XII WORKSHOP ON HIGH ENERGY SPIN PHYSICS (DSPIN-07)
Dubna, September 3 - 7, 2007

Progress in the Determination of Polarized PDFs and Higher Twist

E. Leader (London), A. Sidorov (Dubna), D. Stamenov (Sofia)

OUTLINE

- **Method of analysis – higher twist corrections are taken into account**

- **Two new sets of very precise data are included in the analysis**

  - **- *low* Q^2 *CLAS* data**
  - **- *COMPASS* data mainly at *large* Q^2**

  Very different kinematic regions

- **Impact of the new data on *LSS'05* polarized PD and HT**

- **The sign of the gluon polarization**

- **Summary**

LSS: PR D75, 074027, 2007

Theory

In QCD

$$g_1(x,Q^2) = g_1(x,Q^2)_{LT} + g_1(x,Q^2)_{HT}$$

$$g_1(x,Q^2)_{LT} = g_1(x,Q^2)_{pQCD} + \frac{M^2}{Q^2} h^{TMC}(x,Q^2) + O(\frac{M^4}{Q^4})$$

$$g_1(x,Q^2)_{HT} = h(x,Q^2)/Q^2 + O(\frac{\Lambda^4}{Q^4})$$

dynamical HT power corrections (τ =3,4)
=> non-perturbative effects (model dependent)

target mass corrections which are calculable
A. Piccione, G. Ridolfi

In NLO pQCD

$$g_1(x,Q^2)_{pQCD} = \frac{1}{2}\sum_q^{N_f} e_q^2 [(\Delta q + \Delta\bar{q}) \otimes (1 + \frac{\alpha_s(Q^2)}{2\pi}\delta C_q) + \frac{\alpha_s(Q^2)}{2\pi}\Delta G \otimes \frac{\delta C_G}{N_f}]$$

$\delta C_q, \delta C_G - Wilson$ coefficient functions

N_f (=3) - the number of flavors

polarized PD evolve in Q^2 according to **NLO DGLAP** eqs.

- **An important difference between the kinematic regions of the unpolarized and *polarized* data sets**

- **A lot of the present data are at moderate Q^2 and W^2 :**

$$Q^2 \approx 1-5\,GeV^2,\ 4 < W^2 < 10\,GeV^2$$

preasymptotic region

While in the determination of the PD in the unpolarized case we can cut the low Q^2 and W^2 data in order to eliminate the less known non-perturbative HT effects, it is impossible to perform such a procedure for the present data on the spin-dependent structure functions without loosing too much information.

$$O(\Lambda^2/Q^2)$$

⇨ **HT corrections** have to be **accounted for** in **polarized** DIS !

Method of analysis

$$\left[\frac{g_1(x,Q^2)}{F_1(x,Q^2)}\right]_{\exp} \overset{\chi^2}{\Longleftrightarrow} \frac{g_1(x,Q^2)_{\mathrm{LT}} + h^{g_1}(x)/Q^2}{F_1(x,Q^2)_{\exp}}$$

F_2^{NMC}, R_{1998}(SLAC)

in model independent way

Input PD

$$\Delta f_i(x,Q_0^2) = A_i x^{\alpha_i} f_i^{MRST}(x,Q_0^2)$$

$Q_0^2 = 1\,GeV^2,\ A_i, \alpha_i - free\ par.$

$h^p(x_i), h^n(x_i) - 10\ parameters\ \ (i = 1,2,\ldots 5)$ to be determined from a fit to the data

8-2(SR) = 6 par. associated with PD; positivity bounds imposed by **MRST'02** unpol. PD

SUM

RULES

$$a_3 = g_A = (\Delta u + \Delta\bar{u})(Q^2) - (\Delta d + \Delta\bar{d})(Q^2) = F - D = 1.2670 \pm 0.0035$$

$$a_8 = (\Delta u + \Delta\bar{u})(Q^2) + (\Delta d + \Delta\bar{d})(Q^2) - 2(\Delta s + \Delta\bar{s})(Q^2) = 3F - D = 0.585 \pm 0.025$$

Flavor symmetric sea convention: $\Delta \mathrm{u}_{\mathrm{sea}} = \Delta\bar{\mathrm{u}} = \Delta \mathrm{d}_{\mathrm{sea}} = \Delta\bar{\mathrm{d}} = \Delta \mathrm{s} = \Delta\bar{\mathrm{s}}$

Higher twist effects

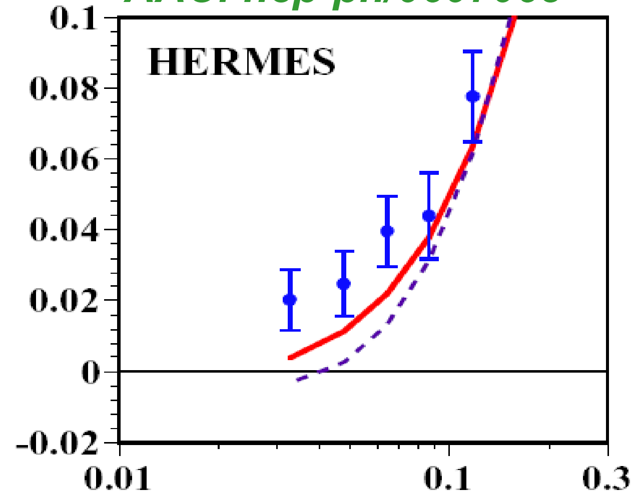
(CLAS'06 and COMPASS'06 not included)

$$g_1 = (g_1)_{LT} + h^{g_1}(x)/Q^2$$

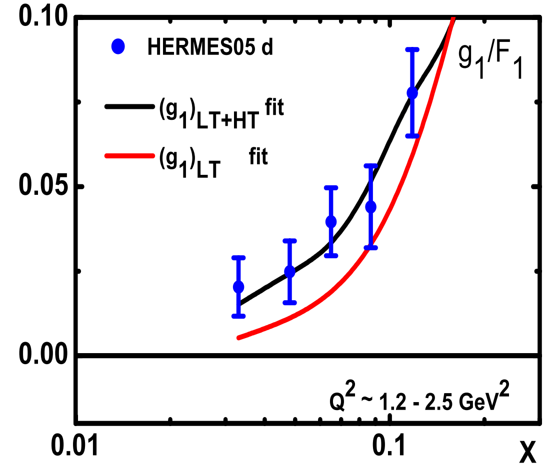
- **The low x and low Q^2 (1.2 ~ 2.5 GeV^2) HERMES/d data can not be described by the LT (logarithmic in Q^2) term in g_1 => red curves**

- **Excellent agreement with the data if the HT corrections to g_1 are taken into account in the analysis**

AAC: hep-ph/0607063



LSS: PR D73 (2006)



DATA (old set)

CERN EMC - A_1^p SMC - A_1^p, A_1^d COMPASS'05 - A_1^d

DESY HERMES - $\frac{g_1^p}{F_1^p}$, $\frac{g_1^d}{F_1^d}$

SLAC E142, E154 - A_1^n E143, E155 - $\frac{g_1^p}{F_1^p}$, $\frac{g_1^d}{F_1^d}$

JLab Hall A - $\frac{g_1^n}{F_1^n}$

$$A_1^N \approx (1+\gamma^2)\frac{g_1^N}{F_1^N}$$

$\gamma^2 = 4M^2x^2/Q^2$ - kinematic factor

Number of exp. points: 190

LSS'05 polarized PD and HT *(PR D73, 2006)*

DATA

CERN EMC - A_1^p SMC - $A_1^p,\ A_1^d$ COMPASS'05 - A_1^d

DESY HERMES - $\dfrac{g_1^p}{F_1^p},\ \dfrac{g_1^d}{F_1^d}$

SLAC E142, E154 - A_1^n E143, E155 - $\dfrac{g_1^p}{F_1^p},\ \dfrac{g_1^d}{F_1^d}$

JLab Hall A - $\dfrac{g_1^n}{F_1^n}$ CLAS'06 - $\dfrac{g_1^p}{F_1^p},\ \dfrac{g_1^d}{F_1^d}$

$$A_1^N \approx (1+\gamma^2)\frac{g_1^N}{F_1^N}$$

$\gamma^2 = 4M^2x^2/Q^2$ - kinematic factor

Number of exp. points: 190 $\Longrightarrow$ 823

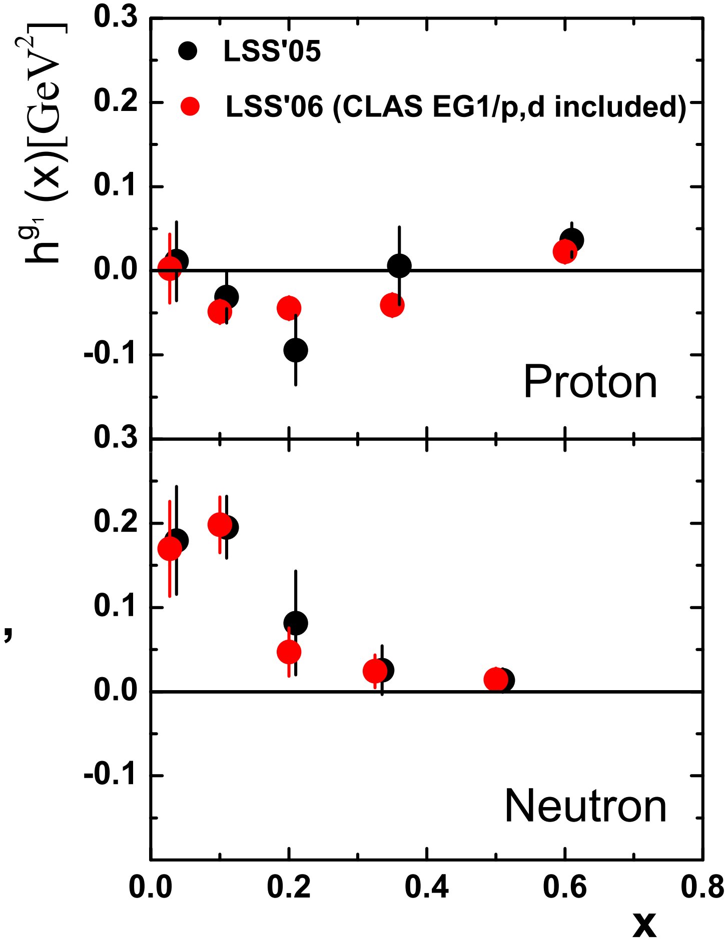
Effect of CLAS'06 p and d data *(PL B641, 11, 2006)* on polarized PD and HT

LSS'05: PR D73 (2006)

- **Very accurate data on g_1^p and g_1^d at low Q^2: 1~ 4 GeV^2 for x ~ 0.1 - 0.6**

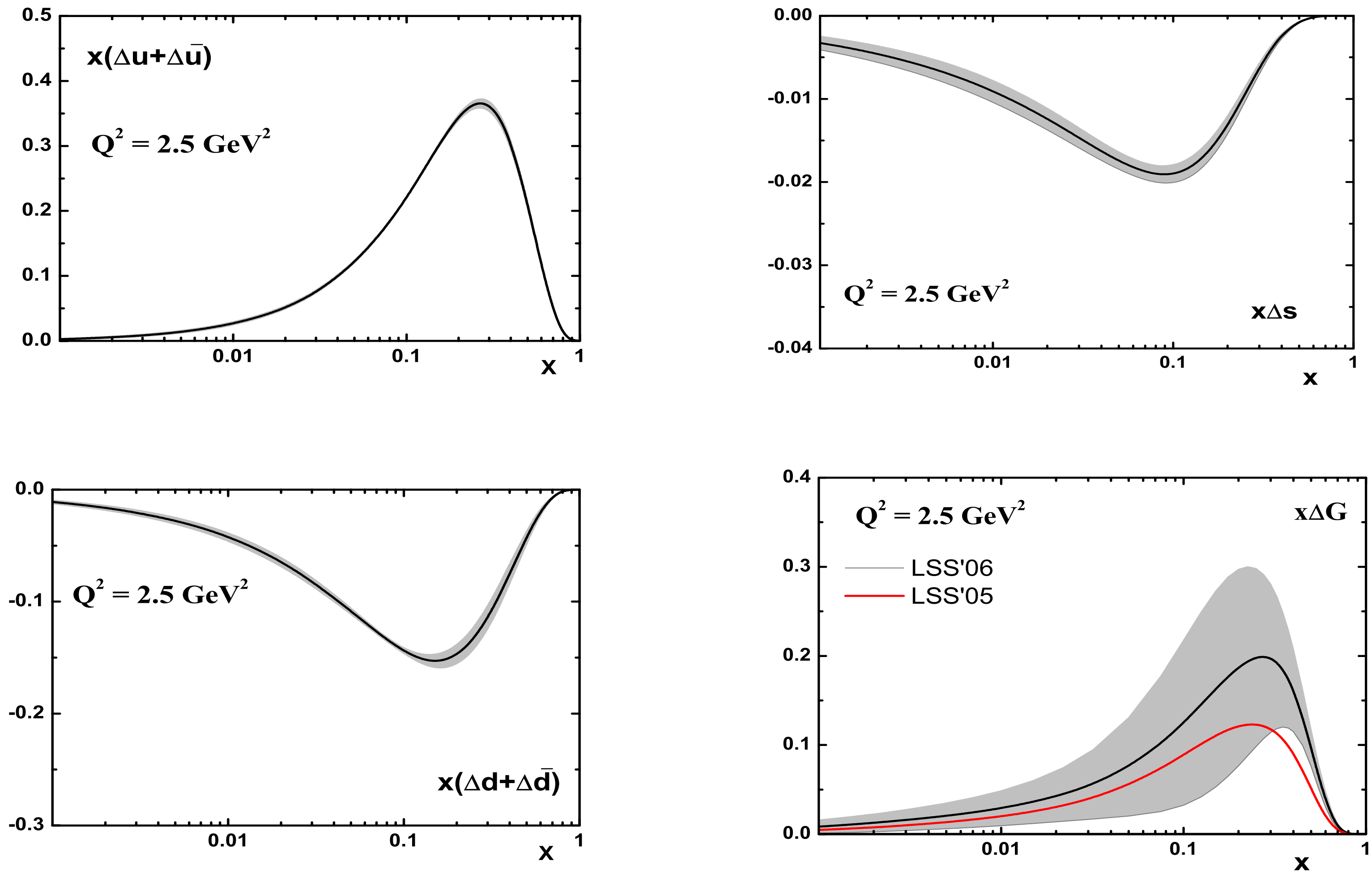
- **The determination of HT/p and HT/n is significantly improved in the *CLAS* x region compared to HT(LSS'05)**

- **As expected, the central values of PPD are practically not affected by *CLAS* data, but the accuracy of its determination is essentially improved (a consequence of much better determination of HT corrections to g_1)**

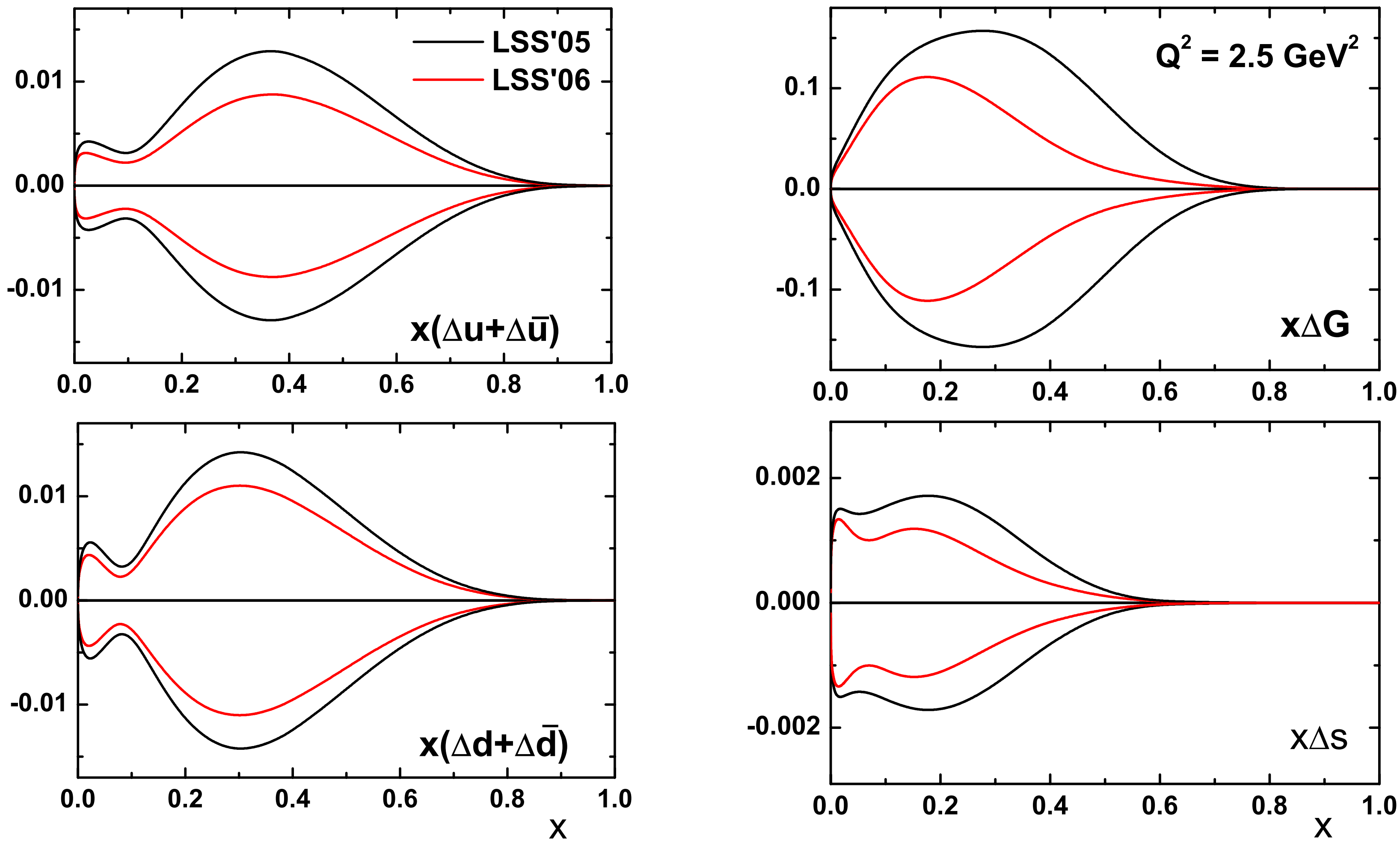


LSS'06 NLO($\overline{MS}$) polarized PDFs

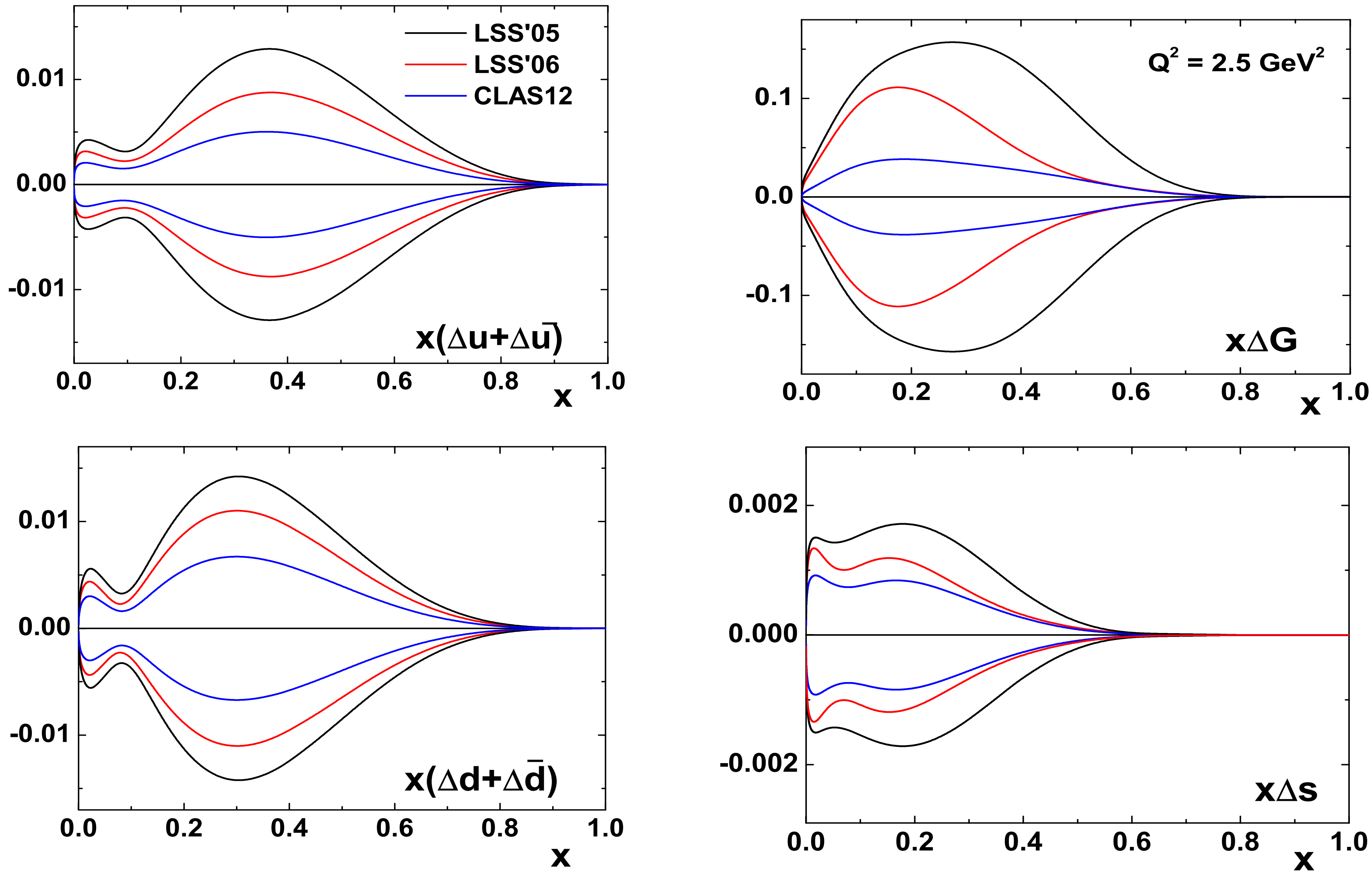
The quark densities (central values) are identical with those of LSS'05.



Impact of CLAS'06 data on the uncertainties for NLO polarized PD

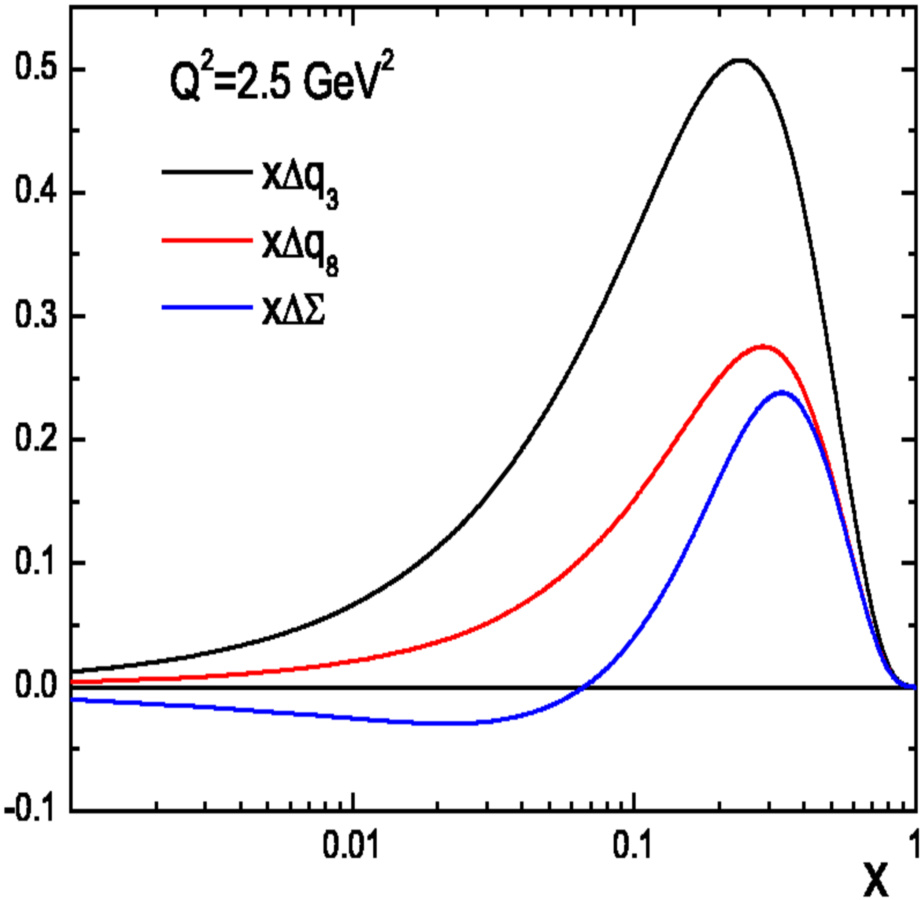


The expected uncertainties for NLO($\overline{MS}$) polarized PDFs including the CLAS12 “data” set



Why deuteron best for $\Delta G(x)$?

$$g_1^{p(n)}(x,Q^2) = \frac{1}{9}[(\pm\frac{3}{4}\Delta q_3 + \frac{1}{4}\Delta q_8 + \Delta\Sigma) \otimes (1 + \frac{\alpha_s(Q^2)}{2\pi}\delta C_q) + \frac{\alpha_s(Q^2)}{2\pi}\Delta G \otimes \delta C_G]$$



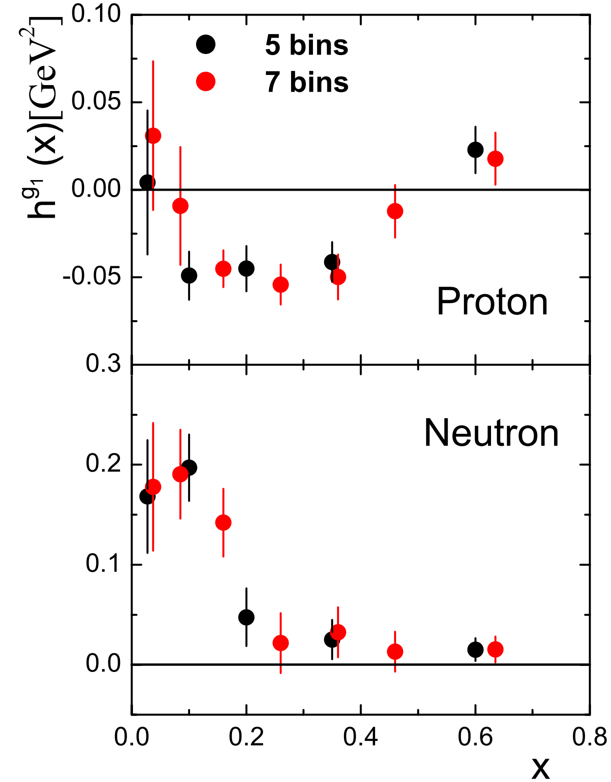
- The Δq_3 terms from p and n about twice size of Δq_8 and $\Delta\Sigma$ terms, **cancel** in deuteron.

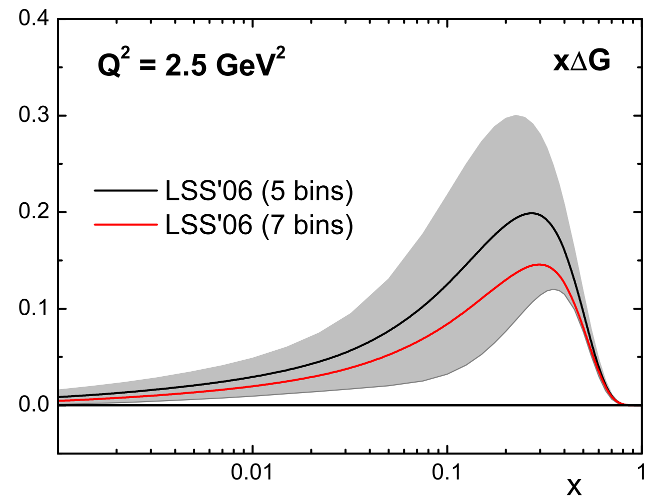
⟹ **Relative** gluon contribution largest in deuteron.

- Due to the good accuracy of the *CLAS* data, one can split the measured x region of the *world+CLAS* data set into 7 bins instead of 5, and to determine more precisely the x-dependence of HT

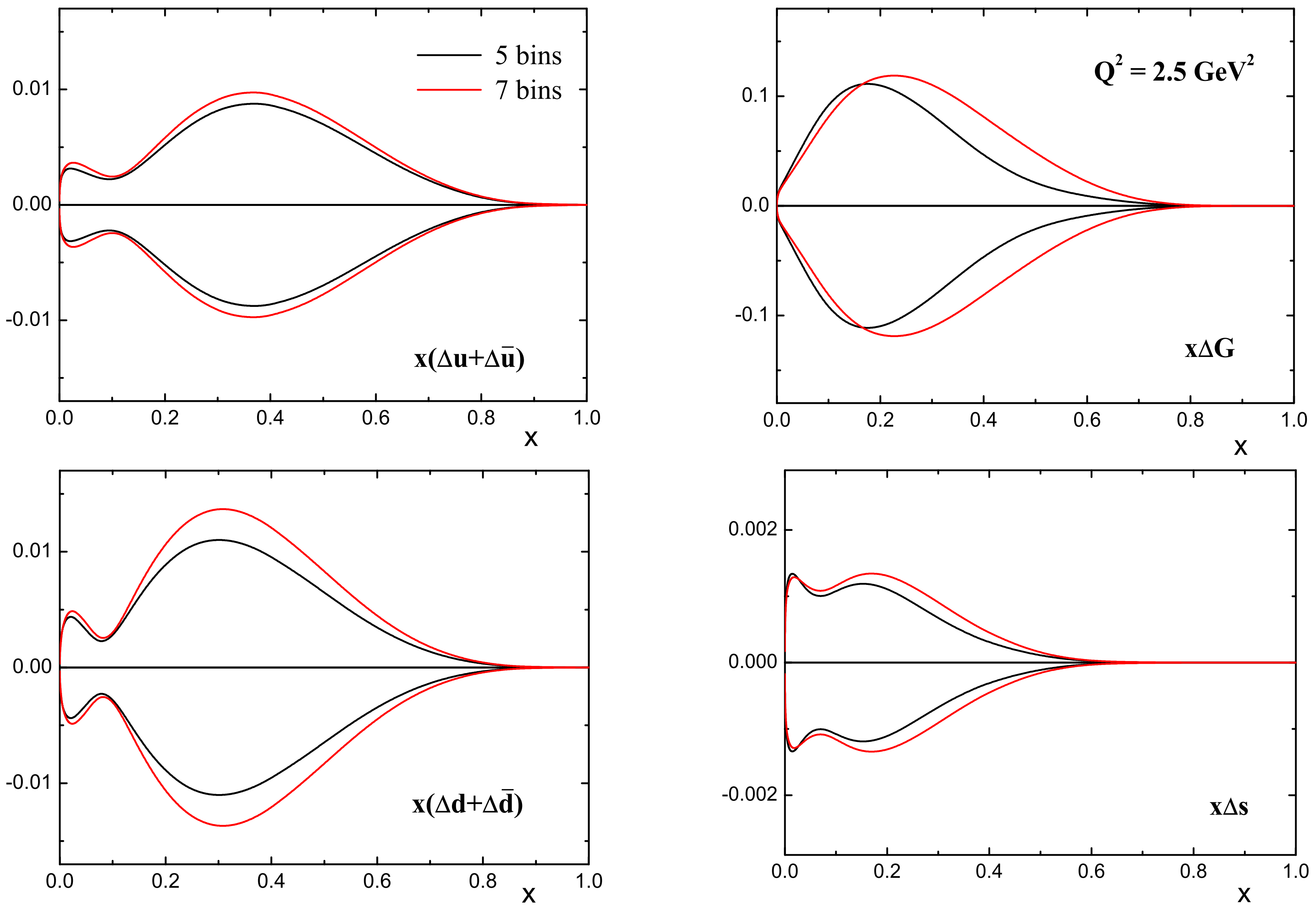
- The corresponding PPD are practically identical with those of LSS'06 (5 bins)

- The only exception is $x\Delta G$, but it lies within the error band of $x\Delta G$ (5 bins) → small correlation between gluons and HT





5 → 7 x-bins
Impact on the uncertainties for NLO polarized PDFs



The first moments of higher twist

- Thanks to the very precise CLAS data the first moments of HT corrections are now much better determined.

$$\overline{h}^N = \int_{0.0045}^{0.75} dx\, h^N(x), \quad \mathrm{N} = \mathrm{p,n}$$

$$\overline{h}^p = (-0.014 \pm 0.005)\, GeV^2 \qquad \overline{h}^n = (0.037 \pm 0.008)\, GeV^2$$

$$\overline{h}^p - \overline{h}^n = (-0.051 \pm 0.009)\, GeV^2 \qquad \overline{h}^p + \overline{h}^n = (0.023 \pm 0.009)\, GeV^2$$

- $\overline{h}^p - \overline{h}^n < 0$ ← In agreement with the instanton model predictions and sum rules in QCD
- $\overline{h}^p + \overline{h}^n < |\overline{h}^p - \overline{h}^n|$ ← In agreement with $1/N_C$ expansion in QCD (*Balla et al., NP B510, 327, 1998*)

The main message from this analysis

→ **It is impossible to describe the very precise CLAS data if the HT corrections are NOT taken into account**

NOTE: If the low Q^2 data are not too accurate, it would be possible to describe them using only the leading twist term (logarithmic in Q^2) of g_1, *i.e.* to mimic the power in Q^2 dependence of g_1 with a logarithmic one (using different forms for the input PDFs and/or more free parameters associated with them) which was done in the analyses of another groups before the CLAS data have appeared.

DATA

CERN **EMC -** A_1^p **SMC -** $A_1^p,\ A_1^d$ **COMPASS'06 -** A_1^d

DESY **HERMES -** $\frac{g_1^p}{F_1^p},\ \frac{g_1^d}{F_1^d}$

SLAC **E142, E154 -** A_1^n **E143, E155 -** $\frac{g_1^p}{F_1^p},\ \frac{g_1^d}{F_1^d}$

JLab **Hall A -** $\frac{g_1^n}{F_1^n}$ **CLAS'06 -** $\frac{g_1^p}{F_1^p},\ \frac{g_1^d}{F_1^d}$

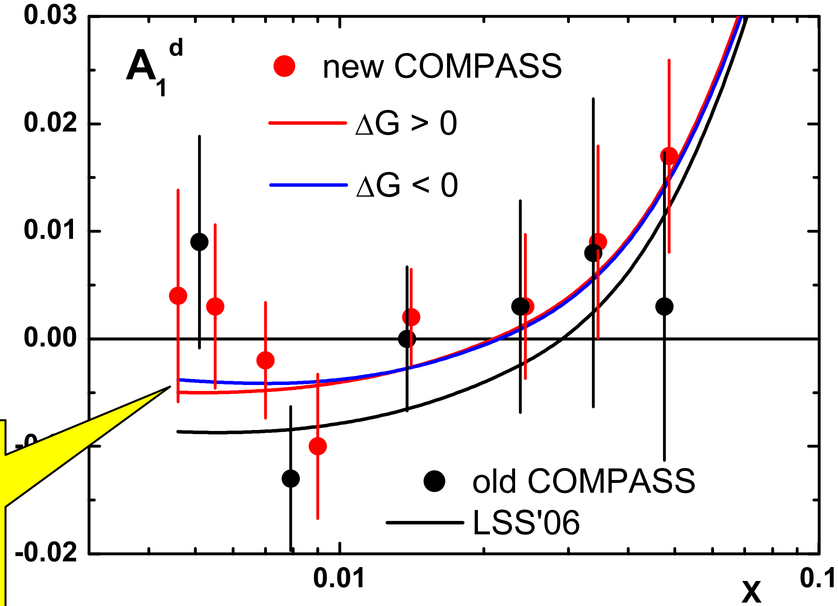
$$A_1^N \approx (1+\gamma^2)\frac{g_1^N}{F_1^N}$$

γ^2 = 4M^{2}x^2/Q^2 - kinematic factor

Number of exp. points: 823 ⟹ 826

Effect of COMPASS'06 A_1^d data (*hep-ex/0609038*) on polarized PD and HT

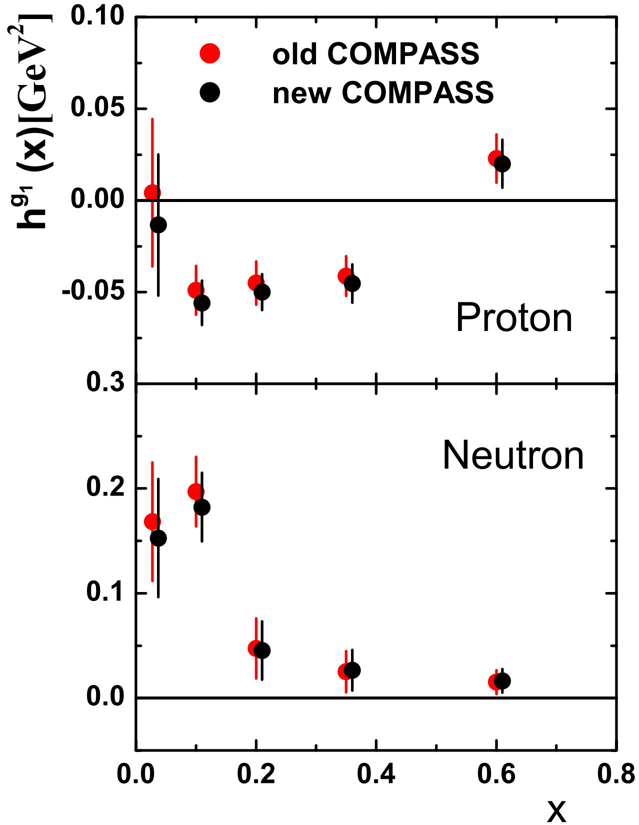
In contrast to the *CLAS* data, the *COMPASS* data are mainly at large Q^2 and the only precise data at small x: $0.004 < x < 0.02$. The new data are based on 2.5 times larger statistics than those of *COMPASS'05*

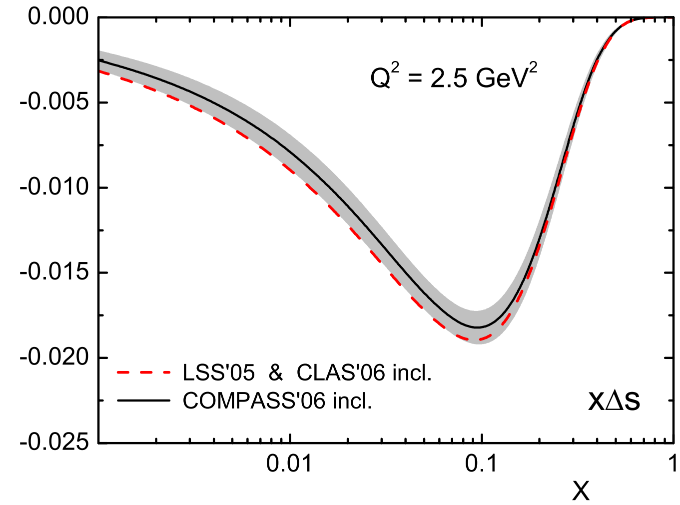


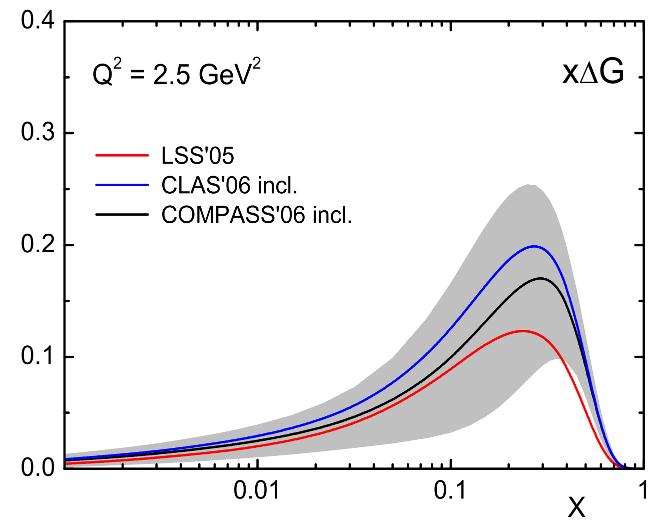
The new QCD curves corresponding to the best fits lie above the old one at $x < 0.1$

- $(\Delta u + \Delta\bar{u}),\ (\Delta d + \Delta\bar{d})$ do NOT change
- $x|\Delta s(x)|$ and $x\Delta G(x)$ and their first moments Δs and ΔG slightly decrease

5 x-bins for HT

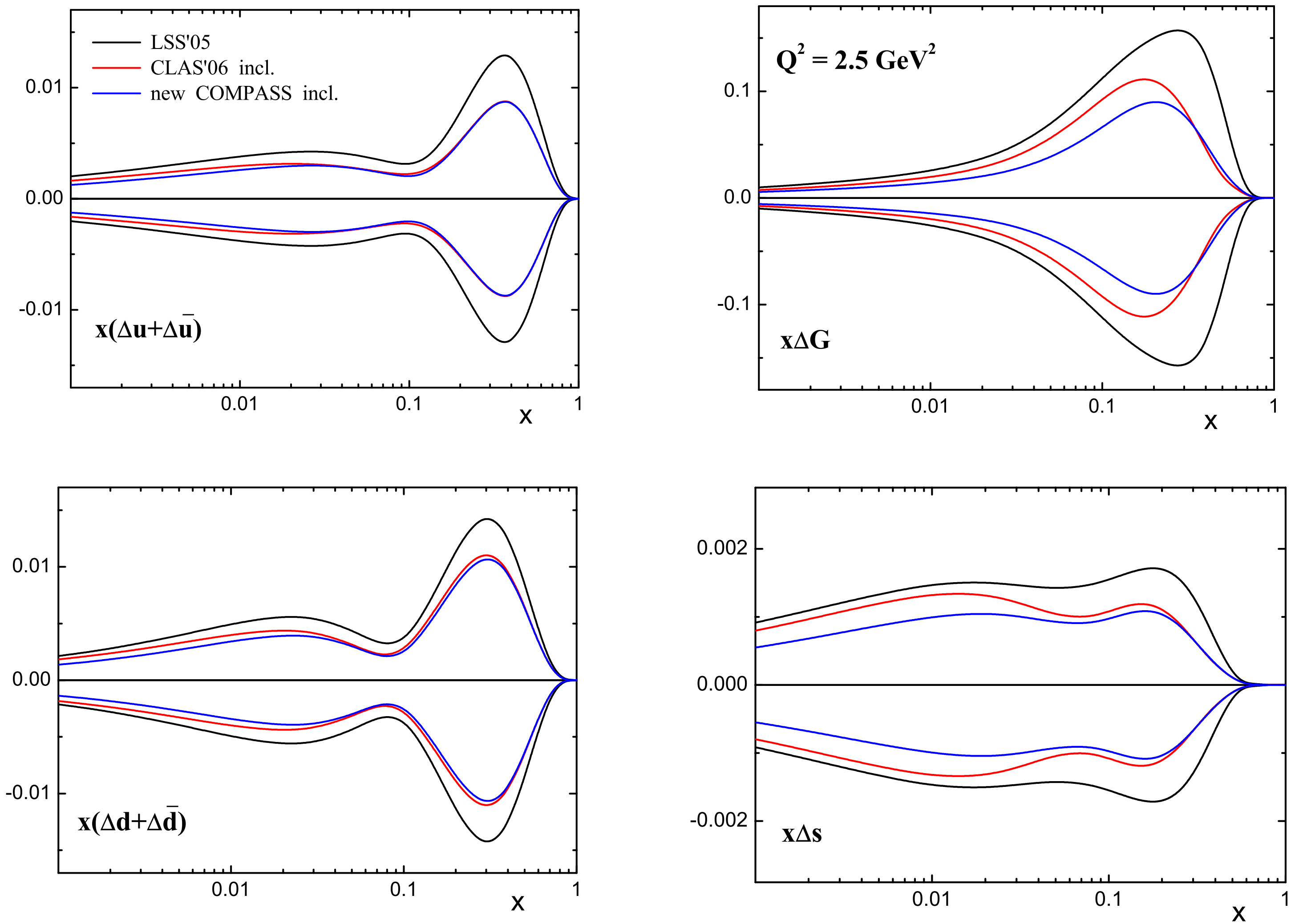






The values of HT are practically NOT affected by *COMPASS* data excepting the small x where Q^2 are also small

Impact of C0MPASS'06 data on the uncertainties for NLO polarized PD



$Q^2 = 1\ GeV^2$

COMPASS	Δs	ΔG	$a_0 = \Delta\Sigma_{MS}$
old	-0.070 ± 0.007	0.296 ± 0.197	0.164 ± 0.048
new	-0.063 ± 0.005	0.237 ± 0.153	0.207 ± 0.039

Spin of the proton

$$S_z = 1/2 = 1/2\ \Delta\Sigma(Q^2) + \Delta G\ (Q^2) + L_q\ (Q^2) + L_g(Q^2)$$

$$= 0.34 +/- 0.16 + L_q\ (Q^2) + L_g(Q^2)$$

The big uncertainty is coming from gluons

To be determined from forward extrapolations of generalized PD

Spin puzzle ?

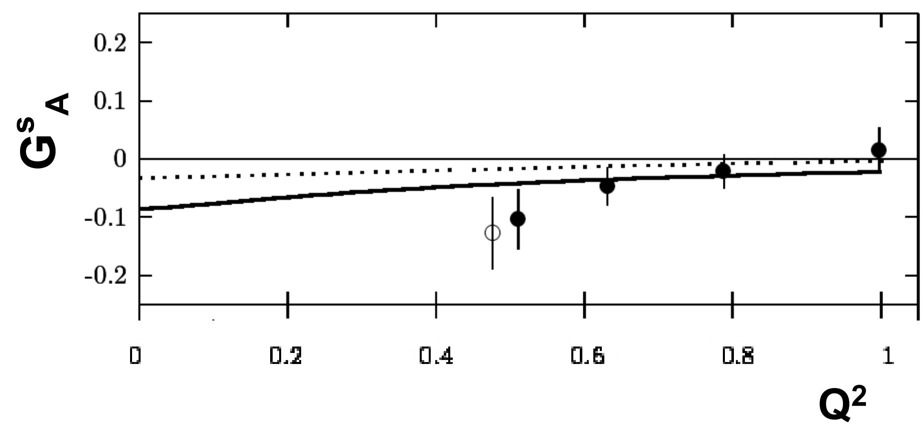
$$\Delta\Sigma(Q^2 \sim \Lambda^2_{QCD}) = \begin{cases} 0.6 \leftarrow \text{relativistic constituent QM} \\ < 0.6 \leftarrow \text{Nonpert. vacuum spin effects (instanton models) - Shore, Veneziano; Forte, Shuryak; Dorokhov, Kochelev (negative quark sea)} \end{cases}$$

$\Delta\Sigma = \Delta u_V + \Delta d_V + \Delta q_{sea}$

$\Delta\Sigma(Q^2)$ in QCD is a scheme dependent quantity !

From combined analysis of elastic $e\vec{p}$ (JLab), $\nu(\bar{\nu})p$ (BNL) data → the strange axial form factor $G^S_A(Q^2)$ at $Q^2 \leq 1$ GeV^2

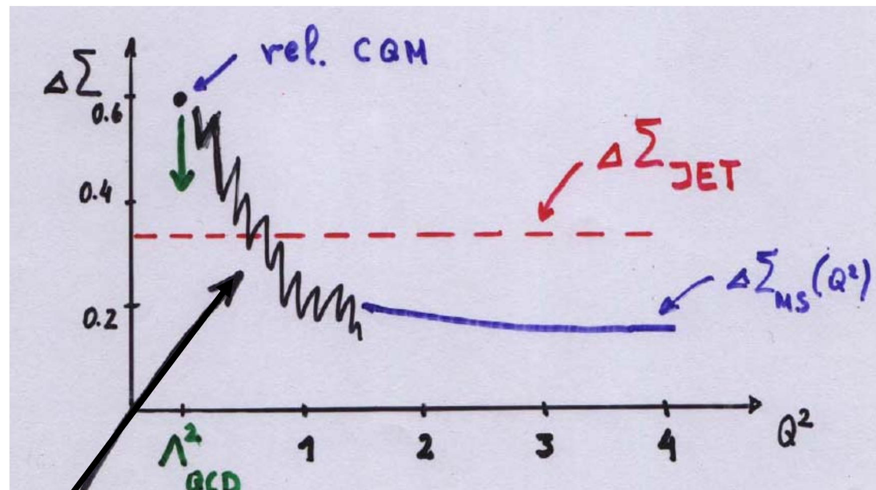
$G^S_A(Q^2 = 0) = \Delta s$



S. Pate, hep-ex/0611053

$$\Delta\Sigma_{JET}(\text{DIS}) \Leftrightarrow \Delta\Sigma(Q^2 \sim \Lambda^2_{QCD})$$

0.3 ? 0.6



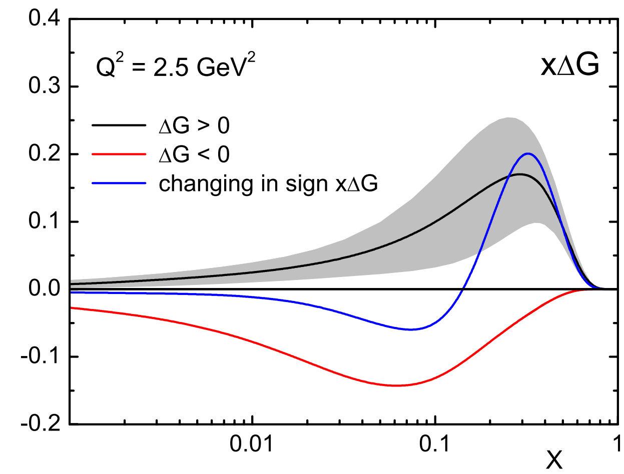
Nonperturbative effects !

The sign of gluon polarization

- The present **inclusive** DIS data **cannot rule out** the solutions with negative and changing in sign gluon polarizations

$$\chi^2_{DF}(\Delta G > 0) = 0.892$$

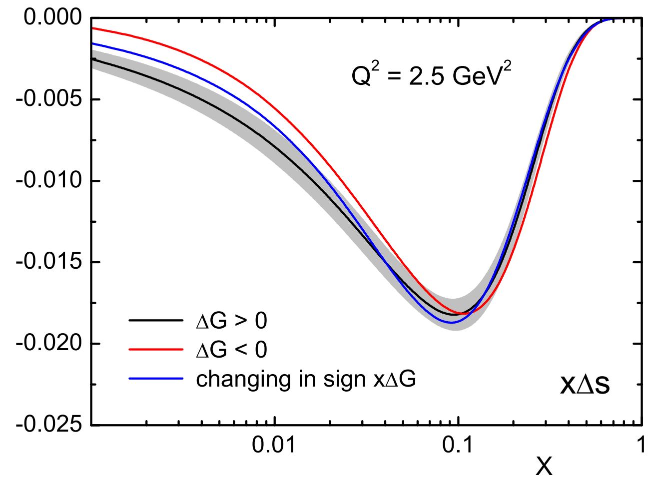
$$\chi^2_{DF}(\Delta G < 0) = 0.895, \chi^2_{DF}(x\Delta G / chsign) = 0.888$$



- The shape of the negative gluon density **differs** from that of positive one

- In all the cases the magnitude of ΔG is small: $|\Delta G| \leq 0.4$ at $Q^2 = 1\ GeV^2$

- The corresponding polarized quark densities are **very close** to each other



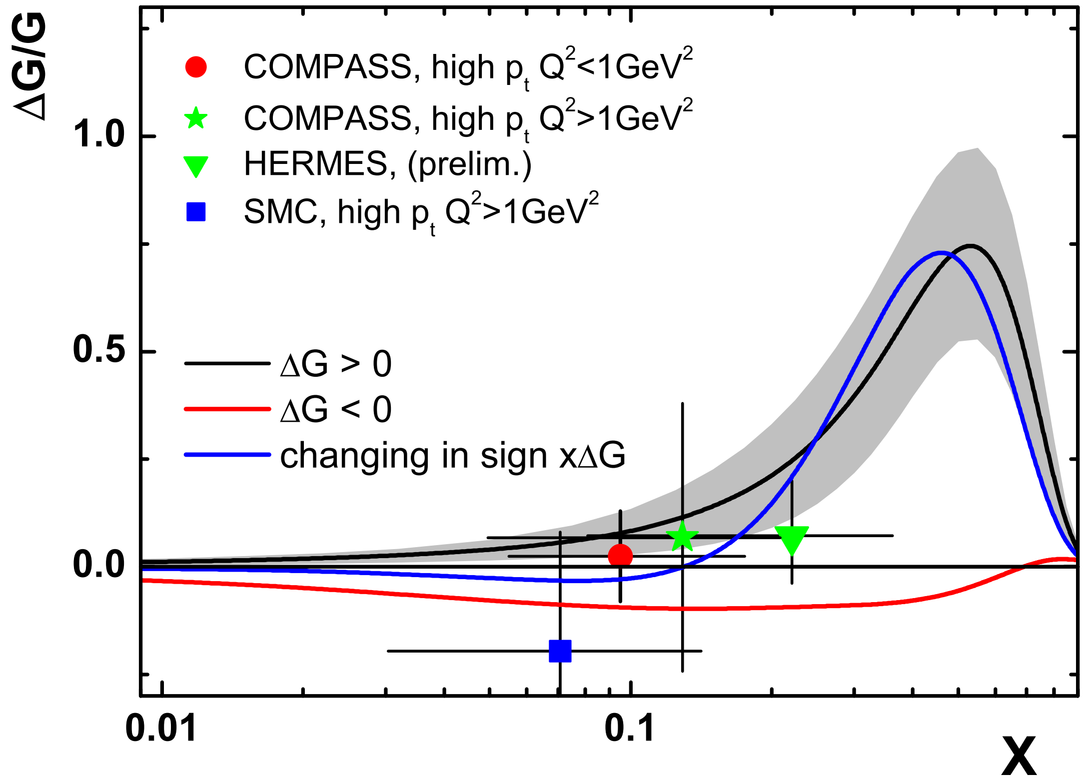
Comparison with directly measured ΔG/G at $Q^2 = 3\ GeV^2$

MRST'02 unpolarized gluon density is used for G(x)

The error band corresponds to statistic and systematic errors of ΔG

The error bars of the experimental points represent the total errors

The most precise value of ΔG/G, the *COMPASS* one, is well consistent with any of the polarized gluon densities determined in our analysis



LSS'06 *vs* C0MPASS'06

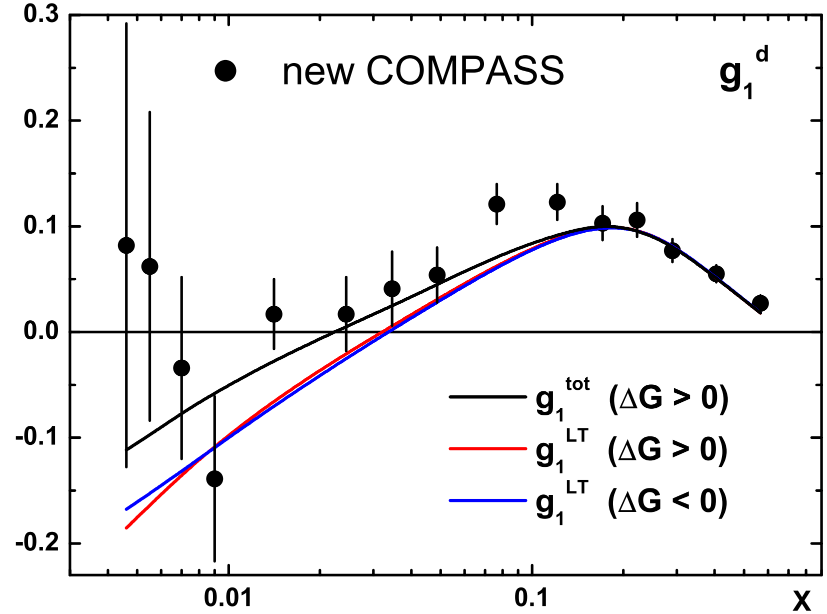
- At small x: 0.004 – 0.02 (Q^2 ~ 1-3 GeV^2) our results differ from those of *COMPASS*

$$(g_1)_{exp} \leftrightarrow$$
$$(g_1)_{LT}(COMPASS) \approx$$
$$(g_1)_{LT}(LSS) + h^d(x)/Q^2$$

- *COMPASS* → significant difference between $(g_1)_{th}$ corresponding to the best fits for $\Delta G > 0$ and $\Delta G < 0$

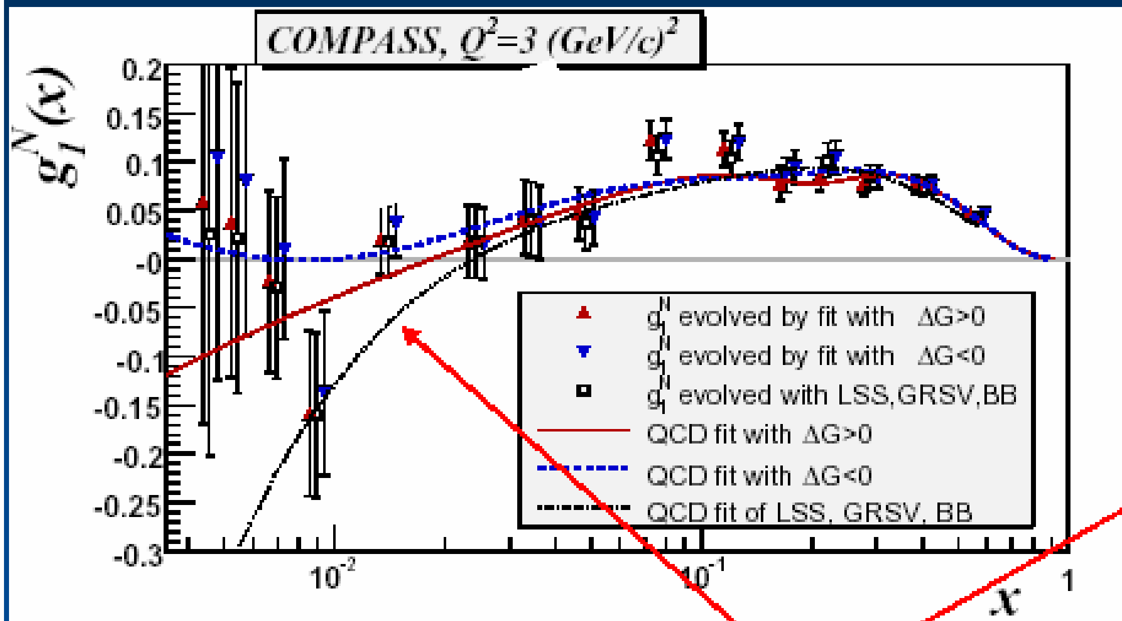
- *LSS'06* → the theoretical curves for both cases are very close to each other

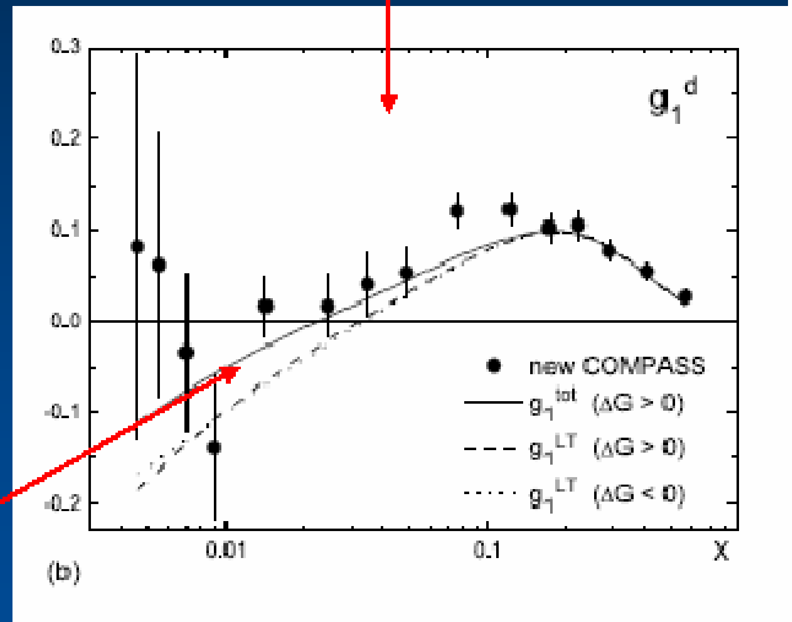
- The reason → HT effects (40% at small x) which are NOT taken into account by *COMPASS*



QCD analysis of the world data on structure function g_1

Comparison of data and fits - LSS06 (hep-ph/0612360

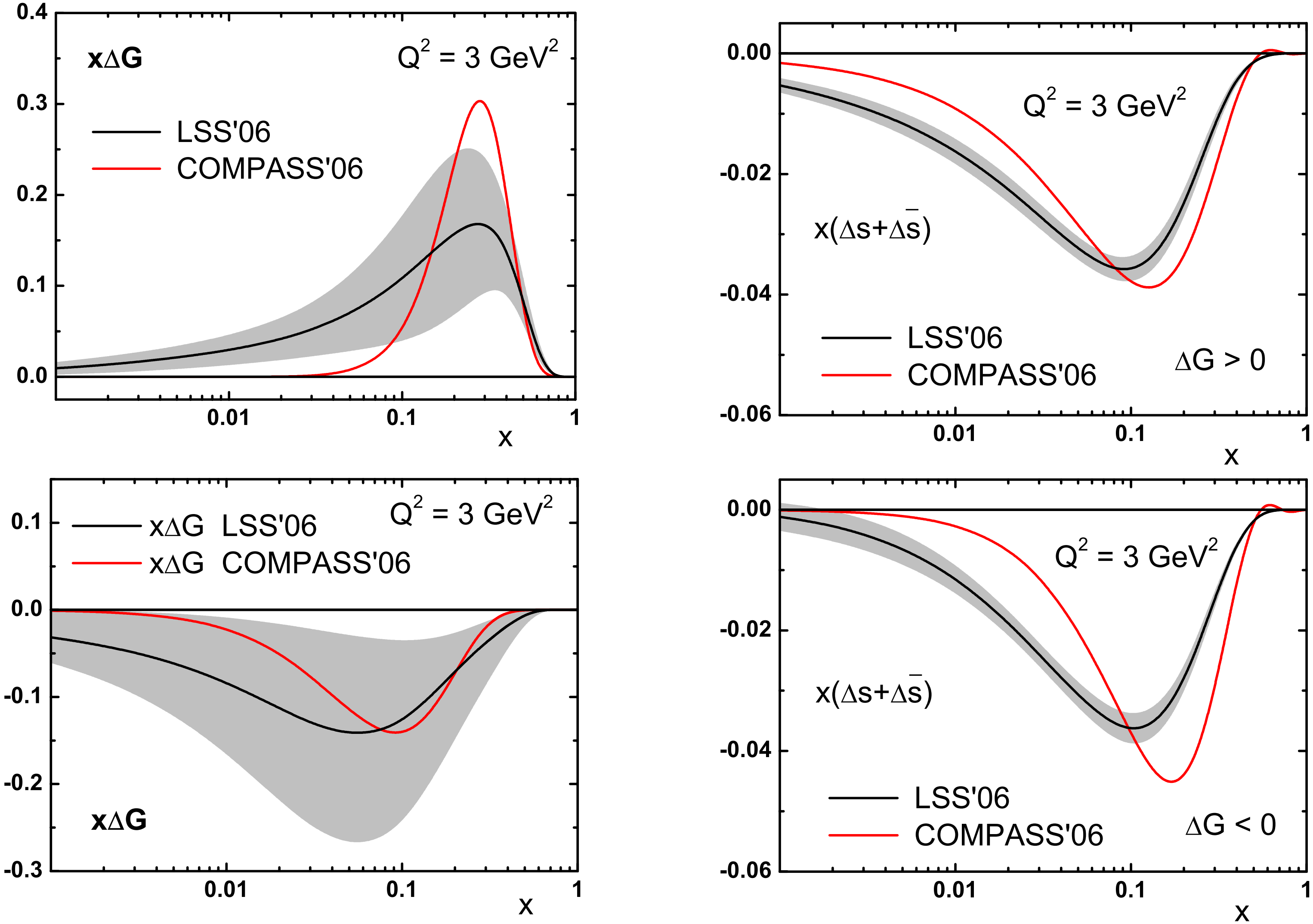




LSS05 vs LSS06

- **$x\Delta s$ are different, especially in the case of $\Delta G < 0$**

- **$x\Delta G$ positive obtaned by COMPASS is more peaked than our**



SUMMARY

- The low Q^2 *CLAS* data improve essentially our knowledge of higher twist corrections to g_1 structure function

- The central values of polarized PD are NOT affected, but the accuracy of its determination is essentially improved

- The *COMPASS* data (mainly at large Q^2) influence $|\Delta s|$ and ΔG which slightly decrease, but practically do NOT change HT

  → **Strong support of the QCD framework**

- Large (40%) contribution of HT to $(g_1)^d$ at small x (low Q^2)

- The present inclusive DIS data cannot rule out the negative and changing in sign gluon densities

- Good agreement with the directly measured $\Delta G/G$

OPEN QUESTIONS

- To constrain better ΔG $\Longrightarrow$ directly from *COMPASS, RHIC*;

  more precise experiments on g_1^d - *JLab Hall C*

- $\Delta\bar{u}$, $\Delta\bar{d}$ $\Longrightarrow$ from SIDIS (*COMPASS, JLab*) and $A_L(W^{+(-)})$ at *RHIC*

- L_q (from generalized PD - *HERMES, COMPASS, JLab*) and L_g ?

- $a_8 \neq 3F - D = 0.585$? (how much $SU(3)_f$ is broken) → NA48 at CERN

- HT corrections in SIDIS, $O(\Lambda^4/Q^4)$ term in HT expansion in Bjorken x-space

  …*etc.*