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# Polarized parton densities and higher twist corrections in the light of the recent CLAS and COMPASS data

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# 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*

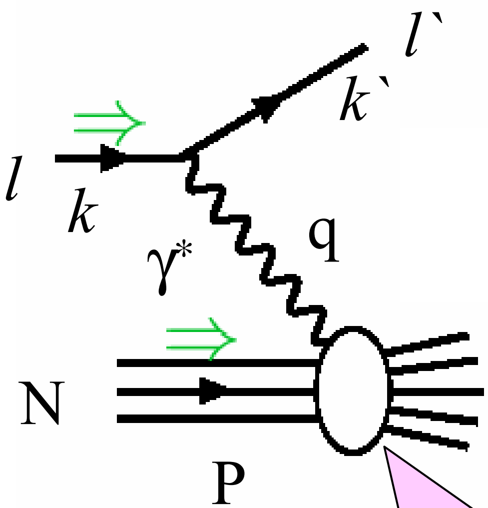
- **Impact of the new data on *LSS'05* polarized PD and HT**

- **The sign of the gluon polarization**

- **Summary**

*LSS: PR D75, 074027, 2007*

**Inclusive DIS** ⇒ one of the best tools to study the structure of **nucleon**




$Q^2 = -q^2 = 4EE`\sin^2(\theta/2)$

$x = Q^2/(2M\nu) \qquad \nu = E - E`$

DIS regime ==> $Q^2 \gg M^2,\ \nu \gg M$

$F_i(x, Q^2)$ $g_i(x, Q^2)$

unpolarized SF

polarized SF

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

**preasymptotic region**

As in the unpolarized case the main goal is:

- to test **QCD**
- to extract from the DIS data the **polarized** PD

$$\Delta q(x,Q^2) = q_+(x,Q^2) - q_-(x,Q^2)$$

$$\Delta \bar{q}(x,Q^2) = \bar{q}_+(x,Q^2) - \bar{q}_-(x,Q^2)$$

$$\Delta G(x,Q^2) = G_+(x,Q^2) - G_-(x,Q^2)$$

where "+" and "-" denote the helicity of the parton, along or opposite to the helicity of the parent nucleon, respectively.

The knowledge of the polarized PD will help us:

- to make predictions for other processes like polarized **hadron-hadron** reactions, etc.

- more generally, to answer the question how the helicity of the nucleon is divided up among its constituents:

$$\mathbf{S_z = 1/2 = 1/2\, \Delta\Sigma(Q^2) + \Delta G\,(Q^2) + L_z\,(Q^2)}$$

$$\Delta\Sigma = \Delta u + \Delta\bar{u} + \Delta d + \Delta\bar{d} + \Delta s + \Delta\bar{s}$$

the parton polarizations $\Delta q_a$ and $\Delta G$ are the first moments

$$\Delta q_a(Q^2) = \int_0^1 dx \Delta q_a(x, Q^2) \qquad \Delta G(Q^2) = \int_0^1 dx \Delta G(x, Q^2)$$

of the helicity densities: $\Delta u(x, Q^2), \Delta\bar{u}(x, Q^2) \ldots, \Delta G(x, Q^2)$

# DIS Cross Section Asymmetries

Measured quantities $$A_{\parallel} = \frac{d\sigma^{\downarrow\Uparrow} - d\sigma^{\uparrow\Uparrow}}{d\sigma^{\downarrow\Uparrow} + d\sigma^{\uparrow\Uparrow}}, \quad A_{\perp} = \frac{d\sigma^{\downarrow\Rightarrow} - d\sigma^{\uparrow\Rightarrow}}{d\sigma^{\downarrow\Rightarrow} + d\sigma^{\uparrow\Rightarrow}}$$

$$(A_{\parallel}, A_{\perp}) \Rightarrow (A_1, A_2) \Rightarrow (g_1, g_2)$$

where $A_1$, $A_2$ are the virtual photon-nucleon asymmetries.

At present, $A_{\parallel}$ is much better measured than $A_{\perp}$

If $A_{\parallel}$ and $A_{\perp}$ are measured $\Rightarrow \quad g_1 / F_1$

If only $A_{\parallel}$ is measured $$\Rightarrow \frac{A_{\parallel}^{N}}{D} \approx (1+\gamma^2)\frac{g_1}{F_1}$$

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

**NB. $\gamma$ cannot be neglected in the SLAC, HERMES and JLab kinematic regions**

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 ($\tau$ =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

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

**$N_f$ (=3) - the number of flavors**

- **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

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

$F_2^{NMC}$, $R_{1998}$(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:* $\Delta u_{sea}=\Delta\bar{u}=\Delta d_{sea}=\Delta\bar{d}=\Delta s=\Delta\bar{s}$

# Higher twist effects

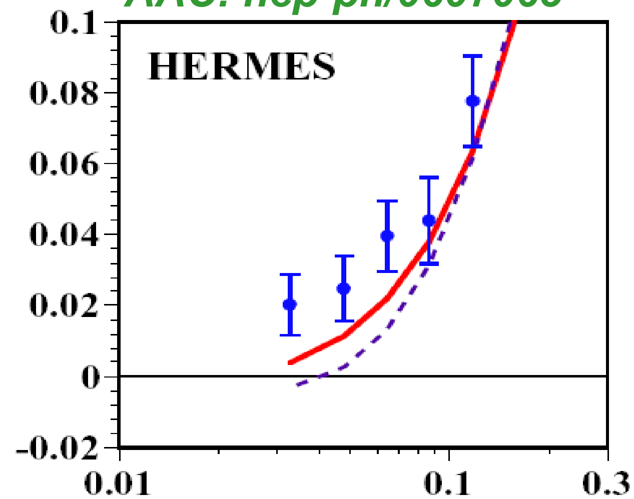
(CLAS'06 and COMPASS'06 not included)

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

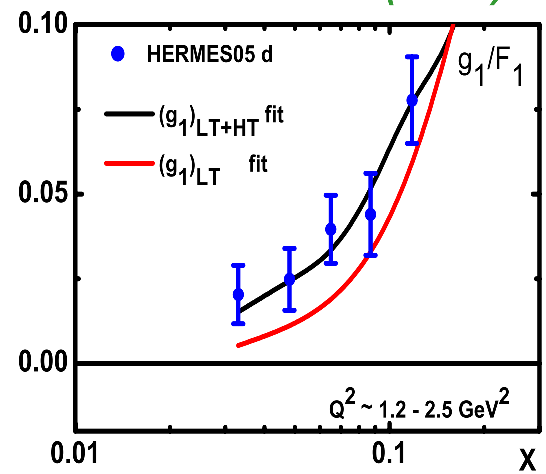
- **The low x and low $Q^2$ (1.2 ~ 2.5 GeV$^2$) HERMES/d data can not be described by the LT (logarithmic in $Q^2$) term in $g_1$ => red curves**

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

***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 -** $\dfrac{g_1^n}{F_1^n}$

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

$\gamma^2 = 4M^2x^2/Q^2$ **- 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 - $\frac{g_1^p}{F_1^p},\ \frac{g_1^d}{F_1^d}$

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

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

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

**Number of exp. points: 190 ⟹ 823**

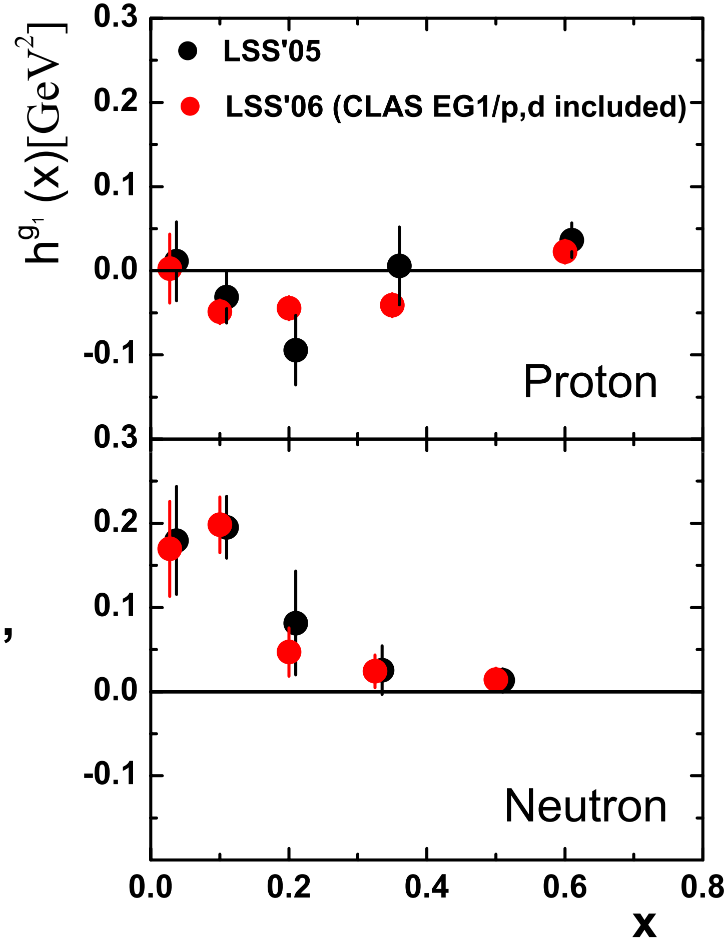
# Effect of CLAS'06 p and d data *(PL B641, 11, 2006)* on polarized PD and HT

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

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

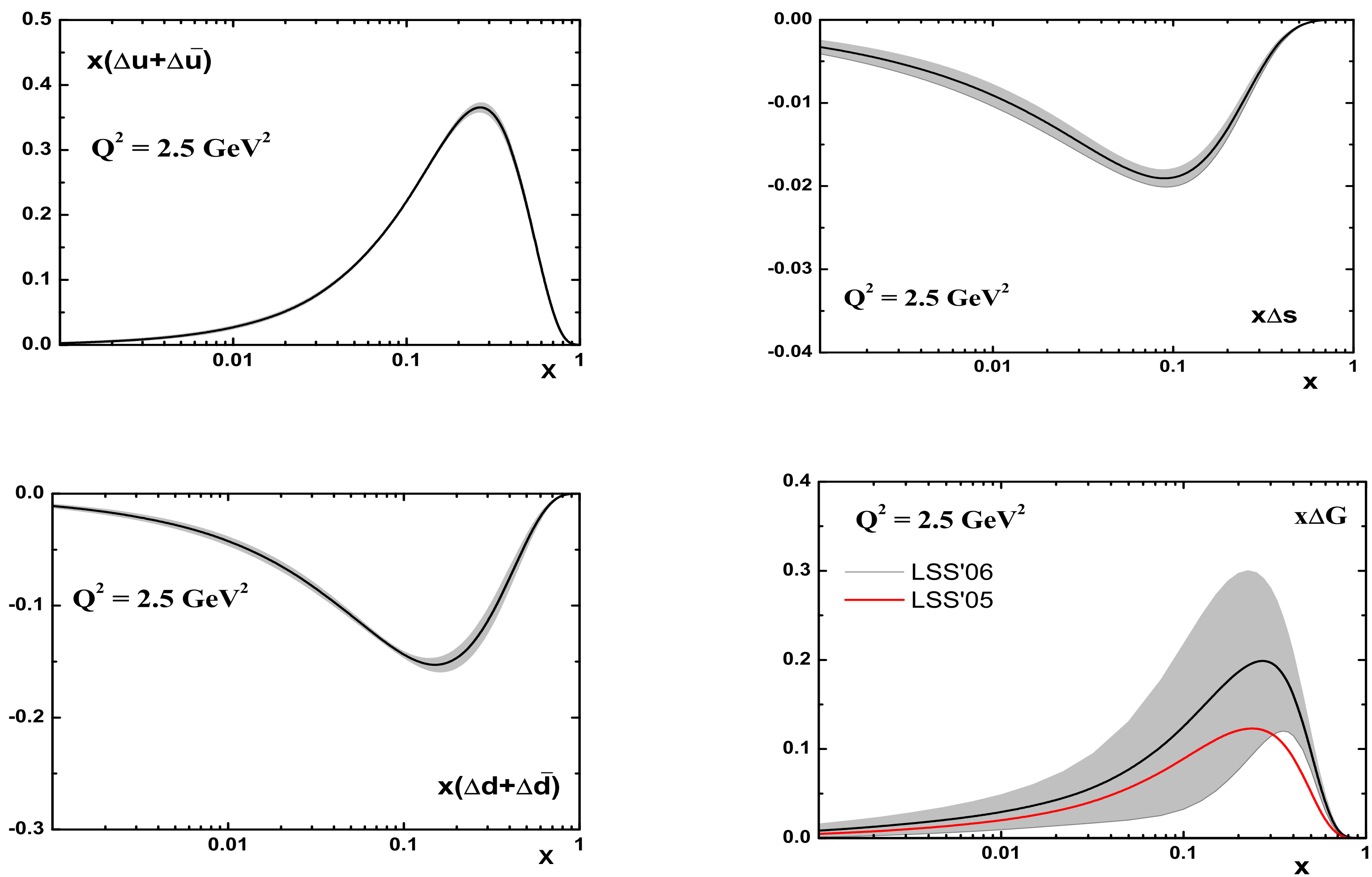
- As expected, the central values of PPD are practically not affected by *CLAS* data, but the accuracy of its determination is essentially improved (a consequence of much better determination of HT corrections to $g_1$)

*LSS'05: PR D73 (2006)*

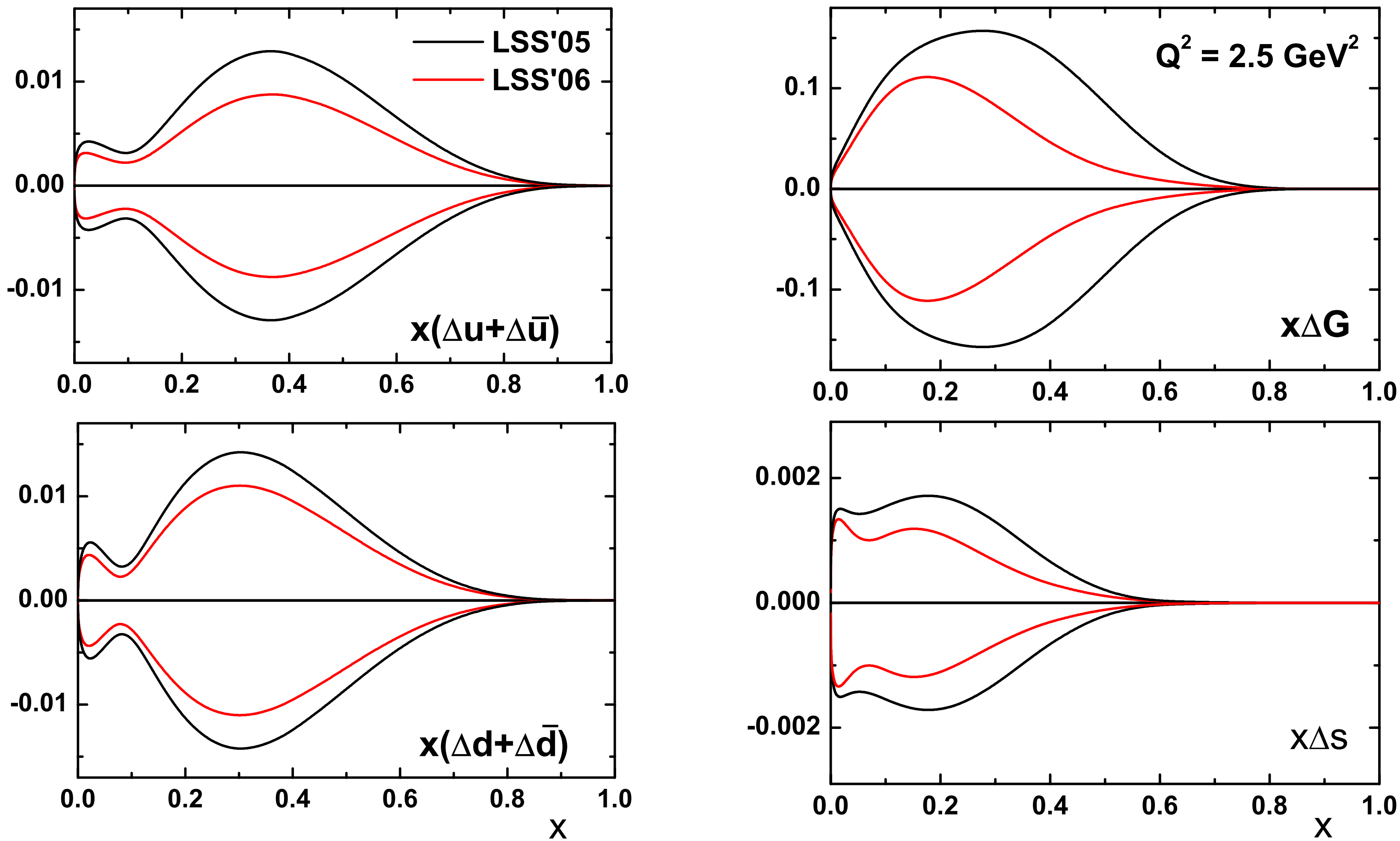


# LSS'06 NLO($\overline{MS}$) polarized PDFs

**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 first moments of higher twist

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

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

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

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

- $\bar{h}^p - \bar{h}^n < 0$ ← In agreement with the instanton model predictions and sum rules in QCD
- $\bar{h}^p + \bar{h}^n < |\bar{h}^p - \bar{h}^n|$ ← 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 -** $\frac{g_1^p}{F_1^p},\ \frac{g_1^d}{F_1^d}$

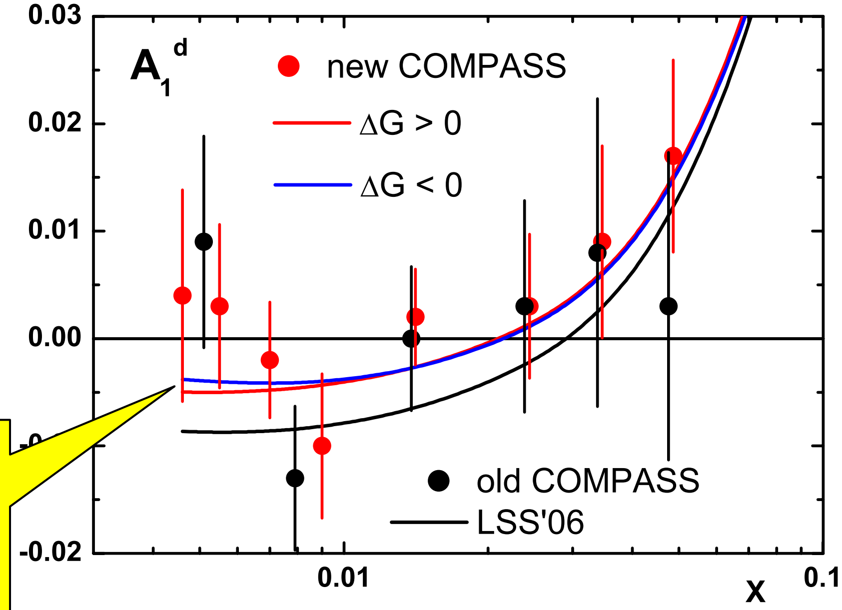
$$A_1^N \approx (1+\gamma^2)\frac{g_1^N}{F_1^N}$$

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

**Number of exp. points: 823 ⟹ 826**

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

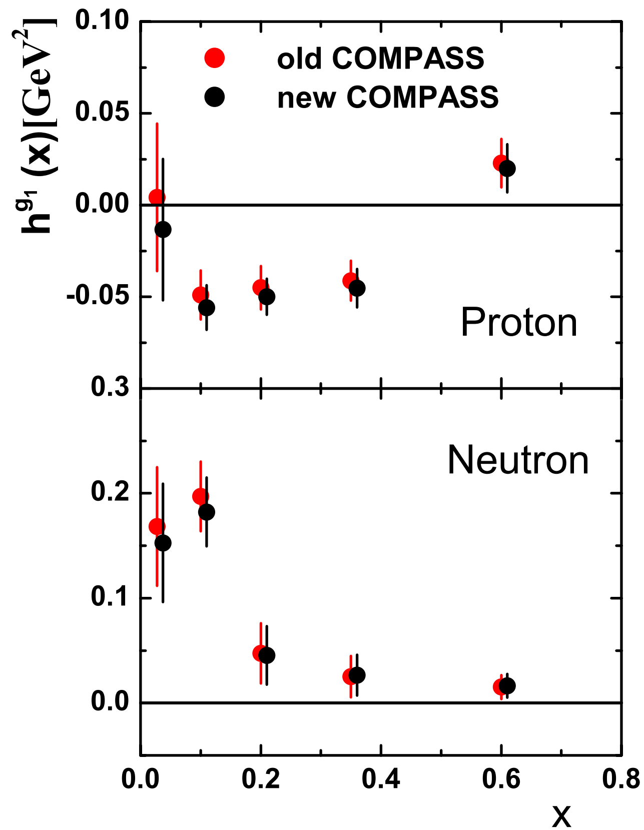
In contrast to the *CLAS* data, the *COMPASS* data are mainly at large $Q^2$ and the only precise data at small x: $0.004 < x < 0.02$. The new data are based on 2.5 times larger statistics than those of *COMPASS'05*

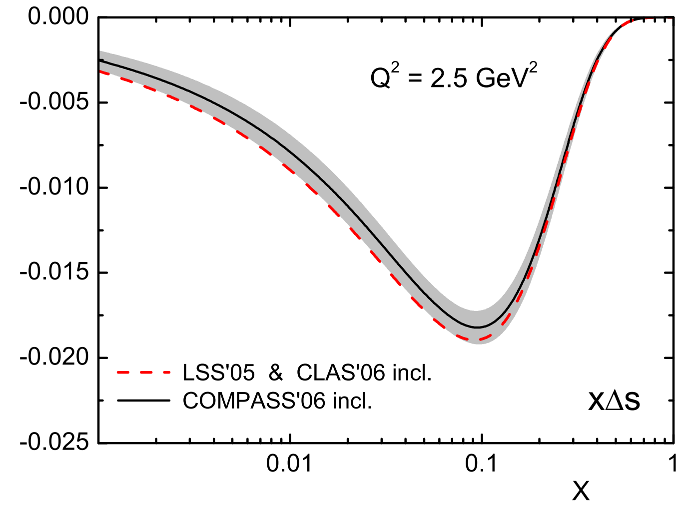


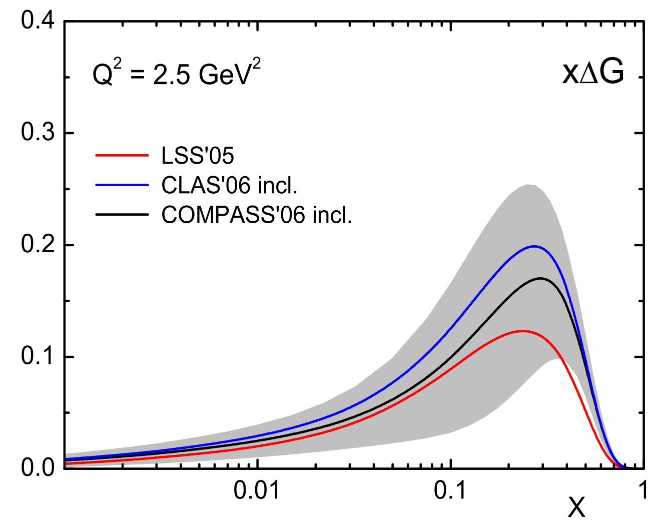

The new QCD curves corresponding to the best fits lie above the old one at $x < 0.1$

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

# 5 x-bins for HT

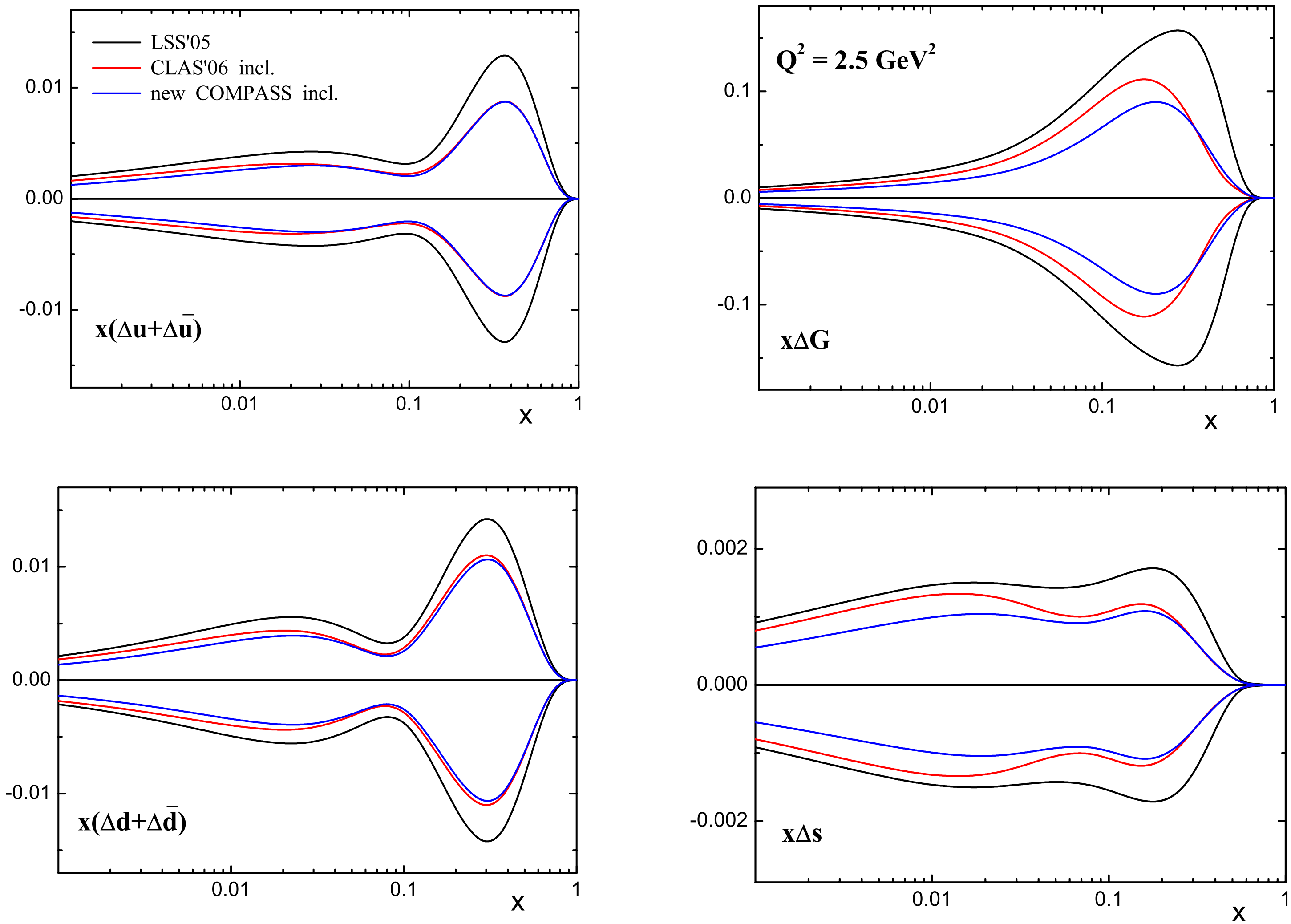



**The values of HT are practically NOT affected by *COMPASS* data excepting the small x where $Q^2$ are also small**

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



$Q^2 = 1\ GeV^2$

| *COMPASS* | $\Delta s$ | $\Delta G$ | $a_0 = \Delta\Sigma_{MS}$ |
|---|---|---|---|
| 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

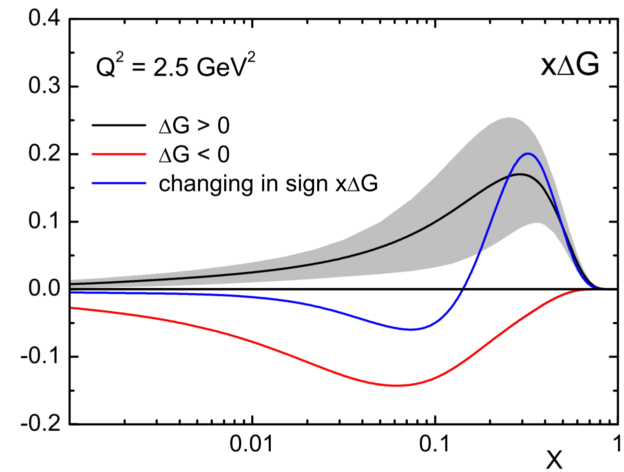
To be determined from forward extrapolations of generalized PD

# The sign of gluon polarization

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

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

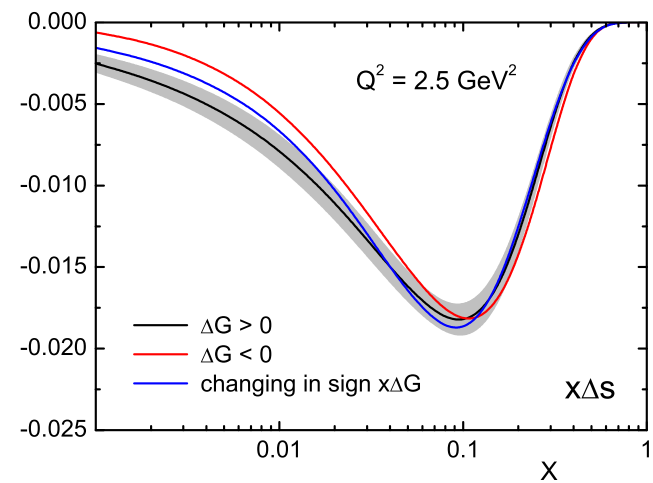
$$\chi^2_{DF}(\Delta G < 0) = 0.895, \chi^2_{DF}(x\Delta G / chsign) = 0.888$$




- 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



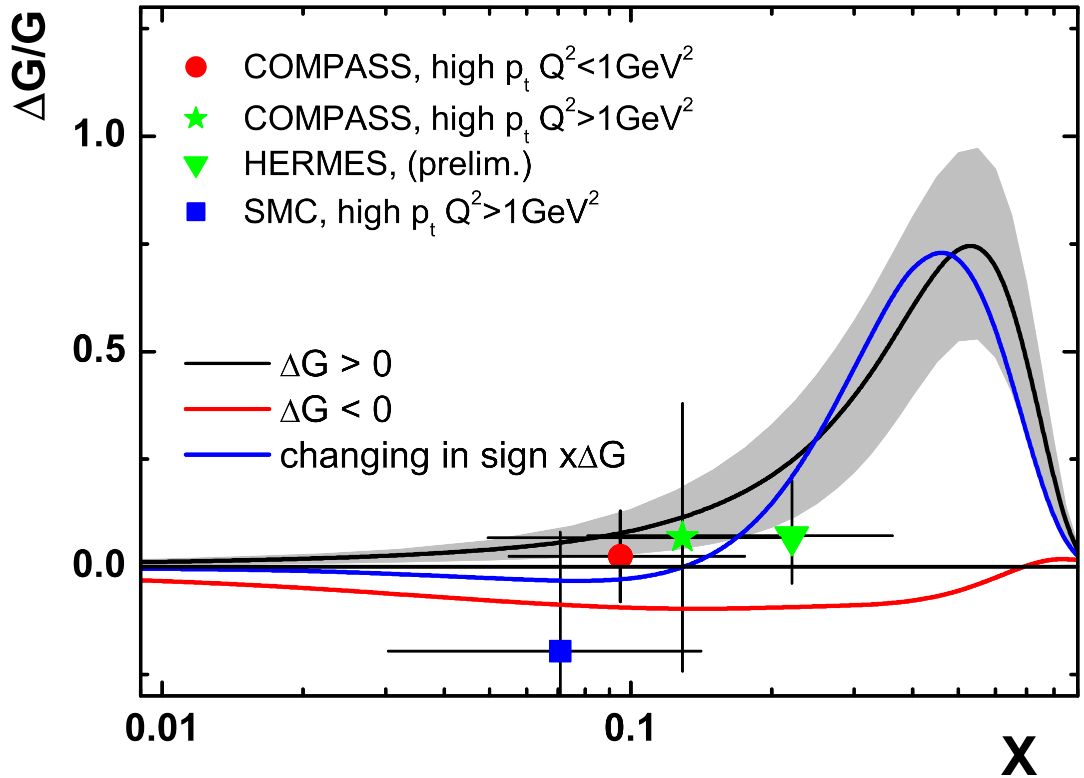
# Comparison with directly measured $\Delta G/G$ at $Q^2 = 3\ GeV^2$

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

**The error band corresponds to statistic and systematic errors of $\Delta G$**

**The error bars of the experimental points represent the total errors**

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



# 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 $\Delta G$ 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 $\Delta G$ $\Longrightarrow$ 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 $L_g$ ?

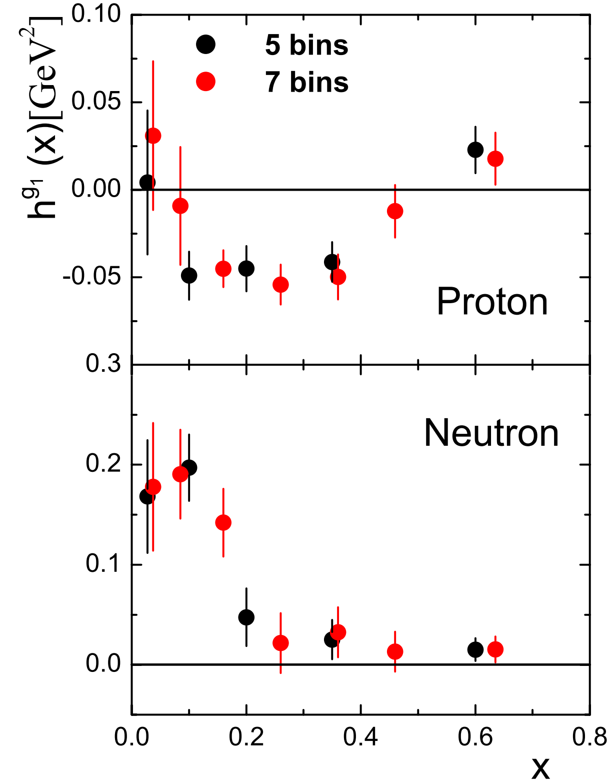
- a_8 ≠ 3F – D = 0.585 ? (how much $SU(3)_f$ is broken) → NA48 at CERN

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

  …*etc.*

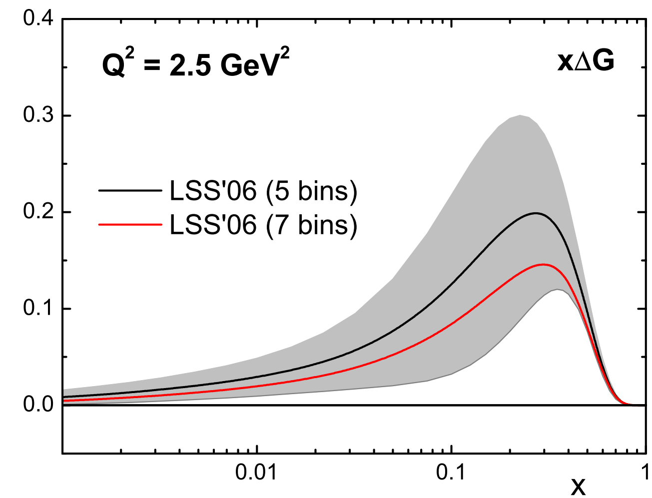
# Additional slides

- 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

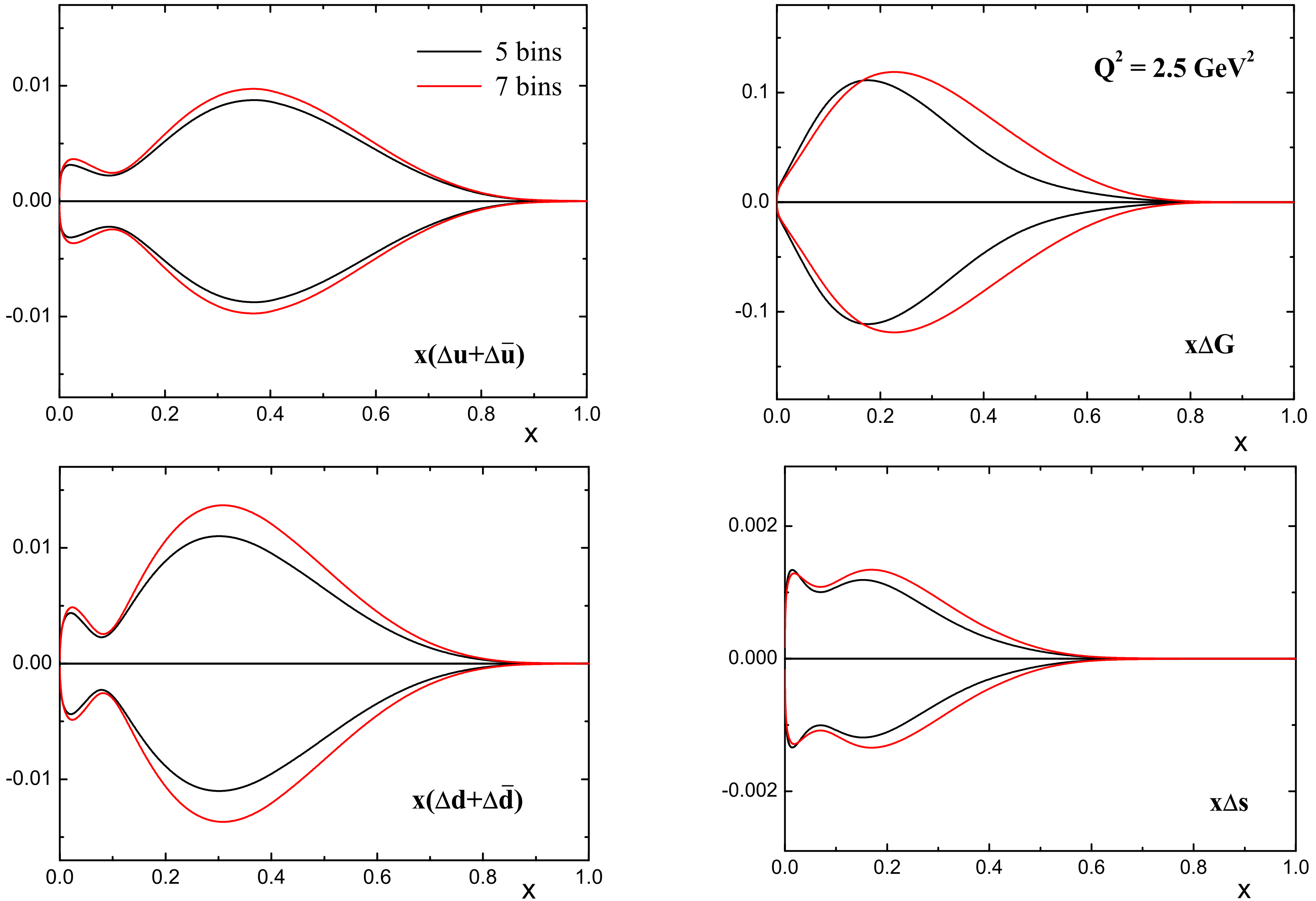



- The corresponding PPD are practically **identical** with those of LSS'06 **(5 bins)**

- 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

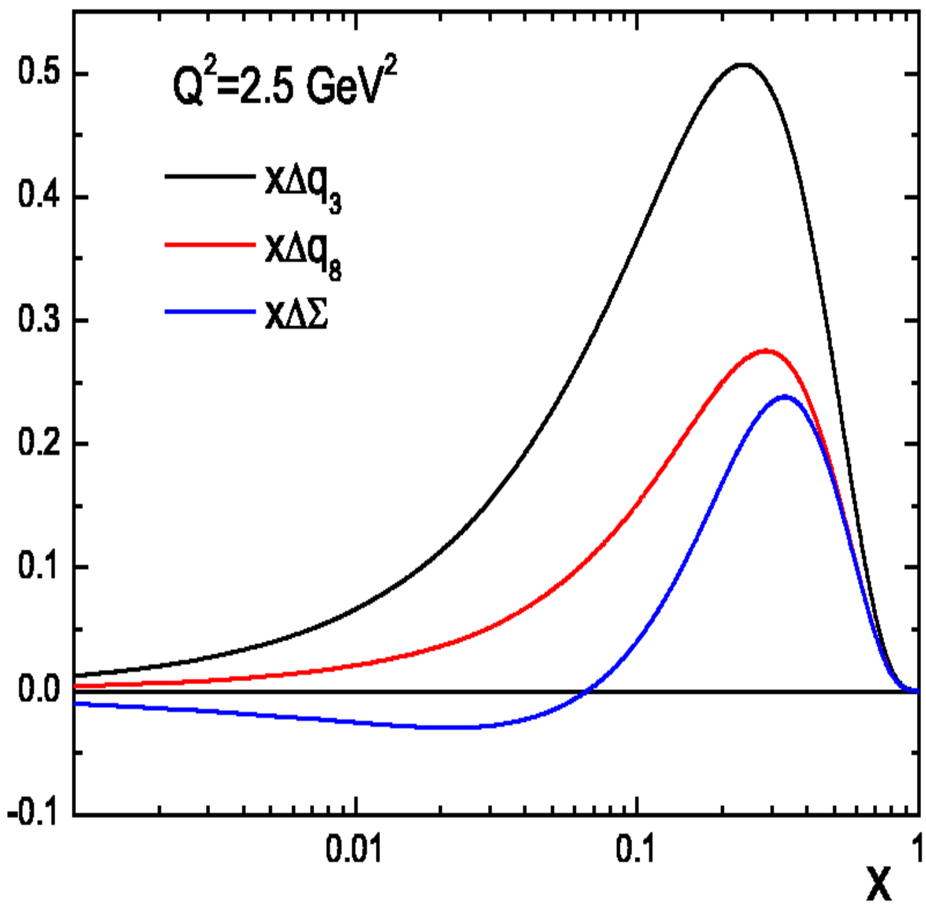


# 5 → 7 x-bins
# Impact on the uncertainties for NLO polarized PDFs



# Why deuteron best for ΔG(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 $\Delta q_3$ terms from p and n about twice size of $\Delta q_8$ and $\Delta\Sigma$ terms, cancel in deuteron.

- Relative gluon contributions largest in deuteron: relevant because experimental errors dominated by systematic scale factors.

# LSS'06 *vs* C0MPASS'06

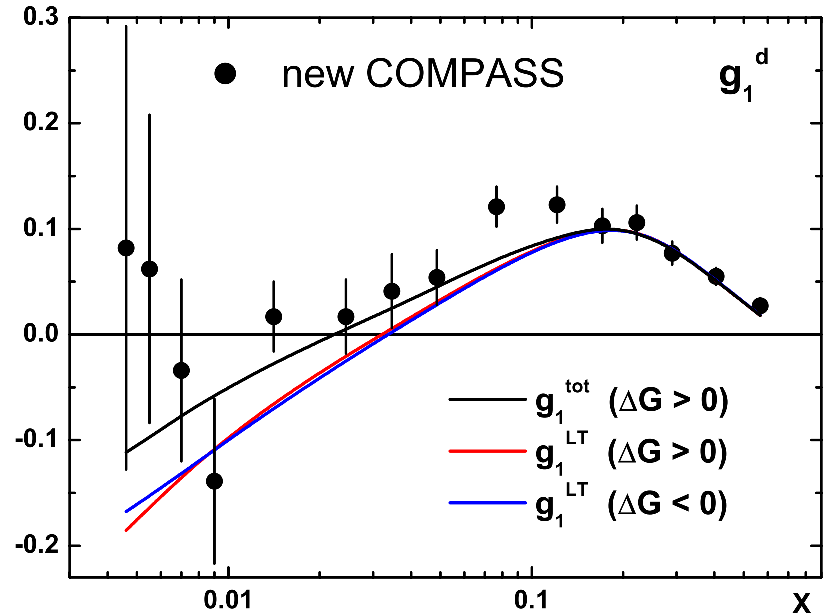
- At small x: 0.004 – 0.02 ($Q^2$ ~ 1-3 $GeV^2$) our results differ from those of *COMPASS*

- *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

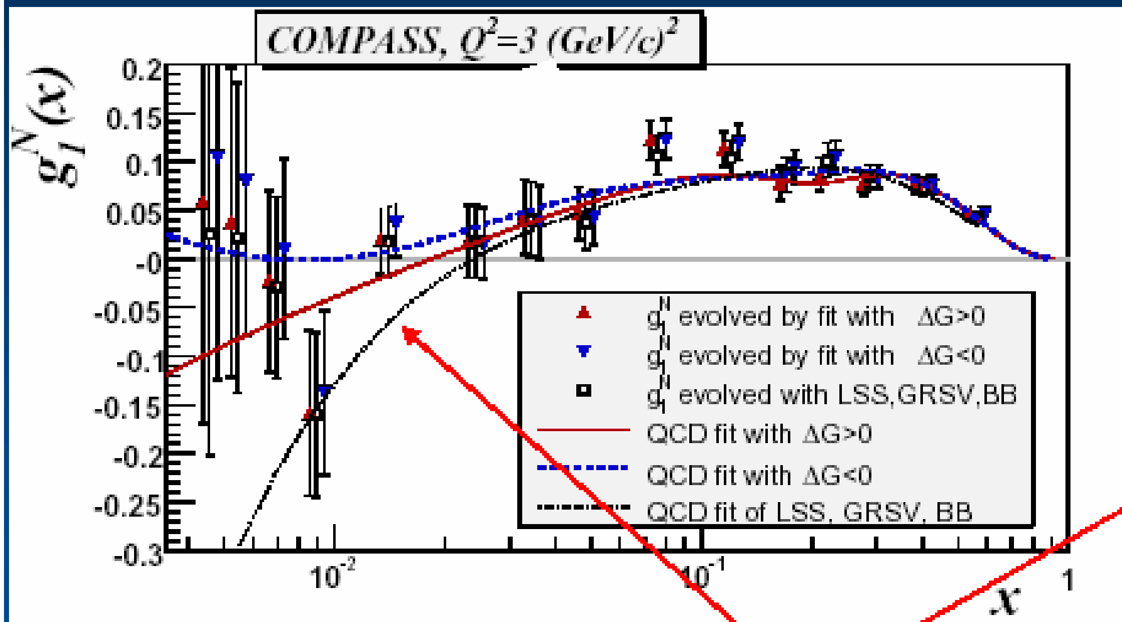
- The reason → HT effects (40% at small x) which are NOT taken into account by *COMPASS*

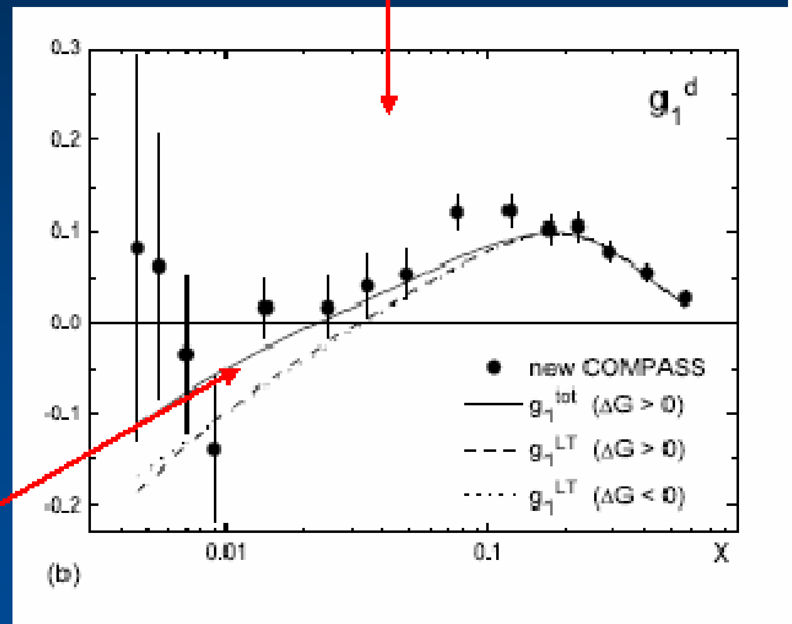
$$(g_1)_{exp} \leftrightarrow$$
$$(g_1)_{LT}(COMPASS) \approx$$
$$(g_1)_{LT}(LSS) + h^d(x)/Q^2$$



# QCD analysis of the world data on structure function $g_1$

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

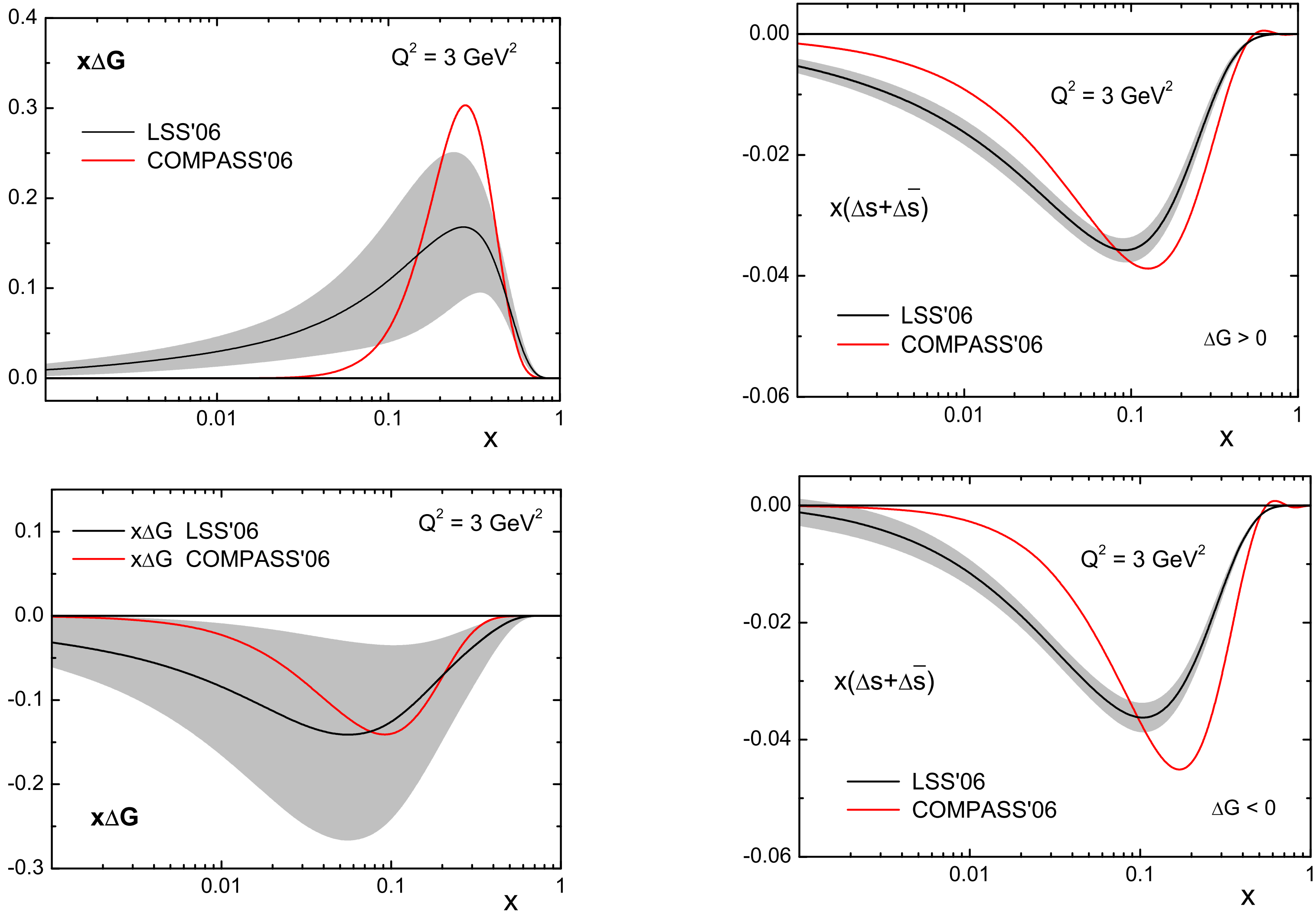



LSS05 vs LSS06

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

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



# Constraint on $\Delta G$ from $\pi^0$ production at RHIC *(AAC, hep-ph/0612037)*

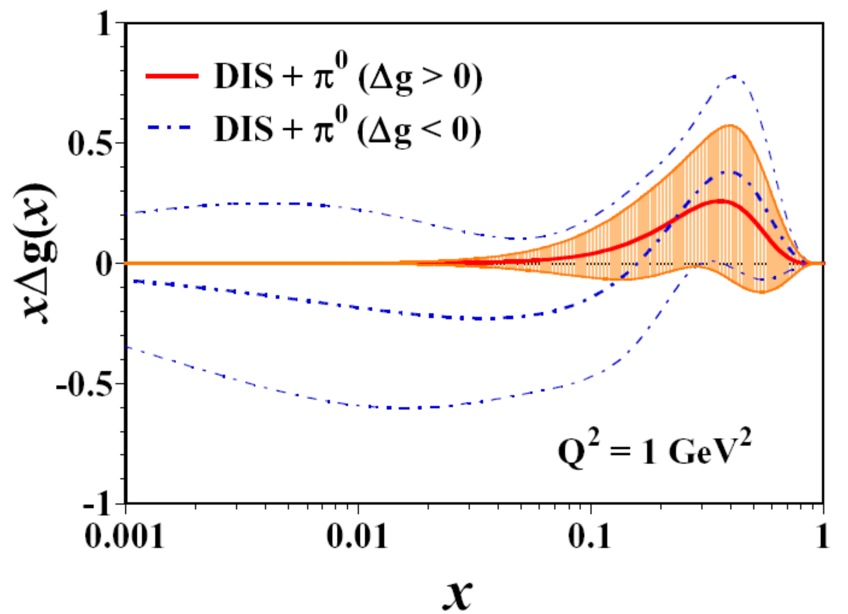
$\vec{p} + \vec{p} \rightarrow \pi^0 + X$

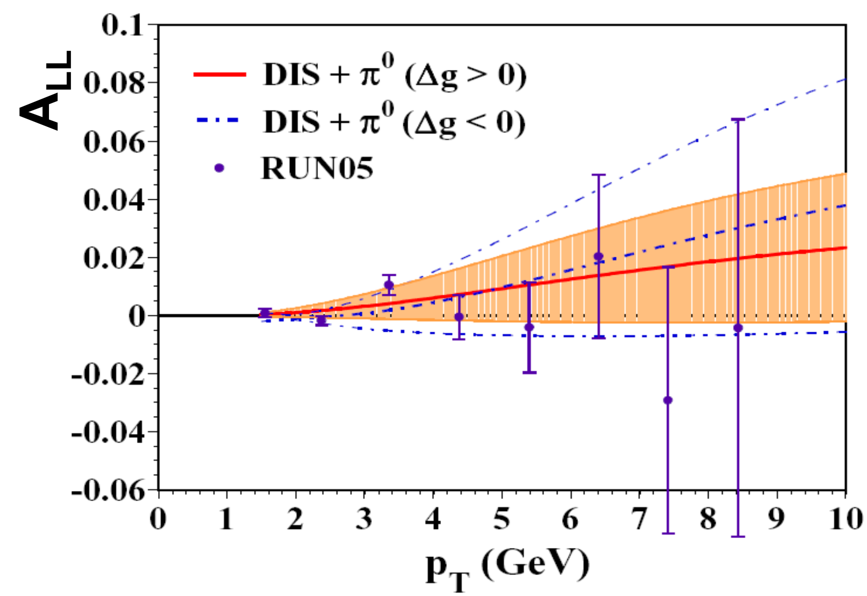
From DIS + $\pi^0$ analysis:

$\Delta G = \ 0.31 \pm 0.32$

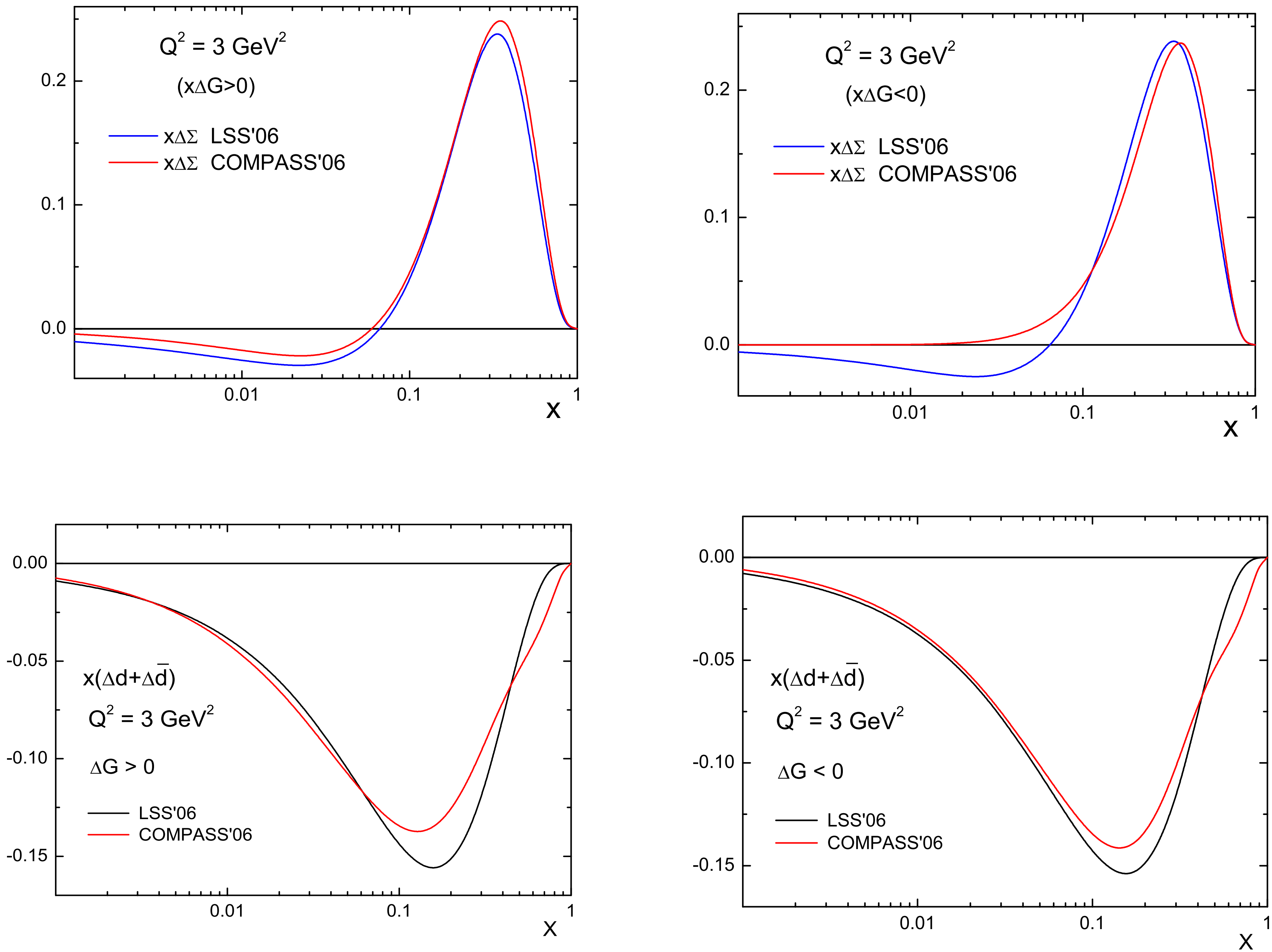
$\Delta G = -0.56 \pm 2.16$

($Q^2 = 1$ GeV$^2$)




**Note**: In contrast to LSS changing in sign $x\Delta G$, which for $Q^2 > 6$ GeV$^2$ is positive for any x, $x\Delta G_{AAC}$ becomes negative for large x too with increasing of $Q^2$.



$Q^2$ = 3 GeV$^2$
(xΔG>0)
xΔΣ LSS'06
xΔΣ COMPASS'06
0.2
0.1
0.0
0.01
0.1
1
x
$Q^2$ = 3 GeV$^2$
(xΔG<0)
xΔΣ LSS'06
xΔΣ COMPASS'06
0.2
0.1
0.0
0.01
0.1
1
x
0.00
-0.05
-0.10
-0.15
$x(\Delta d+\Delta\bar{d})$
$Q^2$ = 3 GeV$^2$
ΔG > 0
LSS'06
COMPASS'06
0.01
0.1
1
x
0.00
-0.05
-0.10
-0.15
$x(\Delta d+\Delta\bar{d})$
$Q^2$ = 3 GeV$^2$
ΔG < 0
LSS'06
COMPASS'06
0.01
0.1
1
x

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