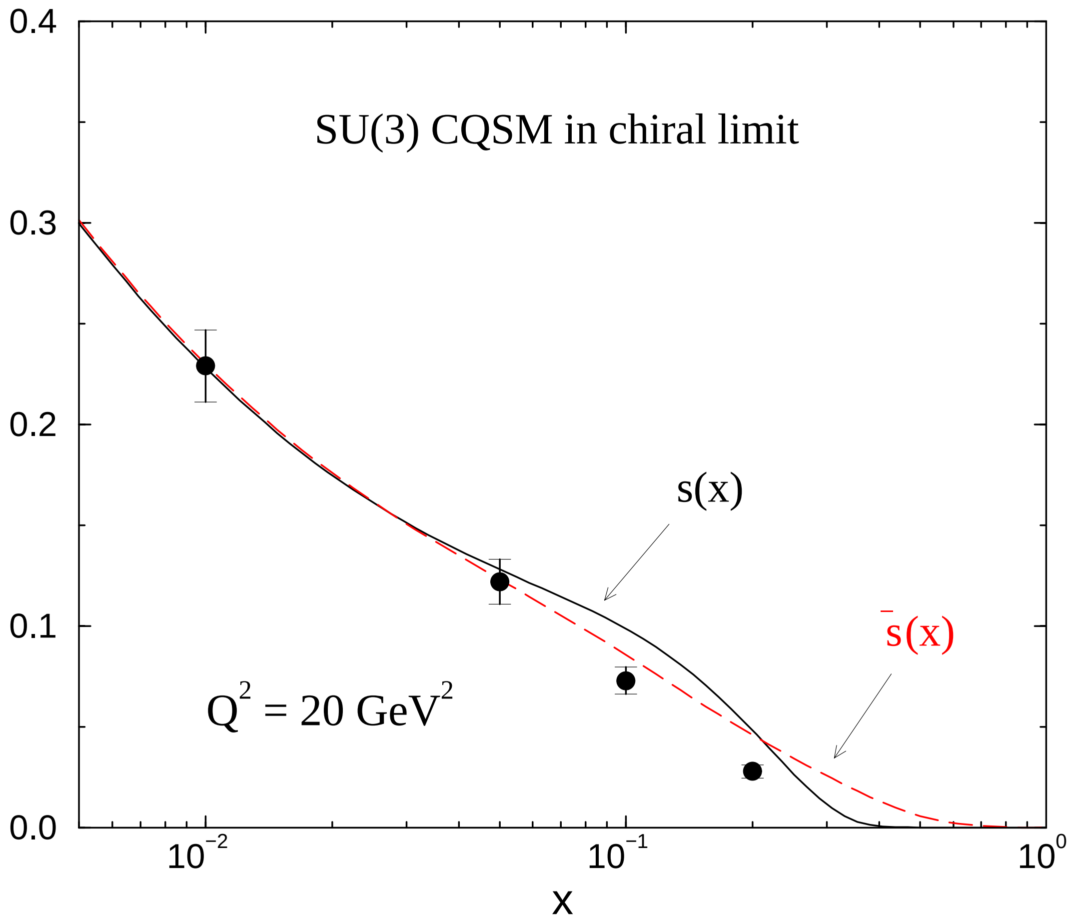
preliminary comparison with existing data

theoretical distributions $s(x)$ and $\bar{s}(x)$ at $Q^2 = 20\,\mathrm{GeV}^2$

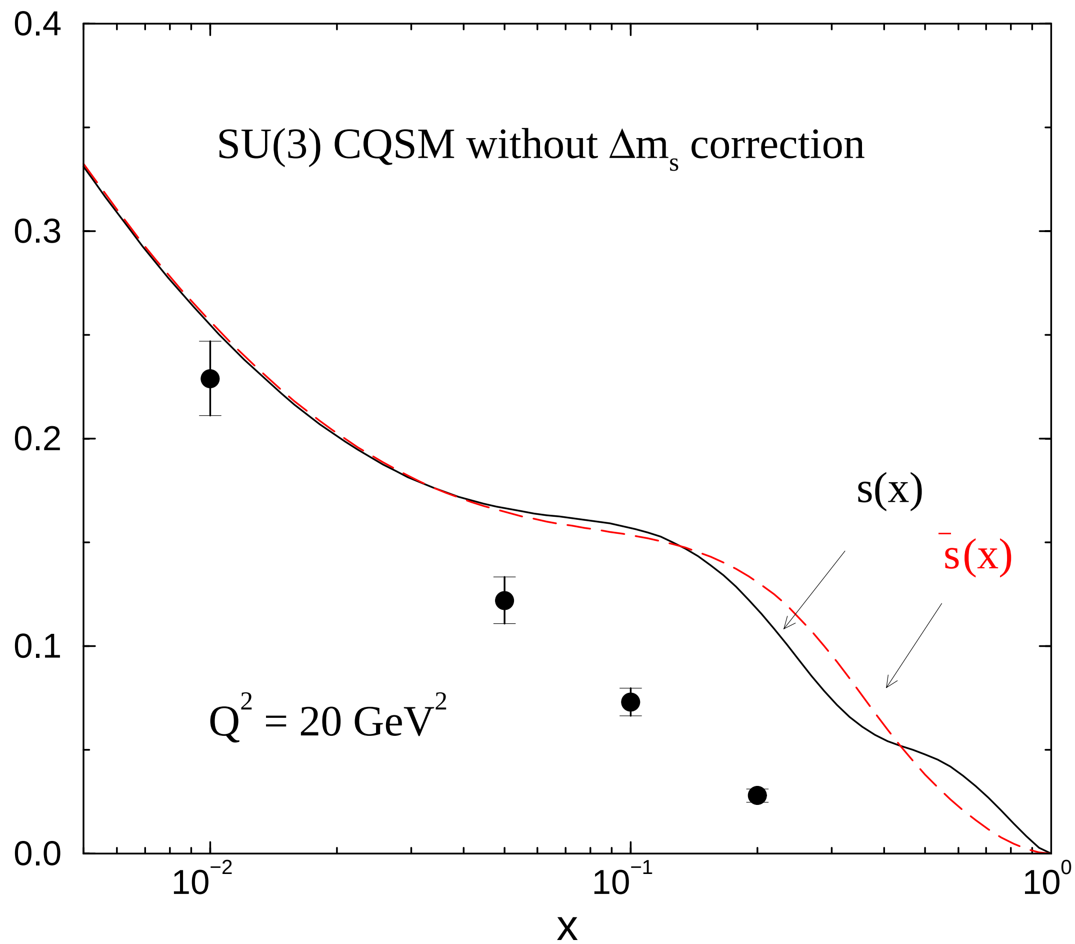
CCFR analysis of **neutrino-induced charm productions**

with the constraint $\bar{s}(x) = s(x)$

A.O. Bazarko et al., CCFR Collab., Z. Phys. C65 (1995) 189



inclusion of SU(3) symmetry breaking correction



- **Contrary to our naive expectation**, $\boldsymbol{\Delta m_s}$ correction **increases** both $s(x)$ and $\bar{s}(x)$, and the agreement with the CCFR fit becomes worse ?

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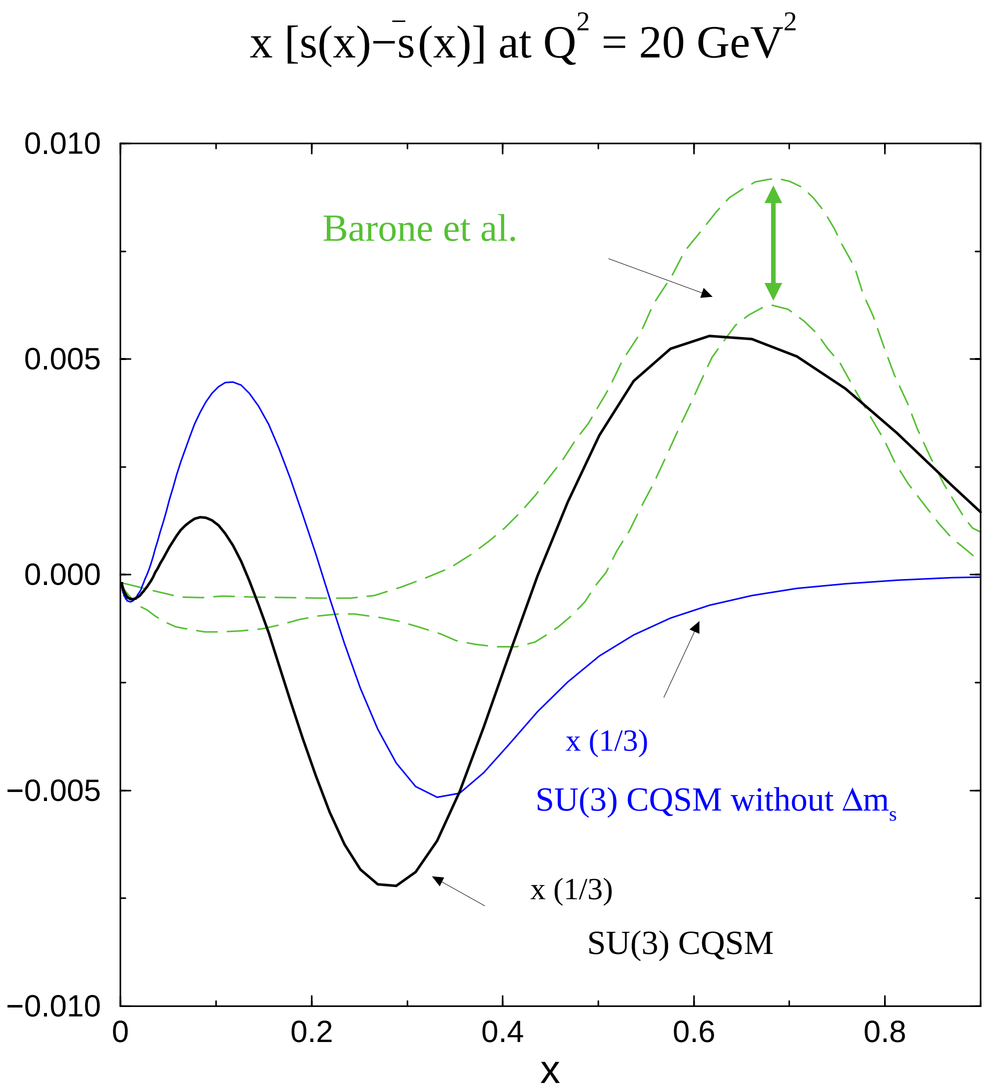
justification of **perturbative treatment** of Δm_s correction ?

comparison with global analysis by

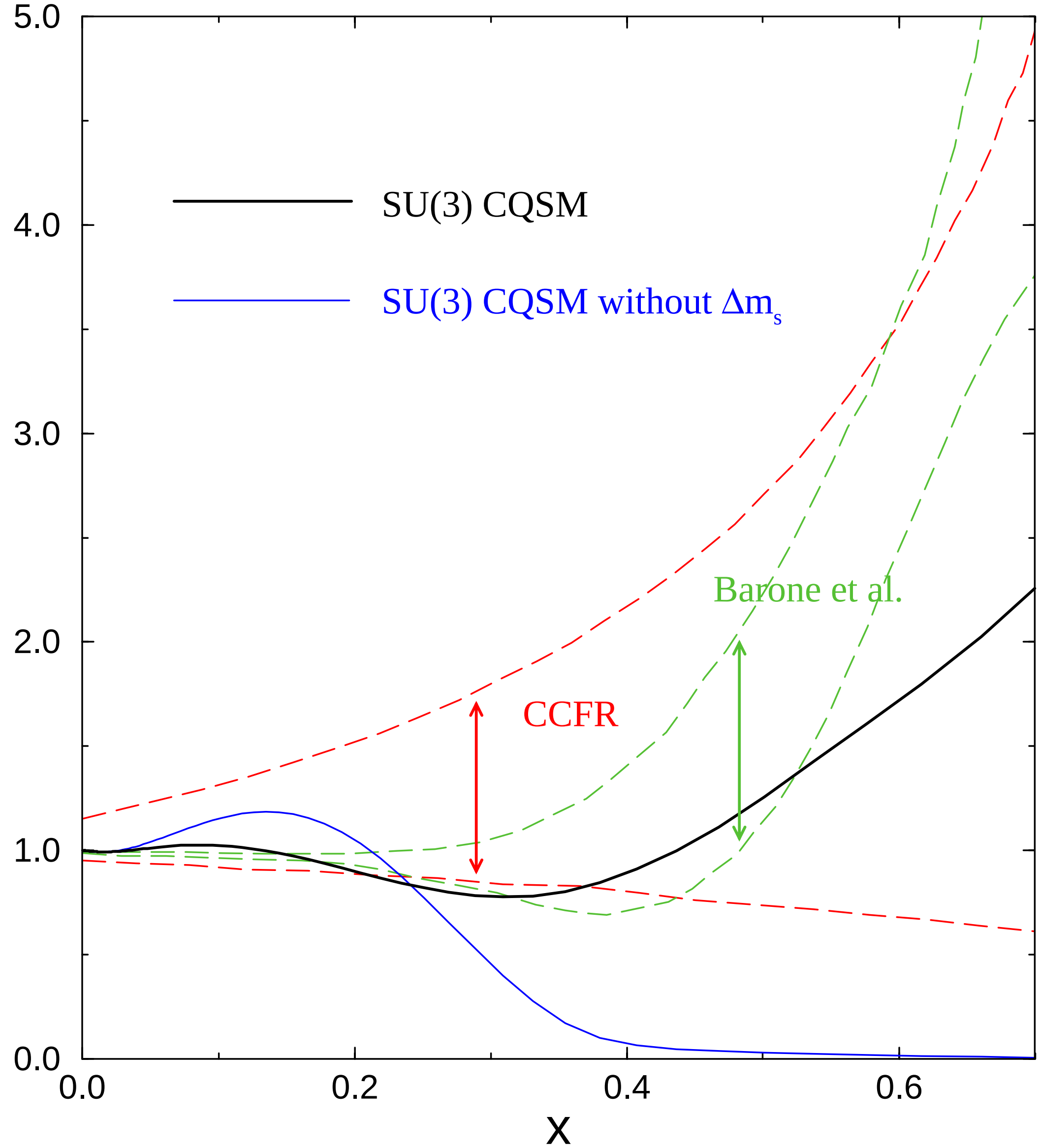
- V. Barone et al., Eur. Phys. J. C12 (2000) 243

difference of $s(x)$ and $\bar{s}(x)$



ratio of $s(x)$ and $\bar{s}(x)$

$s(x) / \bar{s}(x)$ at $Q^2 = 20 GeV^2$

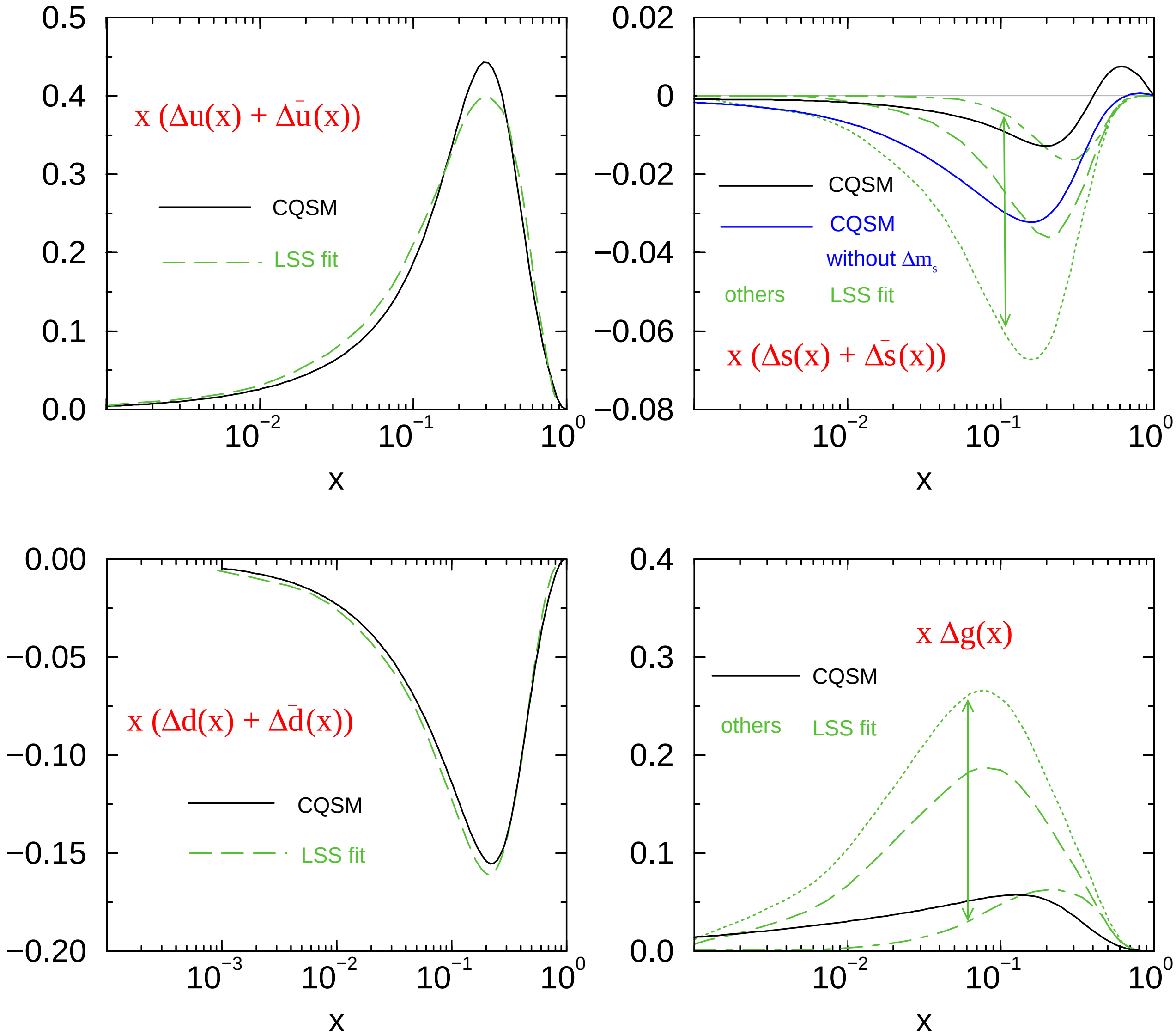


LSS NLO fits of **polarized DIS data** at $Q^2 = 1\,\text{GeV}^2$

E. Leader, A.V. Sidorov, D.B. Stamenov, P.L. B488 (2000) 283

relaxing groundless assumptions of past analyses like

— **flavor symmetric sea** —

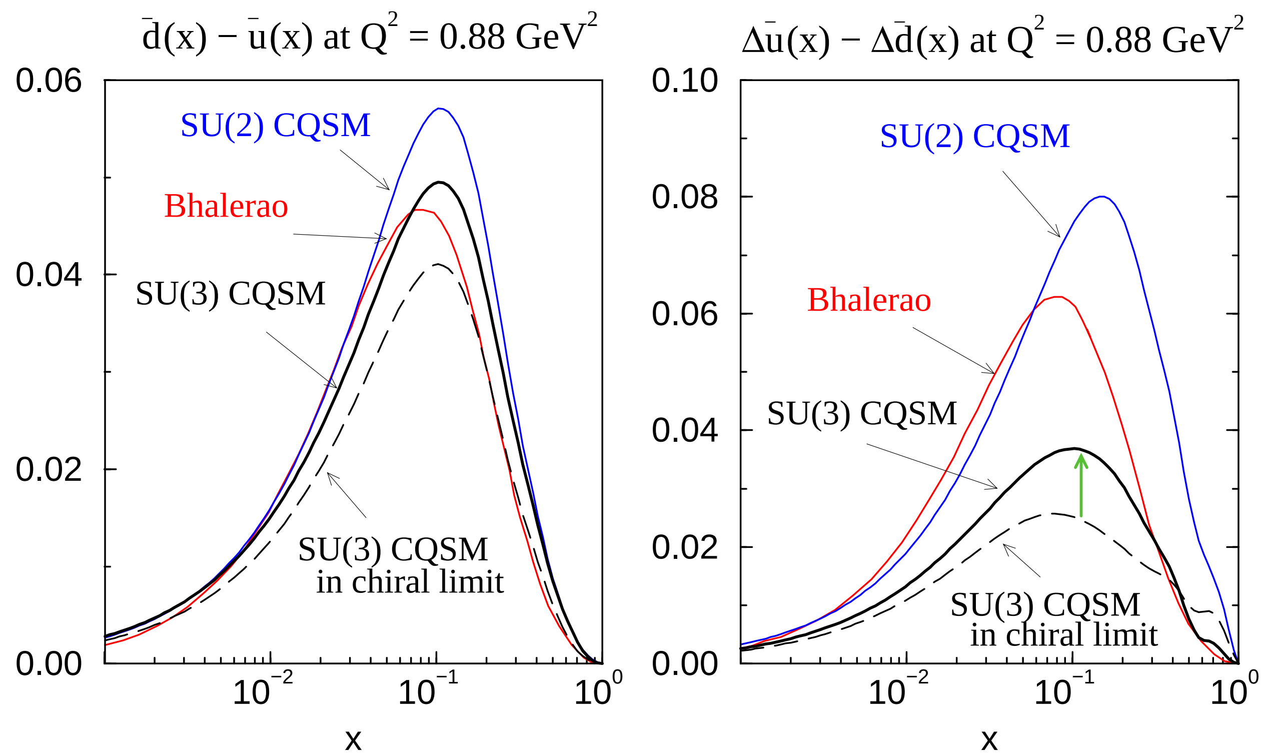


turning back to **isospin asymmetry** of sea quark distributions

SU(2) CQSM predicts
$$\begin{cases} \bar{u}(x) - \bar{d}(x) < 0 \\ \Delta\bar{u}(x) - \Delta\bar{d}(x) > 0 \end{cases}$$

$$\Downarrow$$

SU(3) CQSM ?



statistical model with **phenomenological inputs**

R.S. Bhalerao, P.R. C63 (2000) 025208

5. Conclusion

♣ An **incomparable** feature of the Chiral Quark Soliton Model as compared with other effective models like the MIT bag model is that it can give reasonable predictions also for the **antiquark distribution functions**

- **possitivity constraint** for $\bar{u}(x) + \bar{d}(x)$
- **Soffer inequality** for **antiquarks**

♣ This feature is essential also for giving any reliable predictions for **strange** distributions in the nucleon, which totally have

non-valence character

SU(3) CQSM predicts

- $s(x) - \bar{s}(x)$ has some **oscilatory x dependence** due to
  - ∗ **positivity constraint** for $s(x)$ and $\bar{s}(x)$
  - ∗ **strangeness quantum number conservation**

- **x dependence** of $s(x) - \bar{s}(x)$ and $s(x)/\bar{s}(x)$ are qualitatively consistent with global analysis of **Barone et al.**

- s-$\bar{s}$ **asymmetry** of **longitudinally polarized sea** is more **profound** than that of **unpolarized sea**

$$\begin{cases} \Delta s(x) & : \quad \text{large and negative !} \\ \Delta \bar{s}(x) & : \quad \text{slightly positive ?} \end{cases}$$

- model also predicts **large isospin asymmetric sea**

$$\left. \begin{array}{rcl} \bar{u}(x) - \bar{d}(x) & < & 0 \\ \\ \Delta\bar{u}(x) - \Delta\bar{d}(x) & > & 0 \end{array} \right\} \quad \text{in proton}$$

Important lesson

nonperturbative QCD dynamics due to **spontaneous** χ**SB** manifests most clearly in the **spin** & **flavor dependence**

of

antiquark distributions

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What is **absolutely** required in future experiments is

$$\left\{ \begin{array}{c} \text{flavor} \\ \\ \text{valence} \quad \oplus \quad \text{sea} \end{array} \right\} \quad \textbf{decomposition} \text{ of } \textbf{PDF}$$