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Progress in Determination of Polarized PDFs and Higher Twist

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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 ⟶ a good test of QCD

  - *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

- Impact of future EIC data on PDFs and their uncertainties

- Spin of the proton, ΔG and Δs – new developments

- Summary

LSS: PR D75, 074027, 2007

- The main goal → 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 Δq_a and ΔG 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: $\Delta u(x, Q^2), \Delta\bar{u}(x, Q^2) \ldots, \Delta G(x, Q^2)$

→ To determine the shape of the polarized parton densities

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

logarithmic in Q^2

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 half of the present data (53%) are at moderate Q^2 and W^2:

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

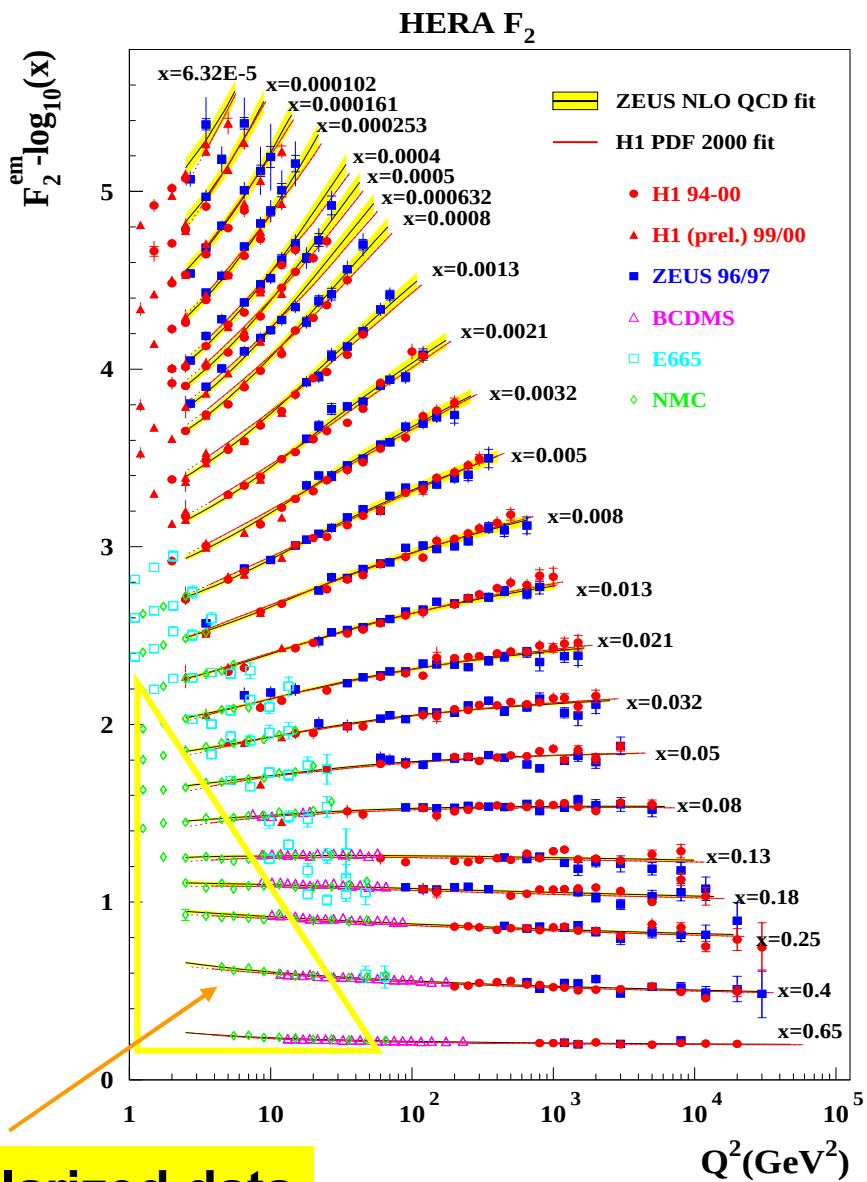
preasymptotic region

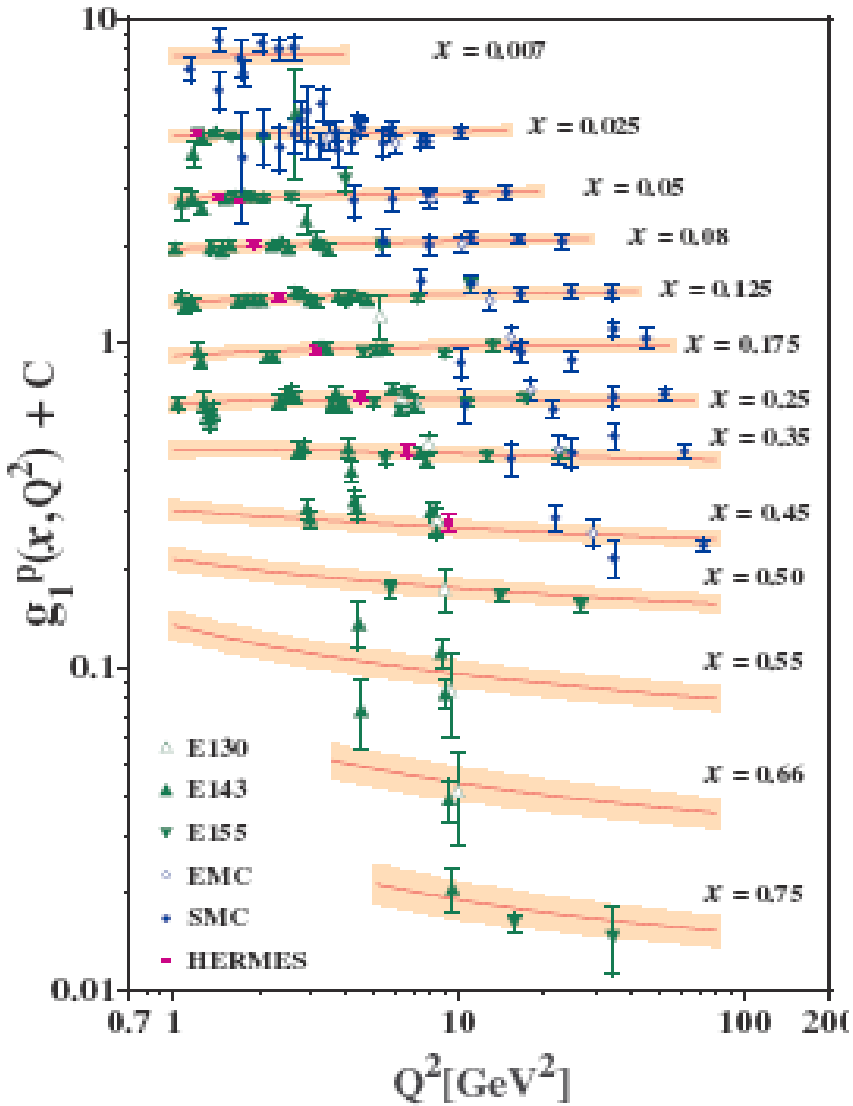
While in the determination of the PD in the unpolarized case we can cut the low Q^2 and W^2 data in order to eliminate the less known non-perturbative HT effects, it is impossible to perform such a procedure for the present data on the spin-dependent structure functions without loosing too much information.

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

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

x-Q^2 range of F_2 and g_1 structure functions





Polarized data

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: $\Delta u_{sea} = \Delta\bar{u} = \Delta d_{sea} = \Delta\bar{d} = \Delta s = \Delta\bar{s}$

Test of QCD and determination of PDFs and HT

$$(\Delta q_i, \Delta\overline{q}_i, \Delta G)(x, Q_0^2; a_k) \xrightarrow{\text{pQCD}} (\Delta q_i, \Delta\overline{q}_i, \Delta G)(x, Q^2; a_k)$$

DGLAP eqs.

Input PD

a_k – 6 free par.

$Q_0^2 = 1\ \text{GeV}^2$

$$\longrightarrow \quad g_1(x, Q^2; a_k)_{\text{LT}}$$

$$\chi^2 = \sum_{i,j} \frac{[g_1(x_i, Q_j^2)_{\text{exp}} - g_1(x_i, Q_j^2; a_k)_{\text{LT}} - h_{(l)}(x_{(l)})/Q^2]^2}{\Delta g_1(x_i, Q_j^2)_{\text{exp}}^2}$$

10 free parameters

$$\longrightarrow \quad a_k \pm \Delta a_k, h_l \pm \Delta h_l \rightarrow$$ 16 free parameters

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

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

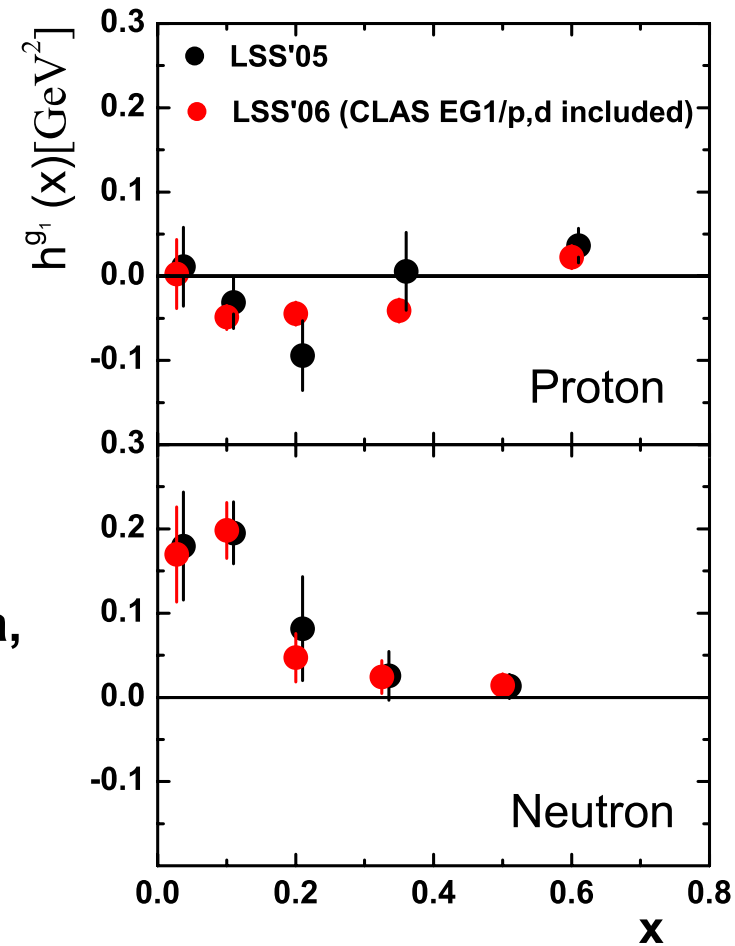
Effect of CLAS'06 p and d data *(PL B641, 11, 2006)* on polarized PD and HT

- Very accurate data on g_1^p and g_1^d at low Q^2: 1~ 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)

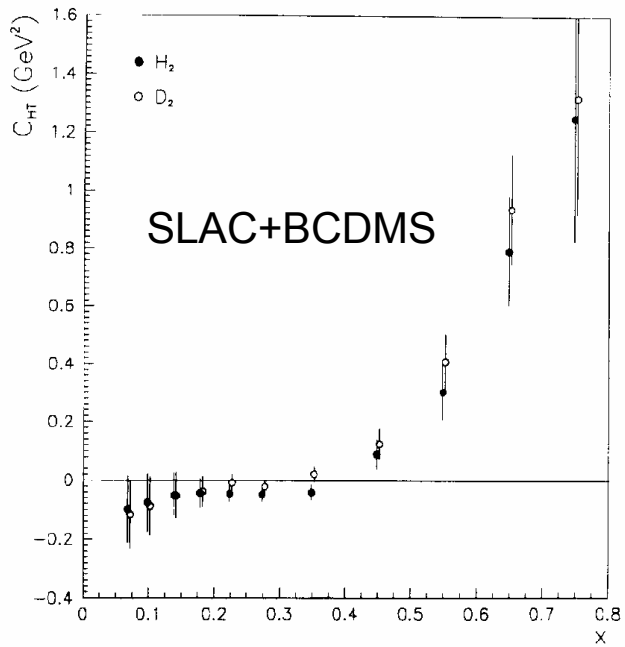
- As expected, the central values of PPD are practically not affected by *CLAS* data, but the accuracy of its determination is essentially improved (a consequence of much better determination of HT corrections to g_1)

LSS'05: PR D73 (2006)



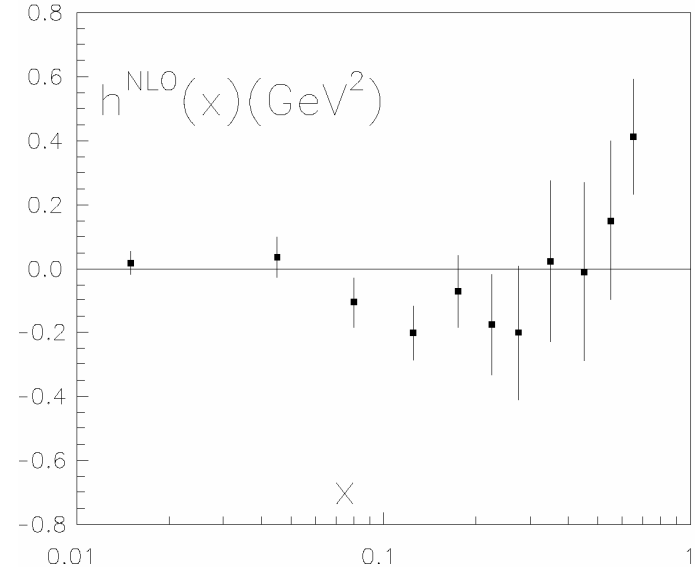
Virchaux, Milsztajn, Phys. Lett. (1992)

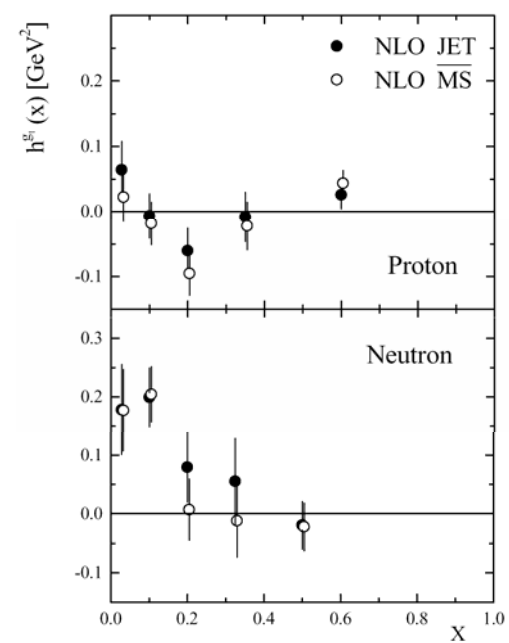
$$F_2^{HT}(x,Q^2) = F_2^{LT}(x,Q^2)[1 + C(x)/Q^2]$$



A.S., Phys. Lett. (1996)

$$xF_3(x,Q^2) = xF_3^{LT}(x,Q^2) + h(x)/Q^2$$



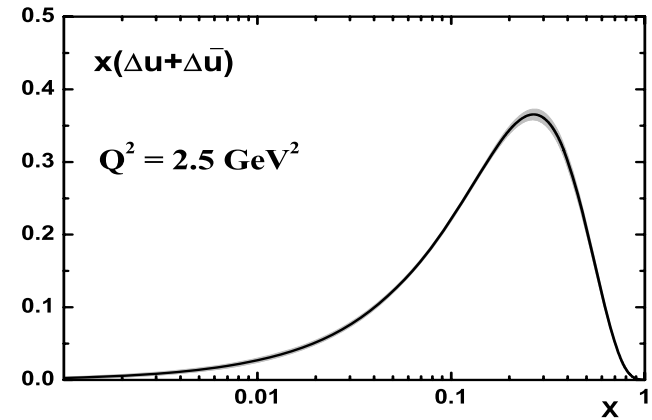


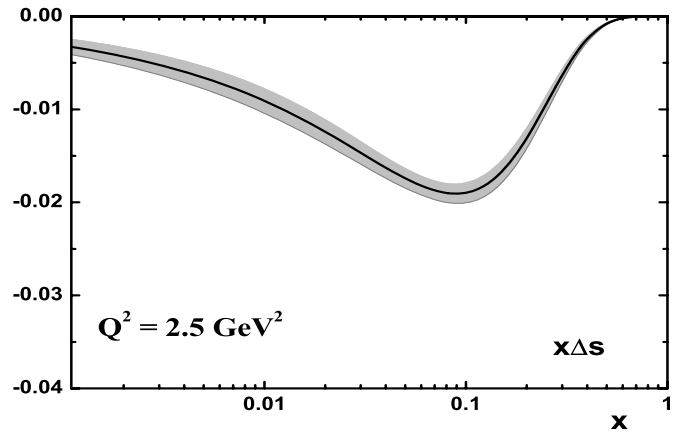
Leader, A.S., Stamenov, Phys. Rev. (2003)

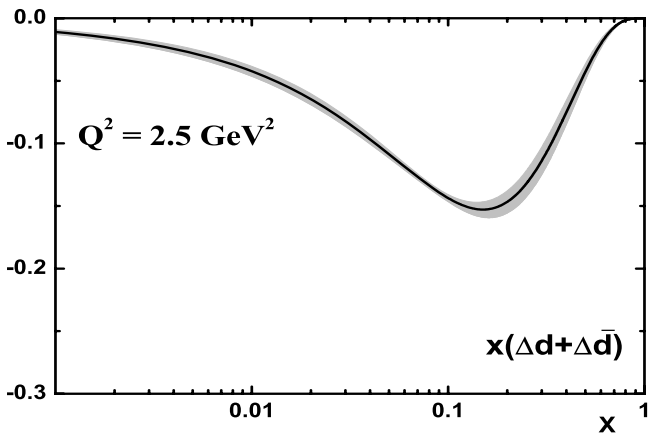
$$g_1(x,Q^2) = g_1^{LT}(x,Q^2) + h(x)/Q^2$$

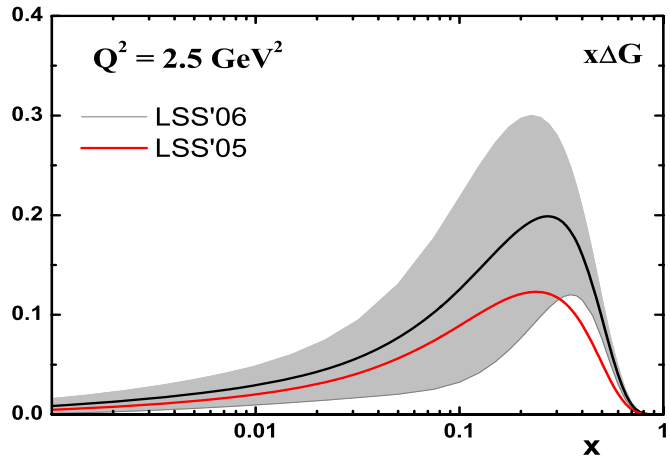
LSS'06 NLO($\overline{\text{MS}}$) polarized PDFs

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









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

Details*: If one calculates the χ^2- probability for the combined *world + CLAS data set using the* LSS'05 polarized PDFs and HT, the result for χ^2 is 938.9 for 823(190 + 633) experimental points, which significantly decreases to 718.0 after the fit. This big change of χ^2 is achieved mainly through the changes in the HT values. Excepting the gluons the parameters for the input quark densities did NOT change. This strongly supports the theoretical framework in which the leading twist QCD contribution is supplemented by higher twist terms of *$O(\Lambda^2/Q^2)$.

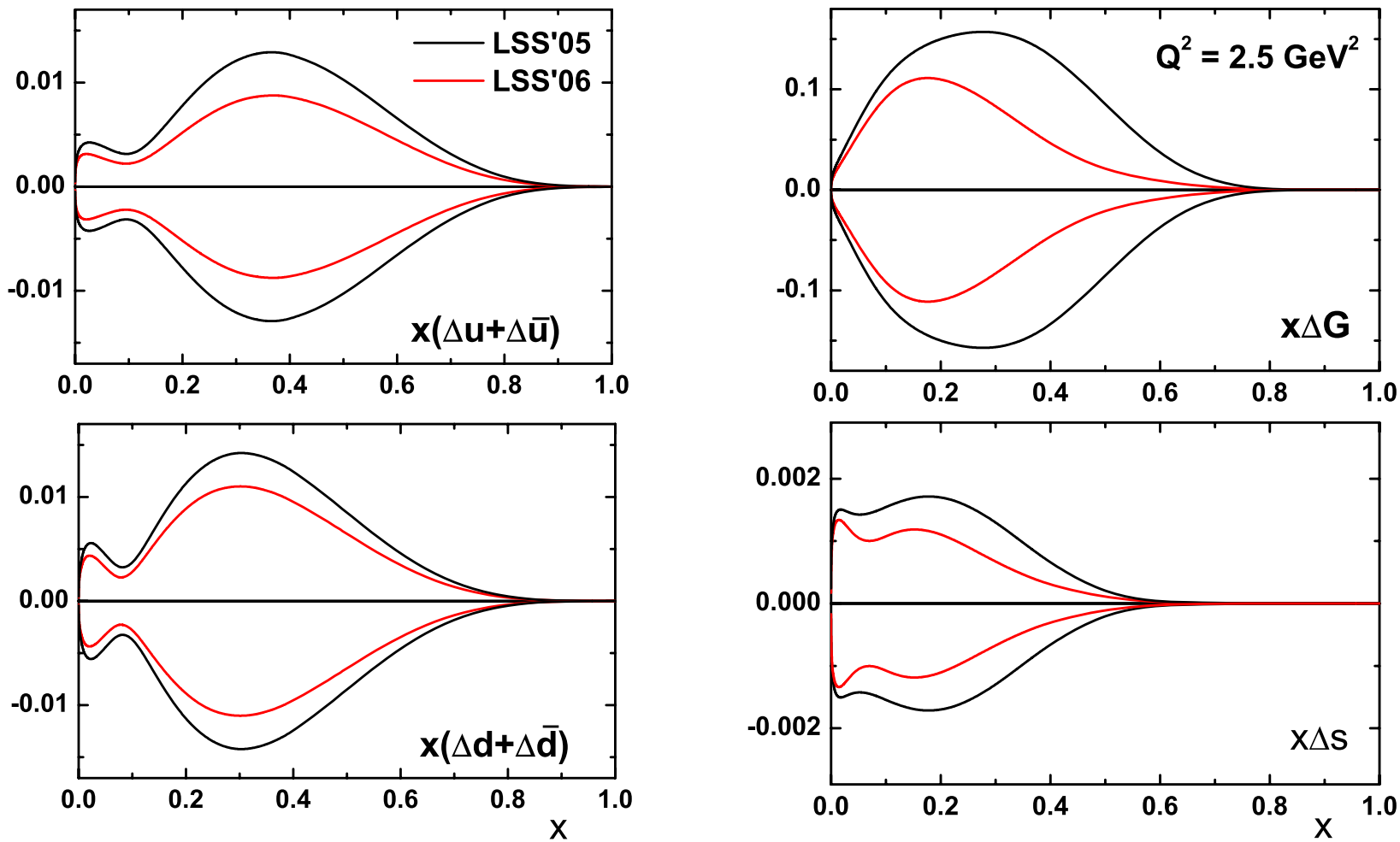
PDFs: $\Delta f(x, Q^2)$ → $\Delta f(x, \tilde{Q}^2)$

LSS'05 can be continued **LSS'06~LSS'05**

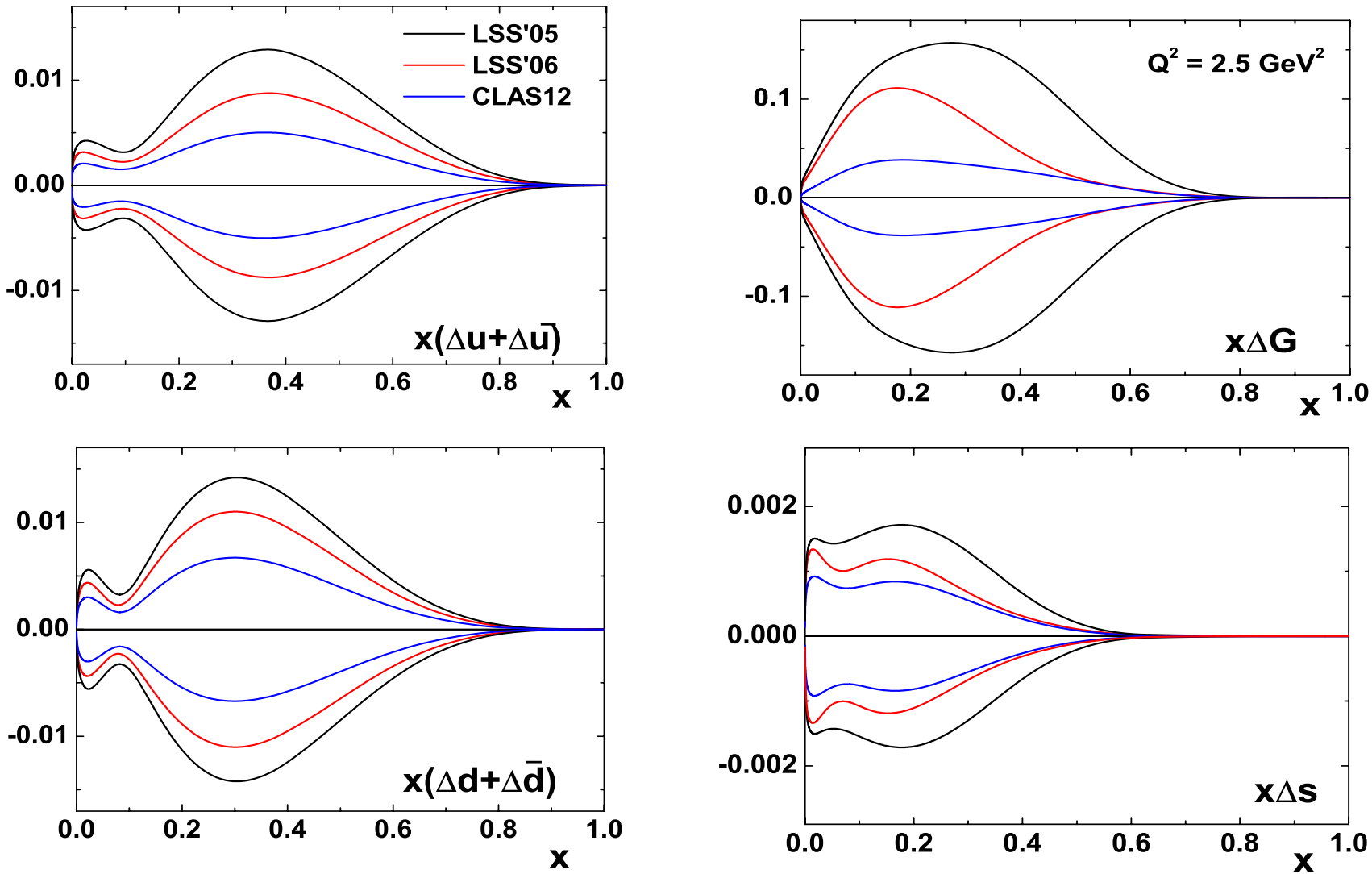
determined from DIS world data (in the presence of HT) before the CLAS data were available

preasymptotic (CLAS data) region where $\tilde{Q}^2$ are much smaller than Q^2 at the same x

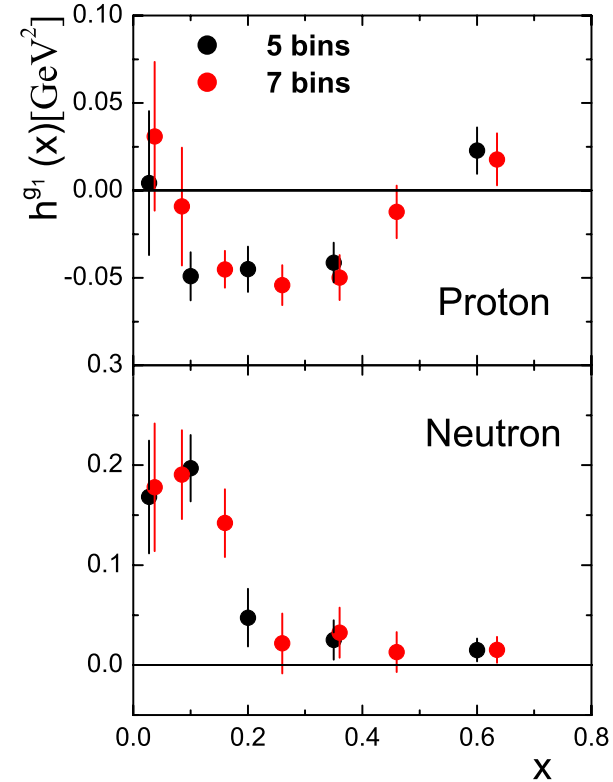
Impact of CLAS'06 data on the uncertainties for NLO polarized PD



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

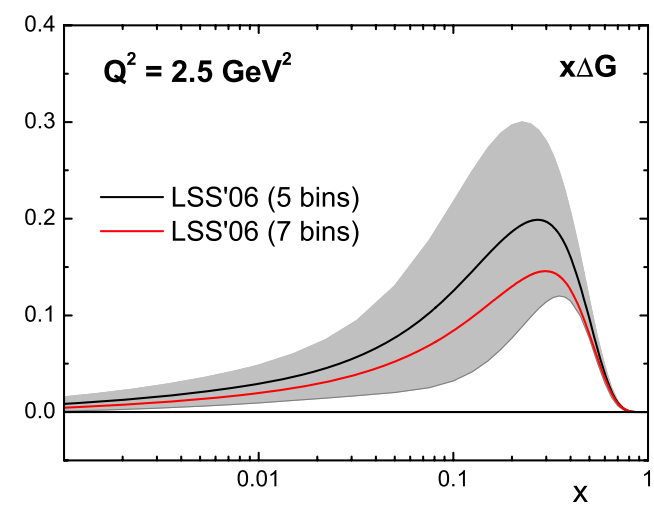


- Due to the good accuracy of the *CLAS* data, one can split the measured x region of the *world+CLAS* data set into 7 bins instead of 5, and to determine more precisely the x-dependence of HT

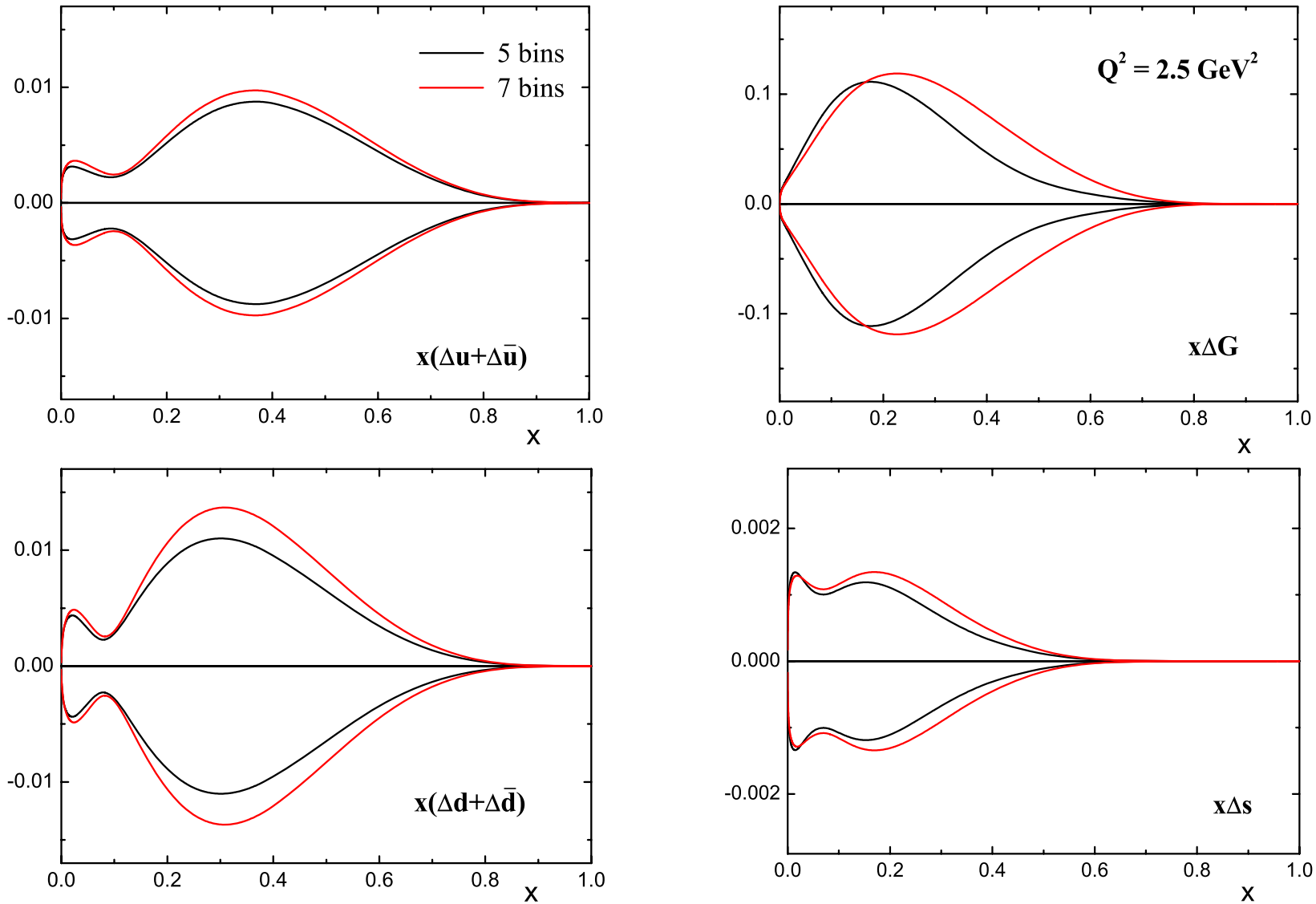


- The corresponding PPD are practically identical with those of LSS'06 (5 bins)

- The only exception is xΔG, but it lies within the error band of xΔG (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.

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

$$\bar{h}^p = (-0.015 \pm 0.005)\, GeV^2$$

$$\bar{h}^n = (0.040 \pm 0.009)\, GeV^2$$

$$\bar{h}^p - \bar{h}^n = (-0.055 \pm 0.010)\, GeV^2$$

$$\bar{h}^p + \bar{h}^n = (0.025 \pm 0.010)\, GeV^2$$

- $\bar{h}^p - \bar{h}^n < 0$ ← In agreement with the instanton model predictions and the value obtained from the analysis of the first moment of g_1 (*Deur et al., arXiv:0802.3198*)

- $\bar{h}^p + \bar{h}^n < |\bar{h}^p - \bar{h}^n|$ ← 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 g_1 data if the HT corrections are NOT taken into account

NOTE: If the low Q^2 g_1 data are not too accurate, it would be also 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 - $\frac{g_1^p}{F_1^p}$, $\frac{g_1^d}{F_1^d}$

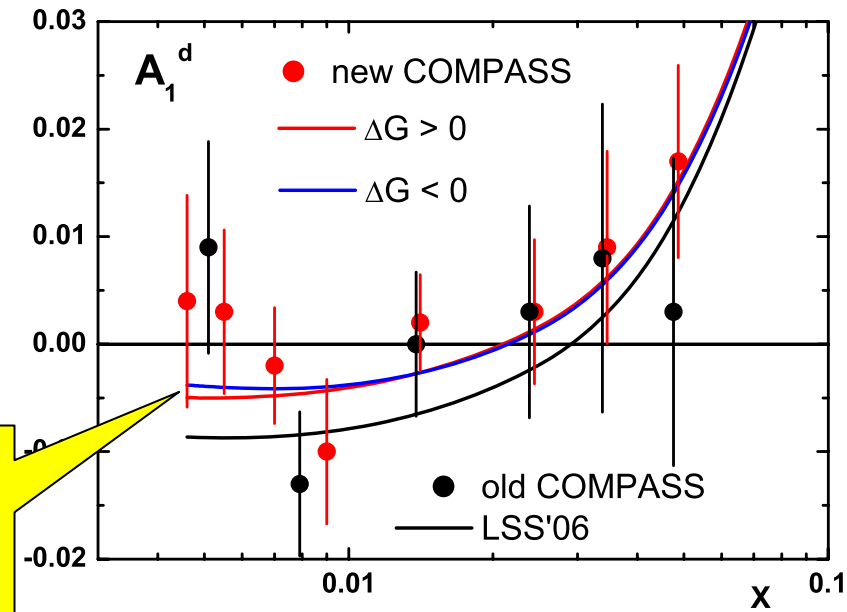
$$A_1^N \approx (1+\gamma^2)\frac{g_1^N}{F_1^N}$$

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

Number of exp. points: 823 ⇨ 826

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

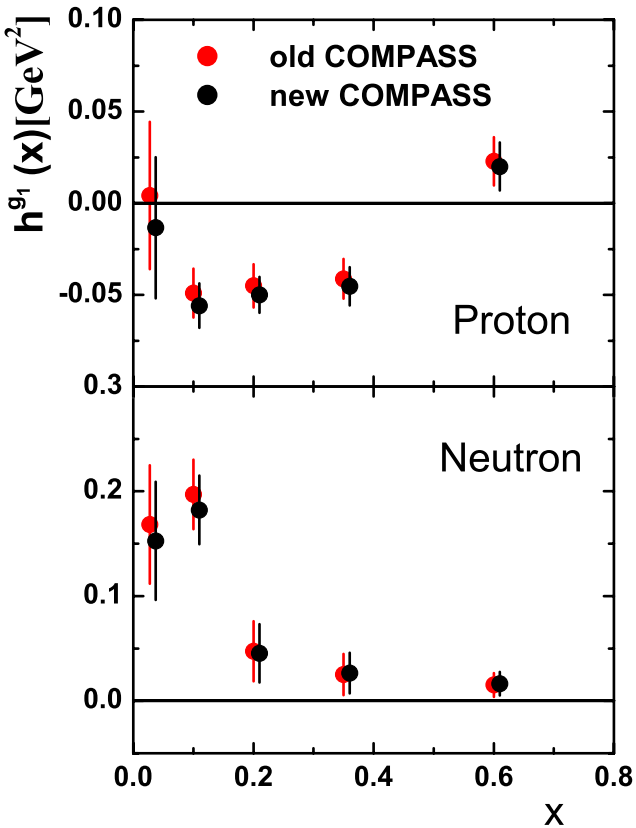
In contrast to the *CLAS* data, the *COMPASS* data are mainly at large Q^2 and the only precise data at small x: $0.004 < x < 0.02$. The new data are based on 2.5 times larger statistics than those of *COMPASS'05*

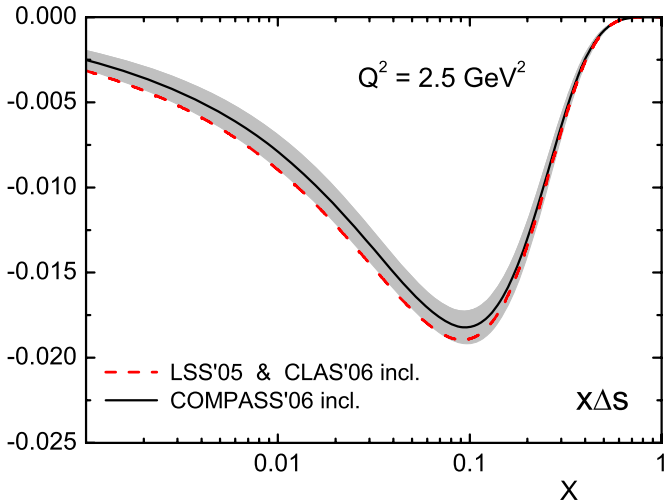


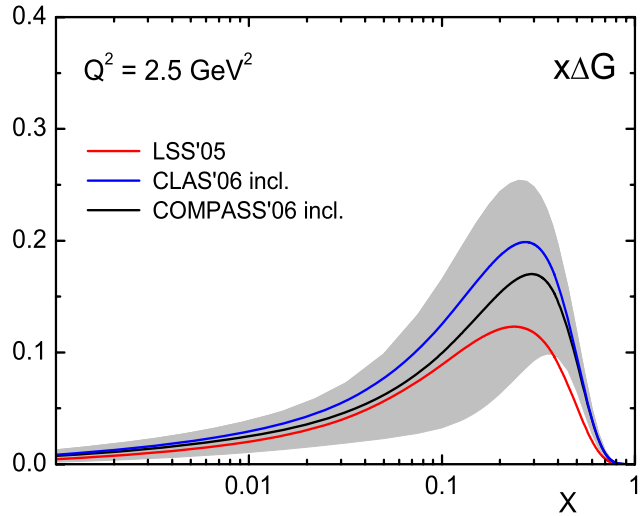
The new QCD curves corresponding to the best fits lie above the old one at $x < 0.1$

- $(\Delta u + \Delta\bar{u})$ and $(\Delta d + \Delta\bar{d})$ practically 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

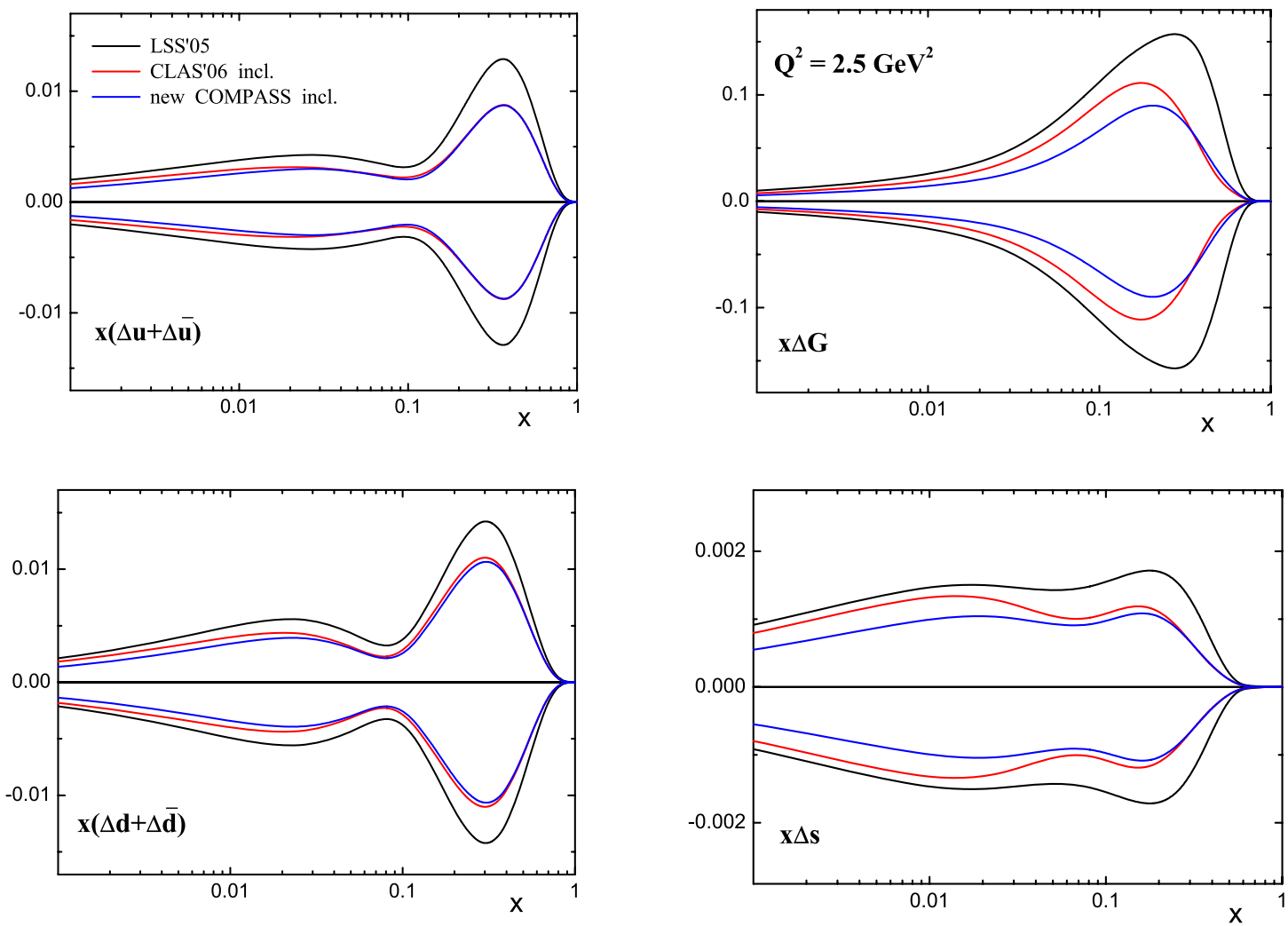






The values of HT are practically NOT affected by *COMPASS* data excepting the small x where Q^2 are also small

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

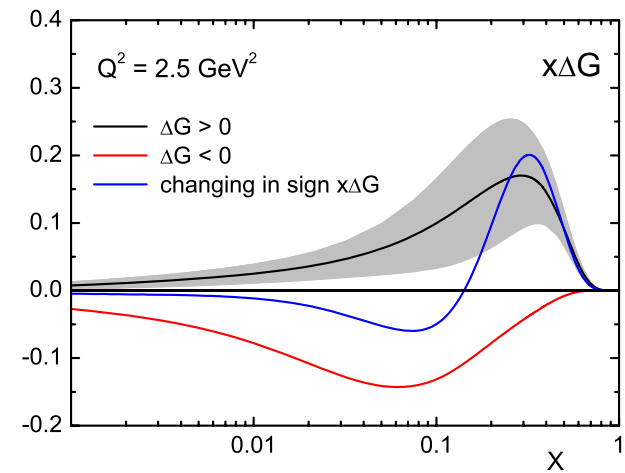


The sign of gluon polarization

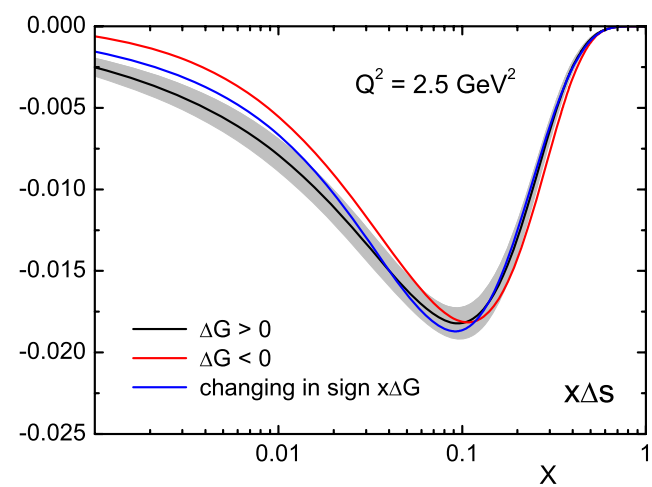
- The present inclusive DIS data cannot rule out the solutions with negative and changing in sign gluon polarizations

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

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



- 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



!! **We cannot find negative ΔG if the HT are not included in the analysis**

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

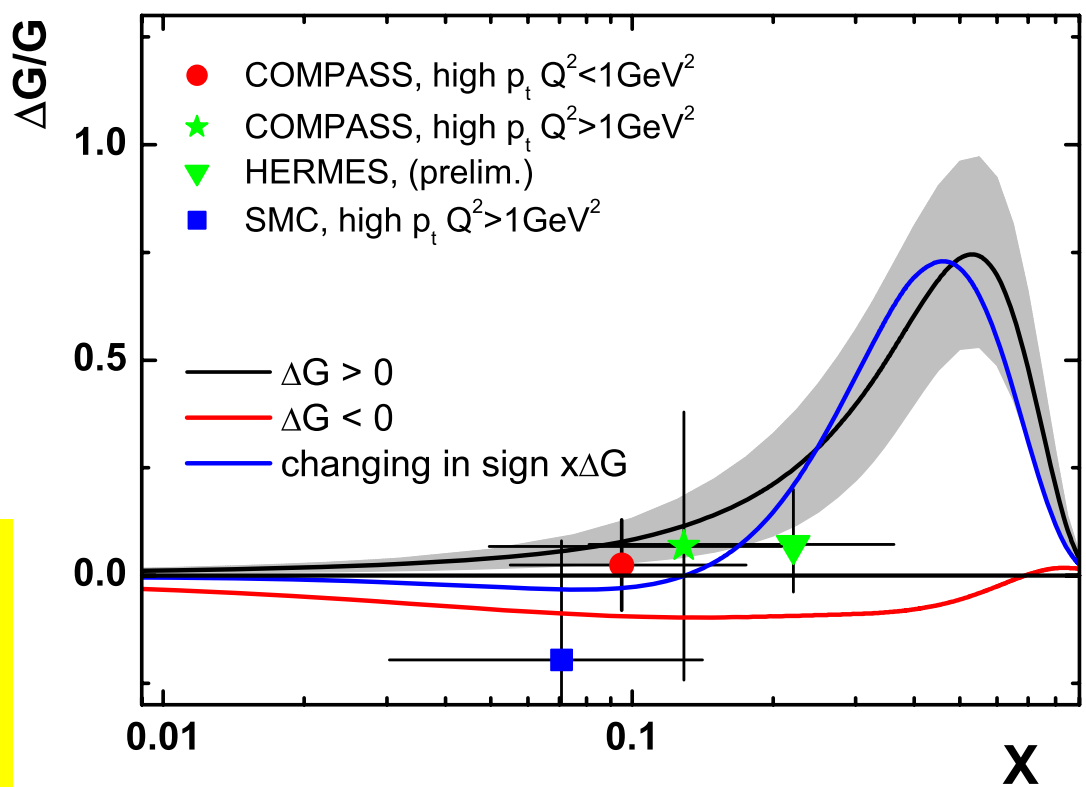
MRST'02 unpolarized gluon density is used for G(x)

The error band corresponds to statistic and systematic errors of ΔG

The error bars of the experimental points represent the total errors

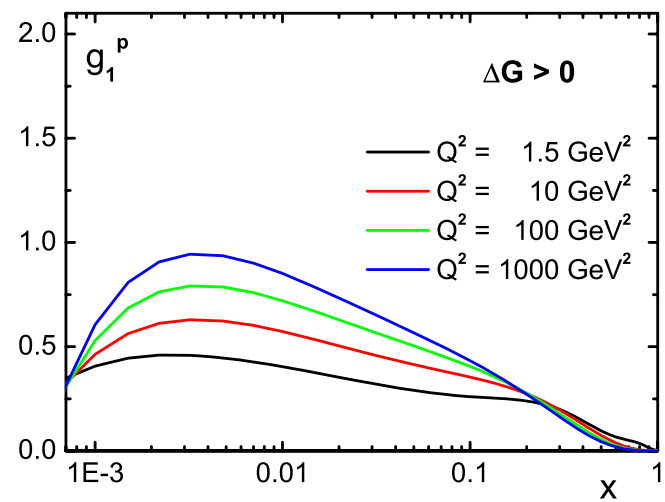
The most precise value of ΔG/G, the *COMPASS* one, is well consistent with any of the polarized gluon densities determined in our analysis

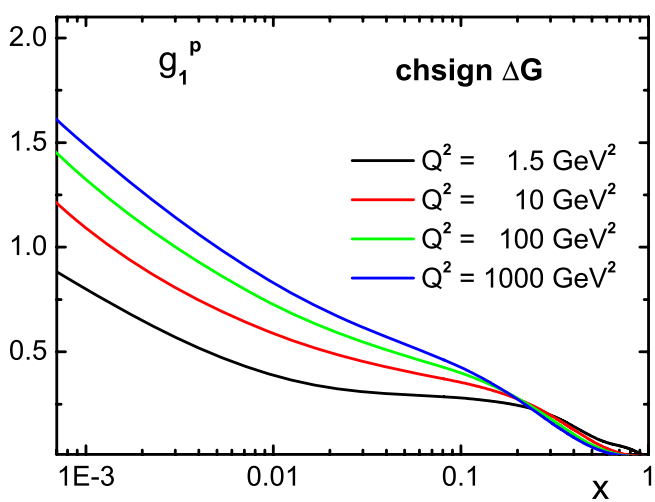
The high p_t measurements cannot also distinguish between different solutions for ΔG

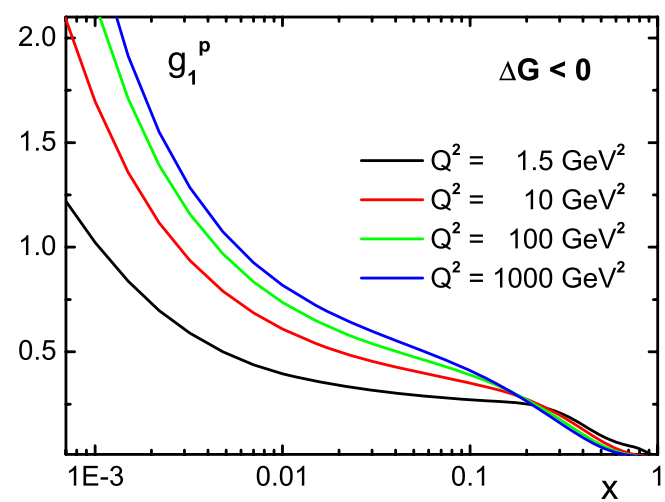


Measurements of $g_1^p(x, Q^2)$ at very small x (EIC) could settle the ΔG problem

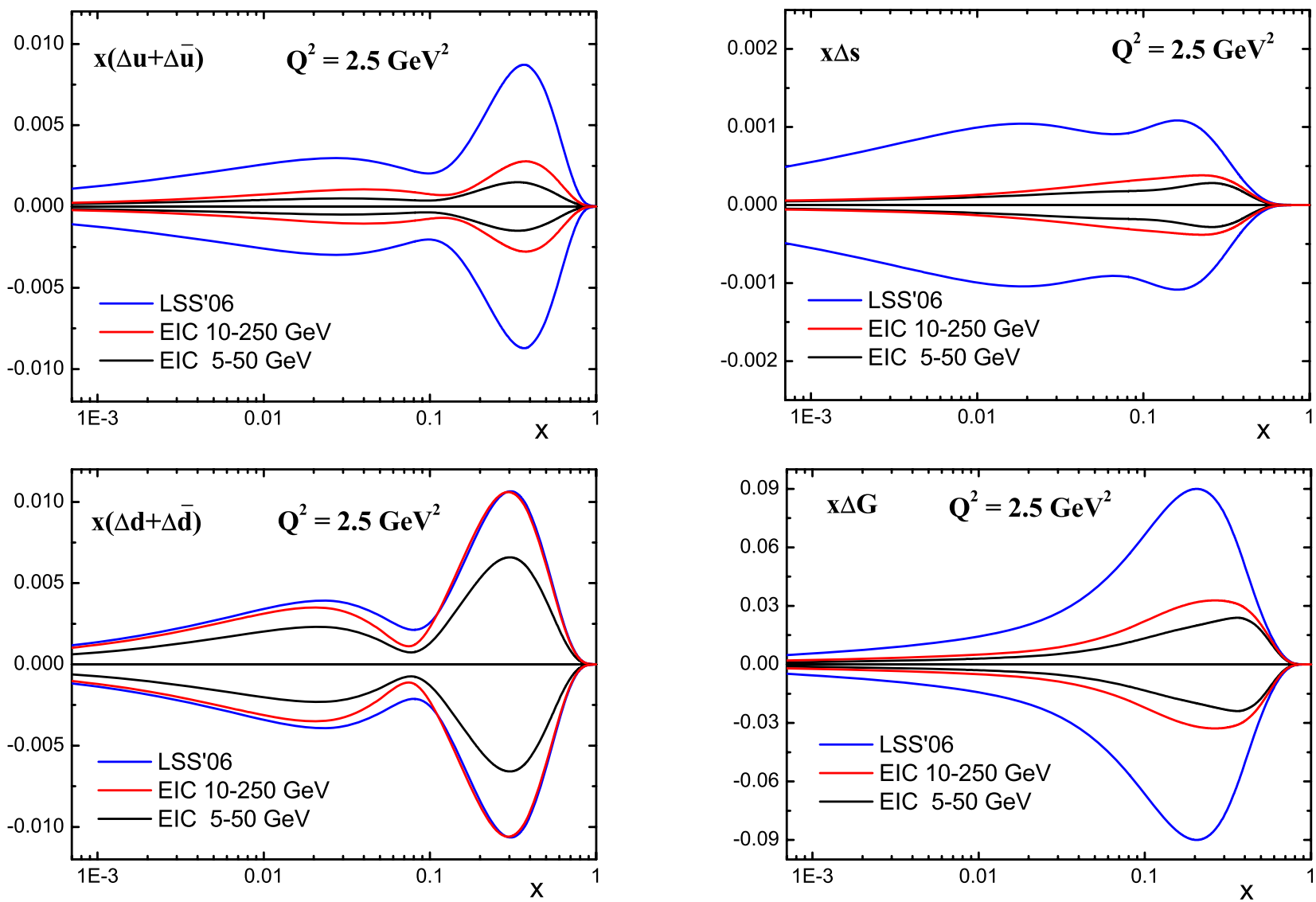
The behaviour of $g_1^p(x)$ at small x is quite different in the three cases (LSS'06)





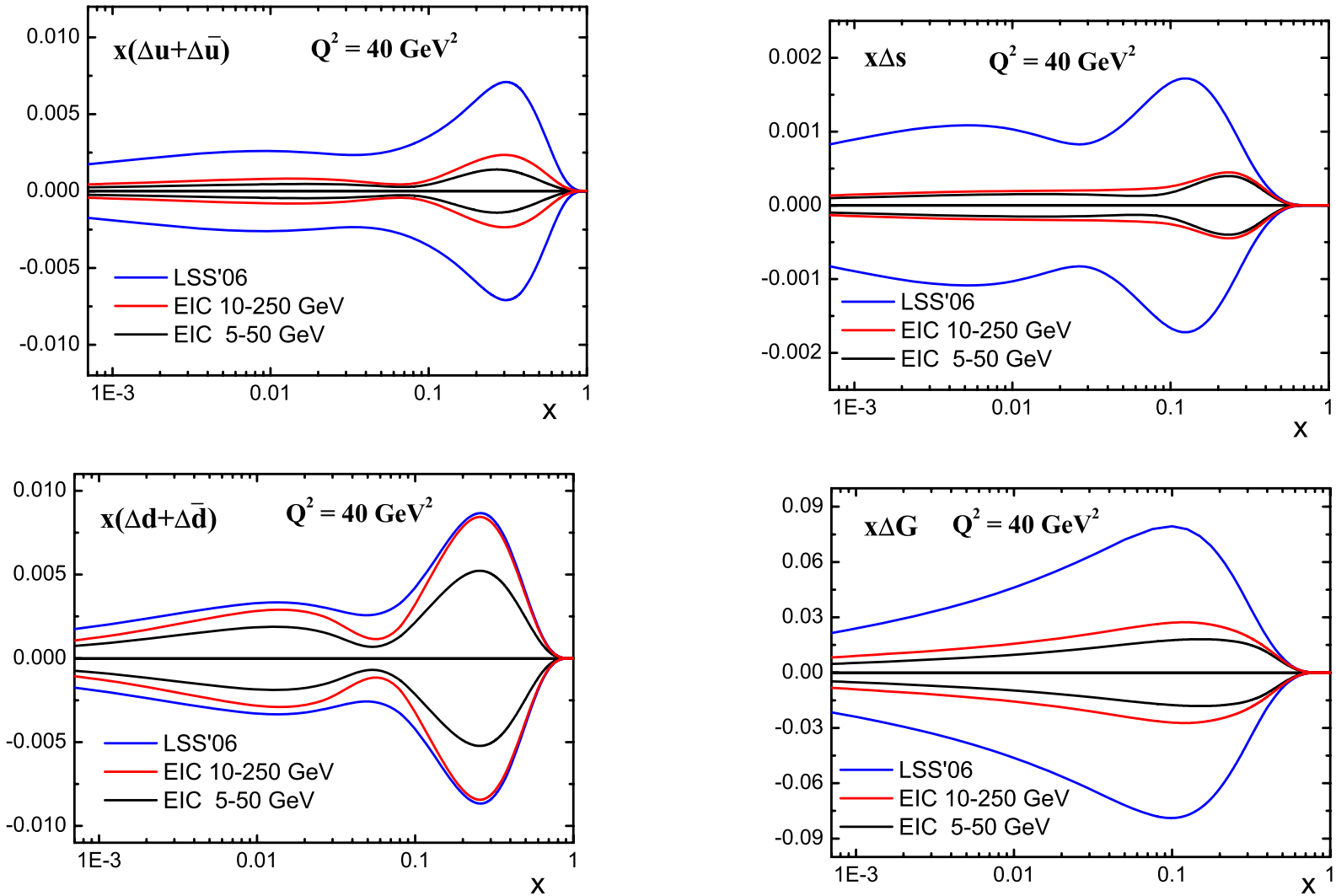


Impact of future EIC data on the uncertainties for NLO polarized PDFs



EIC

Uncertainties for PDFs at Q^2 = 40 GeV^2



The parton contribution to spin sum rule of the nucleon is very different for the three kinds of gluon polarization

$Q^2 = 1\ GeV^2$

COMPASS data included	Δs	ΔG	$a_0 = \Delta\Sigma_{MS}$
Old	-0.070 ± 0.007	0.296 ± 0.197	0.164 ± 0.048
New ($\Delta G>0$)	-0.063 ± 0.005	0.237 ± 0.153	0.207 ± 0.039
New ($\Delta G<0$)	-0.050 ± 0.008	-0.441 ± 0.347	0.283 ± 0.055
New (+/-ΔG)	-0.057 ± 0.006	-0.014 ± 0.235	0.244 ± 0.046

$Q^2 = 4\ GeV^2$

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

$$= 0.55(-0.50)(0.17) +/- 0.26(0.59)(0.40) + OAM$$

The big uncertainty is coming from gluons

To be determined from forward extrapolations of generalized PD

- L_{u+d} ~ 0.00 ± 0.04 from lattice QCD (*Ph. Haegler, DIS'08*)

Spin puzzle ?

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

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

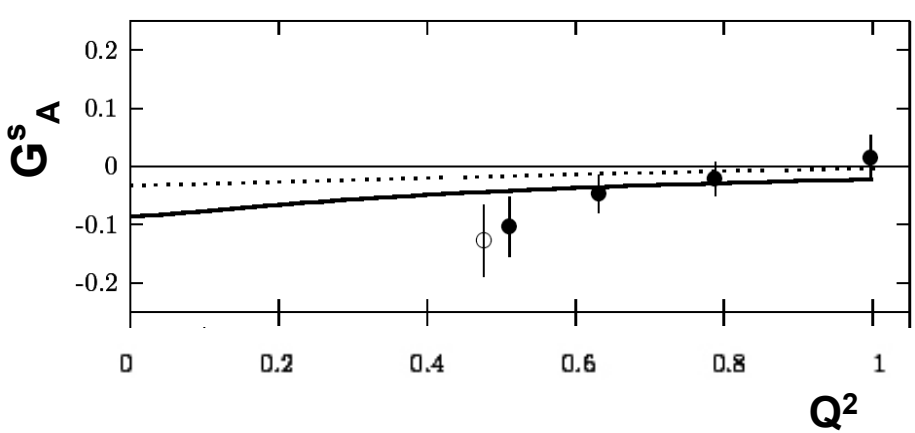
$\Delta\Sigma(Q^2)$ in QCD is a scheme dependent quantity !

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

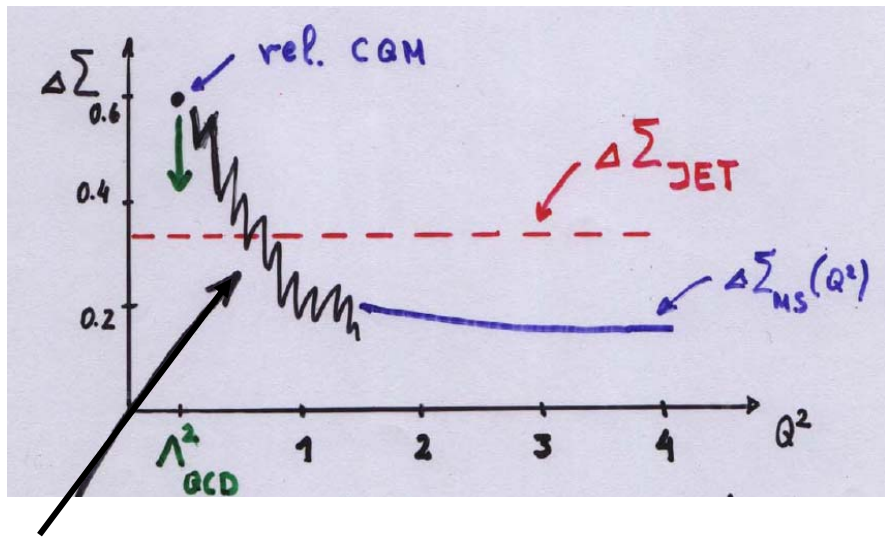
$$\Delta\Sigma_{JET}(DIS) \Leftrightarrow \Delta\Sigma(Q^2 \sim \Lambda^2_{QCD})$$

0.3 ? 0.6

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



S. Pate, hep-ex/0611053



Nonperturbative effects !

In JET factorization scheme

$$\Delta\Sigma_{\mathrm{JET}} = \Delta\Sigma_{\overline{\mathrm{MS}}}(Q^2) + 3\frac{\alpha_s(Q^2)}{2\pi}\Delta G(Q^2)$$

$\Delta\Sigma_{JET}$ does NOT depend on Q^2

⟹ it is meaningful to directly interpret $\Delta\Sigma$ as the contribution of the quark spins to the nucleon spin

Change sign xΔs !! ??

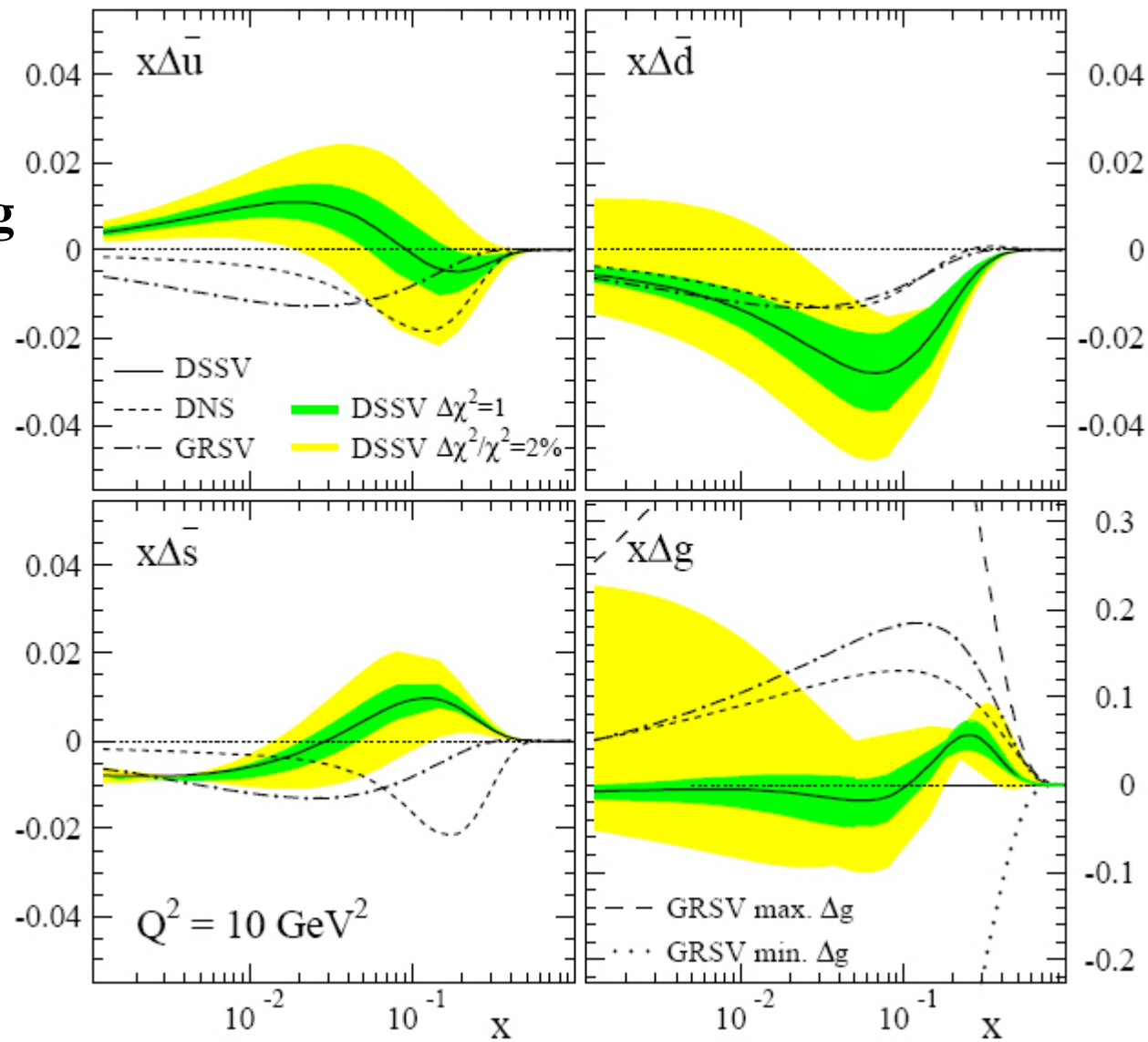
DSSV, arXiv:08040422

(a big progress)

PDFs – from a global NLO QCD analysis of DIS, SIDIS and RHIC polarized pp scattering data (technically challenging !)

It seems to be that the RHIC data and new FF are crucial for such a behavior of xΔs

$\Delta\bar{u} \neq \Delta\bar{d} \neq \Delta\bar{s}$



First moments at $Q^2 = 10\ GeV^2$

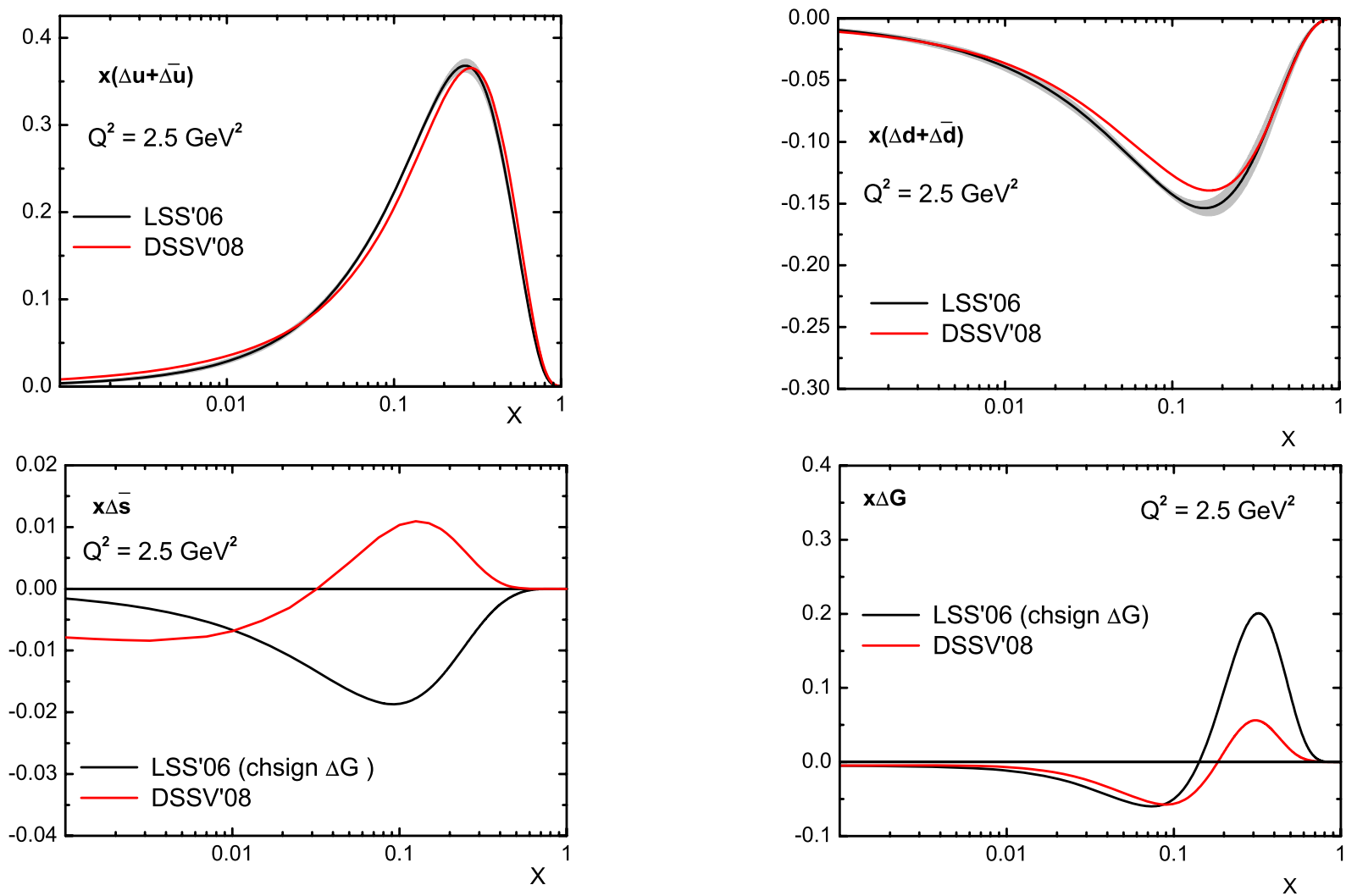
	$\Delta u+\Delta\bar{u}$	$\Delta d+\Delta\bar{d}$	$\Delta s+\Delta\bar{s}$	ΔG	$\Delta\Sigma$	Spin SR
LSS06	0.810	-0.461	-0.118	0.089	0.231	0.20
DSSV	0.813	-0.458	-0.114	-0.084	0.242	0.04

- Excepting the gluons our first moments are practically identical with those of DSSV
- However, the truncated moments for x_{min}=0.001 are different, especially for $\Delta\bar{s}$ and ΔG - in the non-measured x region $\Delta\bar{s}$ is 5 times larger than $\Delta\bar{u}$ and 2.5 times than $\Delta\bar{d}$

DSSV: Very small contribution to the spin sum rule → 0.04 ?

LSS'06 ↔ DSSV PDFs at $Q^2 = 2.5\ GeV^2$

Although the first moments for the strange quarks are almost identical the shape of the densities is rather different ??!!



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**

- The present inclusive DIS data and the high pt measurements cannot rule out the changing in sign and negative gluons

- **The future EIC data**
  - could fix the form of polarized gluons
  - a big reduction of the PDFs uncertainties

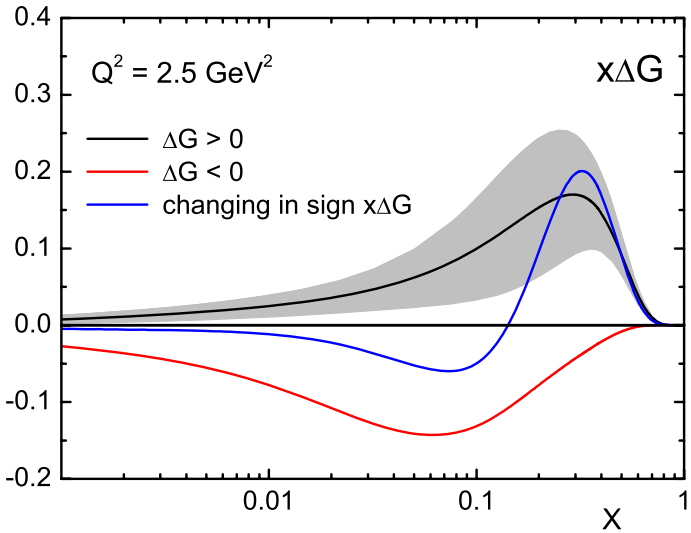
OPEN QUESTIONS

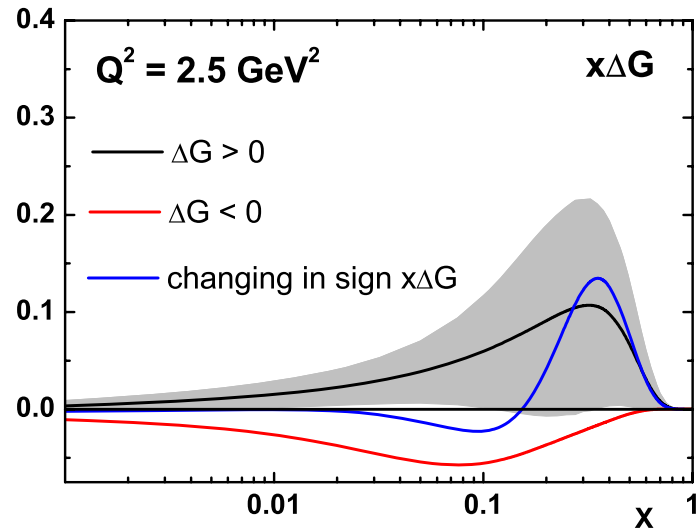
- To constrain better ΔG → directly from *COMPASS, RHIC*; more precise experiments on g_1^d (*JLab*), g_1^p at small x (*EIC*)
  global NLO QCD analysis
- $\Delta\bar{u}$, $\Delta\bar{d}$, $\Delta\bar{s}$ → SIDIS (*COMPASS, JLab*) and $A_L(W^{+(-)})$ at *RHIC*
- Why $\Delta\bar{s}$ obtained from DIS and *global analysis* are too different?
- Very small ΔG from the global analysis → very small contribution to spin sum rule of the proton (0.04) → a big challenge ???
- L_q (lattice QCD, generalized PD - *COMPASS, JLab*) and L_g ?
- HT corrections in SIDIS, *…etc.*

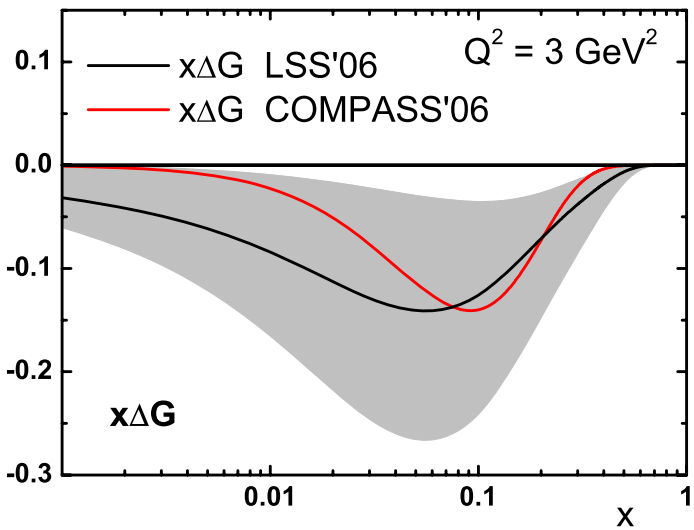
Additional slides

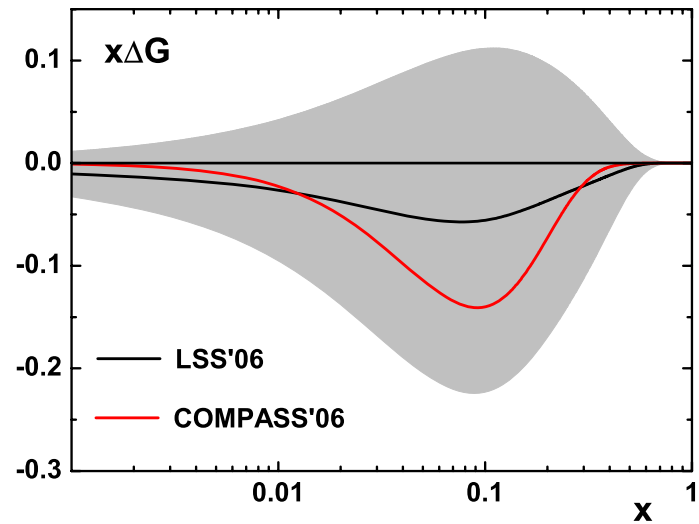
5 x-bins for HT

7 x-bins for HT









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*

$$(g_1)_{exp} \leftrightarrow$$

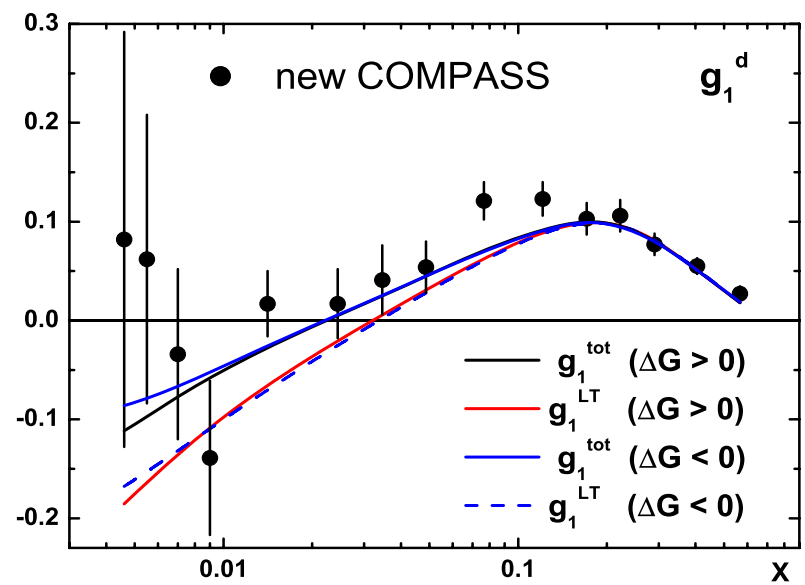
$$(g_1)_{LT}(COMPASS) \approx$$

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

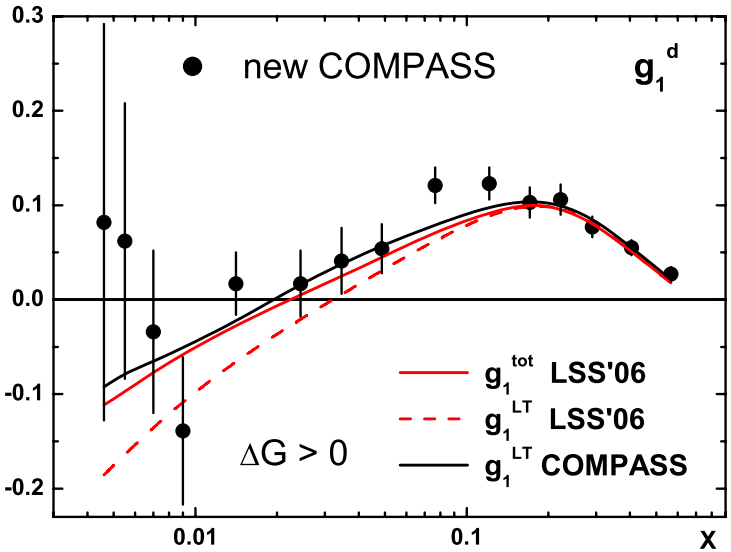
- *COMPASS* → significant difference between $(g_1)_{th}$ corresponding to the best fits for $\Delta G > 0$ and $\Delta G < 0$

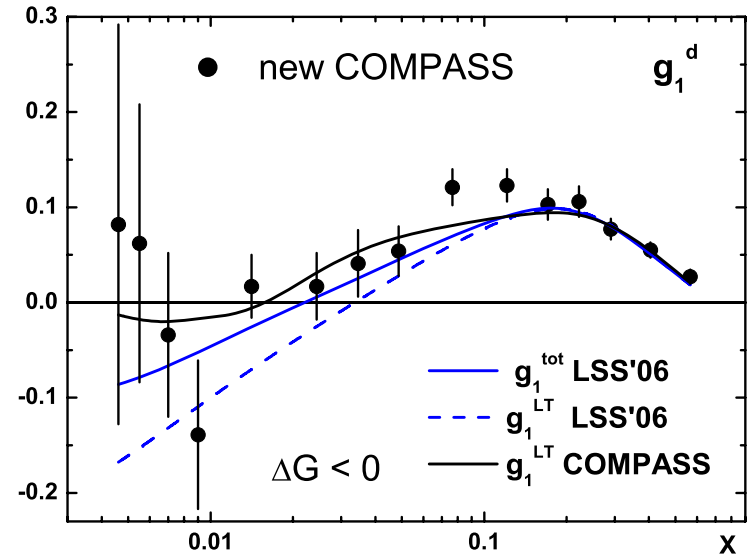
- *LSS'06* → the theoretical curves for both cases are very close to each other

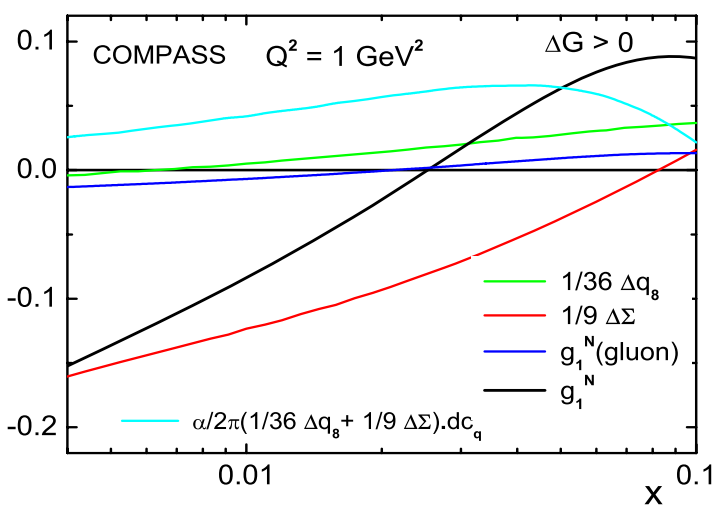
- The reason → HT effects (40% at small x) which are NOT taken into account by *COMPASS*

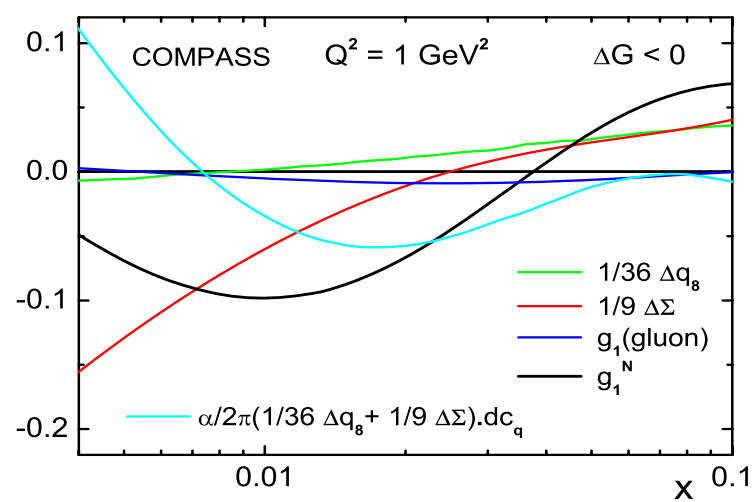


$$g_1^{N} = \frac{1}{9}\left[\left(\frac{1}{4}\Delta q_8 + \Delta\Sigma\right) \otimes \left(1 + \frac{\alpha_s}{2\pi}\delta c_q\right) + \frac{\alpha_s}{2\pi}\Delta G \otimes \delta c_g\right]$$

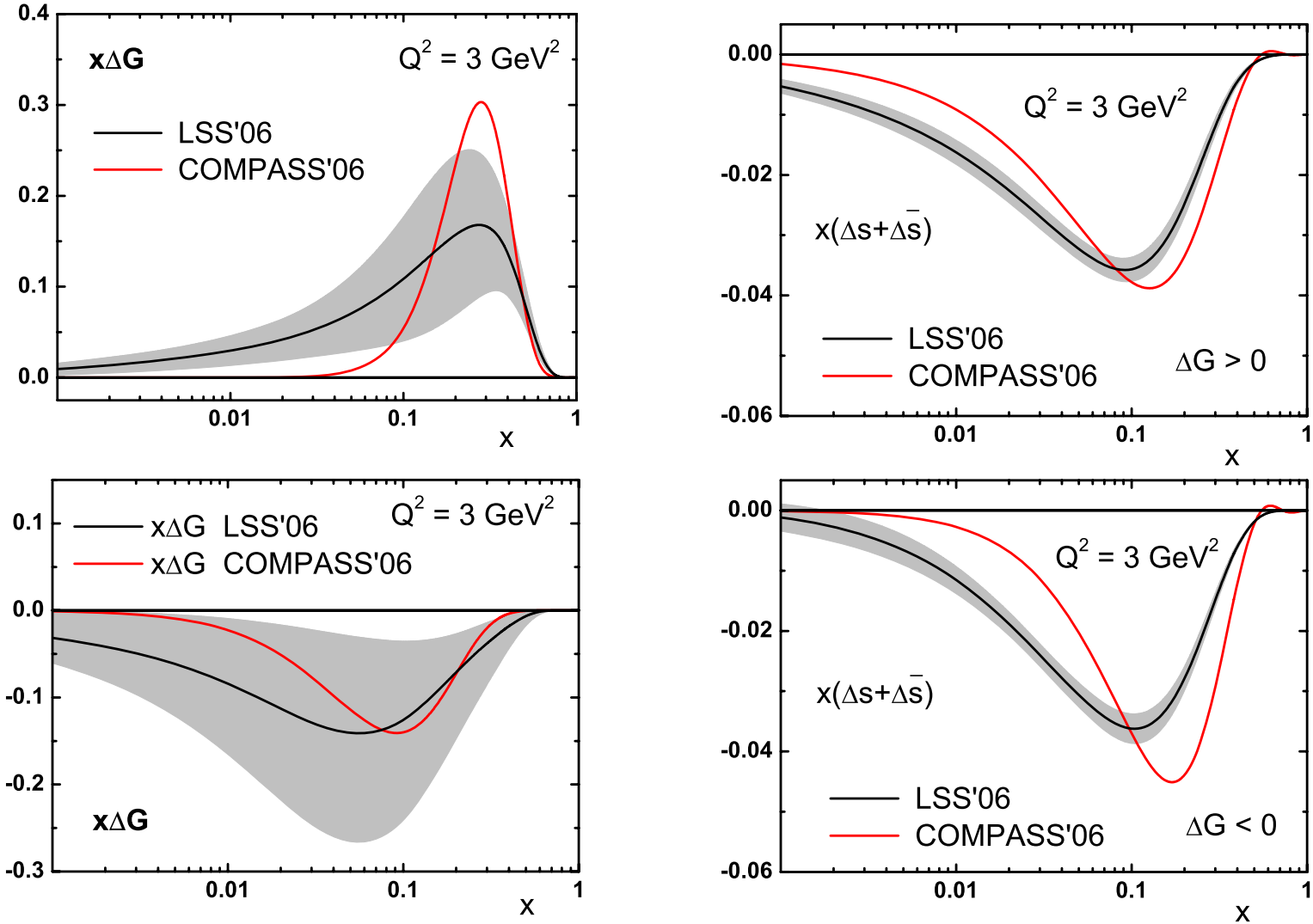
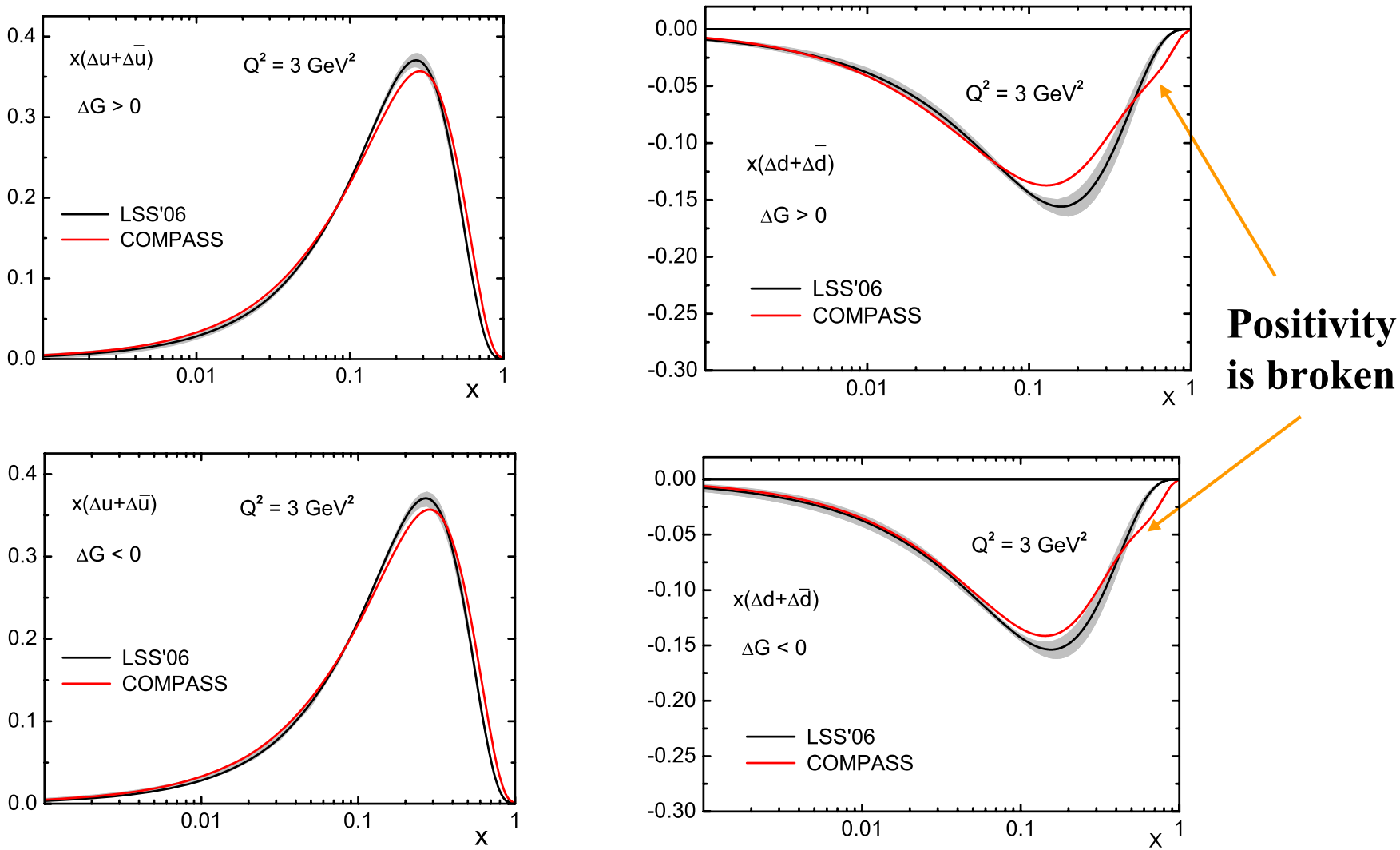








- **$x\Delta s$ are different, especially in the case of $\Delta G < 0$**
- **$x\Delta G$ positive obtaned by COMPASS is more peaked than our**



- $(\Delta u + \Delta\bar{u})$ and $(\Delta d + \Delta\bar{d})$ **are closed to each other for both $\Delta G > 0$ and $\Delta G < 0$ cases**