Chiral models for nucleon structure functions

Masashi Wakamatsu, Osaka University, at KEK, 2013.01.18

- To the memory of the late Dmitri Diakonov -

Plan of talk

1. **Introduction**
2. **CQSM for parton distribution functions in the nucleon**
3. **Flavor SU(3) CQSM and strange sea distributions in the nucleon**
4. **NuTeV anomaly and CSV parton distributions**
5. **Phenomenology of nucleon spin decomposition**

1. Introduction

Quantum Chromo Dynamics (QCD)

Color confinement (no free quarks, gluons)

$\oplus$

Chiral symmetry (Chiral Dynamics)

Nonperturbative QCD

hard to solve analytically !

- Effective models
- Lattice QCD

hadron spectroscopy, structures, reactions

Asymptotic freedom

$$\lim_{Q^2 \to \infty} \alpha_S(Q^2) = 0$$

Perturbative QCD (pQCD)

established framework based on

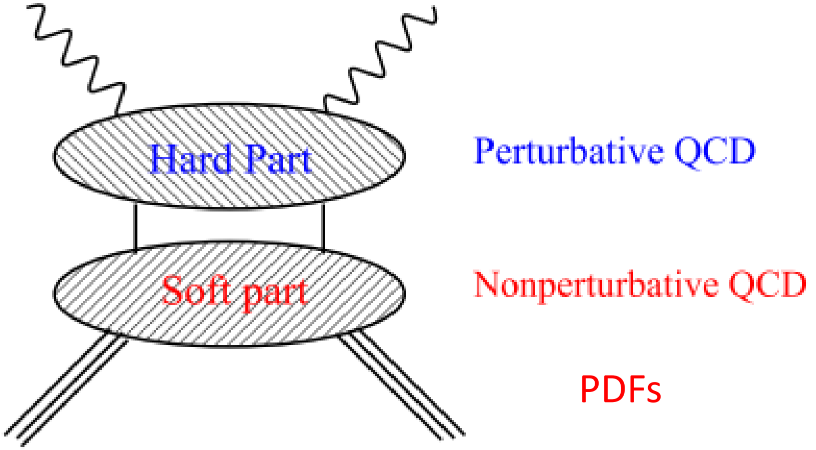
- Factorization theorem
- Renormalization group

Deep-inelastic-scatterings (DIS)

How can we connect nonperturbative physics of QCD with perturbative DIS physics ?

- Standard approach to DIS physics

factorization theorem



Soft part is treated as a **black box**, which should be determined via experiments !

reasonable strategy !

We however believe that, even if this part is completely fixed by experiments, one still wants to know why those PDFs take the form so determined !

- Nonstandard but complementary approach to DIS physics is necessary here to understand **hidden chiral dynamics** of soft part, based on models or on lattice QCD

2. CQSM for parton distribution functions in the nucleon

There are so many models of baryons, but I would say that the chiral quark soliton model (CQSM), first proposed by Diakonov et al., is the best one, at least as a model of internal partonic structure of the baryons.

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

Merits of CQSM over many other effective models of baryons :

- It is a relativistic mean-field theory of quarks, with infinitely many Dirac-sea levels.
- The mean-field is of hedgehog-shape in harmony with

  large N_c QCD and $1/N_c$ expansion
- Its field theoretical nature enables reasonable estimation of antiquark distributions.
- Only 1 parameter of the model (dynamically generated quark mass M) is already fixed from low energy phenomenology . ($M \sim 375\,\mathrm{MeV}$)

parameter-free predictions for PDFs

a shortcoming : lack of explicit gluon degrees of freedom

Noteworthy achievements of CQSM for low energy baryon observables :

(1) reproduces small quark spin fraction of proton consistent with EMC observation !

$$\Delta\Sigma \sim 0.35$$

(2) reproduces large πN sigma term !

$$\Sigma_{\pi N} \simeq 60\,\mathrm{MeV}$$

(3) resolves underestimation problem of $g_A^{(I=1)}$ in the Skyrme model !

$$g_A^{(Skyrme)} = g_A(\Omega^0) + g_A(\Omega^1) \simeq 0.8 + 0 = 0.8$$

$$g_A^{(CQSM)} = g_A(\Omega^0) + \boxed{g_A(\Omega^1)} \simeq 0.8 + 0.4 = 1.2$$

- Still, most low energy baryon observables are insensitive to model differences !

- We shall demonstrate that the potential ability of CQSM manifests most clearly in its predictions of internal partonic structure of the nucleon (or baryons) !

How to harmonize two domains of QCD ? : nonperturbative and perturbative

model predictions of PDFs given at low Q^2

empirically extracted PDFs given at high Q^2

related through QCD **evolution (DGLAP) equation**

matching problem

- difficult to specify the exact initial energy scale of evolution !

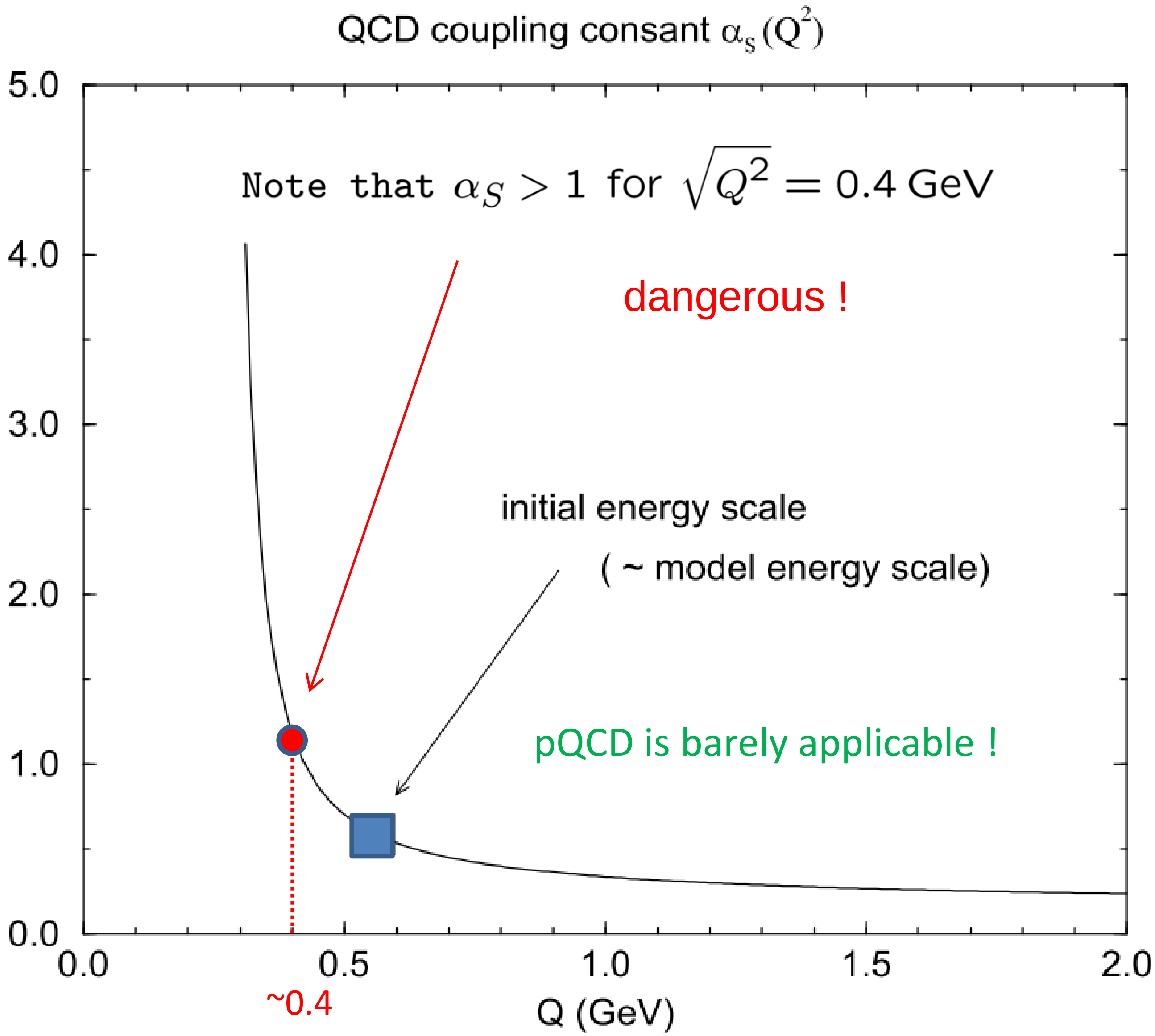
  most effective models like MIT bag model : $Q_{ini}^2 \simeq (400\,\mathrm{MeV})^2$

  Chiral Quark Soliton Model (CQSM) : $Q_{ini}^2 \simeq (600\,\mathrm{MeV})^2$

- validity of using perturbative RG eq. (DGLAP eq.) at low energy scale ?

  diverging behavior of QCD running coupling constant $\alpha_S(Q^2)$!

QCD running coupling constant at the next-to-leading order (NLO)



parameter free predictions of SU(2) CQSM for **3 twist-2 PDFs**

- unpolarized PDFs

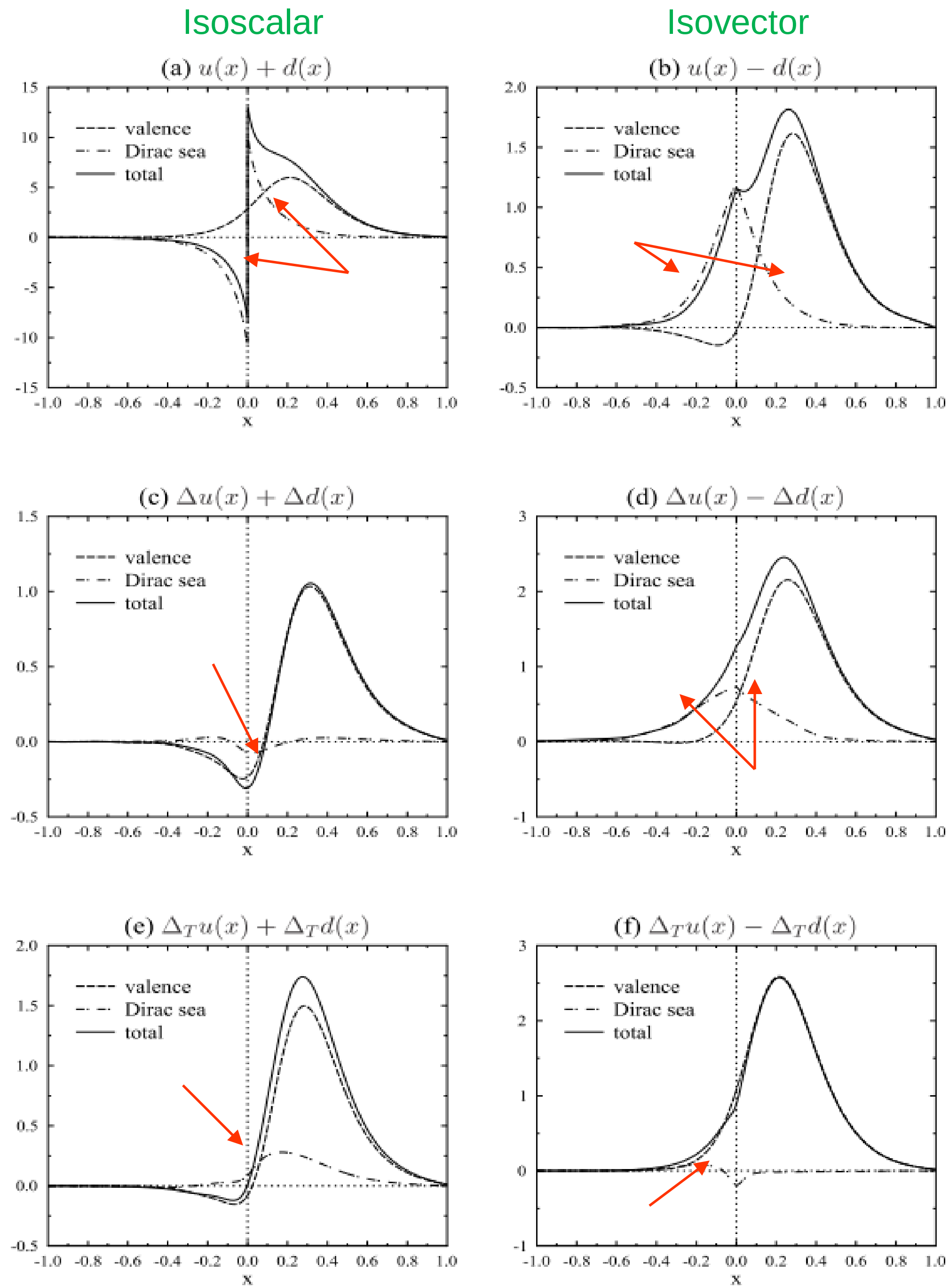
$$q(x)$$

- longitudinally polarized PDFs

$$\Delta q(x)$$

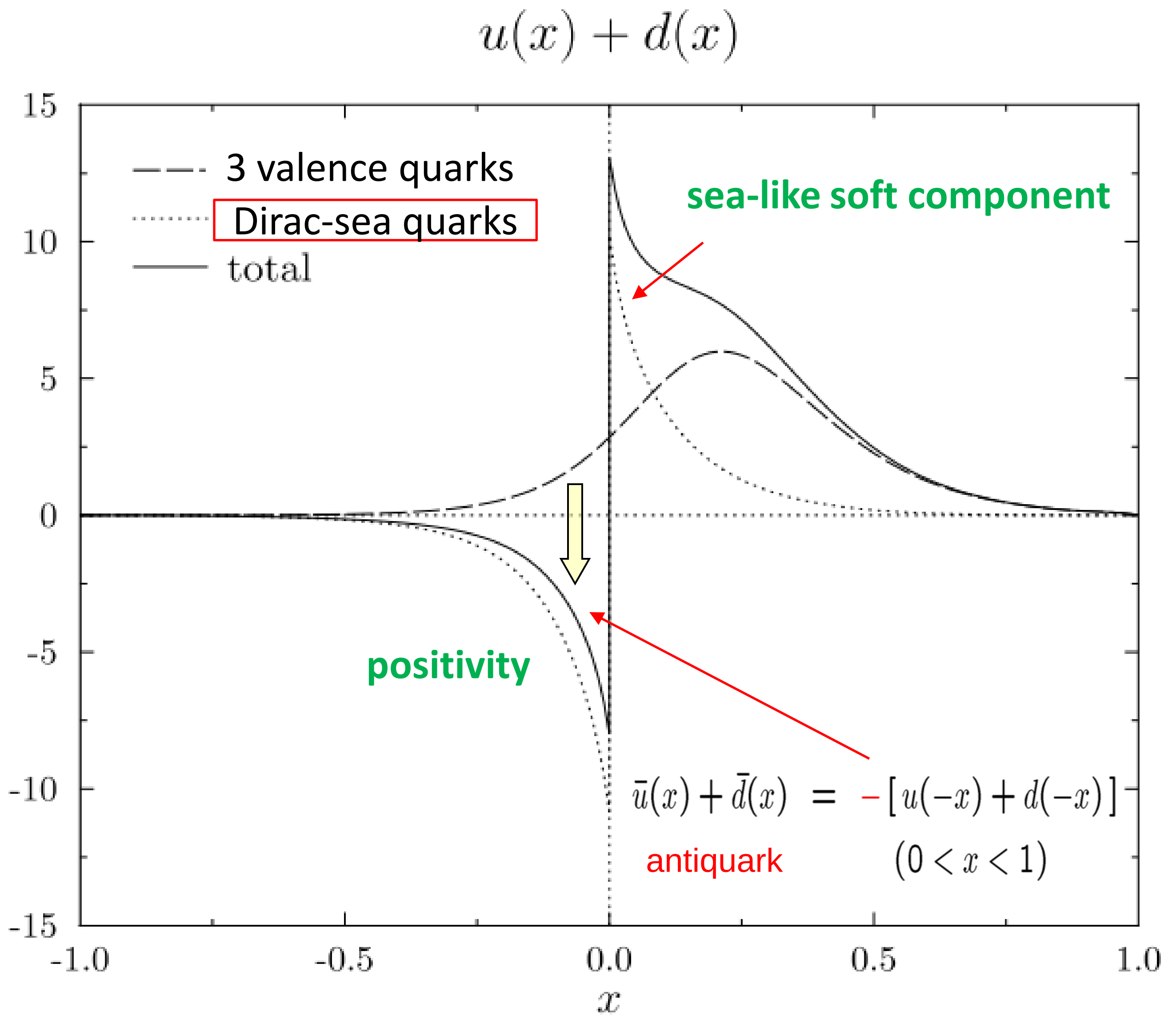
- transversities (chiral-odd)

$$\Delta_T q(x)$$



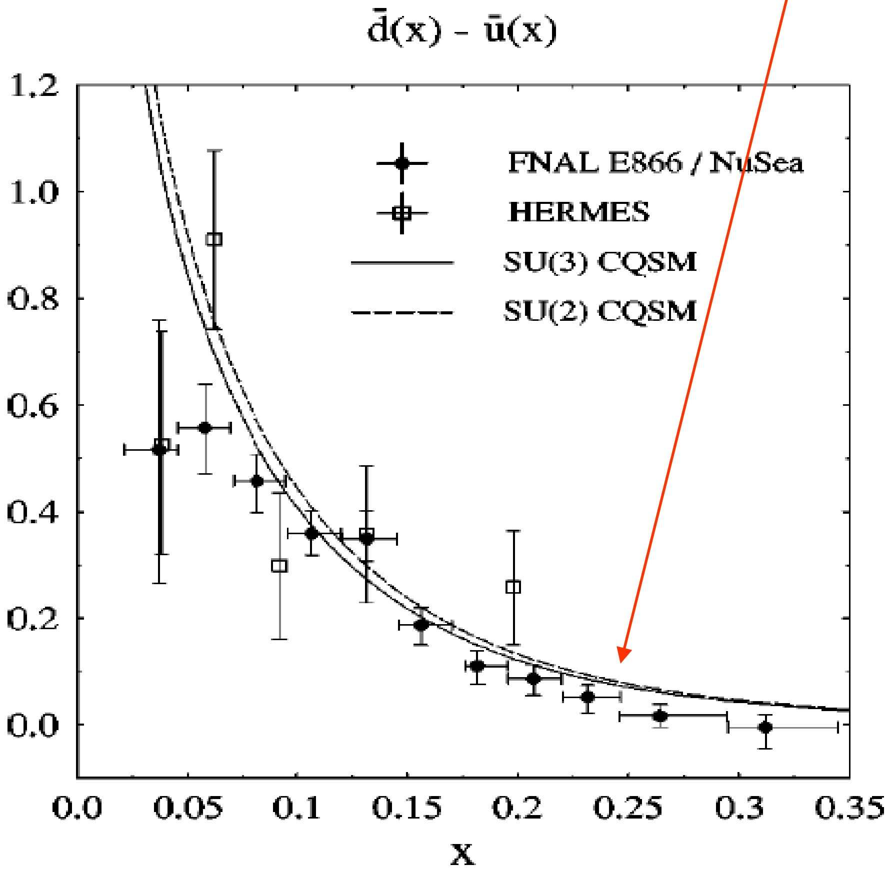
totally different behavior of the Dirac-sea contributions in different PDFs !

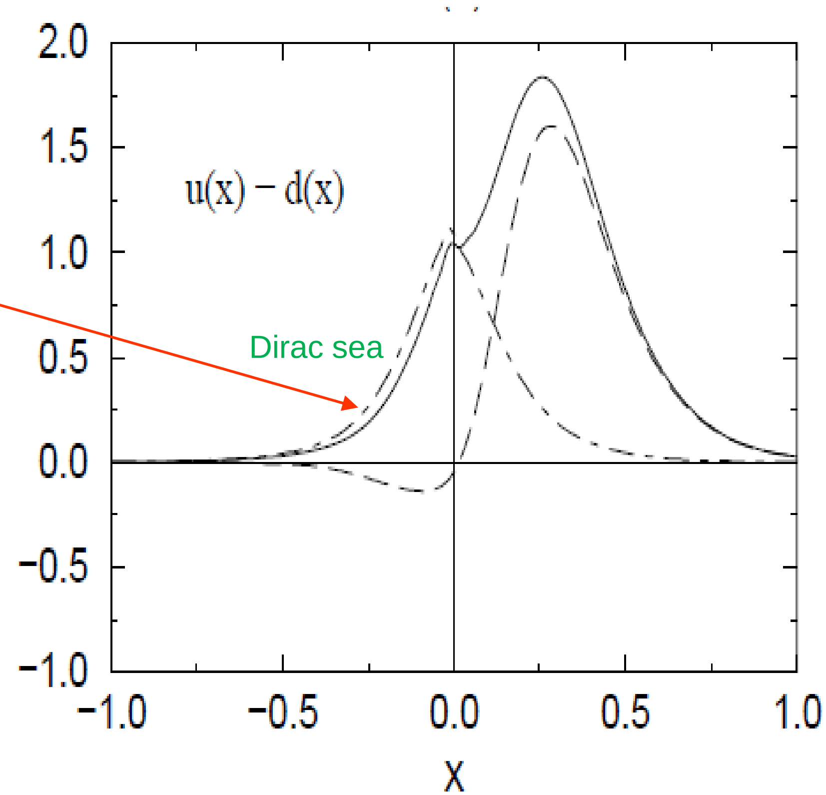
Isoscalar unpolarized PDF



Isovector unpolarized PDF

- **NMC observation** -





$$\bar{u}(x) - \bar{d}(x) = -\left[u(-x) - d(-x)\right] \quad (0 < x < 1)$$

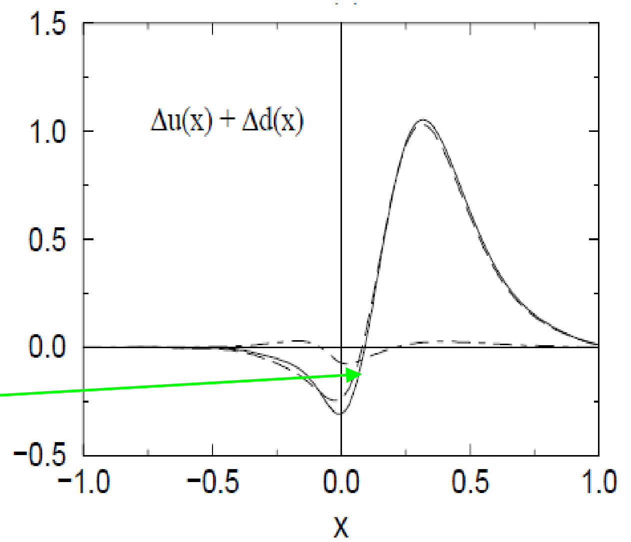
⇓

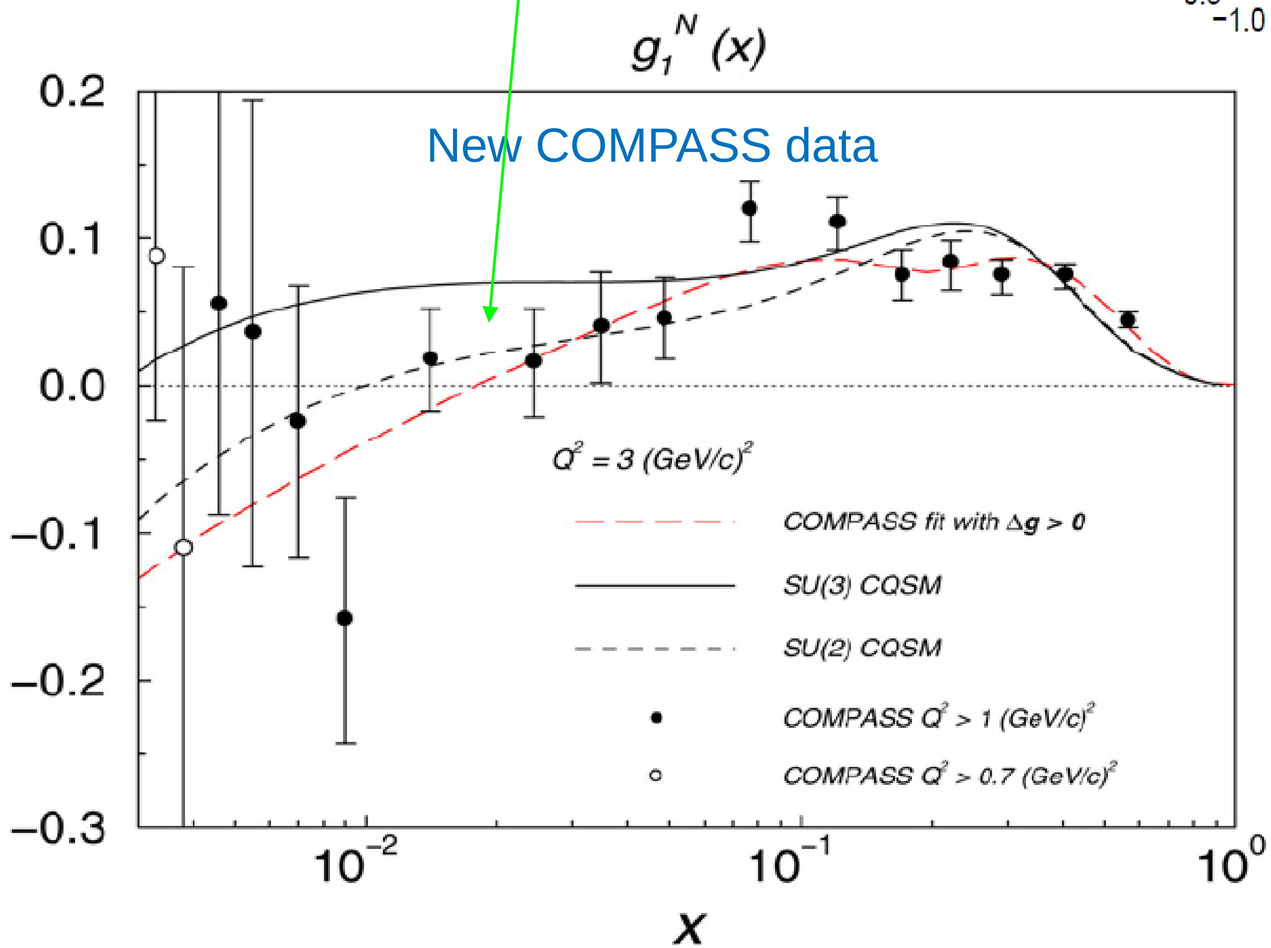
$$\bar{u}(x) - \bar{d}(x) < 0 \quad !$$

Isoscalar longitudinally polarized PDF

$$\Delta u(x) + \Delta d(x) \;\simeq\; g_1^{d}(x) \,/\, (\, 1 - 1.5\,\omega_D\,) \;\; :$$

deuteron



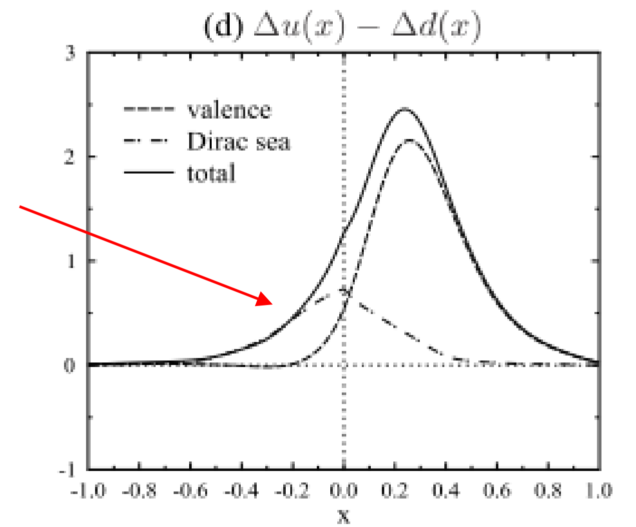


sign change in low x region !

Isovector longitudinally polarized PDF

CQSM predicts $\Delta \bar{u}(x) - \Delta \bar{d}(x) > 0$

This means that antiquarks gives sizable positive contribution to Bjorken sum rule



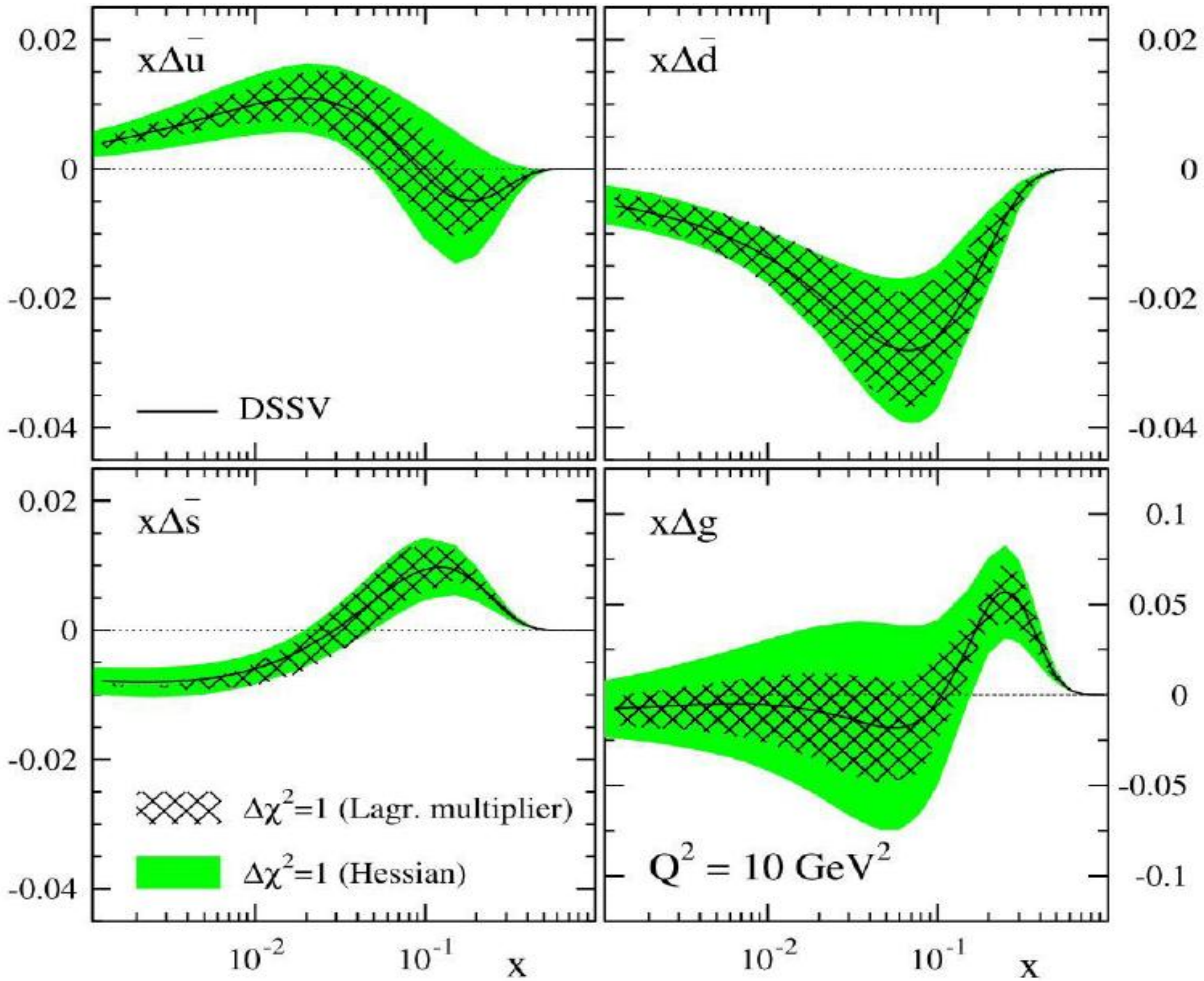
1st moment or Bjorken sum rule in CQSM

CQSM	$-1 < x < 0$	$0 < x < 1$	$-1 < x < 1$
$\Delta u + \Delta d$	-0.0472	0.399	0.352
$\Delta u - \Delta d$	0.2315	1.092	1.323
Δu	0.092	0.745	0.838
Δd	-0.139	-0.346	-0.485

$$\Delta \bar{u} \simeq 0.092, \quad \Delta \bar{d} \simeq -0.139, \quad |\Delta \bar{u}| < |\Delta \bar{d}|$$

A global fit including polarized pp data at RHIC

- D. Florian, R. Sassot, M. Strattmann, W. Vogelsang, Phys. Rev. D80, 034030 (2009).



$$\Delta\bar{u} > 0, \quad \Delta\bar{d} < 0$$

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

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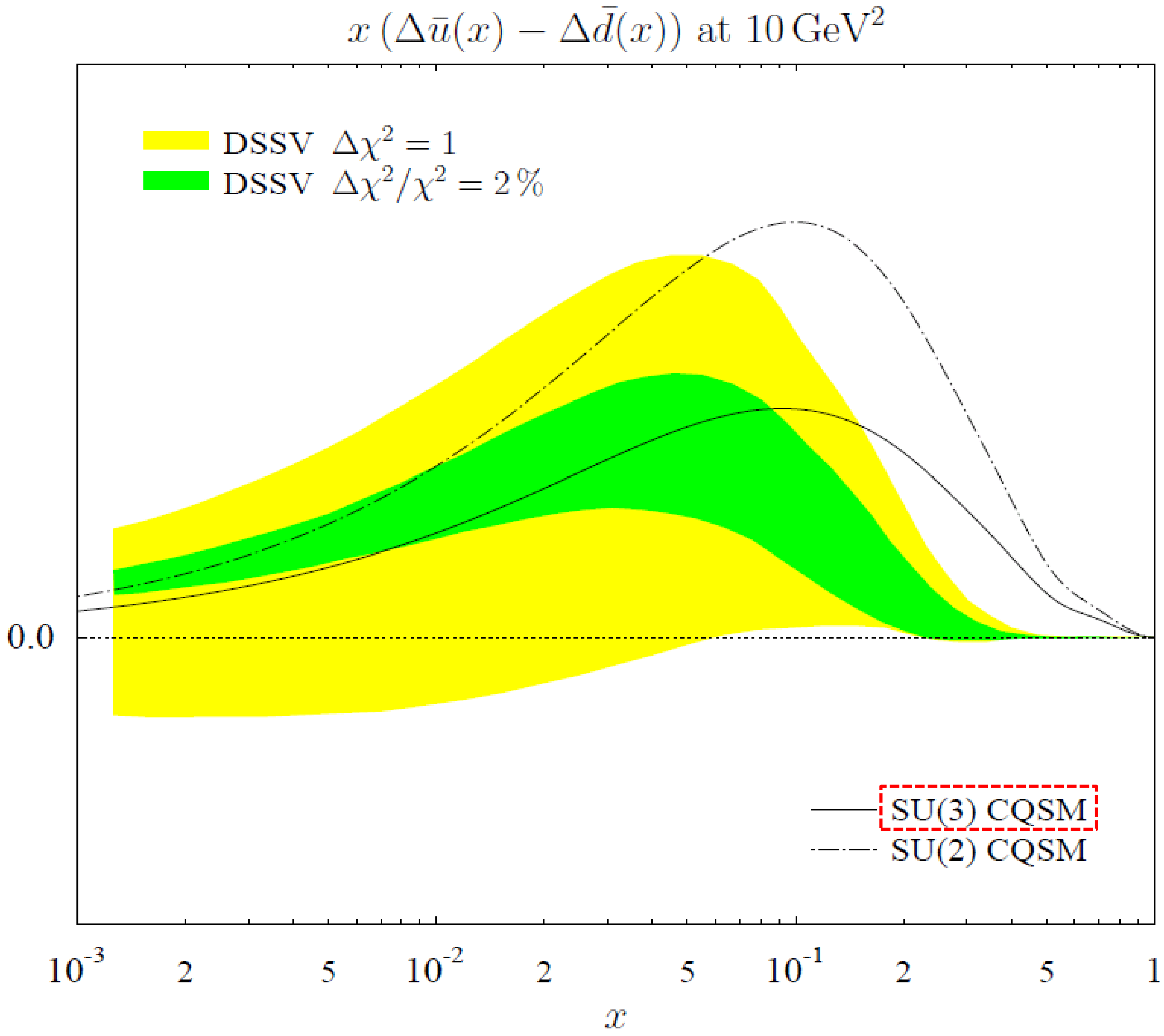
consistent with CQSM ?

DSSV fit versus CQSM predictions



FNAL and J-PARC proposals for measuring polarized sea-quark distributions

private communication with Xiaodong Jiang

Drell-Yan longitudinally polarized beam-target double-spin asymmetry

$$A_{LL}^{DY} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}} = \frac{\Delta\sigma_{DY}}{\sigma_{DY}}$$

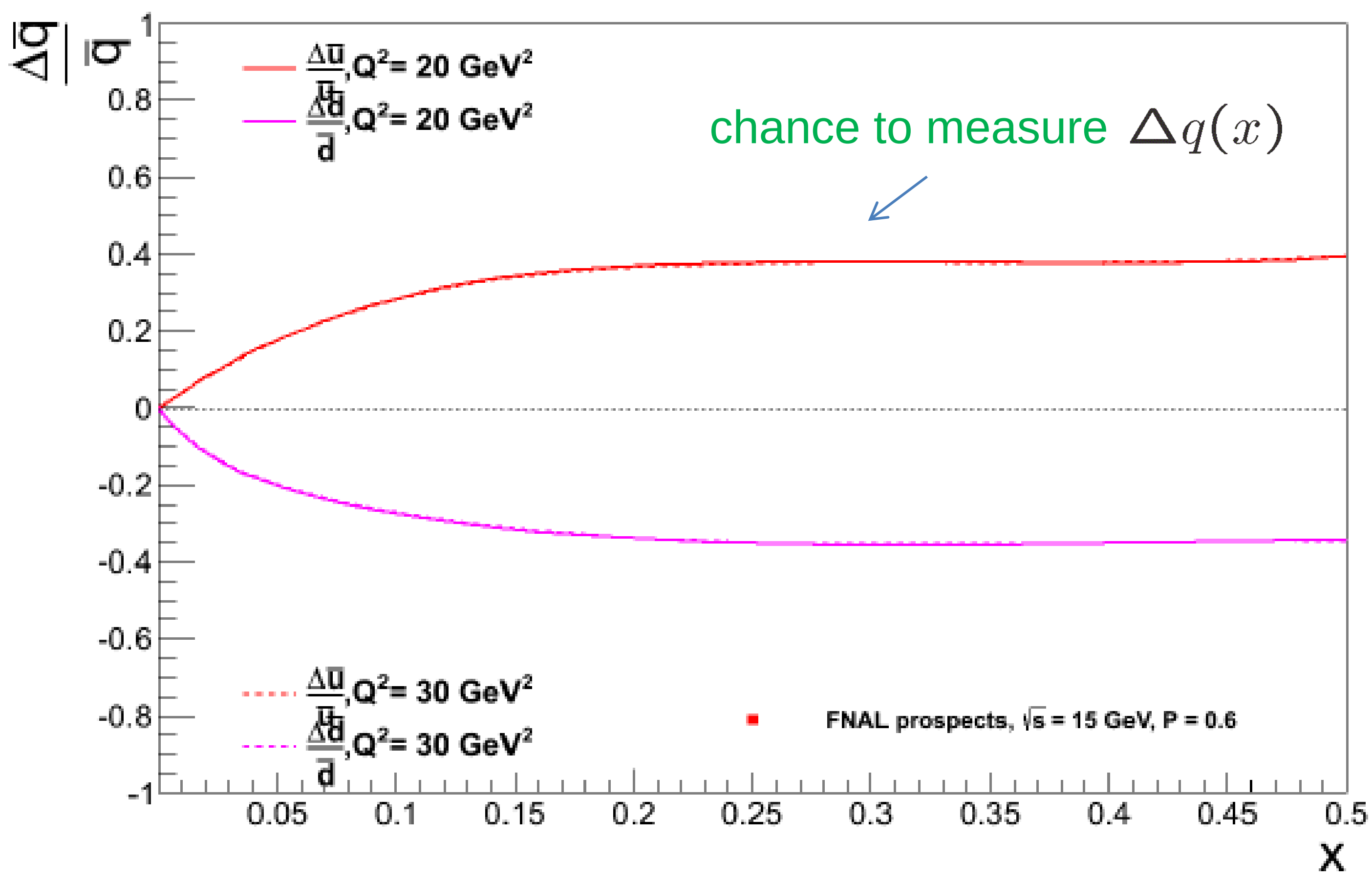
asymmetry between the spin-aligned and spin-anti-aligned D-Y cross sections

Leading order expression

$$A_{LL}^{DY} = -\frac{\sum_q e_q^2 \{\Delta q(x_1)\,\Delta\bar{q}(x_2) + \Delta\bar{q}(x_1)\,\Delta q(x_2)\}}{\sum_q e_q^2 \{q(x_1)\,\bar{q}(x_2) + \bar{q}(x_1)\,q(x_2)\}}$$

CQSM prediction corresponding to FNAL, JPARC kinematics

Δqbar/qbar



Transversities versus longitudinally polarized distributions

We are interested in the difference between

$$\Delta q(x) \quad \text{and} \quad \Delta_T q(x)$$

The most important quantities characterizing these are their 1st moments, called

axial charge g_A & tensor charge g_T

$$g_A^{(I=0)} = \int_0^1 \left\{ [\,\Delta u(x) + \Delta d(x)\,] + [\,\Delta \bar{u}(x) + \Delta \bar{d}(x)\,] \right\} dx$$

$$g_A^{(I=1)} = \int_0^1 \left\{ [\,\Delta u(x) - \Delta d(x)\,] + [\,\Delta \bar{u}(x) - \Delta \bar{d}(x)\,] \right\} dx$$

$$g_T^{(I=0)} = \int_0^1 \left\{ [\,\Delta_T u(x) + \Delta_T d(x)\,] - [\,\Delta_T \bar{u}(x) + \Delta_T \bar{d}(x)\,] \right\} dx$$

$$g_T^{(I=1)} = \int_0^1 \left\{ [\,\Delta_T u(x) - \Delta_T d(x)\,] - [\,\Delta_T \bar{u}(x) - \Delta_T \bar{d}(x)\,] \right\} dx$$

Understanding of isospin dependencies is a key to disentangle nonperturbative chiral dynamics contained in the PDFs

Well-known basic facts

(A) Non-relativistic quark model

$$g_A^{(I=1)} = g_T^{(I=1)} = \frac{5}{3}, \qquad g_A^{(I=0)} = g_T^{(I=0)} = 1$$

(B) MIT bag model

$$g_A^{(I=1)} = \frac{5}{3} \cdot \int \left(f^2 - \frac{1}{3} g^2 \right) r^2 \, dr, \qquad g_A^{(I=0)} = 1 \cdot \int \left(f^2 - \frac{1}{3} g^2 \right) r^2 \, dr$$

$$g_T^{(I=1)} = \frac{5}{3} \cdot \int \left(f^2 + \frac{1}{3} g^2 \right) r^2 \, dr, \qquad g_T^{(I=0)} = 1 \cdot \int \left(f^2 + \frac{1}{3} g^2 \right) r^2 \, dr$$

$f(r), g(r)$: upper & lower components of g.s w.f.

Important observation

$$\frac{g_A^{(I=0)}}{g_A^{(I=1)}} = \frac{g_T^{(I=0)}}{g_T^{(I=1)}} = \frac{3}{5} = 0.6$$

shortcoming !

in both of NRQM & MIT bag model

CQSM gives totally different predictions !

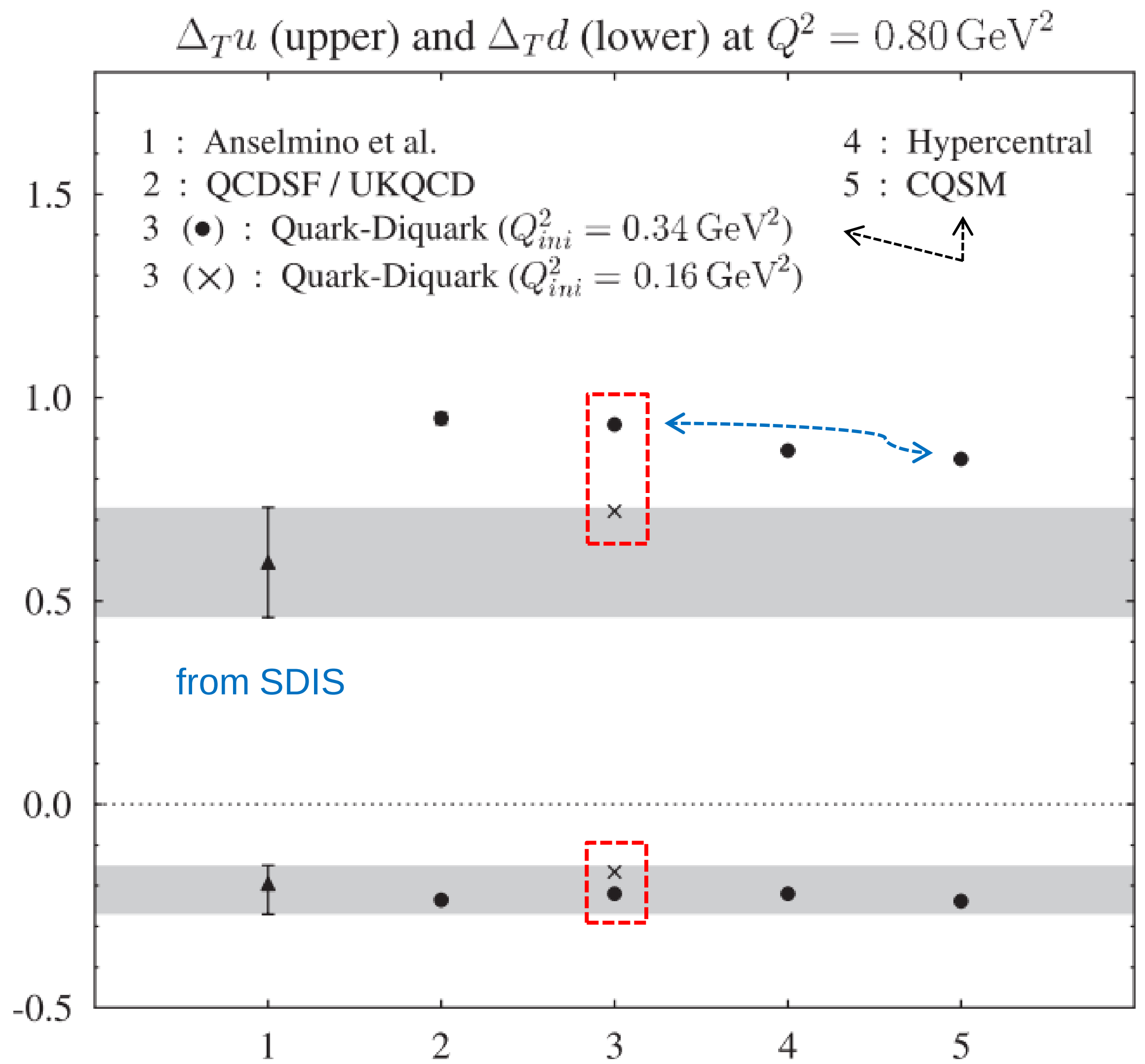
Pasquini et al.

	NRQM	MIT bag	HO(LFCQ)	HYP(LFCQ)	CQSM
$g_A^{(I=1)}$	1.5	1.06	1.25	0.76	1.31
$g_A^{(I=0)}$	1.0	0.64	0.75	0.46	0.35
$g_T^{(I=1)}$	1.5	1.34	1.46	1.21	1.21
$g_T^{(I=0)}$	1.0	0.88	0.88	0.73	0.68
$g_A^{(I=0)}/g_A^{(I=1)}$	0.6	0.6	$\sim$ 0.6	$\sim$ 0.6	0.27
$g_T^{(I=0)}/g_T^{(I=1)}$	0.6	0.6	$\sim$ 0.6	$\sim$ 0.6	0.56

3 quark model cannot resolve EMC observation ?

Caution about strong scale dependence of transversity around model energy scales

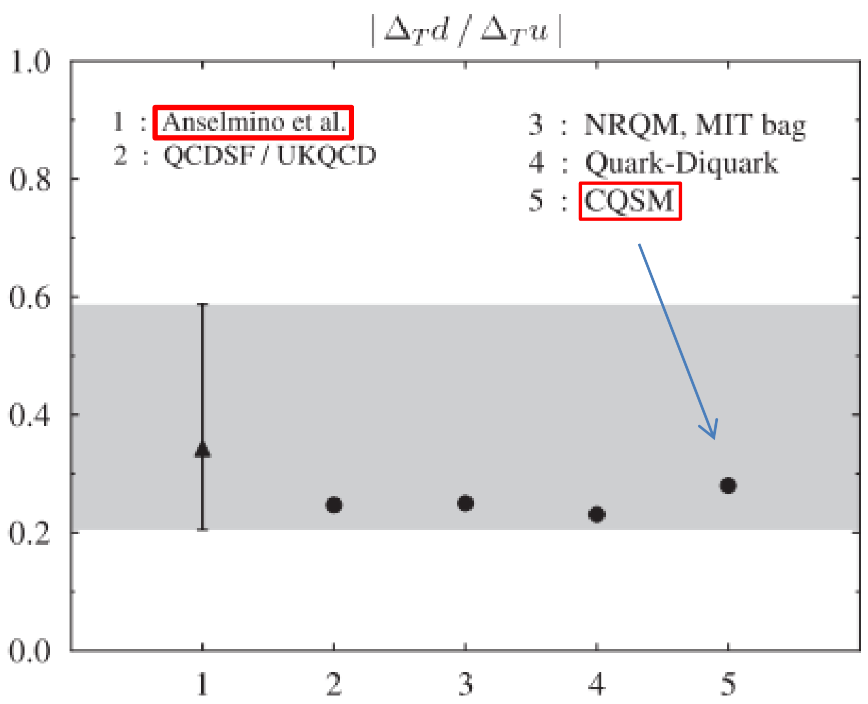
• M. W., Phys. Rev. D79 (2009) 014033.



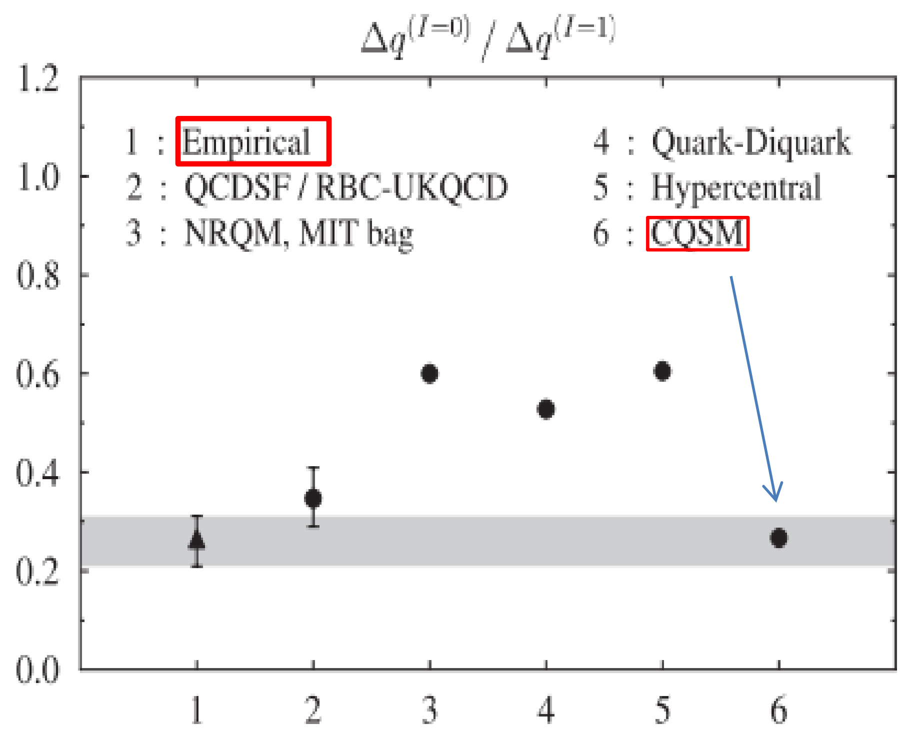
Comparison of various model predictions for scale independent ratios

• M. W., Phys. Rev. D79 (2009) 014033.

tensor-charge ratio



axial-charge ratio



scale independent !

nearly scale independent !

Short remarks on the transversity distributions

♣ When one compares the model predictions of transversities with the empirical ones extracted from high-energy SDIS measurements, one must be very careful about the strong scale-dependence of transversities in the nonperturbative low energy domain.

♣ Model predictions are very sensitive to the starting energy scale of evolution !

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♣ A safer comparison would therefore be made for the ratios like

$$\Delta_T u \,/\, \Delta_T d \quad \text{and/or} \quad \Delta q_T^{(I=0)} \,/\, \Delta q_T^{(I=1)}$$

which are scale-independent, because of the flavor-independent nature of evolution equations for chiral-odd transversities, which does not couple to gluons !

3. flavor SU(3) CQSM and strange sea distribution in the nucleon

model lagrangian

$$\mathcal{L} = \bar{\psi}(x) \left(i \not\partial - M U^{\gamma_5}(x) - \Delta m_s P_s \right) \psi(x)$$

with

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

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

basic dynamical assumptions

(1) lowest energy classical solution is obtained by **embedding** of SU(2) hedgehog configuration.

$$U_0^{\gamma_5}(x) = \begin{pmatrix} e^{i \gamma_5 \boldsymbol{\tau} \cdot \hat{\boldsymbol{r}} F(r)} & 0 \\ 0 & 1 \end{pmatrix} \in \textbf{SU(3)}$$

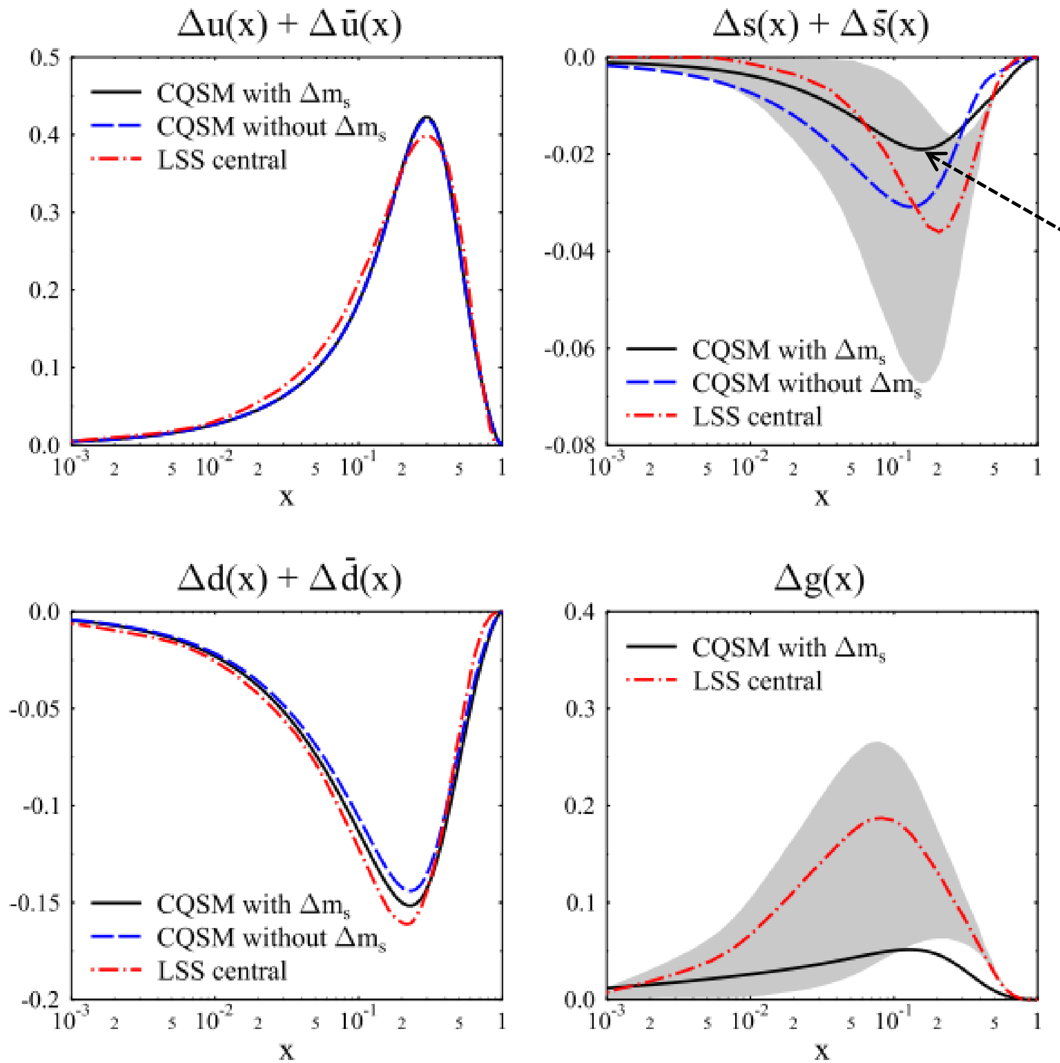
(2) quantization of soliton **rotational motion** in SU(3) collective coordinate space.

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

$$\Delta \tilde{H} = \Delta m_s \cdot \gamma^0 A^\dagger(t) \left(\frac{1}{3} - \frac{1}{\sqrt{3}} \lambda_8 \right) A(t), \qquad \Delta m_s = 100 \pm 20 \, \mathrm{MeV}$$

some typical predictions of the SU(3) CQSM

(A) longitudinally polarized strange quark distributions

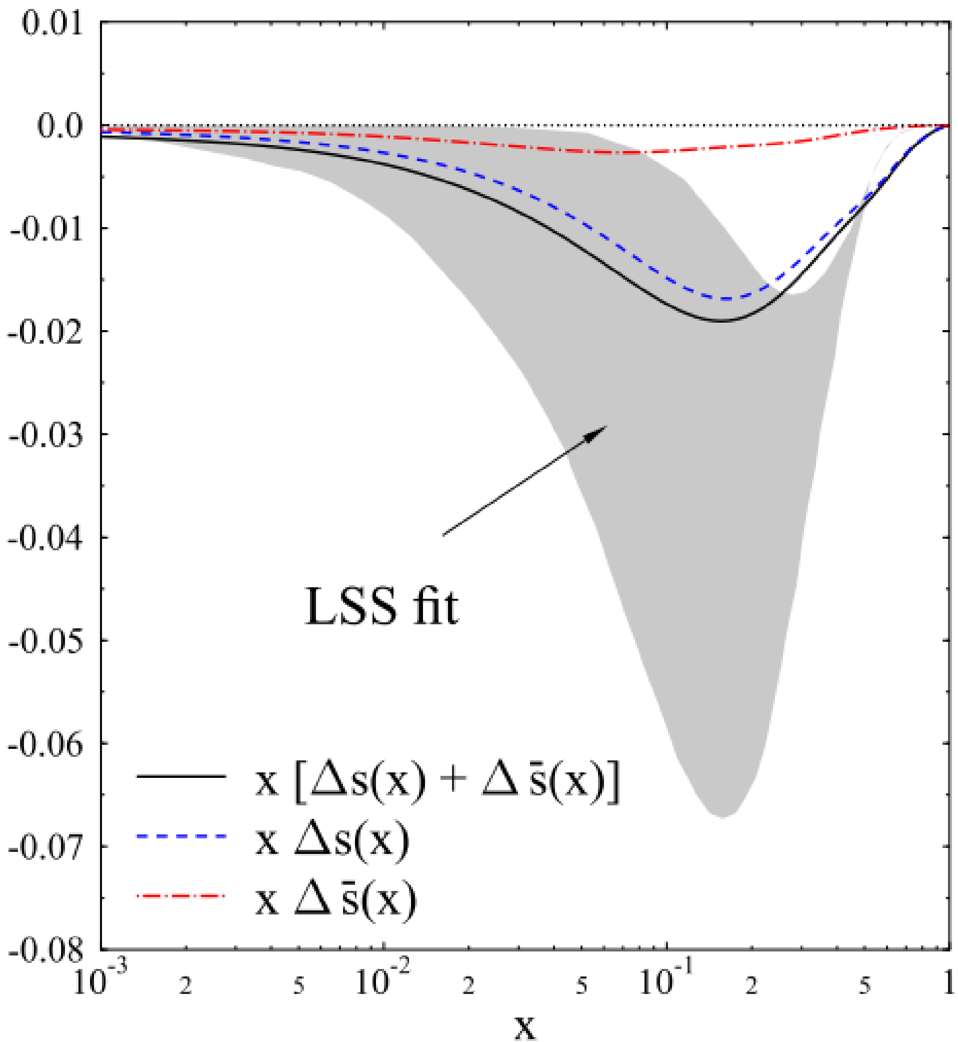


negative polarization

$\Delta s(x) + \Delta \bar{s}(x) < 0$

LSS NLO fits
at $Q^2 = 1\,\mathrm{GeV}^2$

separate contributions of $\Delta s(x)$ & $\Delta \bar{s}(x)$



We find that

$$|\Delta \bar{s}(x)| \ll |\Delta s(x)|$$

⇩

consistent with the physical picture of Kaon cloud model

Signal-Thomas, 1987

Brodsky-Ma, 1996

$$p \rightarrow \Lambda + K^+$$

$$(\Lambda \sim uds, \; K^+ \sim u\bar{s})$$

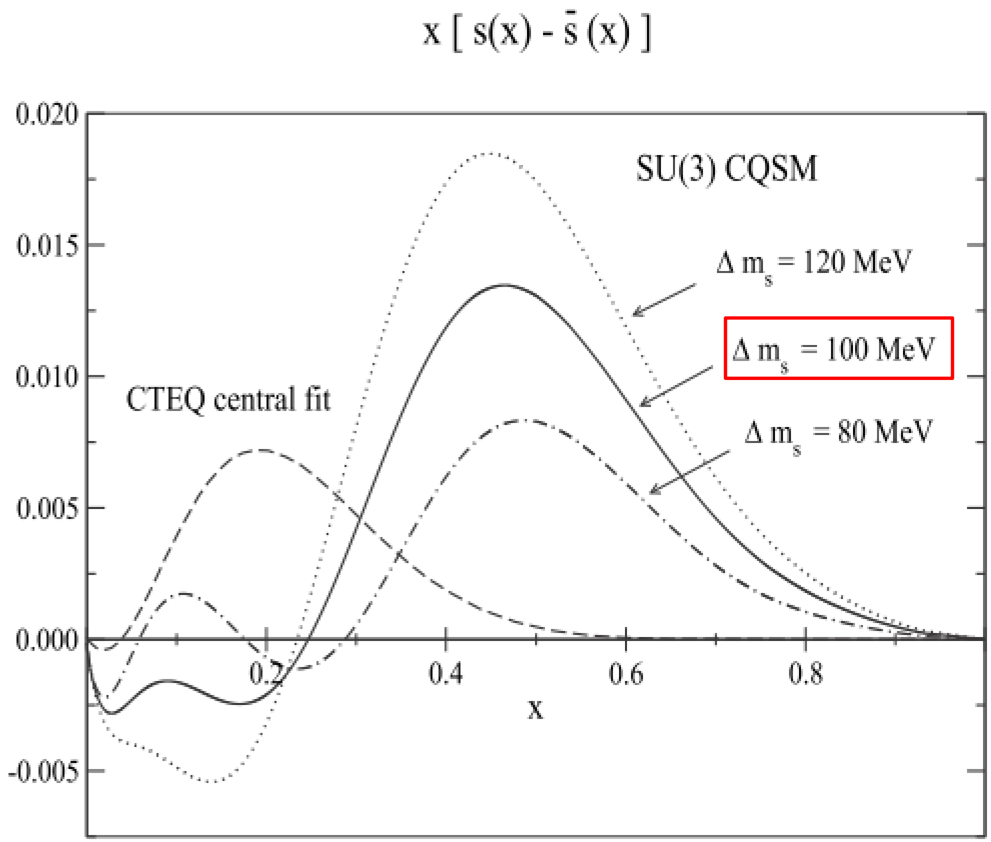
Note the asymmetry

$s \in$ spin 1/2 baryon

$\bar{s} \in$ spin 0 meson

asymmetry of unpolarized strange sea

$$\int_0^1 [\, s(x) - \bar{s}(x) \,] \, dx \; = \; 0 \quad : \quad \text{net strange-quark number}$$



This is also consistent with the picture of Kaon cloud model

$$p \to \Lambda + K^+$$

$$(\Lambda \sim uds, \;\; K^+ \sim u\bar{s})$$

Note the asymmetry

$$s \in \text{baryon}$$

$$\bar{s} \in \text{meson}$$

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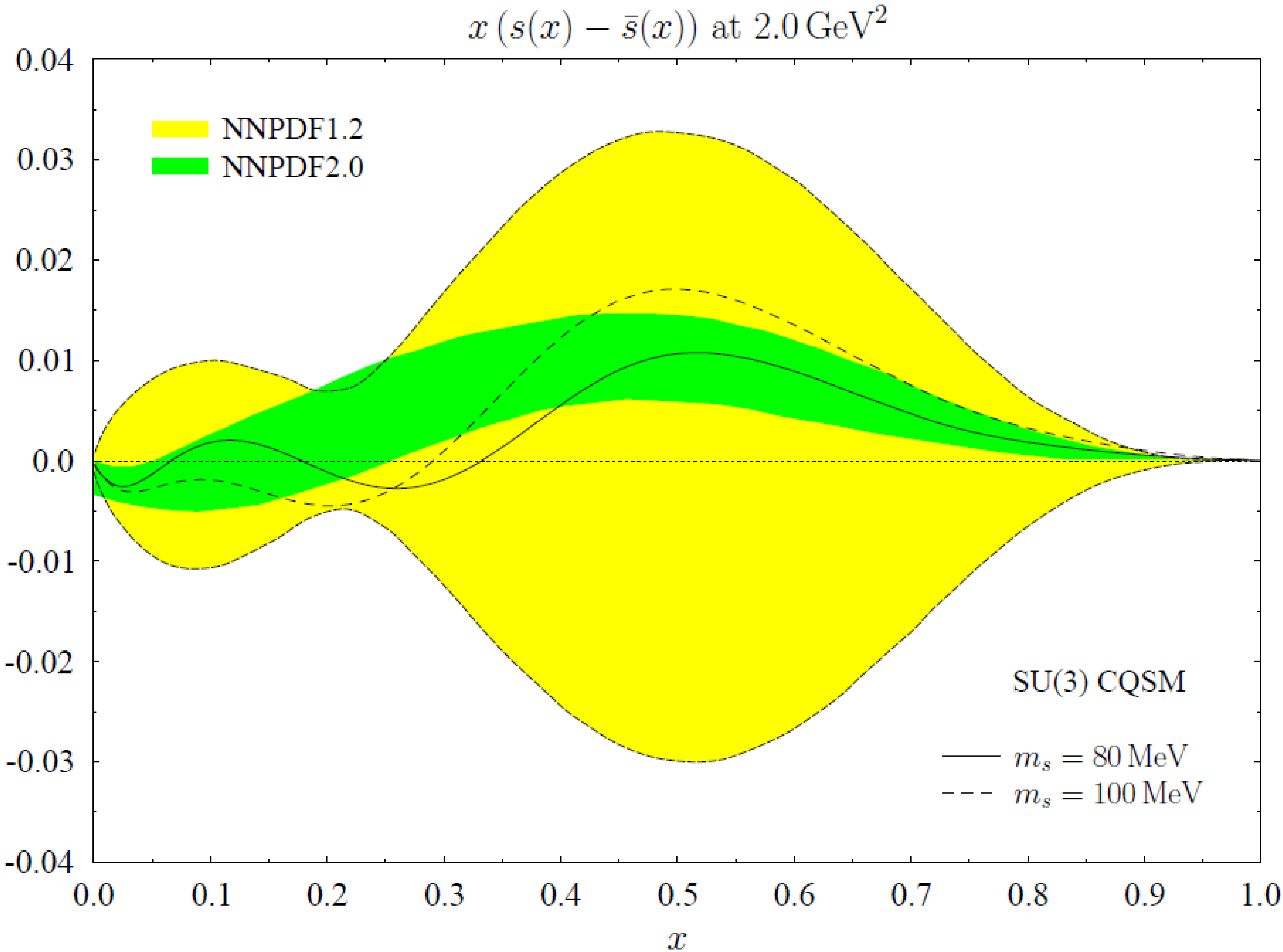
s-quark has valence-like harder component ?

Comparison with the recent unbiased fits based on neural-network framework



4. NuTeV anomaly and CSV parton distribution functions

NuTeV measured the Paschos-Wolfenstein ratio

$$R^{PW} = \frac{\sigma(\nu\,\mathrm{Fe} \to \nu\,\mathrm{X}) - \sigma(\bar{\nu}\,\mathrm{Fe} \to \bar{\nu}\,\mathrm{X})}{\sigma(\nu\,\mathrm{Fe} \to \mu^-\,\mathrm{X}) - \sigma(\bar{\nu}\,\mathrm{Fe} \to \mu^+\,\mathrm{X})}$$

The result shows significant deviation from the predictions of the standard model :

$$\frac{1}{2} - \sin^2\theta_W \qquad (\,\theta_W \;:\; \texttt{Weinberg angle}\,)$$

Main QCD corrections to the P-W ratio

$$\Delta R^{PW} \sim \left(1 - \frac{7}{3}\sin^2\theta_W\right) \frac{\langle x\,(\delta u - \delta d) - x\,(s - \bar{s})\rangle}{\langle x\,(u_V - d_V)\rangle}$$

where

$$\delta u - \delta d \equiv (u_V^p - d_V^n) - (d_V^p - u_V^n) \quad : \quad \texttt{charge symmetry violation}$$

$$s - \bar{s} \quad : \quad \texttt{strange quark asymetry}$$

Theoretical analyses for charge symmetry violating PDFs

Recent review : J.T. Londergan, J.C. Peng, and A.W. Thomas, Rev. Mod. Phys. 82 (2010)

(1) Sather's ansatz : Phys. Lett. B274 (1992) 433
supplemented with simple quark model like MIT bag model

CSV valence quark distribution

$$\delta q_V(x) \simeq \frac{\partial q_V(x)}{\partial m} \delta m + \frac{\partial q_V(x)}{\partial M} \delta M$$

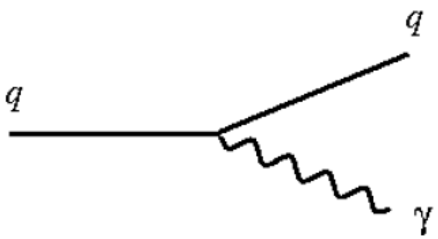
with

$$\delta m = m_d - m_u, \qquad \delta M = M_n - M_p$$

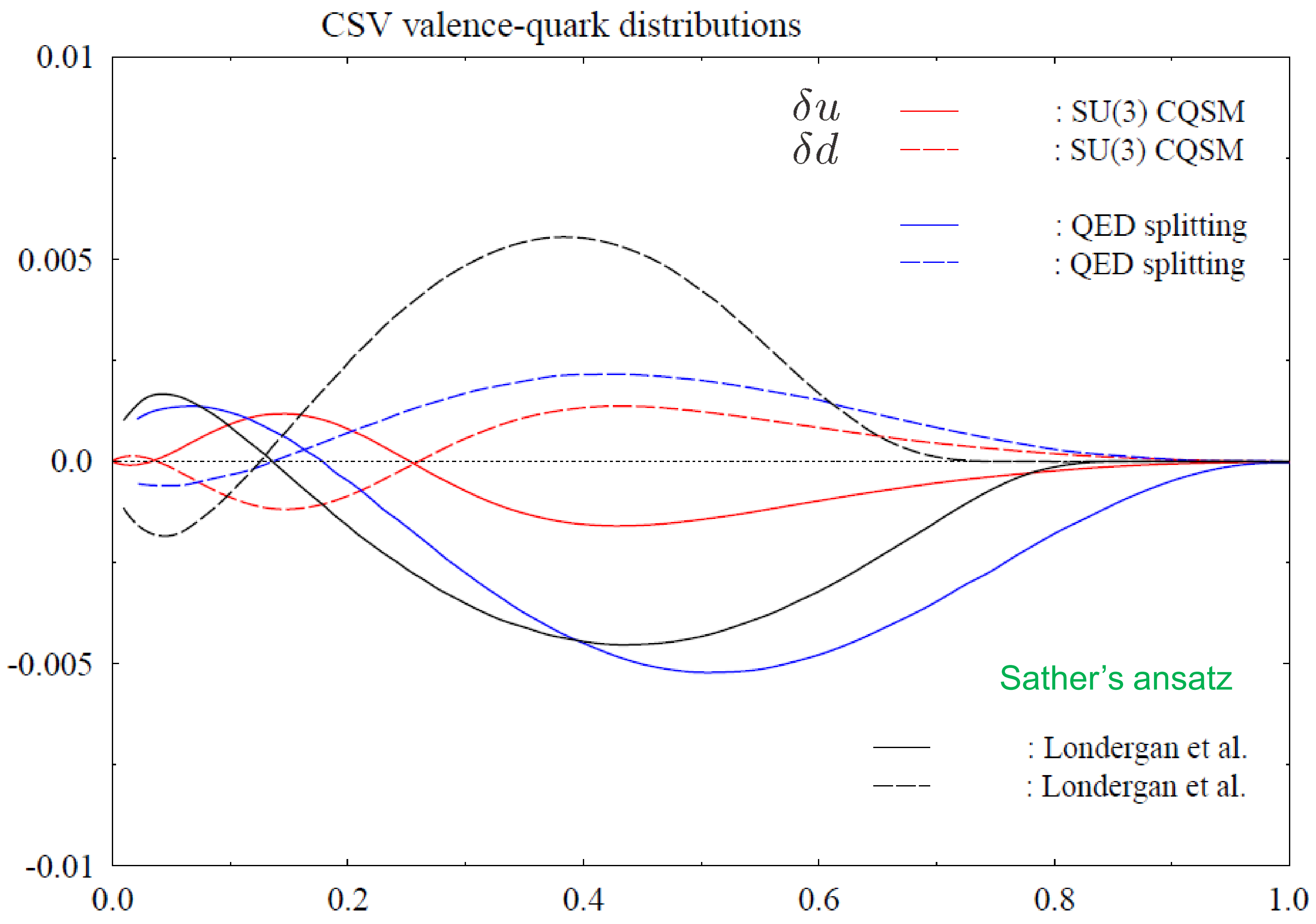
(2) "QED splitting" : MRST (2005), Glueck, Delgado, and Reya (2005)

"QED evolution" , quark radiate photon

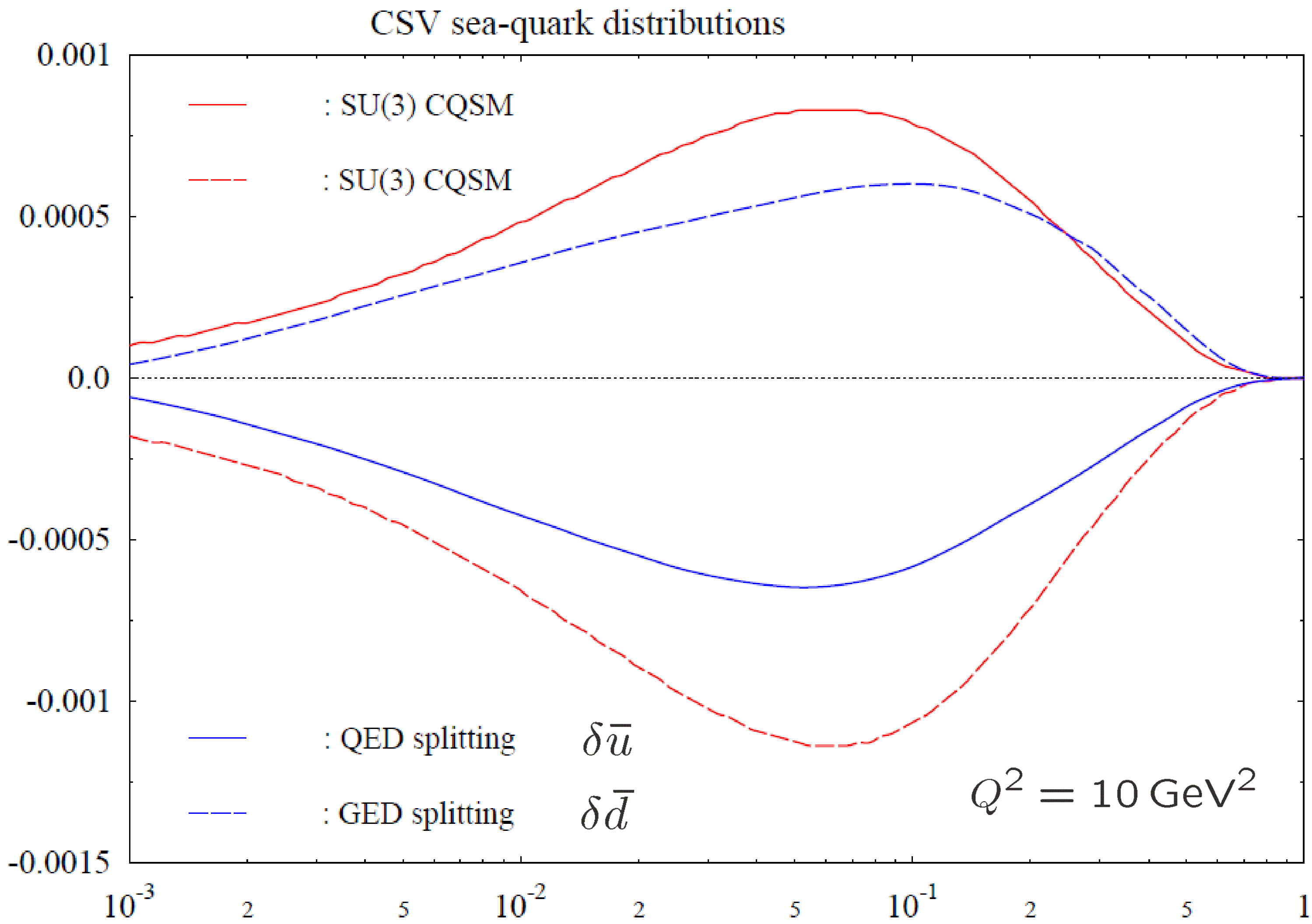
CSV is radiatively generated through evolution



(3) CQSM with perturbative treatment of u-d quark mass difference



The CQSM predictions are much smaller than those based on Sather's ansatz !



The two effects tend to cancel !

Short summary on the CSV effects in PDFs

- The conclusion of Londergan et al's analyses based on Sather's ansats is that the CSV effects in the PDFs gives main ingredients to resolve NuTeV anomaly.

- According to the SU(3) CQSM, which can handle the CSV and flavor symmetry breaking effects **in a unified manner,** the CSV effects to the Paschos-Wolfenstein ratio is much smaller than the effects of strangle quark asymmetry.

- The CSV sea-quark distributions predicted by the SU(3) CQSM due to the up- and down-quark mass difference is of opposite sign as predicted by the "QED splitting" mechanism, and they tend to cancel !

5. Phenomenology of nucleon spin decomposition

concise summary of Lattice QCD predictions for nucleon spin contents

	LHPC [E+06a, H+08a]			QCDSF-UKQCD [K+06, B+07g]		
	$\frac{1}{2}\Delta\Sigma$	L	$J = \frac{1}{2}\Delta\Sigma + L$	$\frac{1}{2}\Delta\Sigma$	L	$J = \frac{1}{2}\Delta\Sigma + L$
u	0.409(34)	−0.195(44)	0.214(27)	0.428(31)	−0.198(32)	0.230(8)
d	−0.201(34)	0.200(44)	−0.001(27)	−0.227(31)	0.223(32)	−0.004(8)
$u + d$	0.207(28)	0.005(52)	0.213(44)	0.201(24)	0.025(27)	0.226(13)

Novel observation

LHPC QCDSF-UKQCD

$$2\,(L^u - L^d) \simeq -0.40 \sim -0.42$$: large and negative !

(Cf.) prediction of SU(6)-like quark model

$$2\,(L^u - L^d)_{\text{MIT bag}} \simeq 0.64$$: large and positive !

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The 2nd nucleon spin crisis ?

[Caution] The energy scale dependence of $L^u - L^d$

$$\texttt{Lattice QCD prediction} \quad \Leftrightarrow \quad Q^2 = 4\,\mathrm{GeV}^2$$

$$\texttt{MIT bag model prediction} \quad \Leftrightarrow \quad Q^2 \simeq 0.16\,\mathrm{GeV}^2 \quad ?$$

Thomas pointed out that the strong scale dependence of $L^u - L^d$ might resolve the discrepancy.

- A. W. Thomas, Phys. Rev. Lett. 101 (2008) 102003.

Actually, this possibility was noticed earlier. [See eq.(92) of the following paper.]

- M. W. and Y. Nakakoji, Phys. Rev. D77 (2008) 074011.

We pointed out that the following asymptotic relation holds

$$\lim_{Q^2 \to \infty} 2 \left(L^u - L^d \right) = - g_A^{(3)} \quad \texttt{with} \quad g_A^{(3)} \simeq 1.26$$

neutron beta-decay coupling constant

which means that $L^u - L^d$ is large and negative at least in the asymptotic limit.

This can be easily understood from the well-known evolution equations.

- X. Ji, J. Tang, and P. Hoodbhoy, Phys. Rev. Lett. 76 (1996) 740.

Leading-order evolution eq. in the flavor non-singlet channel

$$L^{u-d}(t) + \frac{1}{2}\Delta\Sigma^{u-d} = \left(\frac{t}{t_0}\right)^{-32/9\beta_0} \left(L^{u-d}(t_0) + \frac{1}{2}\Delta\Sigma^{u-d} \right)$$

with $\beta_0 = 11 - 3\,n_f\,/\,2, \;\; t = \ln\,(Q^2\,/\,Q_0^2)$

Since right-hand-side becomes 0 as $t \to \infty$, we find that

$$\lim_{t\to\infty} L^{u-d}(t) = -\frac{1}{2}\Delta\Sigma^{u-d} = -\frac{1}{2}\, g_A^{(3)}$$

neutron beta-decay coupling constant !

Thomas' analysis

- A. W. Thomas, Phys. Rev. Lett. 101 (2008) 102003.

Thomas carried out an analysis of the proton spin contents in the context of the refined cloudy bag (CB) model, and concluded that the modern spin discrepancy can well be resolved in terms of the standard features of the nonperturbative structure of the nucleon, i.e.

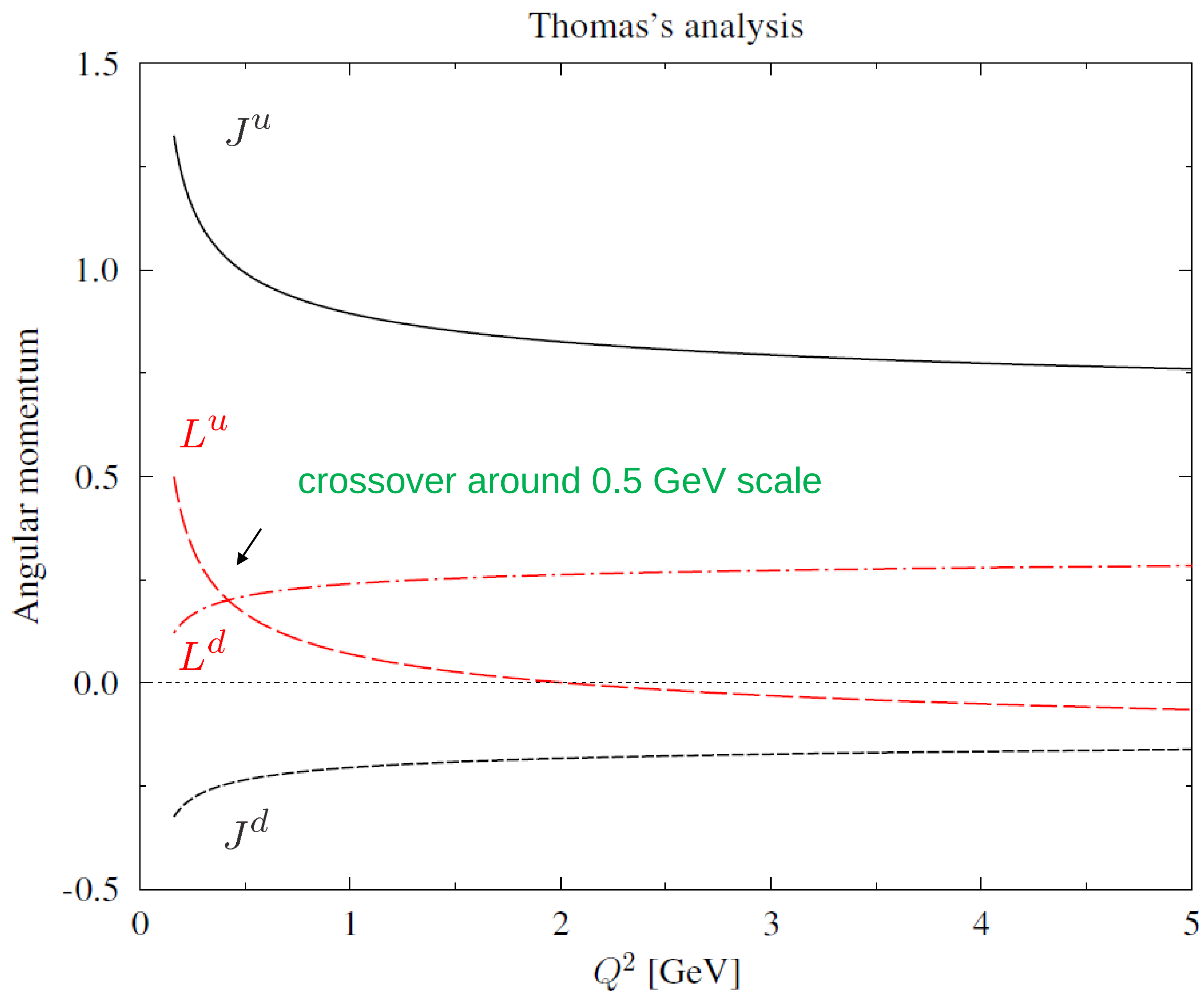
(1) relativistic motion of valence quarks

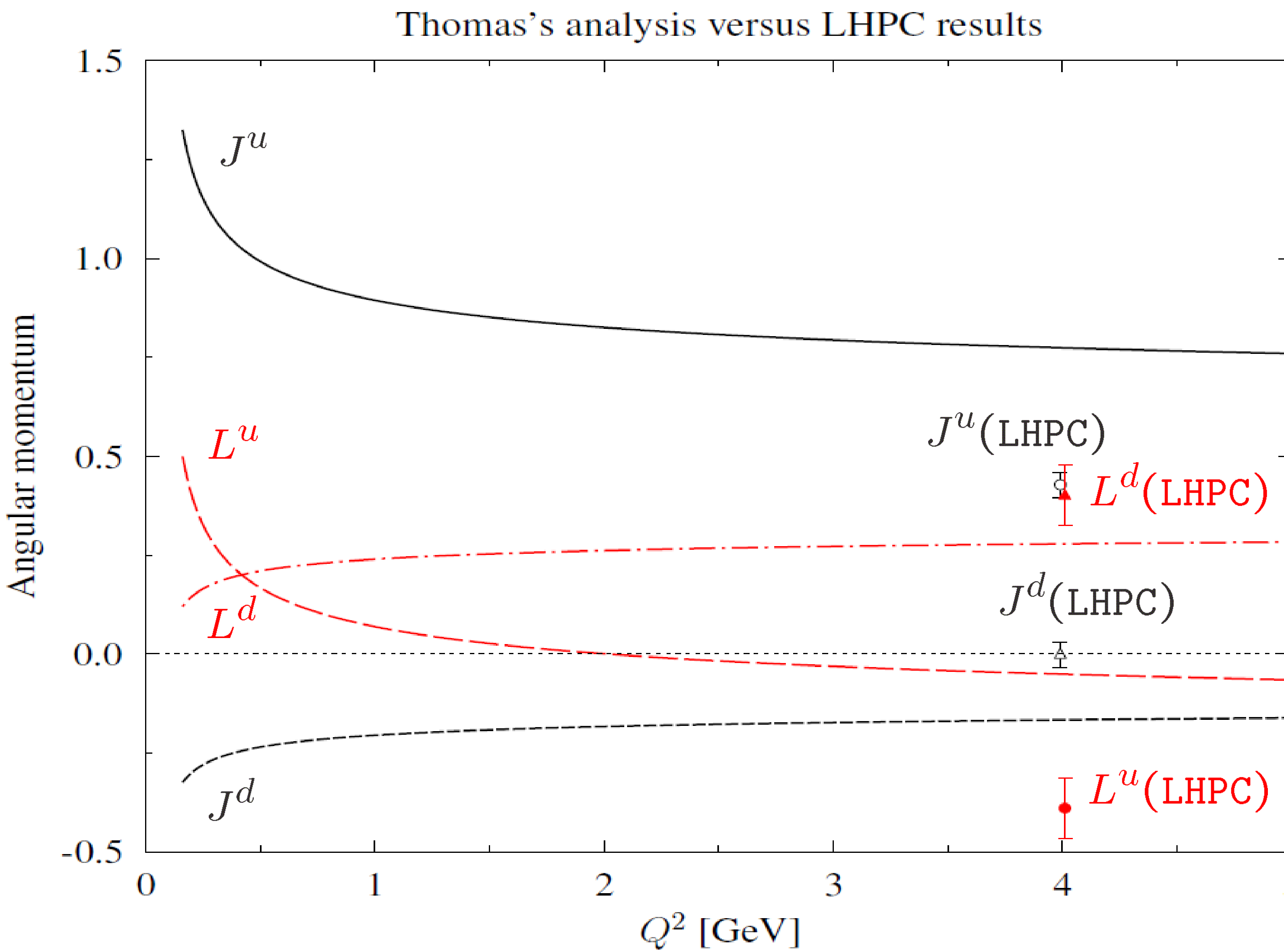
(2) pion cloud required by chiral symmetry

(3) exchange current contribution associated with the OGE hyperfine interactions

supplemented with **QCD scale evolution**.

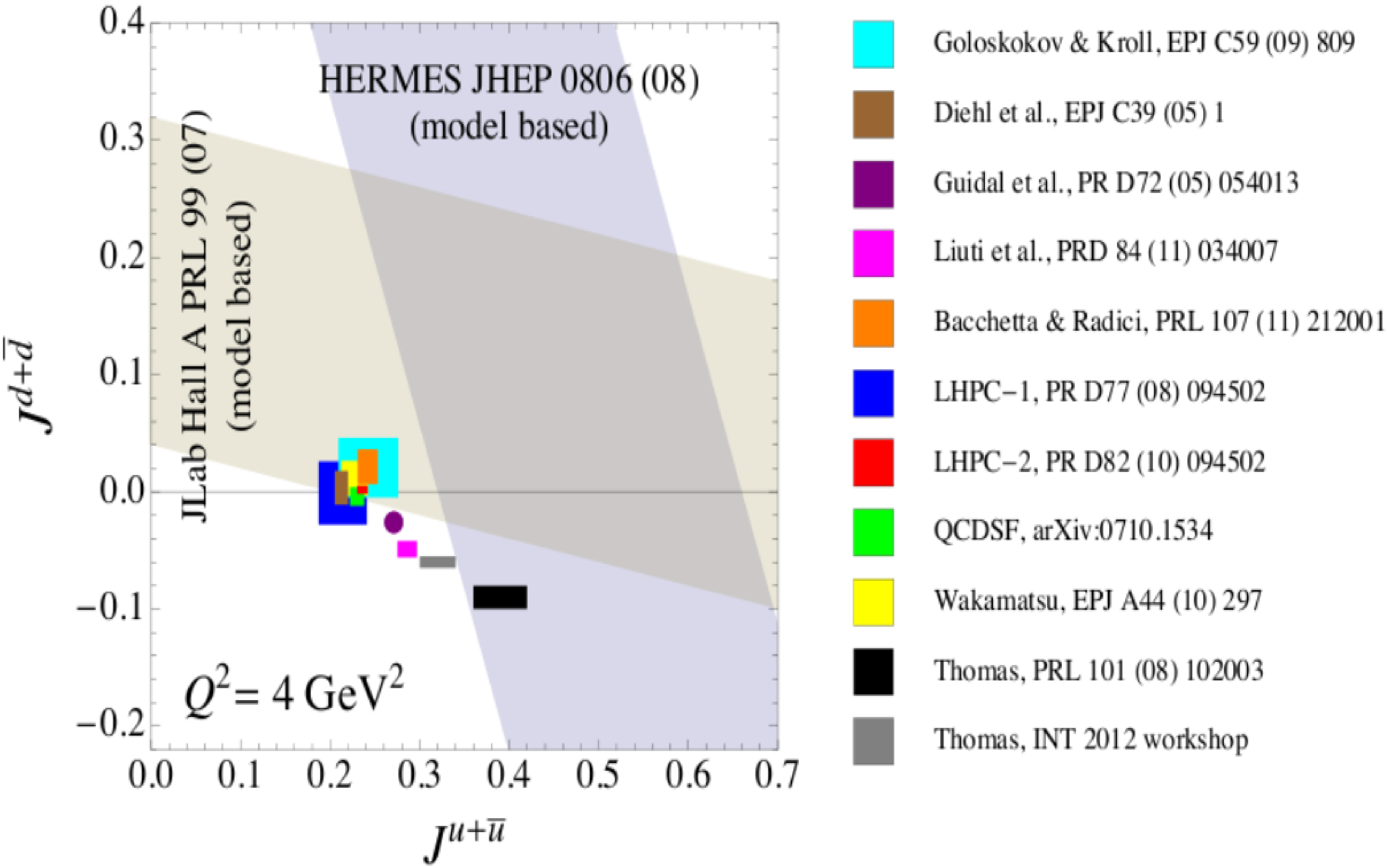
strong scale dependence !


Thomas's analysis
1.5
1.0
0.5
0.0
-0.5
0
1
2
3
4
5
Angular momentum
Q^2 [GeV]
J^u
L^u
L^d
J^d
crossover around 0.5 GeV scale



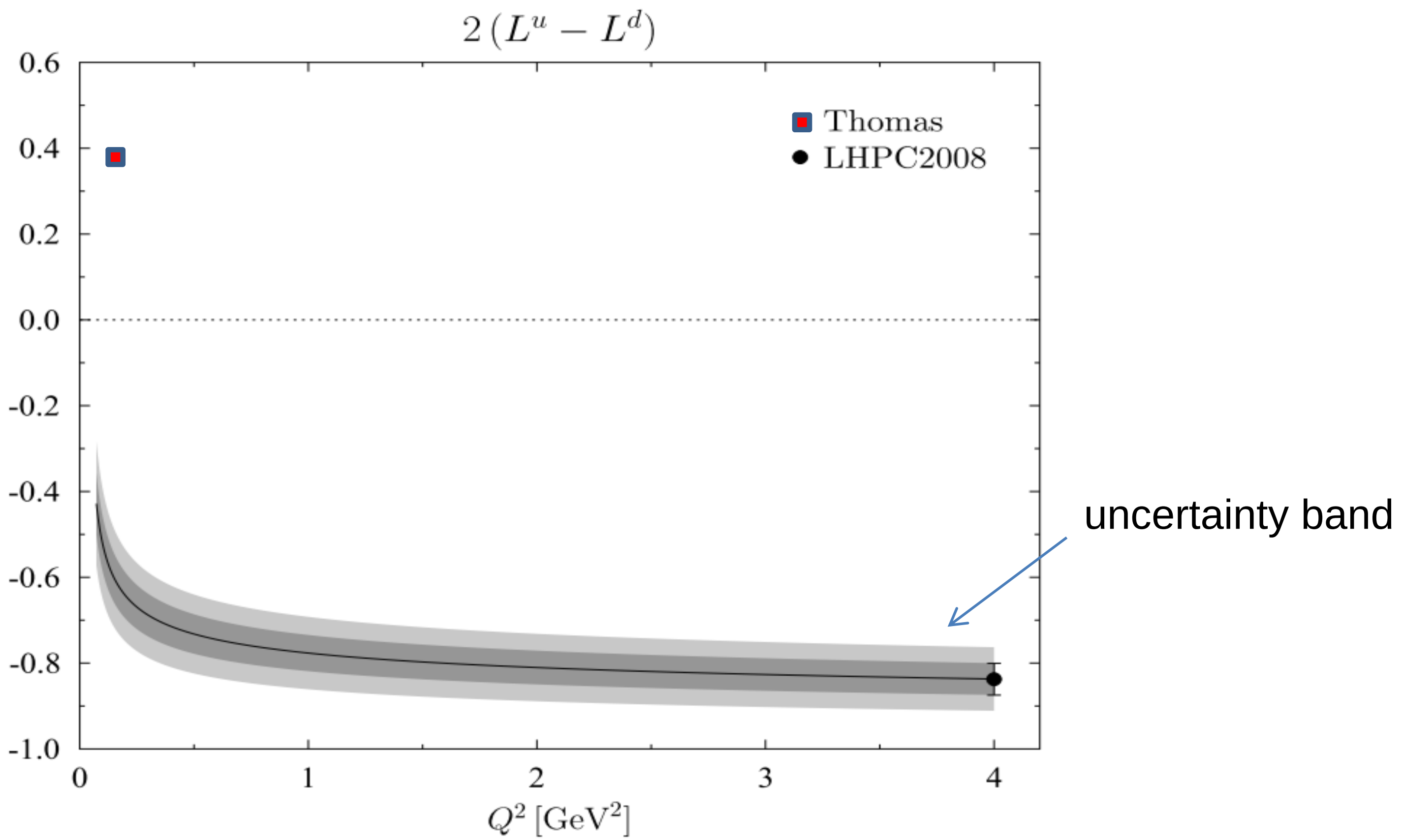
The tendency is OK but the agreement with the Lattice QCD is not very good !

From Radici's talk at QCD-N'12 (Bilbao)



In our opinion, to start the evolution from too low energy scale is dangerous, because of the diverging behavior of the QCD running coupling constant.

We have estimated the orbital angular momentum of up and down quarks in the proton as functions of the energy scale, by carrying out a **downward evolution** of available information from high energy experimental data supplemented with the Lattice QCD data, to find that $L^u - L^d$ remains to be large and negative even at low energy scale of nonperturbative QCD !



The discrepancy with quark models still appears to remain. How can it be solved ?

In recent few years, there have been intensive debate on the theoretical aspect of the nucleon spin decomposition problem, which is still continuing.

In a series of paper (P.R. D81 (2010) 114010, D84 (2011) 037501, D85 (2012) 114039, D85 (2012) 114039), we have clarified that there exist two kinds of quark and gluon OAMs. Confining to the quark sector here, we have

$$L_q = \int \psi^\dagger \frac{1}{i} \boldsymbol{r} \times \boldsymbol{D} \, \psi \, d^3 x \qquad : \quad \text{"mechanical" OAM}$$

$$L'_q = \int \psi^\dagger \frac{1}{i} \boldsymbol{r} \times \boldsymbol{D}_{pure} \, \psi \, d^3 x \qquad : \quad \text{generalized "canonical" OAM}$$

with

$$L'_q - L_q = L_{pot} \qquad : \quad \text{potential angular momentum}$$

An important fact is that the OAM corresponding to the Lattice QCD calculation and the GPD analysis is the “mechanical” OAM not the “canonical” OAM.

Very roughly speaking, the quark OAM involved in Thomas’ analysis is a counterpart of “canonical” OAM not the “mechanical” OAM.

♣ Does the strong scale dependence of $L^u - L^d$ resolve the 2nd nucleon spin puzzle, as Thomas claims ?

♣ Or, is it an indication of a big difference between "dynamical'' & "canonical'' quark OAM ?

♣ A key is a precise measurement of $2\,(J^u - J^d)$ at a few GeV scale.